Natural Resource Management and Policy
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Leslie Lipper
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Climate Smart Agriculture

Building Resilience to Climate Change

Food and Agriculture
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Natural Resource Management and Policy

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There is a growing awareness to the role that natural resources, such as water, land, forests and environmental amenities, play in our lives. There are many competing uses for natural resources, and society is challenged to manage them for improving social well-being. Furthermore, there may be dire consequences to natural resources mismanagement. Renewable resources, such as water, land and the environment are linked, and decisions made with regard to one may affect the others. Policy and management of natural resources now require interdisciplinary approaches including natural and social sciences to correctly address our society preferences.

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Foreword

Eradicating poverty, ending hunger, and taking urgent action to combat climate change and its impacts are three objectives the global community has committed to achieving by 2030 by adopting the sustainable development goals. Agriculture, and the way we manage it in the years leading up to 2030, will be a key determinant of whether or not these objectives are met. Agriculture has been, and can be further, used as an important instrument in eradicating hunger, poverty, and all forms of malnutrition. Climate change however is expected to act as an effective barrier to agricultural growth in many regions, especially in developing country contexts heavily dependent on rain-fed agriculture.

Climate change impacts agriculture through a number of pathways. According to the 2013 IPCC report, all four dimensions of food security are potentially affected by climate change through their effects on agricultural production and the incomes of rural households, food prices and markets, and in many other parts of the food system (e.g., storage, food quality, and safety) (IPCC WGII AR5 Ch 7). Reducing the vulnerability of agricultural systems to climate change – including the increased incidence of extreme weather events – and strengthening its adaptive capacity are therefore important priorities to protect and improve the livelihoods of the poor and allow agriculture to fully play its role in ensuring food security. Reducing emissions that contribute to global warming is crucial to securing global wellbeing, and the agricultural sector has considerable potential for emissions reductions while at the same time playing its important role in poverty reduction and food security. In short, agriculture lies at the nexus of resolving urgent global priorities.

FAO is actively working to support countries in grappling with the challenge of managing agriculture to reduce hunger and poverty in an increasingly climate-constrained world. FAO launched the concept of climate smart agriculture (CSA) in 2009 to draw attention to linkages between achieving food security and combating climate change through agricultural development, and the opportunities for attaining large synergies in doing so. In practice, the CSA approach involves integrating the need for adaptation and the potential for mitigation into the planning and implementation of agricultural policies, planning, and investments. The point of departure for the CSA approach is the emphasis on food security and poverty reduction as the priority in developing countries through enhanced capacity of their agri-food sectors and institutional and technological innovations. This capacity cannot be attained without adaptation to changing conditions. At the same time, reducing the emissions associated with conventional agricultural growth models is one of the largest and most cost-effective means of reducing GHG emissions, and thus the CSA approach integrates the potential for obtaining mitigation co-benefits from agricultural growth strategies.

The CSA concept has gained considerable traction at the international and national levels; however, there is still a fair amount of confusion regarding the concept and its theoretical underpinning. In addition, the empirical evidence base to support country implementation strategies is lacking. In particular, there is a need for defining and operationalizing the concept of resilience and adaptive capacity in the context of agricultural growth for food security. For these reasons, the Economic and Social Development Department of FAO has supported the development of this book, which represents a significant step forward in shedding light to the issues raised above. This volume brings together research, analysis, and opinions of leading agricultural and resource economists and policy experts to develop the conceptual, empirical, and policy basis for a better understanding of CSA and enhanced potential for achieving it on the ground.

The first section of this book provides conceptual frameworks as well as methodological approaches for operationalizing CSA at the country level. Its main focus is comparing and contrasting the conceptual approaches to risk management and resilience used in the agricultural development context with that used in the context of climate change and proposing a consistent approach. It also provides an overview of the development of the CSA concept, the controversies it has sparked, and how they relate to the broader debate of sustainable development.

The second section consists of 19 case study chapters focusing on issues of vulnerability measurement and assessment, as well as ways of improving the adaptive capacity at farm and system level and what could be some of the policy responses to achieve them. These empirical studies showcase a wide range of options (policy instruments) that contribute to building resilience to climate risk. They include policy instruments aimed at changing agricultural practices but also policy instruments in other sectors. Examples include social protection, micro-finance, input subsidies, micro-insurance, and agricultural knowledge and information systems. The case studies cover a wide geographic range and scale, from Asia to Africa and the USA and from households to markets and institutions and the national and global economy. They draw upon the CSA project work of FAO, as well as that of other agencies applying the CSA approach. The breadth of the case studies provides a basis for lessons learned in which contribute to a more comprehensive understanding of policy options to improve the resilience of livelihoods of the rural poor to climate change. They indicate that we do have considerable tools available to measure, reduce, and effectively react to climate change–related vulnerability in the agricultural sector, and that it is essential to utilize these instruments in seeking to improve the agriculture sector's capacity to support hunger, poverty eradication, and sustainable development.

The third and final section of this book presents the results of a consultation with a panel of leading thinkers and practitioners on agricultural and climate change policy. This section is comprised of the responses of these experts to a set of questions based on the main findings, conclusions, insights, and questions that emerged from the set of case studies and conceptual papers. Their varied responses to the issues provide considerable insights into the different approaches and policy priorities for CSA across varying contexts, as well as practical ideas on how to operationalize them.

The FAO is committed to providing support to agricultural and climate change policy-makers and the agricultural producers they serve in their ongoing efforts to end hunger and poverty and effectively combat climate change effects now and in the future. This book offers tools and insights for a range of stakeholders to help meet these challenges in the many forms they are manifested.

Rome, Italy Kostas Stamoulis

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Part I
Overview and Conceptual Framework

Introduction and Overview

Solomon Asfaw and Giacomo Branca

Abstract The climate-smart agriculture (CSA) concept is gaining considerable traction at international and national levels to meet the challenges of addressing agricultural planning under climate change. CSA is a concept that calls for integration of the need for adaptation and the possibility of mitigation in agricultural growth strategies to support food security. Several countries around the world have expressed intent to adopt CSA approach to managing their agricultural sectors. However there is considerable confusion about what the CSA concept and approach actually involve, and wide variation in how the term is used. It is critical to build a more formal basis for the CSA concept and methodology and at the same time providing illustrations of how the concept can be applied across a range of conditions. This book expand and formalize the conceptual foundations of CSA drawing upon theory and concepts from agricultural development, institutional and resource economics. The book is also devoted to a set of country level case studies illustrating the economic basis of CSA in terms of reducing vulnerability, increasing adaptive capacity and ex-post risk coping. It also addresses policy issues related to climate change focusing on the implications of the empirical findings for devising effective strategies and policies to support resilience and the implications for agriculture and climate change policy at national, regional and international levels. The book provide development agencies and practitioners, policymakers, civil society, research and academia as well as private sector with tested good practices and innovative approaches of promoting CSA system at country level.

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Climate change poses a major and growing threat to global food security. Population growth and rising incomes in much of the developing world have pushed demand for food and other agricultural products to unprecedented levels. FAO has estimated that, in order to meet food demand in 2050, annual world production of crops and livestock will need to be 60% higher than it was in 2006. In developing countries, about 80% of the required increase will need to come from higher yields and increased cropping intensity and only 20% from expansion of arable land[1].

Meeting food demand for a growing population is already a formidable challenge for the agriculture sector, but it will be further exacerbated by climate change. The expected effects of climate change – higher temperatures, extreme weather events, water shortages, rising sea levels, the disruption of ecosystems and the loss of biodiversity – will generate significant effects on the different dimensions and determinants of food security by affecting the productivity of rainfed crops and forage, reducing water availability and changing the severity and distribution of crop and livestock diseases. The fifth assessment report of the IPCC released in 2014 found that climate change effects are already being felt on agriculture and food security, and the negative impacts are most likely in tropical zones where most of the world's poor agricultural dependent populations are located. Through its impacts on agriculture, climate change will make it more difficult to meet the key Sustainable Development Goal of ending hunger, achieving year-round food security, and ensuring sustainable food production systems by 2030.

The magnitude and speed of climate change, and the effectiveness of adaptation and mitigation efforts in agriculture, will be critical to the future of large segments of the world's population. Integrating the effects of climate change into agricultural development planning is a major challenge. This requires technology and policy measures to reduce vulnerability and increase the capacity of producers, particularly smallholders, to effectively adapt. At the same time, given agriculture's role as a major source of greenhouse gas emissions and the high rate of emissions growth experienced with recent conventional intensification strategies, there is a need to look for low emissions growth opportunities and adequate policies. Policymakers are thus challenged to ensure that agriculture contributes to addressing food security, development and climate change.

In this frame, Climate Smart Agriculture (CSA) is an approach that calls for integration of the need for adaptation and the possibility of mitigation in agricultural growth strategies to support food security. The concept was launched by FAO in 2010[2], gaining rapid and widespread interest and attention. CSA goes beyond agricultural practices and technologies to include enabling policies and institutions as well as identification of financing mechanisms. There are significant intellectual and policy gaps to be filled in CSA literature. An economic decision-making framework will also assist in identifying challenges for CSA application.

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[1] See http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf.

[2] See http://www.fao.org/docrep/013/i1881e/i1881e00.pdf.

1 Overview of the Book

This book expands and formalizes the conceptual foundations of CSA drawing upon theory and concepts from agricultural development, institutional and resource economics. The book focuses particularly on the adaptation/resilience dimension of CSA, since this is the least well developed in the economics literature. A mixture of conceptual analyses, including theory, empirical and policy analysis, and case studies look at: (1) ex-ante reduction of vulnerability, (2) increasing adaptive capacity through policy response, (3) increasing adaptive capacity through system level response and (4) increasing adaptive capacity through farm level response.

The book provides a wide array of case studies to illustrate that these concepts have strong real-world applicability. The case study approach will provide concrete illustrations of the conceptual and theoretical framework, taking into account the high level of diversity in agro-ecological and socioeconomic situations faced by agricultural planners and policy-makers today. Some case studies assess issues of measurement of vulnerability to climate change and damage caused by it. Others address issues of improving adaptive capacity, and the ex-post impact of different policy measures.

In the book, economists and policy-makers will find an interpretation and operationalizing of the concepts of resilience and adaptive capacity in the context of agricultural growth for food security. The combination of methodological analysis of CSA and an empirical analysis based on a set of case studies from Asia and Africa is unique. We are not aware of other books that contain all of this integrated knowledge in one place and provide a perspective on its lessons.

The book is structured as follows. Part I illustrates the conceptual framework, giving an overview of CSA concept, approach, and its main components. This part relates the main features of the CSA paradigm to core economic principles and seeks to clarify how the concepts of resilience, adaptive capacity, innovation, technology adoption and institutions relate to each other and the economic principles of CSA. Part II reports a set of case studies from leading agricultural development economists aimed at illustrating the economic basis of CSA in terms of reducing vulnerability and increasing adaptive capacity. It makes a clear distinction between responses to building adaptive capacity at policy, system and farm levels. Last, part III addresses policy issues related to climate change and provides a synthesis of the key messages of the book. A detailed overview of each part is presented next.

1.1 Part I. Conceptual Chapters

Chapter 2 presents an overview of the evolution of CSA concept, introduces its major components, and summarizes the key issues associated within the context of climate change and agricultural policy debates. The main message of this chapter is that CSA concept has been reshaped through inputs and interactions of multiple stakeholders involved in developing and implementing it. The first section provides an overview of international climate change policy followed by an introduction and analysis of CSA and its history. This is then followed by a discussion of three broad controversies related to CSA, namely the role of mitigation, the relationship of CSA to sustainable agriculture, and how biotechnology is treated in the CSA approach. CSA provides a tool to identify locally appropriate solutions to managing agriculture for sustainable development and food security under climate change.

Chapter 3 tackles the economic considerations of CSA in addressing sustainable agricultural growth for food security under climate change. It addresses the lack of coherence of the CSA approach by building a conceptual framework to rooted in agricultural development economic theories and concepts. The chapter begins by highlighting the key features of climate change that require a shift in emphasis in research, and for innovations in technologies, institutions, and government policies and programs to consider heterogeneity of impacts and implications of decision-making under uncertainty. The chapter does this by posing a dynamic constrained optimization problem wherein a social planner seeks to maximize expected discounted welfare associated with agriculture of the population they serve, both now and in the future. The objectives are the four pillars of food security, food availability, accessibility, utilization, and stability, as well as reducing emissions growth. The problem is also characterized by current constraints that bound the feasible outcomes, including bio-physical, behavioral, political, institutional and distributional constraints. The chapter stresses that the nature of the optimization, and thus adaptation strategies, are context specific and highlight that the solution to the social planner's problem for climate change must balance adaptation and responsiveness to uncertain climate change with the needed growth and food security objectives of the agricultural sector.

Chapter 4 provides more detailed guidance on the key role of innovation to address the negative impact of climate change. Innovation in agriculture is clearly an important response for effective and equitable adaptation and mitigation – and the chapter highlights the need for managerial and institutional changes that promote innovation to address the heterogeneity and uncertainty of climate change impacts. The chapter discusses the main features and the nature of innovation needed to align these actions with a CSA strategy, suggesting several principles to guide the introduction of innovation and develop capacity and policies to address climate change.

1.2 *Part II. Country Case Studies*

1.2.1 Vulnerability Measurement and Assessment

Chapter 5 shows that near real-time satellite observations can be used to mitigate impacts of extreme events and promote climate resilience. First, the early detection of growing conditions and predicting the availability of food directly improves climate resilience and food security. Second, insurance (risk management) programs can use the indexes in triggers for a quick release of catastrophic bonds to farmers to mitigate impacts of crop failure. Third, these tools provide information useful for farmers in assessing yield potential from various crops under current and changing climatic conditions. Fourth, an early warning system distributed across the globe can help identify and expedite the exportation of food supplies from areas where they are in excess into areas where a deficiency is likely to occur. The chapter also discusses ways of integrating these products with various datasets, such as in situ surface temperature, the greenness index, and soil moisture data, in order to expand their complementary value and utility.

Chapter 6 presents key findings from advanced econometric models of long-term impacts of climate change on rice production in Lao PDR. Results are consistent with previous work in the region, where there is weak evidence that elevated minimum night-time temperatures are highly damaging to rice yields. Conversely, it is found that elevated maximum daytime temperatures increase yields. Overall, the size of the impact and statistical significance is larger for increased maximum temperatures, suggesting that elevated temperatures might have a net positive impact on rice yields in Lao PDR. The chapter also discusses some major caveats to these findings in particular the limitation with the quality data used for the analysis.

The perception of climate change and adaptation choices made by farmers are important considerations in the design of adaptation strategies. Chapter 7 uses a comprehensive dataset of farm households from Thailand and Vietnam to show that farmers do perceive climate change, but describe it in quite distinct ways. Further, adaptation measures are informed by perception and, at least in the case of Vietnam, perceptions are shaped by the respondent's characteristics, location variables and recent climate related shocks.

Chapter 8 illustrates how to assess the yield growth rate requirements needed to compensate yield losses due to climate change. The crop statistical model employed allows for nonlinear effects of temperature on yields. In line with the literature, it suggests that exposure to temperature exceeding 30 °C is detrimental to maize yields in the US Midwest. The chapter reports that a historical rate in maize yield growth in the US Midwest of 17.4%/decade exceeds the rate (6.56%/decade) needed to compensate a plausible warming of 3 °C within the next 3 decades. However, the net yield trend would be substantially diminished under this scenario due to the countervailing effect of a warming climate. The chapter also discusses the possibilities of extending the analysis with a cost-benefit analysis of alternative mean-increasing or variance-reducing technological change.

Chapter 9 shows that a fine-tuned integrative decision support tool can better inform growers and landowners of how changes in climate will impact their operations and their environmental outcomes. The use of a decision support tools such as *AgBiz Logic* can provide farmers better information on the relative impacts of adapting to a change as reflected in changes in future climate conditions, changes in future policies, prices, and costs or changes in terms of lease arrangements. By incorporating both climate change and environmental outcomes, these decision tools can be used to evaluate climate smart options at the farm-scale. The authors discuss the use of different tools such as *AgBizClimate, AgBizProfit, AgBizFinance, AgBizLeasee and AgBizEnvironment* to measure the impacts of climate change to wheat production, the role of adaptation strategies to an annual cropping system, the feasibility of purchasing additional equipment to farm the annual cropping system and also estimate the trade-offs of economic returns to environmental impacts.

1.2.2 Policy Response to Improving Adaptation and Adaptive Capacity

Chapter 10 uses empirical evidence from the Index-based Livestock Insurance (IBLI) project in the pastoral regions in East Africa to answer if insurance can cost-effectively mitigate the increasingly deleterious impacts of climate risk on poverty and food insecurity. The theory reviewed in this chapter suggests an affirmative answer if well-designed insurance contracts can be implemented and priced at a reasonable level despite the uncertainties that attend climate change. At the same time, much remains to be done if quality index insurance contracts are to be scaled up and sustained. Demand has often been tepid and unstable. Outreach and administration costs have been high. Pricing by a private insurance industry made nervous by climate change has pushed costs up. Finally, the effective quality of the IBLI contact has been scrutinized and found wanting. The chapter concludes that insurance is not an easy, off-the-shelf solution to the problem of climate risk and food insecurity. Creativity in the technical and institutional design of contracts is still required.

Chapter 11 synthesizes the key findings of From Protection to Production Project (PtoP) of FAO to show the potential role of cash transfer programmes as a tool to support risk management and build resilience in sub-Saharan Africa. Such programs address household resilience by building human capital and improving food security and potentially strengthening households' ability to respond to and cope with exogenous shocks. This may allow households to mitigate future fluctuations in consumption. Many of the programmes studied increased investment in agricultural inputs and assets, including farm implements and livestock, and improved food security indicators, though results differed across countries. This too was met by increases in consumption and dietary diversity. Although the impacts on risk management are less uniform, the cash transfer programmes seem to strengthen community ties, allow households to save and pay off debts, and decrease the need to rely on adverse risk coping mechanisms. Finally, using the case study of Zambia the authors demonstrates the potential for cash transfers to help poor households manage climate risk.

Chapter 12 shows that Input Subsidy Programs (ISPs) may provide a potentially useful means to encourage system-wide and farm-level changes to achieve CSA objectives in Africa. While many ISPs have not contributed significantly to *ex-ante* risk management at the household level, recent innovations in ISPs may enable them to be more climate smart. In particular, moves toward open voucher systems that induce greater private sector participation hold potential to support the development of profitable and more sustainable input distribution systems providing more heat-, drought- and saline-tolerant seed types. Moreover, moving from a limited range of options to a system that provides farmers with a wide range of input choices has the potential to promote greater livelihood diversification and resilience. Programs that make farmer participation in ISPs conditional on the adoption of certain climate smart practices also have some potential but would require more robust monitoring and setting of targets. These two requirements currently limit the potential of ISPs to achieve widespread CSA benefits. Moreover, using ISPs to contribute to CSA objectives would need to be evaluated against the potential benefits of using comparable resources for investments in irrigation, physical infrastructure, and public agricultural research and extension programs, which may generate higher comprehensive social benefits.

1.2.3 System Level Response to Improving Adaptation and Adaptive Capacity

The expansion of irrigation is often considered as a complementary strategy to enhance the resilience of agriculture to climate. However, irrigation entails large capital expenditures and an adequate sizing of any given irrigation scheme cannot neglect the expected changes in climate trends and variability. Chapter 13 explores these issues using historical climate records as a basis for determining what investment is adequate in water storage or in area equipped for irrigation is likely to result in “regrets,” because the investment will be undersized/oversized, if the climate turns out to be drier/wetter than expected. An investment strategy that minimizes the risk of misjudgements across multiple climate outcomes reduces regrets and allows for greater flexibility of the system: cropping patterns, water use, or other parameters can be adapted for wet or dry years to increase the return on irrigation investment.

Chapter 14 shows how the use of the new simulation-based technology impact assessment methods, developed by the Agricultural Model Inter-comparison and Improvement project (AgMIP), can evaluate the potential for currently available or prospective agricultural systems to achieve the goals of CSA. The approach combines available data (observational and farm performance indicators), with bio-physical and economic models and future climate and socio-economic scenarios. A case study of crop-livestock systems in Zimbabwe illustrates the potential for these methods to test the usefulness of specific modifications to raise incomes, reduce vulnerability to climate change and to enhance resilience. It is important to note that the framework presented can also incorporate greenhouse gas emissions as part of a technology assessment. The authors point out the need to incorporate livestock herd dynamics and interaction of crop and livestock systems into the methodology.

Chapter 15 tackles four major issues with respect to food supply chain in the context of climate change. First, the importance of analysing climate short-term shocks and long-term change on the full food supply chain (inputs, farms, processing, and distribution). Second, the authors show the importance of viewing a given supply chain as an interdependent set of segments and sub-segments.

Climate shocks upstream in the supply chain can disrupt a wide complex of midstream and downstream activities. Third, supply chain analysis is greatly benefited by using "hot spots" of vulnerability to understand climate impacts, both before and after the farm gate. Fourth, climate shocks, and strategies to mitigate them, can be viewed from as (i) strategic supply chain design choices by actors along the supply chain, of sourcing and marketing systems, geography, institutions, and organization; and (ii) threshold investments by actors (firms and farms) along all supply chains.

Chapter 16 uses a conceptual model and empirically-based simulations to investigate the effectiveness of extension-driven informational programs, rain-indexed crop insurance, and the interaction of the two programs in driving adaptation and providing a safety net for farmers. Based on options between diversification strategies and land management practices, different potential welfare outcomes for agricultural households are investigated. The findings show that CSA techniques, including advanced information, about changing conditions in Malawi can mitigate expected losses. The value of this information is greater for farmers with less-binding subsistence constraints and under scenarios for which the effects of climate change are larger. Rain-indexed insurance appears to drive farmers to increase their usage of cash crops and higher yield/higher variability hybrid crop options. Such information is even more important in addressing larger expected losses among farmers with greater flexibility.

The mixed crop-livestock systems of the developing world will become increasingly important for meeting food security challenges of the coming decades. Chapter 17 addresses the gap in understanding of the synergies and trade-offs between food security, adaptation, and mitigation objectives based on a systematic review protocol coupled with a survey of experts. The chapter also discusses constraints to the uptake of different interventions and the potential for their adoption, and highlights some of the technical and policy implications of current knowledge and knowledge gaps.

The effectiveness of a policy depends on specific climate, demographic, environmental, economic and institutional factors. Chapter 18 introduces temporal aspects of household vulnerability to a conceptual model building on available econometric results. The method is based on a factorial design with two vulnerability levels and two production methods. Farms are classified into groups based on cluster analysis of survey data from Zambia. The chapter shows that small, vulnerable farms are more likely to face labor and cash constraints, which may prevent them from adopting technologies that have the potential to sustainably improve food security and enhance their adaptive capacity, i.e. be climate-smart. Widespread adoption, however, will require policies that address the barriers identified here to provide: (i) improved techniques that are less labor intensive, (ii) improved availability of fertilizers, and (iii) credit to cover the up-front costs of investing in soil health that takes several years to bear fruit.

1.2.4 Farm Level Response to Improving Adaptation and Adaptive Capacity

Chapter 19 uses Mali and Nigeria as case study countries to show that sustainable land and water management (SLWM) could more than offset the effect of climate change on yield under the current management practices. Despite the benefits, adoption rates of SLWM remain low. The authors discuss policies and strategies for increasing their adoption including improvement of market access, enhancing the capacity of agricultural extension service providers to provide advisory services on SLWM, and building an effective carbon market that involves both domestic and international buyers.

Chapter 20 identifies the key barriers, opportunities and impacts for a wider adoption of climate smart technologies by differentiated groups of agricultural producers, with a focus on the poor in Central Asia. It is found that access to markets and extension, and higher commercialization of household agricultural output, may serve as major factors facilitating the adoption of CSA technologies. The adoption of CSA technologies has a positive impact on the farming profits of both poorer and richer households, although these positive impacts may likely to be higher for the richer households. Even still, adoption rates among the poorer households are lower than among the richer households.

Chapter 21 shows the implications of farm households' past decision to adapt to climate change on current downside risk exposure in the Nile Basin of Ethiopia. Using moment-based specification to capture the third moment of a stochastic production function as measure of downside yield uncertainty, it finds that past adaptation to climate change (i) reduces current downside risk exposure, and so the risk of crop failure; (ii) would have been more beneficial to the non-adopters if they had adopted, **in terms of reduction in downside risk exposure**; and (iii) is a successful risk management strategy for adopters.

Chapter 22 uses case studies from Zambia and Malawi to discuss the drivers of diversification and its impacts on selected welfare outcomes with a specific attention to climatic variables and institutions. Geo-referenced farm-household-level data merged with data on historical rainfall and temperature as well as with administrative data on relevant institutions are used to demonstrate that diversification is an adaptation response, as long term trends in climatic shocks have a significant effect on livelihood diversification, albeit with different implications. Access to extension agents positively and significantly correlates with diversification in both countries. The results also demonstrate that the risk-return trade-offs are not as pronounced as might be expected.

Chapter 23 presents a case study on potential impacts and implications for adoption of CSA solutions in the Northern Mountainous Region (NMR) of Viet Nam. The authors use primary data collected through *ad hoc* household and community surveys in the study area, on the costs and benefits of agricultural practices, as well as on socio-economic information relevant for households' adoption decisions. A profitability estimate and technology adoption analysis indicate that the potential of some sustainable farming practices to increase productivity and incomes and provide adaptation benefits under the specific climate patterns being experienced in NMR of Viet Nam, particularly in “critical growing periods” of crops. However, such practices often have higher capital and labour requirements, which are likely to prevent or impede adoption. The findings suggest the importance of local climate and socio-economic contexts in determining which practices will actually be climate-smart. Results highlight the importance of using climate information for targeting the promotion of improved practices, and building adaptive capacity amongst farmers.

1.3 Part III. Policy Synthesis and Conclusion

Chapter 24 focuses on the implications of the empirical findings for devising effective strategies and policies to support resilience and the implications for agriculture and climate change policy at national, regional and international levels. This section is built upon the analysis provided in the case studies as well as short “think” pieces on specific aspects of the policy relevance issues from policy makers as well as leading experts in agricultural development and climate change. Lastly, Chapter 25 is a synthesis to identify and reconcile the common themes across all the chapters and draws some major economic conclusions and policy recommendations.

A Short History of the Evolution of the Climate Smart Agriculture Approach and Its Links to Climate Change and Sustainable Agriculture Debates

Leslie Lipper and David Zilberman

Abstract Climate Smart Agriculture (CSA) is an approach to guide the management of agriculture in the era of climate change. The concept was first launched in 2009, and since then has been reshaped through inputs and interactions of multiple stakeholders involved in developing and implementing the concept. CSA aims to provide globally applicable principles on managing agriculture for food security under climate change that could provide a basis for policy support and recommendations by multilateral organizations, such as UN's FAO. The major features of the CSA approach were developed in response to limitations in the international climate policy arena in the understanding of agriculture's role in food security and its potential for capturing synergies between adaptation and mitigation. Recent controversies which have arisen over CSA are rooted in longstanding debates in both the climate and sustainable agricultural development policy spheres. These include the role of developing countries, and specifically their agricultural sectors, in reducing global GHG emissions, as well as the choice of technologies which may best promote sustainable forms of agriculture. Since the term 'CSA' was widely adopted before the development of a formal conceptual frame and tools to implement the approach, there has been considerable variation in meanings applied to the term, which also contributed to controversies. As the body of work on the concept, methods, tools and applications of the CSA approach expands, it is becoming clearer what it can offer. Ultimately, CSA's utility will be judeged by its effectiveness in integrating climate change response into sustainable agricultural development strategies on the ground.

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1 Introduction

Climate Smart Agriculture (CSA) is an approach to guide the management of agriculture in the era of climate change. The concept was first launched in 2009, and since then has been reshaped through inputs and interactions of multiple stakeholders involved in developing and implementing the concept. CSA aims to provide globally applicable principles on managing agriculture for food security under climate change that could provide a basis for policy support and recommendations by multilateral organizations, such as UN's FAO. The major features of the CSA approach were developed in response to debates and controversies in climate change and agricultural policy for sustainable development.

The purpose of this paper is to give an overview of the evolution of CSA, introduce its major components, and summarize the key debates associated with it within the context of climate change and agricultural policy debates The first section provides an overview of international climate change policy followed by an introduction and analysis of CSA and its history. This is then followed by a discussion of three broad controversies related to CSA, namely the role of mitigation, the relationship of CSA to sustainable agriculture, and way biotechnology is treated in the CSA approach.

1.1 The Evolution of Climate Change Policy

To put CSA and its controversies in context, it is necessary to understand the evolution of global climate change policies over recent years. We use the framing of Gupta (2010), who traces the history of international climate change policy, from 1979 to 2010. He distinguishes between five phases of evolution. He refers to the pre-1990 phase as the period of framing the problem, beginning with the World Climate Conference in 1979 and including the establishment of the International Panel on Climate Change (IPCC) in 1988. The main focus of global climate change policy during this period was the need for global action to stabilize greenhouse gas (GHG) emissions, to be supported and guided by a globally cooperative framework for undertaking scientific research in the form of the IPCC, and with the understanding that developed and developing countries would bear different responsibilities to mitigate climate change. Because of the high uncertainty associated with climate change, a precautionary approach to climate change policy was adopted. This implies the need to take preventive action even before full certainty about human-induced climate change was obtained, and secondly, to emphasize no-regrets actions that would be valuable even in the absence of climate change. The publication of the Bruntland Commission Report on Sustainable Development in 1987 (WCED 1987) also led to the realization of the links between climate change and sustainable development and the benefits of considering them in an integrated fashion.

During the second period of international climate policy between 1991 and 1996, the initial articulation of a global policy framework was introduced, signified by the Rio Convention in 1992 and the adoption of Agenda 21. An important outcome of the Rio Conventions was the establishment of the UN Framework Convention on Climate Change (UNFCCC) which entered into force on 21 March 1994. The ultimate aim of the convention is preventing "dangerous" human interference with the climate system. Article 2 of the convention says this objective should achieved while ensuring that "food production is not threatened". There was much debate on equity and the principle of common but differentiated responsibilities.[1]

Developed countries were assumed to bear much of the responsibility for both causing and reducing GHG emissions. However their response could also include helping developing countries pay for mitigation actions in the developing world. As the policy formation process moved forward, countries began to form coalitions around common interests. For example, small island nations formed one coalition, as did the G77, representing a block of 130 developing countries. Among the developed nations there was clear difference between the EU and the US and furthermore, the division grew between the EU and non-EU nations. Civil society organizations became a major player in the climate change debate with a major division between the northern organizations pursuing environmental and the southern organizations emphasizing development objectives.

The period between 1997 and 2001 saw the emergence of the first global agreement: the Kyoto Protocol. The Protocol emphasized comprehensive targets for GHG reduction in terms of CO2 equivalence rather than individual GHGs. Developed countries were assigned different GHG reduction targets and there was emphasis on flexibility in achieving these via mechanisms including emission trading, joint fulfillment and implementation (countries could form a bloc to share responsibilities to meet their joint targets). There was also recognition of the importance of financial mechanisms to promote the implementation of the agreements. The clean development mechanisms (CDM) was established, which allowed developed countries to use financial incentives to finance GHG emission reductions in developing countries and then use the credits to meet their own targets.

The establishment of the CDM provided a basis for expanding the use of payment for ecosystem services to meet GHG reduction targets. One important category of actions for emissions reductions highly relevant to agricultural development is that of sequestering carbon in soils and forestry. Many opportunities for agricultural related carbon sequestration were identified through improved soil manage-

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[1] The Rio Declaration states: "In view of the different contributions to global environmental degradation, States have common but differentiated responsibilities. The developed countries acknowledge the responsibility that they bear in the international pursuit of sustainable development in view of the pressures their societies place on the global environment and of the technologies and financial resources they command."

Similar language exists in the Framework Convention on Climate Change; parties should act to protect the climate system "on the basis of equality and in accordance with their common but differentiated responsibilities and respective capabilities." http://cisdl.org/public/docs/news/brief_common.pdf.

ment and forestry (McCarl and Schneider 2001). One of the challenges of implementing the Kyoto Protocol (KP) was the need for reliable and cost-effective mechanisms for carbon accounting, monitoring and validation which proved particularly difficult in the case of carbon sequestration. The issue of soil carbon inclusion was hotly debated in the discussions on establishing the CDM (Post et al. 2001; Ringius 2002).

The US, Canada, Brazil, and other countries advocated for the inclusion of soil carbon sequestration as part of the Protocol and developed mechanisms to improve its accounting (Paustian et al. 2004). Lal (2004) argued that payment for carbon sequestration could provide farmers, especially in developing countries, with significant supplementary income. However the EU and others were against its inclusion and ultimately the decision was taken to exclude this category from the international carbon offset markets.

Even more importantly, the global significance of the Kyoto Protocol suffered with the US withdrawl from it in 2001, since the two biggest carbon emitters (US and China) were not a part of it. Nevertheless, the Protocol provided a foundation for international collaboration and established many principles for future policy implementation.

The period between 2002 and 2007 saw a retreat from a global agreement to many bi- and multi-laterial agreements, many of which were initiated by the U.S. The period was characterized by competition for leadership among countries regarding climate change policy strategies. While the EU continued to push for extension and expansion of the Kyoto Protocol, the U.S. emphasized multi-lateral agreements. In particular, the Asia-Pacific Partnership on Clean Development and Climate, signed in 2005 (and concluded, with many of its projects canceled, in 2011) emphasized the desire to introduce technological solutions to reduce greenhouse gases (GHG) through, for example, collaboration on R&D aiming towards ‘clean coal’ (Tan 2010).

The growing emphasis on government support to pursue alternative energy sources also had significant impact on agriculture, especially with the introduction of biofuel policies in much of the world (U.S., Brazil, EU and many other countries). While GHG reduction was one justification for the subsidization of biofuels, perhaps more important was the need to combat rising energy prices, to improve the balance of trade, and to increase the income of the agricultural sector (Zilberman et al. 2014). The increase in the price of food in 2008 as well as the concern about indirect land use led to the curtailment of biofuel policies, but some studies (Huang et al. 2012) found that biofuels can be beneficial for the poor, as long as mechanisms exist to protect vulnerable populations against extreme price shocks. Since national governments were not able to initiate potent global climate change actions during the period, subnational entities like U.S. states and Canadian provinces have established their own climate change programs. Both national and provincial plans have significantly impacted agriculture by introducing demand for biofuel and biomass as well as subsidizing carbon sequestration activities.

The final period of climate policy evolution considered by Gupta (2010) is the financial crisis period (from 2008 and on). In this time period the UNFCCC has moved away from a system where mitigation actions were solely the responsibility of rich countries, to one where mitigation actions in developing countries are now being articulated as part of national policy processes to meet the nation's own mitigation aspirations. The policy and financing issues are significantly different in this context, compared with the situation when developing countries were only participating in greenhouse gas reductions on behalf of rich countries, in the form of a carbon offset.

The main issue on the international climate policy agenda for the UNFCCC COP 15 negotiation held in Copenhagen in 2009 was agreement on a global climate treaty which would lay out responsibilities for reducing emissions. Although COP 15 failed to achieve a global climate agreement, it did produce the "Copenhagen Accord" which called for developing countries to develop mitigation targets to 2020 and included financing commitments of $100 billion/year by 2020 as well as $30 billion for urgent actions up to 2012. In the following year at COP 16, the Green Climate Fund was established as an operating entity of the Financial Mechanism of the UNFCCC to support projects, programmes, policies and other activities in developing countries. Developing countries – including both emerging and least developed countries – have articulated mitigation actions through Nationally Appropriate Mitigation Actions (NAMAs) (result of COP 18 2011), as well as more recently through their Intended Nationally Determined Contributions (INDCs).

It is also important to note that during this period, CDM operations had expanded considerably, with new methodologies and accounting procedures accompanying the expansion. At the same time the volume and value in the voluntary (e.g. non-compliance) carbon offset markets, which generally does allow for the inclusion of agricultural soil carbon, also expanded rapidly, although still only representing a small percentage of the value of the trading in compliance markets (Hamrick and Goldstein 2016) Opposition to soil carbon credits in the context of developing country agriculture was raised by civil society actors. This opposition was based on the argument that soil carbon offsets were a means of putting the mitigation burden on low income developing country farmers and that farmers were unlikely to see any benefit from participating in such markets, but rather could be exposed to losing rights to their land (Action Aid 2011).

In the most recent period of climate policy development, there is a growing realization that significant impacts of climate change are already being felt, and are likely to continue and deepen. The Paris Agreement reached at the 21st Conference of Parties of the UNFCCC in 2015 signifies an increased global commitment to address climate change, as countries agreed to establish legally binding constraints on GHG emissions that aim to contain average global temperature rise by the use of a mixed market approach that induces both introduction of clean energy and conservation (Cooper 2016). All parties recognize the urgency of establishing adaptation strategies, especially to protect the poor and the vulnerable. As of 31 March 2016, 188 countries had submitted "Intended Nationally Determined Contributions" (INDCs) to the UNFCCC which includes statements of intended actions for mitigation as well as adaptation. More than 90% of the countries explicitly include agriculture in their mitigation and adaptation plans, with a particularly strong focus amongst least developed countries (LDCs) (FAO 2016). Adaptation in the agriculture sector is given high priority, and mitigation from agriculture, including sequestration is also quite prominent in the submissions. Thus the importance of considering adaptation and mitigation together and capturing the potential synergies between them is more important than ever. The potential of the CSA approach for supporting this is also increasingly recognized; 31 of the INDCs explicitly mention CSA in the context of seeking joint poverty reduction and environmental benefits (FAO 2016).

2 Overview of CSA

The CSA concept emerged at a moment in time of considerable controversy around the concept and approaches to sustainable agricultural development, and when the specificities of agriculture and its role in food security were not well articulated in the climate change policy process. The former was clearly reflected in the debates and controversies of the development of the International Assessment of Knowledge, Science 2009) Technology for Development (IAASTD) which ran from 2003 to 2008 (Scoones 2009). The main arguments in this fora centered around the role of top-down expert assessments versus local participatory approaches to knowledge generation, as well as the role of biotechnology and specifically transgenic crops in sustainable development. In the global climate change policy arena, agriculture's key role in food security was not clearly articulated and the consideration of adaptation and mitigation in two separate negotiation streams limited capacity to build synergies between them.

The first articulation of the CSA concept was presented in the 2009 FAO report entitled "Food Security and Agricultural Mitigation in Developing Countries: Options for Capturing Synergies, which was launched at the Barcelona Climate Change workshop held in November of that year. In 2010, the FAO paper entitled "Climate-Smart" Agriculture, Policies, Practices and Financing for Food Security, Adaptation and Mitigation" was released as a background paper for the Hague Conference on Agriculture, Food Security and Climate Change held in October of that year (FAO 2010). The conference was organized as a follow up to the Shared Vision Statement agreed at the Seventeenth Session of the Commission on Sustainable Development (CSD-17) in May 2009 and to further develop the agriculture, food security and climate change agenda.

These first expressions of the climate smart agriculture concept argue that the agricultural sector is key to climate change response, not only because of its high vulnerability to climate change effects, but also because it is a main contributor to the problem. It also argued that sustainable transformation of the agricultural sector is key to achieving food security, and thus it is essential to frame climate change responses within this priority. Analysis of the state of knowledge on the adaptation, mitigation and food security benefits of a range of agricultural practices, as well as their potential tradeoffs was given as well (e.g. see table 2.2 of the 2009 report as well as FAO 2010). Finally these reports focussed on one of the key issues that arose in CSD-17 discussions – how to finance the transformative changes needed. The CSA work focused on the potential for linking the emerging and potentially huge new sources of climate finance – including but not limited to carbon markets – to support the transition to sustainable agriculture. However, important barriers such as high transactions costs for smallholder agricultural producers to access and benefit from climate finance were clearly identified as major issues (FAO 2011).

The CSA concept sparked considerable attention and debate in international and national agricultural and climate change policy arenas, and it was quickly taken up as a rallying point for mobilizing actions on climate change and agriculture. In the wake of the Hague conference, two parallel global processes related to policy and science of CSA were established. The policy process involved follow up conferences in 2012 in Hanoi Vietnam and 2014 in Johannesburg South Africa. The global CSA science process was initiated with a global CSA science conference at Wageningen in 2011, with subsequent CSA science conferences held at University of California at Davis in 2013 and at CIRAD Montpelier in 2015. One of the main outcomes of these processes was the proposal to establish a global alliance on climate smart agriculture (GACSA) which would bridge the policy and science aspects by focussing on three key action areas: (1) knowledge; (2) enabling environment and (3) investments.

After considerable debate, the GACSA was launched in September 2014 at the UN Climate Summit. Memberships in GACSA may include governments, civil society member/non-government organizations, farmers, fishers and forester organizations, intergovernmental organization (including UN entities), research/extension/education organizations, financing institutions and private sector organizations. As of January 2016 the GACSA has 122 members, including 22 countries.

CSA developments were not only at international level however, with CSA projects initiated at country and regional levels, generally in partnership with international organizations such as FAO, World Bank, local and international NGOs and the Climate Change and Food Security program of the CGIAR.

The rapid and widespread uptake of the CSA concept took place in advance of a clearly defined methodology and definition of CSA, and thus differences in meanings and application of the concept have arisen, and given rise to controversies, which further clarification and development of the CSA concept could ostensibly resolve. However much of the controversy around the CSA concept is related to more fundamental disagreements in global policy debates on climate change and sustainable agriculture.

3 Key Features and Evolution of the CSA Concept

One of the main features of the CSA concept is that it calls for meeting three objectives: sustainably increasing food security through increases in productivity and incomes, building resilience and adapting to climate change, and reducing greenhouse gas emissions compared to a business as usual or baseline scenario.

From its inception, recognition of possible trade-offs between the three objectives, and the potential to increase synergies amongst them through policies, institutions and financing was a key feature of the CSA concept (FAO 2009). The need for locally specific solutions was also an important component. A general framework for assessing trade-offs and synergies was provided in FAO (2009, p. 25), along with several examples of sustainable land management practices and "modern" inputs. However, no specific guidance was provided on how to define a CSA practice, or prioritize amongst objectives, to develop the site specific solutions. A clear conceptual framing of the link between sustainable agriculture and CSA was also missing, hindered by the complexity of tying together the three main objectives. The lack of a clear methodology together with a rapid uptake of the concept resulted in considerably variability in the use of the term and confusion, which in turn has been a major source of controversy around the concept.

By the second global CSA policy conference held in Hanoi in 2012, the beginnings of a CSA methodology and principles were emerging. A CSA methodology presented in one of the background papers to the conference consisted of three major elements included: (1) building a relevant evidence base for assessing trade-offs and synergies amongst the three main objectives, (2) creating an enabling policy environment that required coordination of climate change and agricultural policies and (3) guiding investments and linking to climate finance. The methodology was based on lessons learned from a CSA project funded by the EC in 2010 and jointly implemented by FAO and three partner countries. As such, it focussed on national level actions; e.g. building evidence on climate impacts and vulnerabilities for the agricultural sector at country level; analysing the effectiveness of varying actions on productivity and incomes and their resilience to site specific climate shocks, and their effects on reducing emissions compared to a business as usual agricultural growth path for the country. Enhanced coordination between national climate change and agricultural policies and strategies is key to creating an enabling policy environment, while analysis of the marginal abatement costs of nationally appropriate mitigation actions gives a clear indication of where potential synergies between the three CSA objectives can best be obtained, and the potential of using mitigation finance to support them.

The Climate Smart Agriculture sourcebook, which was a joint effort of several international organizations, came out in 2013 and provided principles for defining CSA practices as well as conceptual links to sustainable agriculture processes and a wide range of examples from livestock, cropping, fishery and forestry sectors (FAO 2013). The first chapter of the sourcebook lays out two major principles defining CSA practices: (1) increasing resource use efficiency in agricultural systems and (2) enhancing the resilience of agricultural systems and the people who depend upon them. Resource use efficiency is a key component of sustainable agricultural intensification strategies. By using resources such as nitrogen fertilizer, feed for livestock, land and water more efficiently, the net return to farmers and thus incomes increase, while pressure on scarce resources and emissions per unit produced are reduced. Increasing resilience involves reducing vulnerability as well as enhancing adaptive capacity. CSA strategies require that resilience and resource use efficiency are pursued together, although specific technologies and institutional arrangements may affect only one or the other. Rather, efficiency and resilience need to be considered in an overall systems perspective that considers different spatial and temporal scales. The importance of ecosystem services provided through for example, improved soil management, agro-biodiversity and landscape management, in achieving resource use efficiency and resilience is also a major tenet of CSA approaches outlined in the sourcebook.

The CSA methodology and principles were further defined through a consultative process involving representatives from a broad spectrum, including international organizations such as FAO, CCAFS and World Bank, national agricultural and climate change policy-makers, academics, and civil society. This consultative process resulted in the publication of a perspectives piece in Nature Climate Change in 2014 that reaffirmed the key components of a CSA methodology, but also addressed some of the emerging controversies associated with the concept (Lipper et al. 2014). One of these was a response to the heavy emphasis on ex-ante identification of farm level practices that could meet all three CSA objectives. The paper argued that CSA did not imply that every practice in every field would have to contribute to food security, adaptation and mitigation, but that meeting these objectives should be considered at broader spatial and temporal scales. It also highlighted the controversy around mitigation in developing countries.

More recently, the World Bank and the CCAFS program have launched a set of "country CSA profiles".[2] These provide critical stocktaking of ongoing and promising practices for the future, and of institutional and financial enablers for CSA adoption. The profiles provide information on CSA terminology and how to contextualize it under different country conditions. The knowledge product is also a methodology for assessing a baseline on climate smart agriculture at the country level (both national and sub-national) that can guide climate smart development.

The CSA concept and methods were developed by international technical agencies, including FAO, the World Bank, the Climate Change and Food Security Programme of the CGIAR. As such, the concept was built to provide a framework for formulating and taking actions to respond to climate change in agriculture that was broad enough to encompass a wide spectrum of political and economic approaches to managing agriculture. In this way, the concept could be relevant to the wide range of clients served by international agencies and adapted to their specific needs and circumstances. At the same time however, the generality of the

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[2] http://sdwebx.worldbank.org/climateportal/index.cfm?page=climate_agriculture_profiles.

concept has led to multiple interpretations of its core meaning and thus some confusion and controversy. In the next section we look more closely at the most prominent of these.

4 CSA Controversies in the Broader Policy Context

4.1 The Role of Mitigation and Carbon Finance in CSA

One of the main criticisms of the CSA approach has been that it prioritizes mitigation over food security and adaptation, and it mandates a link to carbon offset markets (Action Aid 2011, Neufeldt et al. 2013). By explicitly calling attention to the potential of agricultural transformation to generate mitigation benefits, and actively pursuing links to mitigation finance, the CSA approach raised suspicions that it was a means of pushing the mitigation burden on the world's poorest people (Action Aid 2010). The argument was made that CSA advocated pushing carbon offsets for soil carbon sequestration on poor farmers, and this would shift the burden of reducing greenhouse gas emissions from rich, industrialized countries who had actually created the problem, to poor developing countries that already are facing the biggest burden in adapting to climate change. This argument is rooted in controversies over soil carbon sequestration and the role of developing countries in mitigation in the global climate policy debate (see previous section) as well as misconceptions of the framing of climate finance in CSA.

Before discussing misconceptions and policy debates, it is useful to understand the impetus for connecting mitigation finance to agricultural development. In 2008 the fourth assessment report of the IPCC was released. The report included a detailed analysis of the state of knowledge at the time on the technical and economic potential of mitigation from agriculture (Smith et al. 2008). They found an estimated global economic mitigation potential for 2030 from agriculture of 1500–1600, 2500–2700, and 4000–4300 MtCO2-eq/year at carbon prices of up to 20, 50 and 100 US$/tCO2-eq. The activities with highest economic potential were restoring cultivated organic soils, cropland management, grazing land management, restoration of degraded lands, rice management and livestock. Sequestration of carbon in agricultural soils is a key feature of most of these practices. Within each of these categories the actions analysed had high correspondence with actions promoted for sustainable agriculture, e.g. crop rotation, minimum tillage, nutrient use efficiency, feed efficiency. This analysis from the leading science body on climate change indicated the potential to capture huge synergies between mitigation and sustainable agricultural development.

At the same time, the rapid growth in the development of international carbon offset markets represented a major new and potentially huge source of finance to support sustainable agricultural activities with mitigation co-benefits. At the time of the launching of the CSA concept, the valuation of global carbon markets was $141 billion, composed principally of the clean development mechanism of the Kyoto Protocol and the European ETS system (World Bank 2011). However, as noted in the section on climate policy above, neither of these major financing mechanisms allowed soil carbon sequestration from agricultural practice change as a source of mitigation.

Outside of the formal carbon markets, an alternative voluntary market for carbon offsets was springing up, including projects sponsored by the World Bank Biocarbon Fund, NGOs in developed and developing countries, as well as some regional exchanges. The Chicago Climate Exchange which developed a protocol for soil carbon offsets from reduced tillage and improved pasture management (FAO 2012). However the financing flows through these voluntary markets was miniscule compared with those of the formal carbon markets (FAO 2012).

Essentially, there was very little demand for carbon offsets from soil carbon sequestration from developing country farmers due to their exclusion from the major carbon financing mechanisms. However the question of whether or not they should be allowed in order to open the doors to new financing that could generate both mitigation and development outcomes was an important thrust of early CSA work. If the barrier to accessing a significant new source of financing was simply a lack of good research on how much soil could be sequestered from changes in developing country farming systems, then surely the response should be developing a research agenda to provide the needed science. However as research into the potential of carbon offsets as a source of finance for developing country farmers proceeded, it became clear that issues of weak institutional capacity in developing countries was a more serious barrier. In particular, the rights of people with unclear and informal systems of land tenure to reap carbon benefits was very problematic Leach & Scoones 2015). Experience with payment for environmental service programs, and particularly the REDD+ process had indicated this was a particularly difficult issue to address, but very commonly found. The REDD+ experience indicated that there was indeed potential for poor farmers and land managers with insecure title to land to be dispossesed through the implementation of a REDD+ program, but that there was also potential for stimulating improvements in tenure systems through the impetus of such programs (Larson et al. 2013). Ultimately, it was well recognized that weak and inequitable institutions were a key barrier to making carbon finance work for small and poor farmers, and thus greater attention should be given to linking international public sources of finance such as the Global Environment Fund to support climate smart agriculture (FAO 2013). At the same time, major shifts in the international climate policy negotiations reduced the importance of international carbon offset markets as the main source of climate finance. The newly reconfigured international climate policy regime with its emphasis on nationally determined contributions to mitigation and adaptation and the prominence of agriculture in the contributions from developing countries has created interest in the capacity of agricultural mitigation sources to contribute to developing country's own nationally determined contributions. It also implies a greater need for an approach that can identify how mitigation can be integrated into agricultural transformation strategies without compromising food security, which is of course a major focus of CSA.

To summarize, a major thrust of CSA is building the enabling conditions for a major transformation in agriculture, and developing adequate financing streams adapted to the specific conditions of agriculture is important in this regard. At the time of the launching of the CSA concept, the international carbon offset markets were the largest source of climate finance and thus much attention initially was given to its potential for supporting agricultural transformation in developing countries. Due to the problems with linking carbon finance to smallholder agriculture countries, together with the emergence of new funds for supporting mitigation actions on the part of developing countries in recent years, the emphasis of CSA has shifted away from carbon markets to international public climate finance such as the Green Climate Fund and the Global Environmental Facility. Given the high importance of agriculture in the national expressions of mitigation actions on the part of developing countries, the importance of identifying mitigation actions that are synergistic with food security and adaptation and building financing mechanisms to support them is of greater importance than ever.

5 CSA and Sustainable Agriculture

Another major criticism of CSA has been the lack of clear principles by which to define a CSA practice, and thus concerns that the concept and branding could to be used to advance non-sustainable and non-desirable forms of agricultural development. This debate was fuelled by the mistaken notion that CSA was essentially a proposal for a new type of agricultural practice, giving rise to concerns directly related to ongoing and fierce debates about technologies for sustainable agriculture.

CSA is not intended to provide a new set of sustainability principles, but rather a means of integrating the specificities of adaptation and mitigation into sustainable agricultural development policies, programs and investments. CSA strategies and practices then should adhere to the principles that underpin sustainable agriculture and food systems. Recently FAO published a new set of guidelines and approach to achieving sustainable agriculture and food systems (SFA) as ones which meet the following criteria: (1) improving the efficiency of resource use, (2) conserving, protecting and enhancing natural resources, (3) protecting and improving rural livelihoods, (4) enhancing resilience of people, ecosystems and communities and (5) responsible and effective governance mechanisms.

Of course, these principles are very broad and do not mandate any specific balance or weighting between them in terms of defining a sustainable technology. Nonetheless, the links between the sustainability principles and CSA can be seen. Increasing resilience, conservation and protection of natural resources and increasing resource use efficiency are key components of adaption and mitigation. Protecting and improving rural livelihoods is closely related to the CSA objective of sustainably increasing productivity and incomes. A major thrust of CSA is improvement of climate change and agricultural governance through better coordination and institutional strengthening.

With its emphasis on assessing trade-offs and synergies between its three main objectives, as well as the barriers to adoption, CSA actually addresses one of the most essential issues in sustainable agriculture: what will it take to actually achieve a large scale transformation? The emphasis on explicitly identifying trade-offs in the CSA approach is a reaction to the lack of such consideration in many of the sustainable agricultural approaches which focus only on the benefits obtainable, ignoring costs and barriers. The result has been disappointly low adoption of sustainable agricultural techniques, despite decades of efforts and funds to support them. In the end it is the farmers, fishers, livestock keepers and forest managers that are assigning weights to environmental, social and economic criteria through the decisions they make on how to manage their production systems. However the tradeoffs they face between the objectives are determined by the institutional environment they operate under. For example, sustainable land management techniques such as land restoration or agroforestry can take some years to generate benefits, and they require up-front investments and can involve reductions in income during the initial phase. While over a 20 year time frame such actions can result in higher economic, environmental and social benefits, in the initial phases there are significant tradeoffs between them. This is essential to understanding how to effectively induce transformative change – and it has all too often been ignored in the literature on sustainable agricultural development.

A key issue in the debate on technologies for sustainable agricultural growth focuses on the relationship between natural capital inputs (e.g. ecosystem services such as soil quality or genetic diversity) and manufactured capital inputs (inorganic fertilizer, machinery, improved seed) in an agricultural production system. This debate is rooted in a reaction to the great push in capital inputs (improved seed and inorganic fertilizers) which began in the 1960s, which to a large extent built upon a model of substituting manufactured capital inputs for natural capital; e.g. inorganic fertilizer use could substitute for soil quality, or pesticides for genetic diversity (Tilman et al 2002; IAASTD 2009). Particularly in initial phases, increasing manufactured capital inputs to agricultural production systems was the main thrust of this model of development, although in later phases, the focus has shifted in most cases to increasing the efficiency of manufactured capital inputs (FAO 2012). While the results in terms of production increases have been dramatic, these positive results have been accompanied by high rates of natural resource depletion and degradation, as well as negative environmental impacts on land, air and water (Tilman et al. 2002, IAASTD 2009). The social impacts have been the subject of much debate. On the one hand the expansion of food production and lowering of food prices a major benefit to the consumers, particularly the poor (Pingali 2012). On the other hand, the model of a top down technology delivery focussed primarily on favorable production areas, excluded many of the poorest from its benefits.

Sustainable agriculture is part of the larger concept of sustainable development that according to the Brundtland Commission is a development strategy that aims to ensure that future generations would not be worse off compared to the present generation. Sustainable development contains economic, social, and environmental elements, but in principle has limited restrictions on technology, per se, and the use of technologies are judged based on their impacts. Zilberman (2014) argues that one of the major features of sustainable development is the emphasis on conservation technologies that enhance input use efficiency and reduce pollution, introduction of strategies that include resilience and ability to withstand environmental risk, adoption of recycling technologies, and transition from non-renewable to renewable technologies. Renewable technologies include both energy production using solar and wind as well as extension of the bioeconomy, which relies on biological processes to produce food, fuel, and fine chemicals. This approach to sustainable development that allows some substitution among resources and encourages production systems that enhance human welfare subject to constraints should have bearing on the definition of CSA.

The CSA approach is criticized by some advocates of alternative development models, because it does not explicitly exclude the use of manufactured capital inputs and while incorporating participatory and bottom up approaches, it also allows for integration of science-based technology transfers. The CSA literature does however explicitly call for enhancing the complementarity between ecosystem services and manufactured capital, such as improving soil quality to enhance the productivity gains from inorganic fertilizer use, improving livestock breeds to enhance their feed conversion efficiency, or planting trees in agricultural landscapes to reduce flood risks.

The issue of biotechnology use in agriculture is perhaps the most highly contested, with most of the focus on genetically modified organisms (GMOs). The use of GMOs has been limited to few crops, used mostly for fiber (cotton) and feed and oil (maize, soybean, canola) with limited use for direct human consumption (papaya, maize, canola). Furthermore, while adoption of GMOs on farm has been quite broad in the U.S., Canada, Brazil, Argentina, and South Africa, and in cotton in other major countries (India, China), its use in Europe and most of Africa has been limited or even practically banned. Most major national academies of science and international organizations have argued that it poses no new health risks compared to other sources of food, and there is evidence that GMOs have reduced the price of major agricultural commodities as well as the extent of GHG emissions (Barrows et al. 2014). There is also significant evidence that it has improved the well-being of poor farmers, especially in cotton production (Klümper and Qaim 2014; Qaim 2015).

Nonetheless, significant concern about environmental and social effects of GMOs persists and there is ongoing debate on the application of the precautionary principle by opponents of the technology. Another source of concern is the large role of the private sector in the development of the technology and its control of intellectual property rights. But the heavy regulatory requirements associated with the development of GMOs has led to the concentration of the industry in the hands of a few major companies (Bennett et al. 2013). More recently however, the reduction of the cost of genome mapping and the introduction of new technologies like gene editing increase the capacity of a broader range of stakeholders to utilize and control modern biotechnology to provide effective and quick solutions to address the challenges of climate change.

The issue of which technologies to consider, and specifically whether biotechnologies should be included has been addressed in different ways under current applications of the CSA approach. To a large extent, the technologies and practices considered under CSA approaches are ones that governments have already included in their national agricultural plans, which often do not include biotechnology at present. Under the EC funded FAO CSA project, consultations with national policymakers and stakeholders including representatives from farmer's associations and other civil society groups have been held to identify a set of possible options for further detailed analysis. The World Bank/CCAFS profiles analyse a range of technologies and practices that are currently being practiced in the country or that are likely to be beneficial under projected climate change conditions, including from traditional as well as science based sources. They also provide a set of country specific criteria for identifying climate smartness of the technologies which also give information on the economic, environmental and social impacts of the technologies in that country. Ultimately, CSA neither mandates nor excludes the use of biotechnology or GMOs for any specific user of the approach, but it can provide a basis for helping potential users identify the risks and benefits of its use in addressing the challenges of achieving food security under climate change.

6 Conclusion

Climate smart agriculture is a relatively new concept which was launched in 2009 advocating for better integration of adaptation and mitigation actions in agriculture to capture synergies between them and to support sustainable agricultural development for food security under climate change. The rapid uptake of the concept after its launch indicates the tremendous demand for a framework to guide policy and technical interventions in agriculture that integrates the effects of change, the challenges of achieving sustainable agricultural development and the critical role of agriculture in attaining food security. At the same time, the widespread adoption of the CSA term prior to the development of a formal conceptual framing and methodology has lead to considerable variation in meanings applied to the term, as well as confusion and controversy.

The CSA concept has been reshaped through inputs and interactions of multiple stakeholders involved in developing and implementing the concept. At this point there is greater clarification on the definition of the concept and methodology for its application. However controversies over CSA remain. Most of these are related to the controversies in climate change and sustainable agricultural policies. In particular, the role of agricultural mitigation and its financing in developing countries, as well as the development and deployment of technologies for agricultural development are two key areas of continuing controversy in the respective policy circles. CSA does not attempt to provide a prescription to any user of the approach for resolving the controversies, but rather a tool to identify locally appropriate solutions to managing agriculture for sustainable development and food security under climate change. Ultimately the utility of the concept and its implementation will be judged by its effectiveness in integrating climate change responses into sustainable agricultural development actions on the ground.

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Economics of Climate Smart Agriculture: An Overview

Nancy McCarthy, Leslie Lipper, and David Zilberman

Abstract Climate change, especially through greater frequency and intensity of climate extremes, is expected to negatively impact agriculture and food security, particularly in developing countries highly dependent on rain-fed agriculture. Promoting growth and food security must draw on the rich literature of the past 50–60 years while also addressing potential structural shifts in the factors that promote growth. This paper summarizes the economic considerations of Climate Smart Agriculture, a concept developed by the FAO to address the complex issue of how to achieve sustainable agricultural growth for food security under climate change. It addresses the lack of coherence on the CSA approach by building a formal basis of the CSA concept and methodology. We do this by posing a dynamic optimization problem wherein a social planner seeks to maximize expected discounted welfare associated with agriculture of the population they serve, both now and in the future. We analyze constraints, choices, and features of design of CSA to illustrate on the concept can be applied across a range of locations and conditions. This has implications for research, innovation, and policy design.

1 Introduction

Climate change is expected to have negative impacts on agriculture and food security in many regions, particularly in developing countries highly dependent on rain-fed agriculture. The fifth assessment report of the IPCC released in 2014 found that climate change effects are already being felt on agriculture and food security, and

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the negative impacts are most pronounced in tropical zones where most of the world's poor and agricultural-dependent populations are located (IPCC 2012). And yet in the next 20 years, increasing the rate of agricultural growth in these regions is essential to reach the goals of eradicating poverty and meeting growing food demand associated with population growth and dietary transitions.

Over the last 50–60 years, a rich and extensive body of work on agricultural development economics has been developed, aimed at supporting agricultural growth and food security. Over time this work has been augmented with insights and techniques from natural resource and environmental economics, as well as behavioral and institutional economics. The evidence base has also expanded dramatically due to advancements in empirical research design, econometric techniques, data availability and computing power. At the same time, the public sector has invested in agricultural and rural development, accumulating practical experience and knowledge.

Climate change, with its potentially transformative impacts on agricultural systems, means that we need to revisit the key tenets of this accumulated body of knowledge and experience in order to identify its applicability to current and changing circumstances. Does climate change actually require a change in how we go about planning and investing in agricultural growth for food security and poverty reduction? The answer is not obvious – much research and policy design in agricultural development has been concerned not only with enhancing productivity, but also with reducing negative environmental impacts and providing public goods, as well as managing trade-offs between risk and returns and reducing vulnerability of farm households to a wide array of shocks. These are also some of the major concerns raised, perhaps to a more urgent level, with respect to addressing climate change in agriculture. However we need to consider whether the potential magnitude and scale of climate change will result in a structural shift in the factors that will promote growth – and thus how we go about promoting growth and food security.

The increased frequency and intensity of extreme events is clearly one of the most important game-changing effects of climate change. Recent work by Fischer and Knutti (2015) on the link between climate change and extreme events estimated that 75% of extreme hot days and 18% of days with heavy rainfall worldwide can be explained by the warming we've seen over the industrial period. The same study also finds that the probability of extreme events increases nonlinearly with increasing global warming. For instance, the probability of an extreme hot day under a scenario of 2 °C increase over pre-industrial levels is almost double the probability at a 1.5 °C increase, and is more than five times higher than with today's climate. Essentially, the vulnerability of the agricultural sector to adverse events is increasing at a rapid, steep and broad scale, which implies a need for innovative measures to reduce the exposure and sensitivity of the agricultural sector, and also to increase adaptive capacity.

Greater frequency and intensity of climate extremes has implications for research, innovation, and policy design. With respect to research, though the empirical evidence on households' responses to weather shocks is fairly large, most of the data collected has been undertaken under relatively normal weather conditions, with spatially limited idiosyncratic weather shocks. Thus, little is known about the impacts of generalized climate shocks on households' wellbeing, and even less is known about which mechanisms are most effective at minimizing those impacts. Additionally, evidence is lacking on which measures are most effective at increasing the resilience of the agricultural sector as a whole. Part of the problem is the lack of capacity to mobilize resources needed to collect relevant data in the immediate wake of disasters that occur at significant scale, as well as logistical, and potentially ethical, issues involved with collecting data under such circumstances. Valuable information could be obtained by those involved in disaster relief activities, but such information is generally not collected in a systematic manner nor widely shared. As noted by Scott et al. (2016), though everyone agrees that monitoring and evaluation (M&E) should be a critical element in disaster relief, most M&E systems remain weak and data collected remains little shared.

With respect to innovation and policy design, increased frequency and intensity of climate extremes dramatically increases the value of innovations and policies that increase the range of cost-effective options that allow rapid adjustments in the face of climate extremes. This implies a need for a strong shift towards investing in technological and institutional innovations that create options and increase flexibility. This also implies a need for designing policies and regulations that enable different actors – including government agencies as well as the private sector – to exercise various options in response to climate extremes.

The second potential game-changer arises from the possibility of major regional shifts in weather patterns, or "migration" of climate. This effect may be due to spatially and seasonally heterogeneous increases in average temperature and altered rainfall patterns. Such changes may have major consequences in terms of movement of pests and diseases, as well as loss of coastal and certain inland agricultural lands. We can expect that migration of climate will disproportionately affect resource-poor and marginalized farmers who have less adaptive capacity but depend primarily on agriculture for their livelihoods (Hitz and Smith 2004; Thornton et al. 2011). Experience has indicated that intensifying labor migration is a common response to prolonged and chronic environmental degradation, with permanent resettlement less common and generally considered less desirable. However this option is increasingly considered as an adaptation strategy in response to major shifts, such as sea level rise. Current empirical evidence indicates that the poor and most vulnerable to climate risks are again the least capable to undertake effective migration, since they lack the assets and social networks required (Adger et al. 2014; Taylor and Martin 2001).

Successfully adapting to emerging major shifts in weather means that research needs to focus on which factors facilitate the transition to new climate patterns while maintaining growth rates and reducing poverty. Research is needed to evaluate both adaptive, marginal changes within the system to confront such shifts, as well as far-reaching transformational changes. Research is also needed to generate sufficient evidence to compare the relative merits of pursuing incremental adaptation strategies versus transformational strategies. For instance, access to new crop varieties, more suitable livestock, irrigation systems, and pest management strategies can enable farmers to successfully adapt to new climate patterns. At the same time, enabling farm households to relocate may well be a better strategy, especially under more extreme shifts in climate patterns. While there is a fair amount of household-level research on internal and international migration and its impacts on migrant households, much less is known about which institutional structures and mechanisms best support peaceful relocations. While processes of movement in and out of agriculture are ongoing (Taylor and Martin 2001), future research should aim to understand the institutional challenges and planning requirements to address climate related migration within ongoing population transition processes.

More broadly, the interaction between climate change induced changes in agricultural production patterns and structural transformation in the larger food system and rural non-farm sectors need to be better understood (c.f. Haggblade et al. 2007; Reardon and Timmer 2007; Gollin et al. 2002). Given the systems-level focus of such research, this calls for greater integration of sub-discipline research, e.g. linking agro-ecosystem or agri-food sector-wide models with evidence from household surveys. To date, however, such models capture institutional structures and mechanisms in a fairly rudimentary way. While institutions are important for understanding marginal changes, they are particularly important for understanding and promoting transformational changes.[1] Large-scale household surveys and randomized experiments will be of limited value in answering many key questions about systems-level outcomes and optimal institutional structures and mechanisms. Instead improved methodologies for analyzing limited data, e.g. using case studies across disciplines will be required, echoing recommendations of Reardon and Timmer (2007) with respect to agrifood systems.

A third major transformation climate change imposes on agricultural development planning is the need to decouple agricultural growth from emissions growth, given the high share of agriculture in contributing to global emissions. World Resource Institute (WRI) estimated that emissions from agriculture could grow from approximately 6.5 GT in 2010 to 9.5GT per year in 2050 under a conventional agricultural growth strategy. At the same time, the development of the nationally appropriate mitigation actions (NAMAs) and Intended Nationally Determined Contributions (INDCs), has shown that developing countries are interested in pursuing low-emissions agricultural growth strategies, if financing to support such actions can be made available. Reducing emissions from the agricultural sector requires technologies and practices to increase efficiency and reduce leakage from agricultural production systems, and also enhance the sequestration capacity of the sector by increasing trees and shrubs. Improved soil management, sustainable rice intensi-

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[1] Certain institutional mechanisms are relatively well-studied, such as various aspects of property rights. The impacts of increased access to institutions has also been well-studied but mostly in a rudimentary way, e.g. dummy variables capturing access to a health care center, credit, extension, etc. But, specific delivery mechanisms, the range of services offered, service quality, contract clauses etc. are much less well-studied. Such information is crucial to policy design. New research tools and methods are needed to help build this evidence base.

fication, precision farming, and restoration of degraded lands can all contribute to reduced GHG emissions and/or soil carbon sequestration under certain conditions (Burney et al. 2010; Lal 2004; Paustian et al. 2004; Antle and Diagana 2003). But, as many researchers have documented, there has been limited adoption of sustainable land management (SLM) practices that could also contribute to a low-emissions agricultural growth path, particularly in sub-Saharan Africa and parts of Southeast Asia (Barbier 2010; Pender et al. 2006; Barrett et al. 2002).

In terms of research, there is a great deal of evidence on the benefits to adopting SLM, but much less evidence on the costs and barriers that farmers face in adopting such practices (McCarthy et al. 2012; Pender et al. 2006; Nkonya et al. 2004). Given these costs and barriers, there is a need for the public sector to develop innovative policies and mechanisms that alter incentives for actors in the agricultural sector to pursue such strategies. One mechanism that has received a great deal of attention is a carbon-sequestration based payment (Seeberg-Elverfeldt et al. 2009). However, such programs often fail because of the difficulty in monitoring and verifying compliance, and with making and enforcing contracts with, and delivering payments to, many smallholders (Lockie 2013; Alix-Garcia et al. 2012; Cacho et al. 2005). Research needs to shift towards generating better evidence on a wider range of specific institutional structures and mechanisms that link smallholders to financing opportunities, including expanding the innovative use of information and communication technologies (ICTs) and geo-spatial information. This type of evidence is critical if poor smallholders are to benefit from international mitigation financing. At the country level, many governments are still leery of promises of mitigation financing – and the bureaucracy and conditionalities it brings – and there is a clear need to refine the international institutional mechanisms associated with such financing.

To summarize, the need to address an unprecedented level and magnitude of uncertain change poses a challenge to economic analyses aiming to support agricultural growth and food security, particularly as these changes will clearly differ across regions. Research that will identify methods to improve agricultural resource allocation and management strategies to address emerging climate change patterns, as well as empirical research that will identify the effectiveness of existing management tools in addressing some of the early manifestations of climate change, will be of high value. This research needs to be part of multidisciplinary efforts needed to expand the feasible set of technologies and agronomic management practices, explicitly accounting for decision-making under uncertainty. In addition to technologies and management practices aimed at the farm level, research will also be needed to assess the net benefits from investments in public infrastructure and services, and to evaluate the potential benefits from creating or reforming laws and regulations critical to the agricultural sector, such as those related to public and private land use, as well as the finance, communications and insurance sectors. Research is also needed to understand the role of key institutions in meeting growth objectives while minimizing negative impacts of climate change and securing GHG reductions where possible, and what new institutional forms may be required. Land tenure and property rights, water rights, extension and weather information dissemination services, cooperatives and farmers' unions, and credit and insurance markets are but a few such key institutions. Finally, we emphasize that the responses to climate change may consist both of incremental adaptation, primarily based on scaling up existing technologies and modifying institutions, laws and regulations, and transformative adaptation, including new institutions and major reallocation of resources over space and time. These responses vary in their time dimension and are interdependent (Nelson et al. 2007).

Since policy planning addresses multiple objectives, such as higher incomes, more stable incomes, and lower emissions, one of the key areas of focus is highlighting potential trade-offs in meeting multiple objectives. The goal is to be able to evaluate which policy actions can ameliorate trade-offs and harness synergies amongst the multiple objectives. The latter is particularly important since meeting increasing global food demand and local food security objectives requires continued growth in the agricultural sector. There are a number of potential trade-offs that can arise due to impacts from climate change. For instance, increased frequency of extreme weather events increases the value of policy actions that reduce household vulnerability to such events, but may also compromise strategies to enhance average growth levels of agricultural productivity and farmer incomes. Similarly, policies and public investments to address uncertain longer-term shifts in weather patterns can shift resources away from addressing current poverty alleviation goals. Pursuing low-emissions growth strategies can also involve trade-offs with near-medium term growth objectives, which need to be clearly understood – and externally financed – in order to avoid placing additional burdens on smallholders in developing countries.

Understanding the potential impacts of climate extremes and shifting climate patterns and evaluating how different options and strategies can best address these is a complicated process. As a beginning step, the Climate Smart Agriculture (CSA) concept was developed in order to address the complex issue of how to achieve sustainable agricultural growth for food security under climate change (FAO 2009, 2010; Lipper et al. 2014). The concept calls for integration of the need for adaptation and the possibility of GHG mitigation in agricultural growth and poverty reduction strategies. However there is considerable confusion about what the CSA concept and approach actually involve, and wide variation in how the term is used. At this time, it is critical to build a more formal basis for the CSA concept and methodology and at the same time provide illustrations of how the concept can be applied across a range of conditions. This is the primary focus of this book.

2 CSA: The Objectives of the Social Planner

The design of CSA can be analyzed as an economic decision-making problem from the perspective of a social planner. We will not solve the problem formally, but will identify its main features and some of the characteristics of potential solutions. The social planner is concerned with optimizing the welfare of the population they serve, both now and in the future. CSA then is a way of laying out this dynamic optimization problem and its constraints that explicitly incorporates effects of climate change. A plausible objective is maximization of expected discounted welfare associated with agriculture, from a basket of "goods" provided by agriculture. Of course, the agricultural sector is but one sector in the economy, and as noted above, the best option may be to help people transition out of agriculture. Thus, while we emphasize the agricultural sector, other sectors are clearly important. Welfare is comprised of several components. Here we focus on the four pillars of food security: food availability, access, utilization (e.g. food safety), and stability of food supplies. Stability of food supplies is related both to household-level vulnerability as well as resilience of the agricultural system.[2] Finally, we can include environmental objectives, including the global objective to reduce GHG emissions growth as well as local objectives related to improved land quality and water resource management.

The dynamic nature of the optimization problem captures potential trade-offs between choices to improve welfare now versus choices made now to improve welfare under uncertain future outcomes. It also highlights the impacts of uncertainty on decisions made now, and thus the value of additional information and/or the value of choices that increase the flexibility to adapt as more information becomes available. A dynamic framework also enables us to evaluate costs and benefits associated with alternative "weather-migration" scenarios and lower emissions growth strategies.

3 The Constraints Facing the Social Planner

When deciding on the extent and means of pursuing avenues for improving welfare outcomes, the social planner must take into consideration constraints in the form of biophysical relationships and behavioral, institutional and political constraints. The biophysical relationships consist of several elements. First is the production function, which links outputs to ecological inputs and weather. One of the key challenges in designing agricultural policies is in understanding the heterogeneous impacts of climate change on productivity. Furthermore, modeling of the production function needs to consider both continuous as well as discrete variables. This approach allows us to investigate technology adoption in response to climate change (Mendelsohn and Dinar 1999; Antle and Capalbo 2010; Arslan et al. 2015). Understanding the stochastic nature of the production function, particularly due to weather realizations, will also be important in designing programs, such as insurance and inventory, to address the challenges of climate change. The second biophysical element is the externality function, which expresses the relationships between economic activities and the various externalities generated by them

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[2] We basically adopt the IPCC WGII AR5 definitions of vulnerability and resilience, as provided in Appendix 1. However, for conceptual convenience, we are defining vulnerability as a household-level characteristic, and resilience as a system-level characteristic.

(Zilberman 2014). In the context of CSA, the greenhouse gas emissions are the main, but not sole, externality considered. Various agricultural practices and investments also generate both positive and negative local externalities. Overuse of inorganic fertilizer generates greenhouse gas emissions and can also pollute local water sources (Norse 2012). Investment in soil and water conservation structures at the farm and ecosystem levels can generate positive spillover benefits to neighboring farmland productivity (Mirzabaev et al. 2015; McCarthy et al. 2012). Without effective coordination and collective action, too few positive spillovers, and too many negative spillovers, will be generated.

In analyzing both the production and externality functions, we recognize that agriculture is very diverse, and different sectors of agriculture (e.g. irrigated agriculture, rain-fed agriculture, etc.) will experience climate change differently. Livestock husbandry and fisheries will have unique challenges as well, and our analysis should strive to provide appropriate solutions that recognize specific contexts.

The behavioral constraints include market choices made by risk-averse individual agents (both inputs and outputs) operating in contexts where insurance markets are very thin or entirely absent. Our analysis will emphasize the importance of climate conditions on the supply and demand of various goods. The choices will be dependent on risk preferences and market conditions, as well as government policies. An important category of behavioral choices relates to decisions regarding technology adoption, including irrigation, seed varieties and production practices. Almost all empirical evidence suggests that uninsured risk and uncertainty leads to low levels of adoption of new technologies, and this behavioral constraint must be addressed if hoped-for wide-scale adoption is to be realized (Antle and Crissman 1990; Dercon and Christiansen 2011). Furthermore, adopting any new technology is often itself seen to be risky by the farmer who faces uncertainty about its performance (Foster and Rosenzweig 2010). Zilberman et al. (2012) note that, in addition to risk preferences, the diffusion of technology adoption as an adaptation to climate change will also be a function of heterogeneity in farmers' access to capital, the underlying agro-ecology, and prevailing institutions that can foster or hinder adoption.

Technology adoption and institutional innovations are also a function of political constraints. As Hayami and Ruttan (1971) emphasize, innovations of new technologies are outcomes of economic choices that are responsive to incentives and policies. Thus, the literature on innovation also emphasizes the role of learning in innovation and the evolution of new technologies, which in turn affect adoption. Political economic modeling suggests that government policy is affected by economic conditions as well as environmental and political considerations (Buchanan and Tollison 1984; Shepsle 1992; Rausser et al. 2011). These suggest that individual government policy choice problems are derived from their own political economy constraints so that the decision to implement policies that favor certain technologies over others will be a function of this political calculus. Where political weighting favors high economic growth, for instance, the technologies promoted may conflict both with resilience and low-emissions growth goals, for instance.

In addition to political economy considerations, additional political constraints will bound the range of feasible policy and legal actions to address climate change. Some policy solutions to climate change may not be politically feasible, and realistic policy design must consider feasibility of solutions within various local and global contexts. For example, it will be politically easier and it makes common sense to enact policies that improve human well-being and welfare regardless of climate change. A no-regret constraint may bind the set of policies that would be valuable under certain future conditions to those that also address pressing issues of food security or sustainable land use, thereby satisfying distributional and environmental objectives.

The institutional constraints include input, output and labor markets, property rights and tenure security, information dissemination systems such as agriculture extension and weather forecasting, credit and insurance markets and their regulatory framework, social safety net programs, environmental regulations, and the international trading system and local import, export, and foreign direct investment regulations. The institutional environment has a significant impact on farmers' incentives and ability to invest in agriculture practices with CSA characteristics and to adapt to climate change. Thin value supply chains limit farmers' ability to access inputs in timely fashion, and sell their output at a profit. Integrated supply chains can significantly reduce market price swings in response to extreme weather events, thereby reducing vulnerability of rural households to poor crop output and high food prices (Reardon and Timmer 2007). As discussed above, thin or absent credit markets, often combined with very limited insurance mechanisms, dampen incentives to make any types of investment on-farm, and limits the choices available to risk-averse farmers to adapt. Similarly, property rights systems that result in tenure insecurity also limit incentives to invest in land (Mirzabaev et al. 2015; Holden et al. 2009).

The ability to adapt to climate change will also be affected by the information dissemination system and farmers' ability to access weather forecasts and longer-term climate predictions and to incorporate that information into adaptation and coping strategies. Additionally, improving the resilience of the agricultural system as a whole will necessitate making investments and coordinating changing practices at scales higher than the household level. The ability to invest in larger-scale infrastructure to improve the resilience of a watershed (Bassist et al. forthcoming), or coordinating investments in tree planting or check dams across many small communities will depend on local property rights, land use regulations and powers of eminent domain, as well as environmental regulations. The ability to coordinate actions across communities will also be affected by collective active institutions and local-level governance structures (Meinzen-Dick et al. 2004; Pender et al. 2006). The ability to relax institutional constraints will be key in reducing household vulnerability and increasing system resilience in many contexts.

The optimization problem has several dynamic constraints as well. The first constraint is the dynamics of climate change. Because of the nature of agriculture, it is important to have an adequate assessment of climatic variation over space and time in order to make predictions of yields and outputs. There is much uncertainty in climate modeling and it must be incorporated into policy design. Thus, it is not sufficient to get average predictions of climatic patterns over time, but also some indication of variability and reliability thereof. Uncertainty of weather patterns is important because as Dixit and Pindyck (2001) suggested, the pattern and levels of uncertainty delay the optimal timing of investment. With uncertainty, decision-makers value additional information and are willing to wait some time for more information, which can lead to significant delays in investments. This compounds risk-averse farmers' disincentives to invest in land or adopt new technologies.

A second dynamic element is population growth, which affects demand for food as well as urbanization patterns, both of which are important determinants of optimal agricultural growth pathways. Human population growth is also behavioral to some extent and thus population dynamics must take account of behavioral parameters. Furthermore, population dynamics are subject to uncertainty so we must consider outcomes under several scenarios in assessing and designing climate change policies.

The third dynamic element is the ongoing transition in agriculture associated with globalization and the spread of information and technological advances. Global supply chains are spread everywhere, and the expanded use of the internet, cell phones, and improved transportation mechanisms are likely to continue. Technological change is especially important given the role of innovation and adoption in adaptation to climate change, but its diffusion will be a function of both political constraints as well as the need to adapt technologies to site-specific characteristics. One also needs to understand the workings of the supply chain innovations in different regions and how they can be utilized to introduce new technologies in response to climate change. While further integration and connectivity can increase agricultural system resilience by reducing, pooling and transferring risks, positive results will nonetheless be a function of the international and national level regulatory frameworks. To achieve food security objectives, such frameworks need to incorporate regulations that limit monopolistic/oligopolistic power and instead harness the risk-reducing benefits for everyone in the agricultural system, as well as effective enforcement mechanisms.

4 The Social Planner's Choice Set

Returning to the social planner's problem - to maximize constrained expected welfare - the social planner can take actions at the system level, or actions that alter incentives for farmers and other actors in the agricultural sector to adopt technologies and practices that improve welfare outcomes. With respect to system-level actions, the social planner can invest in providing a wide range of public goods that improve welfare and increase system resilience in the face of climate change, including: investing in CSA research and development; investing in large-scale infrastructure projects to increase system resilience to climate extremes and longer-term changes in weather patterns such as irrigation systems and flood control structures; investing in weather information systems; investing in disaster risk management systems, including restructuring social safety-net programs to explicitly incorporate payouts related to climate disasters; and, creating or amending laws and regulations regarding property rights, land use and zoning, contract farming, and insurance markets. At the system-level, improved risk coping measures include the design and implementation of disaster risk management plans at various government scales, rapid repair of damaged infrastructure, and, development of insurance instruments targeted for national and municipal governments.

Reducing household vulnerability and increasing system resilience can be accomplished through expansion and promotion of *ex ante* risk management strategies and/or *ex post* coping strategies. At the household level, *ex ante* risk management strategies include adopting SLM techniques; irrigation; drought, heat and/or flood resistant crop varieties and livestock breeds; and, diversifying land and labor activities. Measures that can be undertaken to improve the capacity of farm households to cope with shocks when they do occur include access to social safety net programs, access to attractive insurance instruments, and access to information and infrastructure to re-allocate labor to less affected areas. With respect to actions that affect farmers' incentives, potential actions include payment for environmental services programs; direct subsidies for adoption of certain investments and/or practices such as irrigation or SLM practices; and subsidies for inputs or participation in insurance schemes.

The social planner can also undertake actions to increase adaptive capacity and to pursue least-cost strategies of adaptation under an uncertain future climate, including the possibility of "weather migration". Adaptive capacity is a function of available risk management and risk coping mechanisms, but also includes broader measures to improve decision-making under uncertainty. Uncertainty increases the value of putting in place sophisticated monitoring and evaluation systems and continual learning (IPCC 2012) Greater adaptive capacity is associated with increasing the range of options to manage climate extremes and potentially changed climate patterns, and increasing the ability to exercise those options when needed. It should be stressed that the ability to exercise options when needed is often as critical as having options to begin with. For instance, many researchers find that it is precisely wealthier farmers who are more able to diversify their income sources, reconfirming longstanding findings in most sub-Saharan African countries (Davis et al. 2014; Arslan et al. 2015). So, allocating labor off-farm in response to a weather shock means not only that there are labor opportunities somewhere in the country, but also that farmers know where those opportunities are, can afford transportation, and have sufficient skills to be hired.

Resilience and adaptive capacity are complementary traits. Greater adaptive capacity can increase a system's capacity to recover from swings in climatic and biophysical conditions. But when the pressures exceed some threshold, adaptive capacity can also enable systems to change completely, to adapt through structural transformation, thereby enabling the people to survive and even flourish. Similarly, greater adaptive capacity can enable farm households to reduce vulnerability, but at some point, the best option may be for at least some family members to leave the agricultural sector or diversify their livelihood in order to best adapt to changing climate conditions. At the system-level, adaptive capacity will also be required to address potential mass migration from areas no longer suitable for agricultural production.

The above discussion on adaptive capacity and adaptation captures a major potential trade-off between pursuing strategies that enable farmers to improve their well-being in the face of climate change within the current agricultural system versus strategies that allow for the system itself to change in response to climate change e.g. the difference between incremental and transformative adaptation strategies (Adger et al. 2014). Insurance and safety net payments are classic examples of policies that enable people to better withstand extreme events within the current system. Access to irrigation, improved tenure security, and investments in flood control infrastructure all have similar impacts. In certain circumstances, particularly changes in weather patterns that make current production systems impossible or unprofitable, the social planner will have to determine whether to continue pursuing incremental strategies, or whether to accommodate and manage migration or promote a structural transformation in the production system.

Finally, the social planner can assess opportunities for pursuing low-emissions growth strategies. Certain practices, such as most sustainable land investments and practices, can generate both greater food security and lower emissions, though as noted above, current incentives are too low to foster wide-spread adoption in many countries. Low-emissions growth strategies that pose greater trade-offs with both immediate and long-term food security objectives require international financing, particularly given that most developing countries have contributed very little to cumulative GHG emissions. Where suitable and/or external financing is available, adaptive capacity will need to be built to foster a switch to low-emissions agricultural growth strategies.

5 Towards a Socially Optimal Solution: Expected Features of Model Outcomes

Optimizing welfare over multiple objectives that include all four elements of food security and potentially reduced GHG emissions first implies that the impacts of any potential policy action be evaluated for each objective, with the aim of identifying synergies and trade-offs. And, by inserting alternative solutions to this constrained optimization problem, we are able to evaluate their relative merits by comparing the balance of outcomes across a range of objectives from each of these proposed solutions, under a wide range of climate change scenarios. Evaluating outcomes across the multiple objectives will highlight the role of weighting these objectives in arriving at a solution, particularly where there are trade-offs. Assigning weights is a necessary step toward defining a socially optimal solution. The modeling exercise provides a framework for highlighting these weighting choices and can thus feed into climate change policy debates at national and international levels.

A second important outcome of this model is the implication that shadow prices of various constraints will allow us to consider alternative policies by changing the constraints and parameters of the system. The most valuable reforms are implied by the solution to the constrained optimization problem and resulting shadow prices. Business-as-usual scenarios can then be contrasted with scenarios under various types of policy reform that relax various constraints, which may induce either incremental or transformative changes.

This formulation provides us a starting point for our analysis and the type of solutions and research needed to inform it. Because of the increased importance of uncertainty, the solution strategy to this problem will involve adaptive learning. The decision makers have the capacity to learn from the past—and improve their estimation of key parameters over time as knowledge is accumulated—so data accumulation and learning will be part of the policy making process, and decision-makers may experiment with various policies to learn more about the system and its constraints. The random pressures on the system give rise to incentives to invest in adaptive capacity—solutions that will allow decision making to respond effectively to a wide range of potential outcomes. Adaptive capacity may include the ability to learn, analyze, and respond effectively. In many situations, it may be through increasing flexibility and adaptability of institutions, capital goods, and the population through enhancing human capital and reducing transactions costs associated with re-allocating resources (e.g. labor, money, goods), including effective information systems that reach all actors in the system.

6 Concluding Comments

In this chapter, we have attempted to lay out a conceptual framework to underpin the CSA concept rooted in agricultural development economic theories and concepts. We began by highlighting the key features of climate change that require a shift in emphasis in research, and for innovations in technologies, institutions, and government policies and programs. These changes include: (1) increased frequency and intensity of climate extreme events, with potentially disastrous impacts on already vulnerable smallholders dependent on rainfed agriculture, (2) permanent changes in weather patterns making certain areas unsuitable for agricultural production under existing conditions, and (3) the need to reduce emissions from the agricultural sector as a whole, while ensuring growth in the sector. These changes strongly highlight the need to consider the heterogeneity of impacts and to understand the implications of decision-making under uncertainty. They also point to the increased value of an expanded set of technological and institutional options to deal with both heterogeneity and uncertainty, and particularly to the increased value of flexibility broadly understood.

To set the framework, we began by viewing CSA as a welfare optimization problem. The problem has multiple objectives, namely the four pillars of food security, food availability, accessibility, utilization, and stability, as well as reducing emissions growth in the sector as a whole. The problem is also characterized by current constraints that bound the feasible outcomes, including bio-physical, behavioral, political, institutional and distributional constraints. Achieving better outcomes can occur by directly increasing food security, for instance by introducing technologies that increase yields and reduce yield losses in extreme years. Or, better outcomes can be achieved by relaxing key constraints. We also stress that the nature of the optimization, and thus adaptation strategies, are context specific.

Adaptation to climate change may take several forms: innovation and adoption of new technologies, adoption of existing technologies, temporary or permanent migration, changes of agricultural activities and trade patterns, and increased range of attractive and viable insurance products. Adaptation in most cases will also include addressing institutional failures and constraints such as reducing tenure insecurity, increasing access to relevant information, and improving the ability to coordinate actions across a watershed or ecosystem. And, some adaptation strategies will imply a discrete system-level change realized through broad-based structural transformation. While the solution cannot provide the exact changes in technologies or institutions that would result in the best outcomes, it can help to define the characteristics, or principles, associated with improved technologies or highly effective institutional structures and mechanisms.

Finally, we highlight that the solution to the social planner's problem for climate change must balance adaptation and responsiveness to uncertain climate change with the needed growth and food security objectives of the agricultural sector. Weighting the multiple objectives is essentially a political process.

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Innovation in Response to Climate Change

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Abstract Climate change impacts on agriculture are varied over space and time. The effects are heterogeneous and highly uncertain. Innovation in agriculture is clearly an important response for effective and equitable adaptation and mitigation – and we need to rethink how to promote innovation to address the heterogeneity and uncertainty of climate change impacts. In moving towards climate smart agricultural (CSA) systems in developing and developed countries, innovation will be key. For CSA we will need greater resilience in agricultural systems and also greater efficiency of resource use for both adaptation and mitigation. Technological innovation will need to play a key role – but its not enough. Managerial and institutional innovations are likely to be even more important in dealing with the heterogeneous and uncertain impacts of climate change. Innovation can complement other forms of adaptation to climate change to form CSA practices. In particular innovation can enhance technology adoption, may prevent or facilitate migration of production/population, enhance trade & aid, and increase efficiency of insurance & feasibility of inventories. We discuss their main features and the nature of innovation needed to align these actions with a CSA strategy.

1 Introduction

The evolution of agriculture in the future will be shaped by its response to climate change. Farmers need to adapt their practices to accommodate climatic conditions, and agricultural activities will need to be modified to reduce greenhouse-gas (GHG)

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emissions. But climate change is only one of the major forces that will change the future of agriculture. Others include population growth and increases in income as well as changes in human capital, knowledge, and infrastructure. Much of the change in agriculture will stem from new innovations, both in terms of technologies and institutions.

This paper aims to provide the background and analyze some of the challenges associated with the development and introduction of new innovations in agriculture and food systems in response to climate change. The analysis will emphasize the role of innovations in CSA. The first section will provide an overview of the impact of climate change and possible mechanisms in response to it. The next section will identify the major categories of innovation associated with CSA. We distinguish between technological, managerial, and institutional innovations and between micro (farm level) vs. macro (farm-system) innovations. This will be followed by a discussion of the barriers to introduction faced by these innovations, and a conclusion.

2 The Impact of Climate Change on Agriculture and the Implications

The research on climate change has identified several avenues that will affect agriculture. They include (1) rising temperatures around the world that lead to migration of climate from regions closer to the tropics to regions closer to the poles, (2) rising sea levels, (3) increased snowmelt and change in the volume and timing of water use for irrigation, and (4) increased probability of extreme events. We will next analyze the implications of each of these events and what they imply for the evolution of agricultural systems focusing on innovations, which are a crucial component for adaptation to climate change (Stern 2006).

2.1 Rising Temperatures and Migrating Weather

Depending on the range of mitigation actions taken in the next decades, we can expect that climate change will lead to increased temperatures throughout the world by 1–3 °C, which is equivalent to a shift of 300–500 km of weather patterns away from the equator and towards the poles. Similarly, temperature variability in regions at higher altitudes will also increase (Ohmura 2012). While climate change may have negative overall impact on agricultural production, the distributional impacts are much more substantial than the aggregate affect. Thus, for instance, some warm agricultural areas in Texas, Oklahoma, Mexico, and Western Africa will become unviable for crop production. While at the same time, regions in Russia, Canada, and even the Arctic will become suitable for agricultural production. Innovations to respond to changes in temperature may involve adopting new crops and varieties in some areas, to migration away from regions unviable for agricultural production in others, or investment in infrastructure and other activities in new regions. The effect of weather migration will not be limited to plants, but rather felt across multiple species. For example, temperature serves as an important barrier to prevent pest infestations and while insects and other pests can move in response to changing conditions, trees are stationary. Pest migration can endanger viable tree-based economies and will require monitoring and interventions (Porter et al. 1991). The people displaced because of these trends may not be the ones that are able to take advantage of new opportunities presented by climate change. Development of new technologies and other economic activities to facilitate adaptation to climatic changes and amelioration of painful displacement will be valuable. Innovations to adapt to migration of weather will vary across location reflecting spatial heterogeneity. In some areas, new solutions will be required to address movement of pests as well as to modify crop varieties to adjust to changing weather conditions. In other areas, entirely new crops may need to be introduced. Finally, in some regions mechanisms may need to be introduced to facilitate out migration of people. The design and implementation of these solutions is challenged due to uncertainty about magnitude and timing of change.

2.2 *Rising Sea Levels*

Sea level rise (SLR) may lead to loss of high value agricultural land as well as important infrastructure that is crucial for exporting and importing food in many regions throughout the world. An estimated 10% of the world's population lives in coastal zones (i.e. at less than 10 m altitude), with wide variation in share of population by country, representing 14% of global GDP (McGranahan et al. 2007). Most notably, close to half of Vietnam, Bangladesh, and Egypt's populations live in these zones, while China and India, with a far smaller portion of overall population, contain over 200 million people living in these zones. The population impacted by SLR will vary significantly by actual rise in sea level – from 56 million people (1.28% of world population) with a 1-m rise to 245 million (5.57%) with a 5-m rise (Dasgupta et al. 2009). Also, large tracts of prime agricultural land will be threatened by rising sea levels especially in tropical regions (Kurukulasuriya and Rosenthal 2013). Given heterogeneity across location, it is important to develop location specific solutions. In areas especially vulnerable to SLR, transformational innovation may be required rather than incremental approaches in order to spur adaptation and protect vulnerable populations (Kates et al. 2012). In few areas, vulnerable coastal regions may be saved by investment in protective infrastructure (e.g. dikes, dams), but in many cases vulnerable areas will need to be abandoned causing problems of displacement. In some areas, there may be opportunities to adopt different types of agricultural production, but these will require innovation.

2.3 Increased Snowmelt and Timing of Irrigation

In addition to changes in precipitation patterns, increased temperatures will increase snowmelt, decreasing the possibility of using water stored in snow accumulated during the wet season to be available for irrigation during the dry season. Furthermore, the likelihood of flooding may increase. Given the relative importance of irrigated agriculture during dry seasons in many parts of the world, this change may have significant impact on food supply, unless some remedial measures are taken. These solutions are dependent on the conditions at each location. Solutions may include investment in new forms of water inventories and storage, for example dams for flood control and storage as well as diversion of water to underground reservoirs. These changes may also prompt changes in crop timing and selection to adjust to water availability. Furthermore, changes in water availability may also affect availability of hydroelectric power for irrigation, which will also affect agricultural supply (Xie et al. 2015). Thus climate change will prompt re-arrangement and new management of agricultural water supplies (Grafton et al. 2013; Chartzoulakis and Bertaki 2015; Basist er al. forthcoming). The substitution of snow as water storage will require significant investment under conditions of uncertainty and require innovative approaches to financial, institutional, and physical structures applying and extending the option-value approach of Dixit and Pindyck (1994).

2.4 Increased Probability of Extreme Events

In addition to the changes in average temperature as well as water availability, climate change is likely to shift the climatic distribution that will increase the probability of extreme events, such as heatwaves, heavy rainfall, storms and coastal flooding. Furthermore, climate change is a gradual process. While average conditions may be changing gradually, there may be increased variability of climatic conditions (Fischer and Schär 2009). There is already evidence of such changes and they require a higher degree of resilience of farmers to fast changing conditions. This requires both innovative efforts in terms of new technologies and management practices, as well as capacity to adopt these technologies and thus enhance resilience.

Furthermore, there is a risk of climate change triggering a tipping point that will lead to abrupt and irreversible changes that increase in severity with rising temperature (IPCC 2014; Barnosky et al. 2012). Such very low probability catastrophic events may include, for example, drastic rise in temperature (of 6 °C and beyond) because of sudden release of methane gas resulting from the loss of permafrost (Lenton et al. 2008). Such extreme events may devastate agriculture throughout much of the world. Nevertheless there is a need for continued research to develop agricultural production and storage systems suitable for more extreme climate conditions as well as institutions for emergency responses that include movement of people and other living creatures and relocation of resources.

2.5 Discussion

As emphasized above, the nature of innovative responses to climate change impacts need to adapt to two characteristics of these impacts. The first is *heterogeneity*. Different regions are affected differentially by climate change: for some desert or low-lying coastal region climate change may be devastating, while for other cold region, climate change may be perceived as "climate improvement". These differences in impacts, as well as differences in gains and losses from engagement in mitigation activities, may contribute to the diverse responses and willingness to participate and contribute to coordinated efforts to avert or slow climate change. Weitzman (2009) studies the economic significance of catastrophic climate change and argues that regardless of the differential impacts of likely climate change scenarios on various regions, humanity as a whole needs to take action to prevent some low probability catastrophic outcomes.

The second factor that affects engaging in action addressing the climate change challenges is *uncertainty*. The timing, magnitudes and locations of different impacts of climate change are not known with certainty. At the same time, there is a wide body of literature that suggests that farmers and other agricultural actors behave in a manner consistent with risk aversion. Sandmo (1971) suggests, in a static framework, that risk aversion reduces the magnitude of actions taken by risk averse enterprises as the risks they face increase. The real option approach of Dixit and Pindyck (1994) argues, within a dynamic setup, that higher uncertainty about future outcomes will lead to a delay of actions. Thus, the uncertainty surrounding the impacts of climate change tend to delay and reduce the magnitude of activities aimed to adapt to and mitigate it. Uncertainty about possible impacts of climate change also increases the need for further research (Dixit and Pindyck 1994) to reduce the uncertainties surrounding climate change.

Heterogeneity and uncertainty will thus increase the difficulty of identifying the full range of responses to climate change from observable data, especially at the present when some of the impacts of climate change (e.g., migration of warm weather toward the pole and a significant rising sea level, triggering of tipping points leading to irreversible changes) are more likely to occur in the longer run—2050 and beyond. Others, for example, that increase the likelihood of extreme events, like flood and droughts, might have already started to occur and are more likely in the near future.

The investment in innovative activities to address the challenges of climate change will evolve over time as knowledge accumulates. The innovative approach must consider new technological and institutional options but also the changes in behavioral responses to climate change and related solutions over time.

We can learn from the responses thus far on some activities, the capacity to adapt to climate change in the future, and the factors that affect responses. The empirical case studies in these chapters cover lessons that have analyzed responses to climate change thus far and their implications for innovation, including technology adoption and adaptation, insurance schemes, and diversification of land and labor, and to a lesser extent internal migration. While these case studies cover a subset of adaptation options for which there is solid empirical evidence in developing country contexts, there is a broader range of adaptation activities that we will also cover, including external migration, use of trade and aid policies, and physical inventories.

3 Innovations for Climate Smart Agriculture

There are many ways to categorize innovations (Sunding and Zilberman 2001). Economic growth theory distinguishes among technologies depending on their impact on inputs and outputs. For example, distinctions can be made between capital saving, labor saving, quality improving, and risk reducing innovations. Another way of distinguishing innovations is according to their form, e.g. technological, managerial, and institutional innovations. Technological innovations are embodied in new machinery, and can be further divided into mechanical (e.g. tractors), biological (e.g. seeds), and chemical (e.g. fertilizers) innovations. Managerial innovations are not embodied in physical capital, but rather are described by better practices such as Integrated Pest Management, improved pruning techniques, and crop rotation. Institutional innovations may include new organizational forms (e.g. cooperatives) and arrangements for trading (e.g. future markets and contract farming). Because of the heterogeneity and randomness of climate change impacts, there are several types of innovation that will be especially valuable, and the following section outlines many of these innovations. Below we present and analyze the innovations that are likely to be required to adapt to climate change. We classify them in three categories: technological innovations, managerial innovations and institutional innovations. The technological and managerial innovations are divided into micro–farm level innovations and macro-farm system innovations. All the institutional innovations we consider are at the macro level.

3.1 Technological Innovations

3.1.1 Micro, Farm-Level Approaches

Resilient crops and livestock Because of rising temperatures and increased variability, development of new crop varieties and livestock breeds that can tolerate these changes will be very important. Due to the frequency of change, it will be important to detect change and develop genetic material that can adapt to this change relatively fast.

Pest control The migration of pests may prompt the need to develop new pest management techniques, which are both environmentally friendly, cost-effective, easy to use, and efficacious. A diverse approach utilizing biological, mechanical, and chemical control, in concert with genetic approaches, will be needed. An on going effort to identify emerging pest problem will need to guide the development these pest control innovations.

Input use efficiency enhancing technologies Frequently, there is a significant gap between the level of applied inputs and the amount utilized by the crop. For example, with flood irrigation, input use efficiency may be 50%, but with technologies like drip irrigation, efficiency may increase to 90%. Frequently the residue (i.e. the input not taken up by the crop) is a source of externalities. Khanna and Zilberman (1997) suggest that adoption of input use efficiency enhancing technologies tend to increase yield, save input, and reduce pollution. Better application technologies may reduce water, fertilizer, and chemicals while reducing the side effect associated with their use. The notion of input use efficiency enhancing technologies applies to crops and even livestock. Some crop varieties may increase output while the change in feeding regimes for livestock may decrease greenhouse gas emissions.

On-farm storage Parfitt et al. (2010) suggest that there is significant post-harvest loss on the farm and much of it occurs among subsistence farmers in developing countries that lack basic storage capacity. Innovative on-farm storage infrastructure can help address yield losses brought on by increased temperature as well as increased frequency of shocks. The challenge is to design systems that are affordable, easy to install and operate, and reliable. The design of the system must address heterogeneity in bioclimatic conditions.

Higher yield and longer shelf life Crop varieties, as well as livestock, that increase yield per area tend to reduce agricultural footprint and the effort required to compensate for production loss due to climate change. Longer shelf life would decrease transportation costs, storage costs, and, especially, waste associated with agricultural distribution. Shelf life enhancement is important in the context of climate change because increased temperatures increase the likelihood of spoilage.

Sustainable Land Management (SLM) Frequently, agricultural practices in developing countries lead to reduced soil quality. Extreme weather associated with climate change may worsen this problem unless improved agronomic practices are introduced. SLM practices aim to increase yield without degrading soil and water resources. In addition, they aim to sequester carbon. There are already several SLM practices such as organic fertilization, minimum soil disturbance, and incorporation of residues, terraces, water harvesting and conservation, and agroforestry (Branca et al. 2013), but there are many opportunities for developing new SLM practices and refining existing ones to accommodate spatial and climatic variability.

3.1.2 Farm System Approaches

Low-cost flood protection and water storage facilities Because of the concern of rising water level, and the resulting instability due to floods, innovation that reduces the cost of protection against rising water levels and floods will be a priority. In assessing such investments, it is important to consider the benefit of avoided conflict due to reduced climate migration.

Weather information distribution technologies There is significant evidence that availability of weather information, including its implications on irrigation (evapotranspiration losses), enable farmers to modify their irrigation and pest control strategies which lead to significant increases in yield and saving of water and other inputs (Parker and Zilberman 1996). Reliable weather information will be especially important during periods of heightened climate change during which farmers face greater uncertainty of weather patterns. But information about weather systems requires both weather stations as well as delivery systems that provide useful and reliable information across many users. This system must be affordable and fit the needs and capacity of poor farmers.

Improved mitigation Reducing GHGs is a key to effective adaptation to climate change in the long run, and an important CSA goal and thus it includes innovation and adoption of cultural practices, crop varieties, management practices, and institutions that will accelerate mitigation. Already, the transition to no- or low-tillage practices has been considered a major source of carbon sequestration, and adoption of higher yield varieties and conservation technologies that reduce the land, atmospheric, and fossil fuel footprint of agriculture is another important mitigation strategy (Lal 2011; McCarthy et al. 2012).

3.2 Managerial Innovations

3.2.1 Micro, Farm-Level Approaches

The differences between technological and managerial innovations are not clear cut. New machinery or input require innovative management practice to be effective and adopted. Here we will emphasize innovation that mostly emphasize improve management – but may also involve use of new technologies.

Input use efficiency management techniques The efficiency of water use or chemical input can be significantly increased through the adoption of information intensive management practices that optimize the timing and quantities of application of inputs. Precision technologies vary variable input application over space and time based improved monitoring of field and weather conditions. Dobermann et al. (2004) suggest that precision farming may save input and/or increase yield and that both mechanisms for monitoring spatial or other sources of variability and methods to utilize this information have a large potential for further improvement. Development of precision techniques for resource poor developing countries is a special challenge as they may be the major beneficiary from these techniques.

Integrated Pest Management (IPM) The likely increases in pest pressure because of climate change may require new technical solutions but also increase effectiveness of pest management in terms of detection and coordination of pest control activities. IPM emphasizes measurement of pest pressure and integration of alternative approaches (cultural practices, chemical, genetic modification and biological) to optimize the net benefits of treatment, taking into account pest dynamic and environmental side effects. The adoption of IPM is constrained by the cost of monitoring pests and difficulty of tailor-made IPM approaches specific to bioclimatic conditions (Waterfield and Zilberman 2012). The effectiveness of responses to climate change will benefit from the development of affordable and easy to implement IPM strategies.

Land use and on-farm management practices Changes in both the mean and variability of climatic conditions accompanied by changes in technologies and economic conditions will require improved management tools used to facilitate the selection of crop types and crop varieties, allocation of land among crops, and selection and implementation of production practices. The improvement of quality of data, computation capabilities and communication will provide opportunities for introducing new management tools that are affordable and accessible even to small farmers in developing countries.

3.2.2 Farm System Approaches

Local collective action for improved input use and management Management practices like IPM, SLM and improved input use efficiency require a knowledge base that is shared by many farmers. For example, both IPM and improved water use efficiency rely on weather information that may be collected by regional weather stations. Developing strategies to address crop diseases as well as controlling build-up of resistance to pest control will require collective action. Effective land use management should take into account externalities among crops and other production activities within a region. Therefore, development of regional institutions for collaboration that will allow for the provision of public goods and capturing economies of scale among small producers will be of high value. Poteete, Janssen, and Ostrom (2010) provide multiple forms of institutions to address various collective action challenges in the development context, but different situations may require different solutions and there are many opportunities for innovative institutional designs to address emerging climate change challenges.

Insurance Products The decreased stability of weather due to climate change raises the value of risk management strategies. For example, Mendelsohn (2006) suggests that crop insurance can be a good strategy to cope with increased risk. Golden et al. (2007) suggest that using weather derivatives and similar financial instruments can be an effective mechanism to address climate change related risk. The story of Joseph in the Bible illustrates the role of inventory as mitigating weather variability; similarly, there is a large literature on the economics of storage management in agriculture (Williams and Wright 2005) that applies to increased weather instability.

The implementation of insurance as an adaptation mechanism is quite challenging. First, risks associated with climate change are difficult to quantity – risks are dynamic, rather than static, and the parameters of key variables change over time and cannot be predicted reliably (Patt et al. 2009). Furthermore, Millner et al. (2010) suggest that some impacts of climate change cannot be captured well by a standard probability distribution, which makes actuarial computation even more challenging. Second, insurance may affect other adaptation strategies. It may lead to a moral hazard by reducing precautionary activities, while other adaptation strategies may reduce the need for insurance. Thus risk and adaptation strategies must be designed simultaneously (Tol 2009). Third, implementation of insurance may require good monitoring of behavior to overcome adverse selection. The design of mechanisms to adverse selection is especially challenging when distributions of risks are evolving or partially unknown. Finally, agricultural insurance programs have served as rent seeking mechanisms (transferring income) indicating that their efficiency has been questionable (Schmitz 2010; Krueger 1990). Thus, the development of insurance strategies to address climate change must proceed with caution.

Resilient supply chain management Design of appropriate supply chains is essential to enhance effective adoption (Lu et al. 2015). Agriculture in developing countries is going through a food system revolution characterized by the introduction of new rationalized supply chains that enable better storage and allow for product differentiation and link farmers in developing countries with super markets (Reardon and Timmer 2012). This modern supply chain led to the adoption of many innovative practices and a substantial effort must exist to enhance supply chains further to allow for coping with the effects of climate change.

3.3 Institutional Innovations

Institutional innovations occur at the macro, *farm system* level. We can distinguish between two types of institutional innovations: (1) Institutions that will enable innovation processes. Some of these institutions that are part of CSA innovations themselves are discussed in this section. Institutional innovations that address the limitations of the existing systems are discussed in next section on ‘Overcoming Barriers to Innovation in the Era of Climate Change’. (2) Institutions that will allow implementing other elements of adaptation strategies besides innovation and adoption.

3.3.1 Innovations as Part of CSA Programs

“Climate Smart” extension programs Innovations are mostly concepts that present new ways of doing things within a context. To be implemented, innovations must be developed, upscaled, and then tested at the implementation level. A program of

marketing and education is then needed to bring an innovation to practitioners. Different countries have their own innovation systems, which are adapted to different types of innovations and contexts (Nelson 1993). The implementation of CSA may require innovative design of networks that will extend the technology from the scientists to the practitioners and this extension effort should include not only the public extension service, but also private firms, cooperatives, and NGOs.

Integrated Pest Management at relevant ecosystem scale Pest control activities generate externalities, especially given the small scale of farms and the movement of pests. These externalities may be positive, for instance through pollination, or negative, for instance through the build-up of resistance. There are some activities that require the full spatial coordination among farmers, such as pest eradication plans (Waterfield and Zilberman 2012). The introduction of CSA pest management programs may require innovative efforts to identify and monitor their possible externalities and develop mechanisms to control them.

Land use regulations and management at ecosystem scale Agricultural production have significant environmental externalities, including chemical contamination of bodies of water and soil erosion, as well as damage to ecosystems and wildlife. The introduction of CSA activities without considering and addressing their potential side effects may lead to counter-productive outcomes. Therefore, innovative efforts are required to design systems of education and regulation to design and implement systems of regulation and implementation that will monitor the externalities of CSA and control them.

3.3.2 Institutions for Enhancing Various Adaptation Strategies

Trade regulations International trade results from differences in relative advantage between regions and is a risk sharing mechanism. Climatic changes and shifts in weather patterns, may result in crop production patterns that will lead to changes in trade. For example, Aker (2012) finds that increases in trade ameliorate the impact of drought in West Africa. A region with a warming climate may switch from growing wheat to corn, export the corn, and import wheat. Changes in trade patterns resulting from climate change may have significant distributional implications. Innovative frameworks that are able to identify new trade opportunities, their implications, and barriers to its implementation will be of importance. The capacity to utilize trade in response to climate change depends on infrastructure (e.g. availability of transportation and processing facilities) as well as international trade policies and institutions (Zilberman et al. 2012). New innovative frameworks can identify, for example, new infrastructure requirements and how to implement them and institutional arrangements that will provide an enabling environment for new trade opportunities.

Aid distribution mechanisms While trade is an exchange between two parties, aid is a transfer from one party to another. Even still, aid can play an important role as a mechanism to address risk associated with climate change. Like trade, the capacity of aid to address climate change depends on the availability of efficient transportation as well as accurate detection and response systems (Donaldson 2010). Both aid and trade could serve as substitutes to migration as a response to climate change. Research and development may lead to innovations that enable trade or to mechanisms that facilitate provision of aid in times of crisis while maintaining overall social welfare. Innovative approaches that reduce the cost of implementation and increase the effectiveness of aid mechanisms is especially important given financial constraints on such efforts.

Movement of water resources (management and conflict resolution) Climate change may drastically change precipitation patterns, as well as lead to significant melting of snow packs, and thus lead to changes in water availability over space and time, water movement and storage patterns. These changes will occur both within and between countries. It will raise issues of property rights that have to be sought and solved before they lead to conflicts. Furthermore, the institutions that currently own and distribute water will lose capacity, and some of them will get into severe financial troubles, as they would not be able to meet their obligations. At the same time, there will be a need to design and develop new water facilities and water distribution organizations that will be able to address the new reality.

Addressing these challenges require significant institutional innovations. There will be a need to develop insurance mechanisms for water districts and other water suppliers against the hydrological risks faced, as well as the resulting financial losses. As the knowledge about the changes in water supply and storage patterns emerge, there will be a need to rethink water infrastructure and supply. Designing water systems is a lengthy process and an early start may provide significant edge. The work of Xie and Zilberman (2016) shows that the investment in water project capacity is affected both by changes in water availability as well as the investment in water technology and thus regional planning of water systems is needed prior to the investment in water system modification.

One of the most challenging aspects of water resource management is the assignment of water rights. Traditional water rights systems, established during periods of water abundance and under colonial arrangements, can be an obstacle to efficient development of water resources (Schoengold and Zilberman 2007), and water right reform is essential for improvement to allocation. Legal and policy research that lead to innovative water right reform will be an important step in designing and implementing strategies to address water supply implications of climate change.

Insurance regulations Risk and uncertainty are the most challenging aspects of climate change. New designs of institutions to address these two facets are a major challenge. It is especially important to develop mechanisms that ensure farmers have insurance against extreme events. Much of the literature on crop insurance argues that it serves frequently as a subsidy rather than insurance *per se*, and farmers tend to undersubscribe to insurance schemes that are self-supporting. Furthermore, subsidized insurance may lead to engaging in risky and environmentally damaging behavior (see survey by Smith and Goodwin 2013). There are new forms of index-based agricultural insurance, but thus far, the quality of their performance has been questionable and there remains a significant need to redesign them (Binswanger-Mkhize 2012). With new sources of information and improved communication technologies, the continued redesign of various forms of insurance is a major challenge for interdisciplinary research and practitioners alike.

Social safety nets A higher frequency of extreme events and loss of livelihood due to changing weather may cause farmers to loss their main sources of income, and in many cases food for subsistence. Society will need to design innovative approaches to sustain individuals and communities that experience significant loss as a result of climate change. These approaches must enable them to survive through tough transitional periods while also providing the foundation for re-engaging in the economy. The design of safety net mechanisms may consist of emergency intervention, relocation, insurance arrangements, credit and financial products, and job training. These mechanisms need to be able to adjust to varying conditions and to recognize the limited capacity of the poor to utilize such assistance and insurance while also having rapid response times in order to be effective (Dercon 2002).

Incentives for farmer-level adoption The most important factor that affects adoption of new technologies is incentives. There is growing research to introduce innovative policies that will provide farmers the incentives to utilize new technologies, engage in preventive practices to reduce the risks of climate change, and adopt resilient new varieties and activities most appropriate for the challenges posed by climate change.

Adoption of existing and new technologies is a crucial element of mitigation of and adaptation to climate change. There is evidence that many barriers to adoption of new valuable technology exist, which are discussed in the literature (Zilberman et al. 2004). New information and communication technologies provide new opportunities to improve the ways that new technologies are introduced and marketed to enhance adoption. These technologies can be used to improve the information that farmers have of new technologies, accelerate the learning curve of using technologies efficiently and effectively, and reduce the fit and reliability risk associated with these technologies. Innovative approaches may be applied by cooperative extension as well as the private sector.

Migration Since climate change will result in relocation of people, design of mechanisms and institutions to facilitate peaceful migration and relocation will become important. As the 2015 migration crisis[1], resulting from the Syrian war and other problems, in Europe suggests, accommodating immigrants is a major policy challenge. Mechanisms to address the increase in migration due to climate change will be a priority of climate smart policy. According to Docherty and Giannini (2009), there is an urgent need to develop innovative approaches to address the climate change refugee problem. They call for a new legal instrument that will establish the

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[1] See for example: "How Climate Change is Behind the Surge of Migrants to Europe" Time Magazine, September 7, 2015.

human rights of climate refugees, mechanisms for humanitarian aid, and develop criteria to share the burden of relocating climate refugees, as well as financing the relocation efforts. Because climate change will also create new agricultural opportunities, it will be ideal to develop an institutional framework that will enable farmers, especially within regions, to relocate from locations that suffer from climate change to ones that offer new opportunities. The development of institutions to address migration and relocation requires multi-disciplinary efforts and international collaboration and it is a major and urgent challenge.

4 Overcoming Barriers to Innovation in the Era of Climate Change

Practitioners have been a major source of innovations throughout history. For example, the wheel, crops for cultivation, and initial farming practices were identified and improved by practitioners. However, science and research are becoming major sources for new innovations in the modern era (Harari 2014). Still further, in the case of climate change, it is important to accelerate the innovative process so that new solutions will be available when and where climatic changes materialize. Scientific research has contributed to the development of new forms of engines, electric appliances, and new medicines, as well as fertilizers and new crop varieties. The innovation process goes through multiple stages. In the case of technological innovation, the process begins with research activities that lead to discoveries of ideas, which are at the core of new innovations. Then through the development process, ideas are refined, tested, and scaled up through further experimentation. For many biological and chemical innovations, the development process also includes government approval for use before commercialization. Upon product feasibility and approval, it is commercialized through activities of production and marketing. Consumers begin to adopt the product, both using and evaluating it, and their feedback leads to product refinement and further innovations. This mostly linear characterization ignores feedbacks and interactions (Etzkowitz 2010) but provides a useful framework to consider some of the major challenges faced by new innovations. In the case of managerial and institutional innovation, the innovation process may also start with research activities that identify alternative options to solve a problem, for example, through economic research or decision theory. Once solutions are identified, there will be a process of experimentation. Managerial and institutional innovations are frequently introduced gradually, for example the reforms in China were first introduced in one location and then spread gradually (Rozelle 1996). The recent increasing use of randomized controlled trials is another mechanism that exist for the introduction and diffusion of new managerial and institutional innovation.

A viable and effective research infrastructure contributes significantly to the introduction of new innovations. The theory of induced innovation suggests that the selection of research priorities is affected by the potential economic gains from innovation and the relative effort required to attain the desired outcome. But obtaining basic research results is not sufficient to achieve practical innovations. The stage of development in scaling up results often requires more funding than the basic research. It requires organization that has the resources necessary to carry out this process. In the developed world, the public sector is more dominant in the research stage while the private sector (start-ups and multinationals) is more dominant in product development and commercialization. Because of the significant investment associated with development, companies would not otherwise engage in it absent some assurance of economic benefit from its outcome, such as intellectual property rights. This assurance is a major reason behind technology transfer from universities and research institutions, through offices of technology transfer, to the private sector (Graff et al. 2002).

The commercialization effort and investment in establishing a supply chain, which includes manufacturing, distribution, and retail outlets, for new product distribution may be more significant than the development of the product itself (Reardon and Timmer 2012). The development of the supply chain, and its subsequent patterns of production and marketing, may vary across products and locations. The private sector will not engage in development of such supply chains without the expectation that investment will result in a positive net return of capital. The private sector is more likely to invest in innovations that are directed to the needs and wants of the developed world than the developing world. For example, the higher willingness to pay by consumers in developed countries for high quality agricultural products may lead the private sector to invest more in innovations that are targeted towards these markets. Research may lead to innovation that will reduce the cost of establishing new supply chains that facilitate a faster adaptation to climate change as part of CSA.

The above analysis suggests that several barriers exist to selecting and implementing climate smart agriculture innovations that will meet the need for growth in agriculture to meet food demand and contribute to poverty reduction in developing countries. The following section presents specific barriers organized by (i) research, (ii) refinement, and (iii) commercialization, approximating the rough order of progression of an innovation.

4.1 Research and Refinement

Knowledge and technology The development of production practices as well as new crop varieties that may enable adaptation to climate change require knowledge that combines understanding of crop systems, current and alternative practices, and biophysical constraints for a given location. Thus, it is important to invest both in basic research as well as applied development efforts especially because the private sector is less likely to tend to the problems of developing countries. The Consultative Group on International Agricultural Research (CGIAR) centers emphasize research on the challenges of the developing world, and national agriculture research centers are supposed to focus on the application of innovations to local needs. However, while this bifurcated system had significant achievements during the Green Revolution, it is unclear to what extent it can meet the challenges posed by climate change. The system was not designed to withstand larger shocks and the increased degree of uncertainty and variability that are associated with climate change. It has not emphasized climate science and building large capacity to adapt to varying conditions. While this system provides a good foundation to local research and innovation, the extra benefit from extra knowledge because the growing risk of climate change suggests that this system should be reevaluated and strengthened (Sanchez 2000).

Many of the technologies required to adapt to and mitigate climate change are developed at universities in the developed world. Developing of mechanisms to accelerate the transfer of knowledge to action in developing countries coping with climate change problems is a major challenge. But to be effective, technology transfer should include local adaptation and adjustments. Furthermore, a key challenge is to develop systems that will incorporate local and traditional knowledge in agricultural production systems. Thus, new systems will incorporate modern methods with traditional models adjusted to local conditions (Nyong et al. 2007). It requires enhancing human capital and research capacity at universities in developing countries, engaging developing mechanisms to identify local knowledge to innovation systems and providing ongoing support for collaborative research between universities.

Intellectual property rights One of the main challenges associated with transfer of information is that much of it is proprietary and thus protected by intellectual property rights. However, several mechanisms exist to address this situation. First, much of the innovation, especially in the area of biotechnology, was generated at universities that sold some of these rights to the private sector (Graff et al. 2003). However, the licensing frequently does not cover application to crops for use in developing countries. And thus, establishment of a clearinghouse would serve to facilitate the transfer of public control intellectual protection rights for use in developing countries can go a long way to solve the IPR challenge (Graff and Zilberman 2001). Indeed, some facilitating organizations for technology transfer exist, including Public-Sector Intellectual Property Resource for Agriculture (PIPRA) and African Agricultural Technology Foundation (AATF). Here should also raise the international treaty for plant genetic resources.

Fit One of the major barriers of technology is that technologies may not fit the specific needs, preferences, or capacities of the intended adopters. Much of the effort of marketing is to reduce fit risk (i.e. probability that the technology is not adopted) through demonstrations, return policies, education & training, etc. (Zhao et al. 2012). However, lack of fit may arise from inappropriate design that does not take account of the needs and desires of the particular population. Therefore, there exists a place for participatory research and wide engagement of community in product design and introduction. This approach builds a bridge between the innovation and extension of the technology. One of the major factors of success of drip irrigation in some regions is that cooperative extension worked with practitioners to redesign complementary aspects of the production system so that the new irrigation system would fit with other components of the extant system. Venot et al. (2014) argue that for a technology to be successfully adopted, the production system and technology must be re-designed to incorporate the multiple contexts and practices of the specific location.

Financing The innovation process serves as an investment to produce new procedures and institutions that can help address climate change. Each stage of the innovation process requires finance, often in unique ways for research, development, production, and adoption. Because mitigation and adaptation to climate change have properties of public goods (as we argued, climate change may result in damage to public infrastructure and human life throughout the world), the finance should rely on public sources in addition to private ones. The role of public finance may be more essential in some aspects of the innovation process (e.g. basic research). But since much of the technological innovations associated with climate smart agriculture will be introduced in developing countries, development of targeted funds to facilitate adoption will be a major priority. For example, this can be accomplished through financial mechanisms[2] that support innovations and adaptations to climate change in the developing world.

4.2 Commercialization/Adoption

Knowledge dissemination systems Dissemination of new technologies in developed countries is done jointly by the public and private sector (Wolf et al. 2001). Farmers receive information about new technologies from agricultural media, commercial vendors, cooperative extension, and commodity associations. Frequently media processes information obtained from cooperative extension. Different sources of information have varying degrees of reliability while also highlighting different aspects of some technology (Just et al. 2002). In many developing countries especially vulnerable to climate change, the knowledge dissemination system may be lacking. For example, the private sector may not invest in distribution networks, extension services may be understaffed and underfunded, and access to information from media may be limited. Frequently, the introduction of new technologies will require the development of a dissemination system. Dissemination will improve with investment in extension services and a communication network.

Limited incentives for farmers to adopt innovations Many of the innovations that are associated with CSA address problems of externalities and public goods. For example, innovations that lead to a reduction of GHG emissions provide a public good. When externalities or public goods exist, there are likely to be problems of market failure. In particular, adopters will not capture the social benefit associated

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[2] a la the Clean Development Mechanism of the Kyoto Protocol that is well-designed.

with reduction of externalities or provision of public goods. Thus, policy interventions are needed to incentivize and enhance adoption. Mechanisms suggested by environmental economists (e.g. financial incentives, direct control, subsidies, voluntary agreements) require design of policies that take into account financial and institutional arrangements (Hanley et al. 2007). The new knowledge of behavioral economics suggests the value of nudges (positive reinforcement and indirect suggestion) as a mechanism to enhance adoption and utilization of new innovations (Thaler and Sunstein 2008).

Limited incentives for governments to adopt progressive regulatory regimes Because climate change may require introduction of new varieties and new crop production systems at various locations, and changes may occur frequently over time, capacity to innovate and adopt in a timely matter will be important. One of the major barriers to introduction of new varieties is a regulatory that hinders dynamic growth. Regulations are of prime importance because much of agricultural technology may pose unforeseen risks. However, the regulatory process may be too lengthy and costly and hinder the creation of institutions that accelerate innovation, such as CSA practices. Efficient regulation should balance risks and benefits, taking account of precautionary measures,[3] but also take into account the cost of not implementing a new technology.[4] A regulatory system should be designed to avoid bureaucratic redundancy and to be transparent. One of the challenges of introducing a portfolio of technologies within CSA is to design and build human capital and procedures to ensure effective implementation with appropriate safety mechanisms (Rennings 2000).

The challenge of regulatory systems is in adjustment of regulation and policy to account for variability of conditions within agriculture and the heterogeneity of impact as well as the uncertainty not only with technology vis-à-vis climate change but also the need for technology to be able to adjust to diverse conditions and respond to unexpected random shocks. A flexible system of regulation would include insurance, credit, land use and property right regimes similar to those described in this chapter, thus acknowledging the challenges of implementing innovations that adequately address the impacts of climate change.

Finance The literature on adoption recognizes credit constraint as a major obstacle to adoption of new agricultural technologies, especially for the poor in developing countries who are further among the most vulnerable to the effects of climate change (Zilberman et al. 2012). Availability of credit depends on an individual's capacity to repay loans with income generated by the technology financed. When CSA does not increase significantly the expected profitability or earned income, but mostly serves to decrease risk or reduce externalities, financial constraints will be even more binding. This constraint can be relaxed through policies that provide increased availability

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[3] For example, using a risk threshold that may occur at 1%, or even lower, for risk analysis (Lichtenberg and Zilberman 1988).

[4] The regulatory delay on the introduction of golden rice is an example of the cost of excessive regulation of a new technology that has the potential to benefit the poor.

of credit directly or by paying for environmental services associated with adoption of the technology.

Certification Innovation or adoption of strategies that will enable mitigation of or adaptation to climate change is likely to be greater if the innovators or adopters are rewarded. Economists prefer to use financial incentives to encourage environmental stewardship. But, when mandatory environmental policies are not feasible, voluntary policies may be attractive. For example, innovative environmental certification has enhanced environmental practices and tourism in Costa Rica (Rivera 2002). In the case of climate change, economists have advocated for introduction of a carbon tax because it provides incentives to reduce emissions of GHGs and enhance mitigation. However, carbon tax mechanisms in agriculture do not yet exist. An alternative mechanism to encourage adoption of climate change reducing strategies is to develop a voluntary mechanism such as certification that increases the value of products produced with practices deemed to effectively address climate change challenges.

A key component of CSA may be to identify practices that are desirable within this context and to develop a mechanism for certification that will reward policy makers that pursue such practices. While this approach has much merit, its implementation is challenging due to issues of fraud and the cost of monitoring (Hamilton and Zilberman 2006). For example, de Janvry and Sadoulet (2015) show how the implementation of a certification program, in this case Fair Trade, may not lead to the desired outcomes. Furthermore, in the case of CSA, the program may backfire if it does not correctly identify activities that contribute to effective management of climate change challenges. Therefore, the design of any certification program must be done in consultation with the latest scientific information available and the performance of the program must be reassessed periodically to ensure it takes into account new knowledge.

Unintended consequences of conservatism While environmental groups are among the most concerned about climate change, and were on the forefront of developing mechanisms to finance mitigation, sometimes they may oppose many innovative technologies and institutions that may be part of the solution to the challenges of climate change. This cautious response is not surprising because the traditional instinct of such groups is to protect and conserve (Douglas and Wildavsky 1983). Yet scientific progress may lead to new outcomes that may change reality and have uncertain outcomes. It is prudent to develop regulatory systems to pre-test new technologies, monitor and reevaluate their performance and then design regulations. But over regulation may lead to underinvestment in research that may stymie the development and implementation of new innovations. The risk of implementing new innovative concepts should be compared with the cost of not utilizing them. There are some special examples where strong objection to new innovations on environmental grounds may be especially counter productive. Changes in weather may lead to initiatives to change land use and in some cases conversion of wilderness areas to agricultural production. These initiatives should be considered and adopted if their expected benefits significantly exceed their costs. New technologies that take advantage of modern molecular biology, including genetic modification, should be considered as part of the solution to climate change (Zilberman 2015) These new technologies have significant potential for fast adaptation and reduced human footprint, and the resistance to such technologies can be counterproductive.[5]

The notion of sustainable development recognizes that dynamic processes are occurring and realities are changing. It aims to enhance human development and growth while protecting human well-being and environmental quality (Zilberman 2014). A defensive environmental strategy justifies mitigation and mechanisms to address it, such as carbon tax, but may provide obstacles to adaptation. For example, with climate change, some areas that are considered wilderness will have to be converted to agricultural use. Thus, zoning will need to be flexible to accommodate changing conditions.

4.3 Discussion

Barriers to innovation may vary across different categories of innovation, as well as over space and time. Scientific knowledge in the biophysical fields may be a significant barrier to cutting edge technological innovation and thus require significant investment in research. Furthermore, the knowledge gap varies across fields and different types of innovation. The knowledge gap in social sciences on understanding human behavior may hinder the development of management innovations. It can be addressed by both advanced conceptual understanding as well as experimentation with various types of management schemes under different conditions. Lack of information on behavior of both socioeconomic and biophysical systems under different conditions is another constraint on further development of innovations and especially refining it to address the specific needs of the end users. Thus improved data collection and methods can reduce these constraints. Financial constraints may be especially limiting for the development of capital intensive technological innovation but also may limit the development of managerial or institutional innovations that require investment in infrastructure. For example, the introduction of a carbon tax or incentive for carbon reduction that would lead to carbon saving practices, might require investment in monitoring to implement the policy.

Policies to reduce barriers to innovation require significant amounts of research on the institutional framework, technology transfer and adoption. This research should investigate the design of institutions that allocate research funding to

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[5] The case of genetically modified (GM) organisms is one example. As Bennett et al. (2013) have shown, GM technologies increase yield and reduce agricultural footprint as well as having a big potential to have environmental protection and adaptation to climate change. Their further use is slowed down by objections from environmental groups. Some of the objections to adoption of GMOs are based on the fact that much of the technology was developed by private sector. Yet there are mechanisms that allow access to the technology to develop new varieties for farmers in developing countries (Graff et al. 2003).

innovative activities in a fair, efficient manner that take into account both costs and benefits as well as various levels of assessed risk. The allocation of resources must have a strong spatial element capable of addressing the needs of remote areas, local communities, and have a cultural understanding to get buy-in for new solutions. Furthermore, a key element in developing policy is alliance between the private and public sector that will allow smooth technology transfer and efficient commercialization of new innovations.

5 Conclusion

Climate change is a dynamic process and its evolution and impacts depend on human actions. Without mitigation and with continuing build up of GHGs in the atmosphere, the severity of climate change impacts increase over time. At the early stages of climate change, adaptation may be *incremental*. It mostly consists of responses to changes in variability, increased mitigation efforts, better learning and understanding of climate change, development of new technologies and design of infrastructure and more transformative adaptation in anticipation of more drastic changes (Sea level rise, significant migration of weather). During these periods the challenge is in the response to crisis, mitigation, and development of capacity that may allow for adaptation to more drastic changes.

At future dates for many parts of the world, the new capacity and preparation in terms of technology and institutions in the near future will allow regional transformations of agriculture, peaceful migration and resettlement, and new reallocation and better management of water and other resources in response to more drastic changes. However, the timing for *transformational* adaptation varies by location. For instance, in low-lying coastal areas, such as Bangladesh, this form of adaptation may be required in the near future (Kates et al. 2012).

Adaptation to climate change does not occur in isolation, but rather in parallel with other dynamic processes. The impact of climate change, and the design of adaptation strategies, depends on these processes. Three processes are of particular mention: technological change, population growth, and consumption per capita. If technological change in agriculture is moving relatively fast and productive capacity outpaces growth in demand for agricultural products (resulting from population growth and growth in per capita demand), then adaptation to climate change will be less painful in terms of its impact on social welfare. If overall demand for agricultural production outpaces the rate of technological change in agriculture, then the attempts to adapt to climate change will be more painful and the challenges of climate smart agriculture will be exacerbated. If and where migration from rural to urban areas continues in many parts of the world and average farm size increases over time,[6] then climate smart agricultural strategies may be more affordable and the impact of climate change may be less harmful than when the landholding of

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[6] As the next generation of people that grew up on farms leave them for the cities.

individual farmers declines. The overall geopolitical situation will be crucial to the ability of technology transfer and peaceful relocation programs in response to climate change. Thus a more peaceful, collaborative world is a necessary condition for the implementation of climate smart agriculture.

While climate change affects average conditions and variability at each location, the impacts of climate change are heterogeneous and uncertain. The heterogeneity suggests that some regions gain, others lose and the magnitude of the impacts vary as well. Furthermore, adaptation and the innovations that are associated with it vary by location.

Climate change will increase the value of good management and flexibility, especially in agriculture. Adaptation, including mitigation, to climate change will require a high degree of technological innovation, both in terms of physical technologies as well as institutions and policies. Thus, a key element to develop policies to adapt to climate change is investment in R&D as well as international collaboration. As CSA requires investments, namely some sacrifice in the present for future benefit, it requires buy-in, education, and building awareness about climate change and the gain from adaptation.

The analysis here suggests several principles to guide the introduction of innovation and develop capacity and policies to address climate change. First, pick up the low-lying fruit. Namely, identify no-regret strategies of R&D and innovation that will address climate change and other pressing needs as well as emphasize cost-effective strategies to mitigate and delay the effects of climate change. Second, invest in R&D focused on the development of resource-conserving technologies and monitoring technologies. Third, emphasize innovations (technological, managerial and institutional) that increase the resilience of agriculture and allow it to withstand severe weather events. Fourth, take advantage of the frontier of knowledge of all types and utilize technologies that enhance human welfare and improve capacity to mitigate and adapt to climate change. Restricting the set of allowable solutions will reduce the capacity to sustain the effects of climate change. Fifth, emphasize the use of efficient mechanisms to incentivize farmers and other contributors to the agricultural sector to adopt smart agricultural practices. Sixth, emphasize adaptive management, which includes continuous monitoring, learning through experience, and adaptation of policies as you go. Seventh, distinguish between short-term emphasis on improved resilience in response to increased variability and long-term changes in spatial patterns that may include relocation of activities and people. Finally, harmonize agricultural and climate change policies that aim towards consistent outcomes.

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Part II

Case Studies: Vulnerability Measurements and Assessment

Use of Satellite Information on Wetness and Temperature for Crop Yield Prediction and River Resource Planning

Alan Basist, Ariel Dinar, Brian Blankespoor, David Bachiochi, and Harold Houba

Abstract Satellite derived measurements are essential inputs to monitor water management and agricultural production for improving regional food security. Near real-time satellites observations can be used to mitigate the adverse impacts of extreme events and promote climate resilience. Population growth and demand of resources in developing countries will increase vulnerability in agriculture production and are likely to be exacerbated by the effects of climate change. This paper introduces wetness and temperature products as important factors in decision and policy making, especially in regions with sparse surface observations. These objective satellite data serve as: (1) an early detector of growing conditions and thus food supply; (2) an index for insurance programs (i.e. risk management) that can more quickly trigger release of catastrophic bonds to farmers to mitigate crop failure impact; (3) an important educational and informational tool in crop selection, resource management, and other adaptation or mitigation strategies; (4) an important tool in food aid and transport; (5) and management of water resource allocation. The two new indices (surface wetness and temperature) are meant to complement currently available datasets, such as the greenness index, soil moisture measurements, and river guages.

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1 Introduction

As world population grows and income increases in developing countries, food consumption habits change, requiring more feedstock for animal production. Furthermore, climate change will have a direct impact on primary and secondary food production, caused by extreme temperatures, precipitation and river flow. This variability will have a direct impact on regional and global food and water supplies. To help vulnerable regions of the world cope with such challenges the concept of climate smart agriculture (CSA) directly addresses the need for adaptation in order to mitigate exposure to the hazards associated with interannual variability and climate change.

The information contained in this chapter demonstrates the value of satellite data (the wetness and temperature products) for monitoring crop production, food security, river flow, and river basin planning in many regions of the world. These products can serve as valuable climate smart decision-making tools in CSA. Specifically, there are several benefits to monitoring growing conditions from objective satellite derived observations:

1. They provide early warning to the available food supply, which mitigates the impact of reduced yields;
2. The wetness and temperature anomalies can be used as indexes in insurance programs as triggers in catastrophic bonds used to compensate the farmers for their losses in near real time;
3. The historic record of growing conditions can be used to identify the return period for various levels of crop failure, which can be used to define vulnerability and return periods for various levels of crop failure, which is essential information for risk management and premium calculation in the insurance industry;
4. Use of the climatology identifies the viability of alternative crop production, beyond the crops traditionally grown in the region. The production of multiple crops is a valuable hedge against catastrophic crop failure. Benefits may be complementary to mitigation activities, agricultural productivity, climate resiliency and natural resource management (Larson et al. 2015).

Since clouds at any one time covers over half of the world, clouds impact most of the surface signal of remotely sensed data across the world (Jackson 2005). Therefore, this study uses satellite derived microwave signals, since they penetrate through most cloud types. Consequently, they are effective in monitoring the surface through most sky conditions. In contrast, before infrared and visible signals can be used, they must be processed by sophisticated and complex cloud clearing algorithms, and can only effectively detect the surface under clear skies (Tucker et al. 2005). Moreover, the most interesting weather usually occurs under partly cloudy to overcast conditions. The microwave signal allows us to observe these events.

In an effort to derive surface temperature from microwave observations, it is necessary to overcome the primary source of noise in the satellite signal: water near the surface. Therefore we developed a technique to identify the magnitude of the water and filter its influence (liquid water reduces emissivity in the microwave spectrum). Specifically, in order to detect land surface temperatures, this low temperature bias must be removed. In the process of accurately identifying the emissivity reduction associated with liquid water and removing its effect on reduction in temperature observations, we were able to accurately identify the magnitude of liquid water near the surface. This byproduct may be more relevant and useful than the surface temperature product we were attempting to observe. Therefore, this chapter will primarily focus on the utility of the surface wetness product and its applications. The wetness product detects: (1) Upper-level soil moisture; (2) Water accumulating into the drainage basins (rivers) of the world; (3) Melting snow packs; (4) Lakes and bogs; (5) Water in the canopy. Upper level soil moisture is effectively used to monitor agricultural yields and river discharge. Consequently, these measurements are essential to water resources management and food production.

There is a need for improvements in crop prediction models, both at high (field level) (Becker-Reshef et al. 2010) and moderate (district level) resolution (Deryng et al. 2011). The satellite-derived wetness index provides data at a moderate spatial resolution. It has been applied in the insurance industry for monitoring likelihood of crop failure throughout the world, and by various governmental and international organizations (e.g. United States, Canada, China, World Bank and UNDP) for assessing yield and food security around the globe, as well as to monitor flow discharge in rivers (e.g. Blankespoor et al. 2012). The goal is to expand the application to a larger client base and provide accurate yield predictions during the growing season. The product can also provide valuable information about adversity thresholds for various levels of crop failure, which is essential for determination of rates for crop insurance underwriting. Moreover, accurate near real monitoring program has several important benefits for CSA: (1) The prediction of yield directly impacts food security and activates infrastructure to move food from where it is in surplus to areas in need; (2) Knowing the wetness and temperature and how they impacts development of the various crops, can be used to optimize the crop types to field conditions, the information can be spread by agricultural extension agents; (3) Planting is one of the most important periods in crop production, it has been shown that the wetness and temperature can be used to optimize planting decisions.

Weather, climate, topography, and vegetation cover have the greatest impacts on the hydrology of a river basin and the variability of natural flow. However, human diversions on river discharge and the effects of climate change confound the predictability of water in the future (Jury and Vaux 2005; Miller and Yates 2006). Since changes in flow affect populations and society in profound social and economic ways, our lack of confidence in future water resources requires mitigations strategies to address the uncertainty (Palmer et al. 2008). Specifically, hydrologic variability creates a significant challenge to countries, since high or low flow events may lead to flooding damage, severe drought, destruction of infrastructure, and/or fatalities. These events promote economic shocks and even generate intra-state violent conflict (Drury and Olson 1998; Nel and Righarts 2008; Hendrix and Salehyan 2012). Moreover, water variability affects international political tensions (Adger et al. 2005; Intelligence Community Assessment 2012). This may even occur in basins where mitigating institutions (like water treaties) have been negotiated (Drieschova et al. 2008). In other words, uncertainty and lack of predictability in flow increases tensions between sectors within a society, as well as between riparian states (Ambec et al. 2013), and the availability of water resources is central to CSA in many areas of the world.

The importance of having a good estimate of the water supply is the foundation of allocation and distribution of irrigation supplies. Since the wetness index is highly sensitive to liquid water near the surface, it effectively quantifies the melting snowpack, and this water feeds many irrigation supplies around the world. Since the origin of the water is monitored, there is a valuable lead-time to communicate with decision makers and allocate the water based on CSA principals and guidelines.

Lakes and bogs are generally permanent features observed by the wetness index, although they may slowly change in size. Since they are a significant component of the surface wetness signal, it is useful to remove these permanent features from the variable signal observed by the index:. specifically, water on the upper section of the soil and held in the canopy. Since water in the canopy has an association with leaf area, part of the signal represents the health of the crop. Our goal is to filter the permanent features, the climatology, and the annual cycles, and focus on the inter-annual variability in wetness, which is driven by the weather. Anomalies are the best tool to achieve this goal. Therefore, the crop models are based on anomalies.

The wetness product is hereafter noted as the Basist Wetness Index (BWI), which detects water near the surface from multiple sources (as mentioned above). In order to simplify the interpretation of the BWI, it is calculated as the percentage of the radiating surface that is liquid water. A reasonable spectrum of this value would be zero percent in desert regions, while agricultural areas have values ranging between 2 and 10% of the surface that is liquid water. Values above 10 usually indicate a very wet surface, such as recently melted snow cover or recent rain.

The following section presents the methodology used to define the BWI, and as well as how it can be used to estimate present and future water supplies under situations where traditional (surface based) observations of surface water are not available, as is the case in many countries. Section 3 illustrates the use of these satellite drived monitoring tools in three different applications (predicting yield of agricultural crops, estimating river flow, and planning in a river basin). The chapter discusses several other applications without demonstrating them, for space consideration.

2 Methodology

The BWI index is derived from a linear relationship between channel measurements (Eq. 1), where a channel measurement is the value observed at a particular frequency and polarization, i.e. the Special Sensor Microwave Imager (SSM/I) observes seven channels (Basist et al. 1998).

$$BWI = \Delta\varepsilon \cdot T_s = \beta_0\left[T_b\left(v_2\right) - T_b\left(v_1\right)\right] + \beta_1\left[T_b\left(v_3\right) - T_b\left(v_2\right)\right] \qquad (1)$$

where the BWI is the percentage of the surface that is liquid water (Basist et al. 2001), Δε, is empirically determined from global SSM/I measurements, T_s is surface temperature from station measurements, T_b is the satellite brightness temperature at a particular frequency (GHz), ϑ_n ($n = 1, 2, 3$) is a frequency observed by the SSM/I instrument, β_0 and β_1 are estimated coefficients that correlate the relationship of the various channel measurements with observed in situ surface temperature at the time of the satellite overpass. Specifically, as wetness values increase, the differences between the observed surface temperature and the observed channel measurements also increase (Williams et al. 2000).

Weekly and monthly average BWI values are very good indicators of the magnitude of water near the surface, which has a relationship to water at greater depths. These observations have proven valuable in agricultural monitoring during the previous 25 years of analytical work. The wetness anomalies have proven valuable in predicting agricultural yields in many areas of the world (Curt Reynold USDA, personal correspondence). Research indicates the wetness product has a gamma distribution, much like precipitation (Gutman 1999); therefore a gamma distribution is used to derive the variation of wetness from the expected value.

Since most regions of the world have annual cycles associated with their liquid water near the surface, it is best to calculate anomalies for each pixel, location and time of year. The resolution of the pixel is 33 km by 33 km, and anomalies are calculated on a monthly and weekly basis. A value of 0.01 means that only 1 year in a 100 would realize a value so low (extremely dry) at the location for a particular time of year. Conversely, a value of 0.99 corresponds with an excessively wet event that only occurs one out of a 100 years. In summary, values progressively less than 0.5 indicate increasingly drier conditions and values progressively greater than 0.5 indicate increasingly wetter conditions than the expected value (Fig. 1).

The period of record for these wetness and temperature products begins in 1988 and they have been maintained in near real time for decades.[1] There is a period of 2 years, 1990 and 1991, when the stability of the microwave satellite instrument was deemed unreliable. Therefore, these 2 years are removed from the analysis. The climatology we use is based on the 23 years of data from 1988 to 2010. A series of operational satellite instruments flown by the United States Meteorological Satellite Service comprise the period of observations. Great effort has been made to seam the observations between the various satellite instruments into one contiguous record. A daily set of observations is composed of 14 orbits across the globe. These observations are sun synchronous over the equator, at an overpass time around 6 a.m. and 6 p.m. every day. The morning and afternoon overpasses are processed independently and then combined together into one set of observations across the globe. Each set of observations is added to this record in near real-time, as both weekly and monthly fields of temperature and wetness values.

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[1] SSMI based temperature and wetness data and algorithms discussed in this chapter are a proprietary technology owned by WeatherPredict Consulting, Inc.

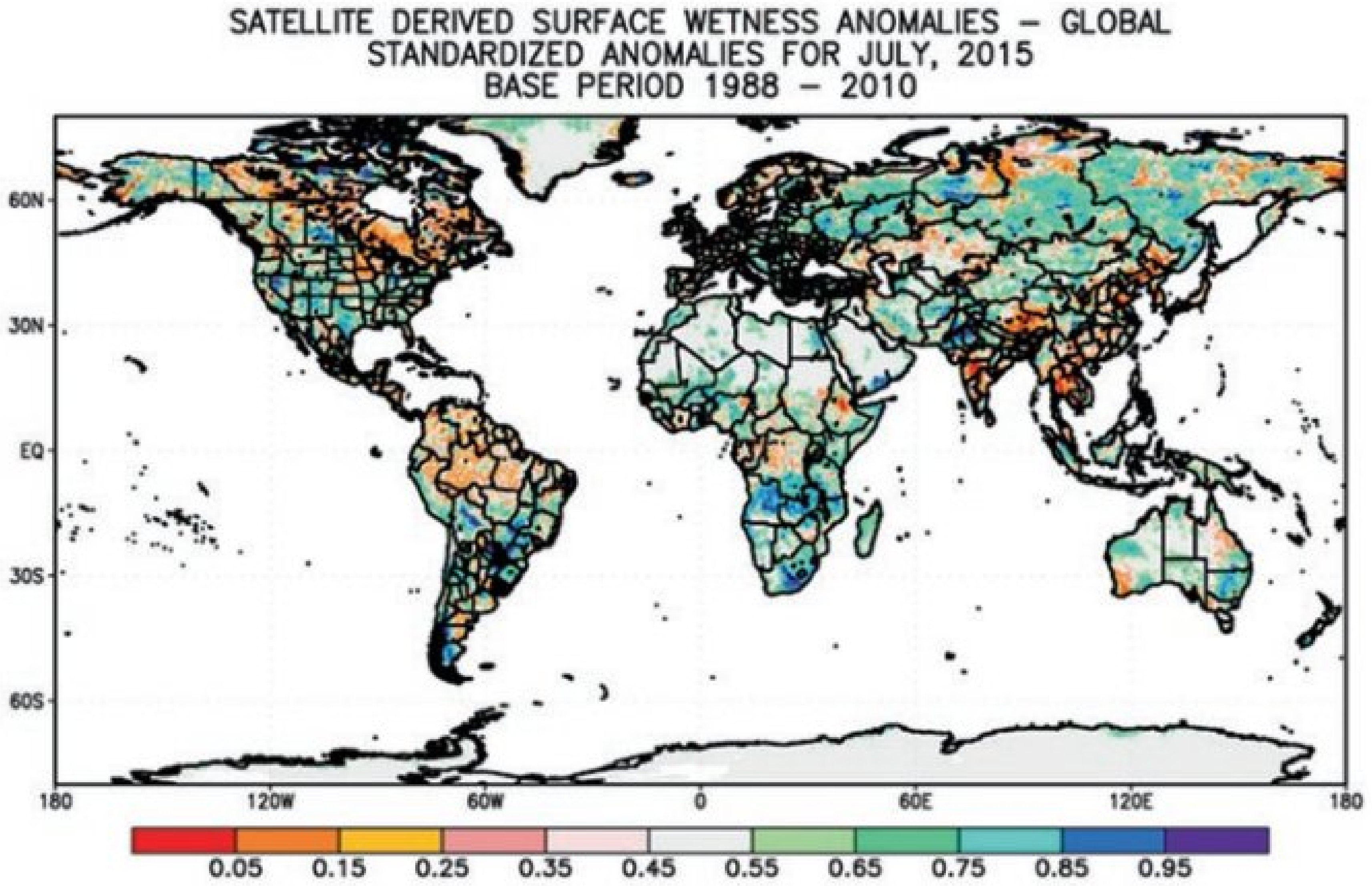

Fig. 1 Global surface wetness anomalies for July 2015. Note: The *grey* shade of the legend corresponds with the expected value, while values to the *left* (*right*) of the *grey* shade correspond with increasingly drier (wetter) than average conditions. For example, the value of 0.05 means that only 5% if the time is it that dry at a location and time of year. Inversely, a value of 0.95 mean that only 5% of the time is it that wet at a location and time of the year

The actual wetness observations (not the anomaly) are valuable for measuring river discharge. These values identify the percentage of the radiating surface that is liquid water. Moreover, in many river basins there is 1–2 months lag in the time it takes for water in the upper section of the watershed to pass a monitoring gauge in the lower section of a river basin (where most people live and economic activity takes place). This lag, which averages prior month(s) BWI with the concurrent month (hereafter noted as the cumulative lag) improves the skill of the model to predict the flow passing through a river gauge. It also provides valuable lead-time to predict and mitigate the magnitude of drought or flood heading into the lower basin, where the impacts are generally most severe. Therefore, the early warning can be used to mitigate the impact of extreme events on society. An added advantage of applying a quantitative flow model, which can predict flow downstream, is that a consortium of riparian states can use the information to determine how the water resources will be distribution under various flow regimes. Therefore, treaties have the capacity to allocate water as a function of an independent and quantitative measure of flow, providing a simple and accurate predictive model for a fair and transparent distribution of water under times of scarcity.

The observations of the BWI spanning national borders allows for an objective (independent of national influence) calculation of water resources under almost all sky conditions. Since the wetness index is an independent tool that integrates the accumulation of water across large areas, it has the potential to be used as an index and/or trigger for: (1) implementation or call to action in mitigation strategies; (2) insurance compensation; (3) allocation of water between sectors of society; (4) distribution of water between riparian states. These are important applications that warrant further research.

The following section demonstrates the use of the BWI tool for: monitoring crop yield, monitoring river flow, and river basin management. The Mekong River is used as an example. While these applications are site specific, the extrapolation from one site to another is easily done and can be accomplished with minimal cost to the agency.

3 Application

Currently, the wetness and temperature anomalies have proven valuable for monitoring crop development and assessing potential yields during the growing season, and have been effectively applied in crop yield prediction models. These models are statistically-based, using linear relationships between the wetness and temperature anomalies and yield, which serves as the calibration. The statistically-derived model parameters are used to predict yield during real time growing conditions and have been applied by many organizations around the world to assess future yields, as well as support planning policies related to the regional, national and global food security (Fig. 2).

There are several limitations in applying the wetness and temperature anomalies across various regions of the world. The first is the large footprint (33 km × 33 km), which is about 1000 km^2. This limits the application into a mesoscale analysis and has limited value for high-resolution assessments. Another limitation is coastal boundaries. Specifically, locations within 30 km of a coastline (ocean or large inland water bodies) will unduly influence the temperature and wetness products, since the presence of more than 50% water destabilizes the model, requiring that those signals be recognized and removed from the data sets. Exposed soils or rocks (dry areas) where minerals are exposed on the surface, introduces noise in the signal. This is particularly true when limestone is exposed on the surface. In these instances the product should be used with caution.

3.1 Monitoring Crop Yield

The yield prediction models are uniquely calibrated for each crop and particular locations. Specifically, yield prediction models are calibrated on historical values, using the linear variations of temperature and wetness anomalies as predictors. In addition, the quadratic of the wetness and temperature interaction is a predictor in the model. The models are run as the crop enters the reproductive stage, and

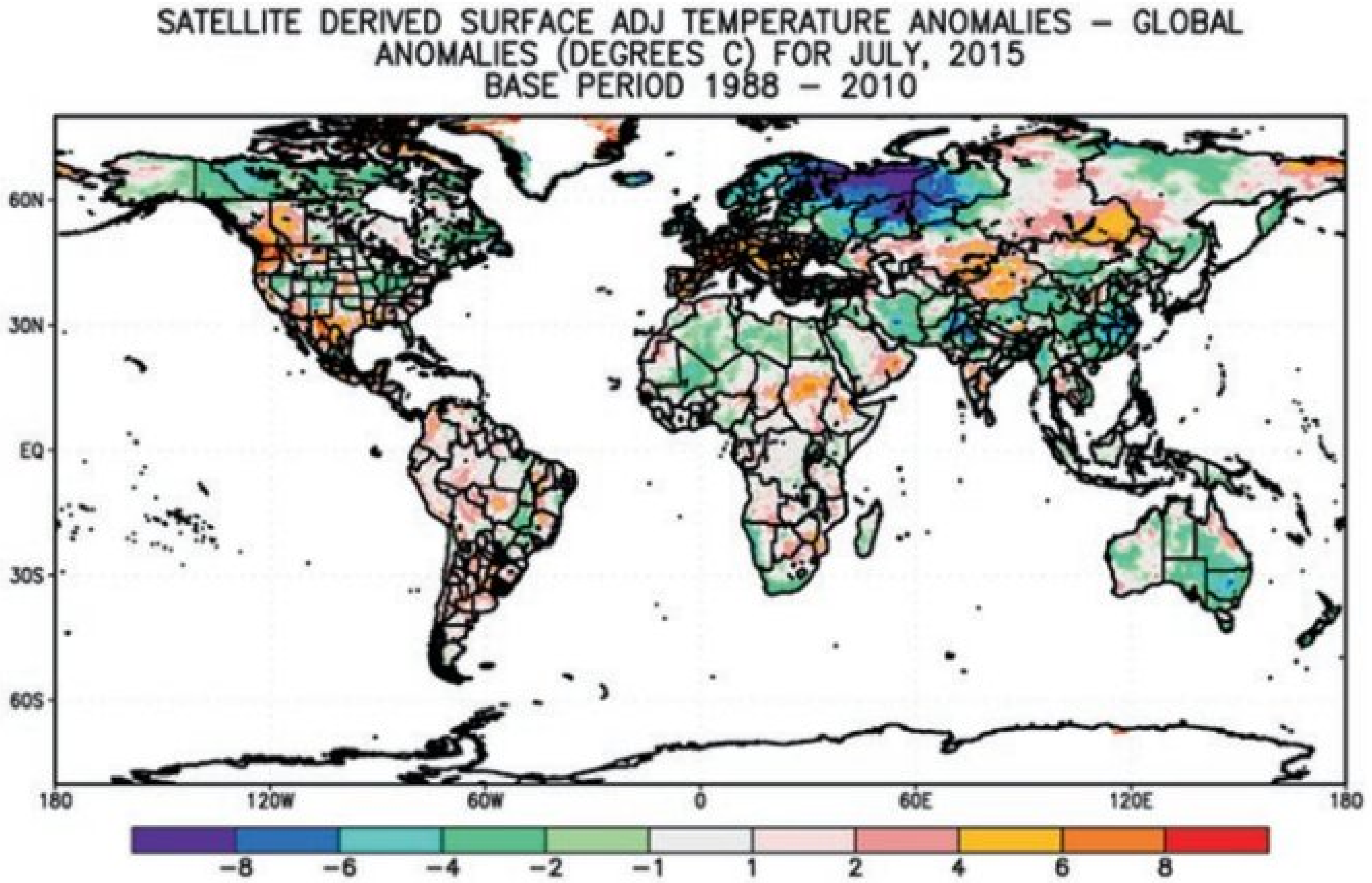

Fig. 2 Global surface temperature anomalies for July 2015. Note: The *grey* shade in the legend corresponds with the expected value, while values to the *left* (*right*) of the *grey* shade correspond with increasing colder (warmer) than average values. For example the value of −8 means that temperatures were −8°C colder than average at the location and time of year. Inversely, a value of 8 means that it was 8°C warmer than average at a location and time of the year

continues to be updated on a monthly basis through the maturation stage of the crop. The most important month of the growing season is usually reproduction, and therefore the influence of this period has a strong relationship to yield. The benefit of the interactive term is multifold. Specifically, linear statistical models tend to be mean-centric, which means they are challenged to capture extreme events. The quadratic component of their interaction generally captures these extreme events in the model.

The models are generally run at the district level. Moreover, each country is unique in the way that it reports yield data. The spatial resolution of the yield data provided by a country serves as the basis of calibration in the model. Both deviation from expected yield and actual yield prediction are presented in the findings of the report. The expected yield has been trended to account for linear improvement of seed stock and improved agricultural practices. These trends are removed, since they are independent of the weather. An example report or the corn belt of the USA during the 2015 growing season is presented below.

Figure 3a shows the predicted deviation from trended (expected) corn yields for the center of the corn-belt in the United States at the end of August 2015. The reasons this region is chosen are twofold; it produces one of the highest yields and is one of the most important growing areas for corn in the world and the sophisticated procedure for calculating yield by the United States Department of Agriculture (USDA) provides one of the best data sets for calibrating the yield prediction

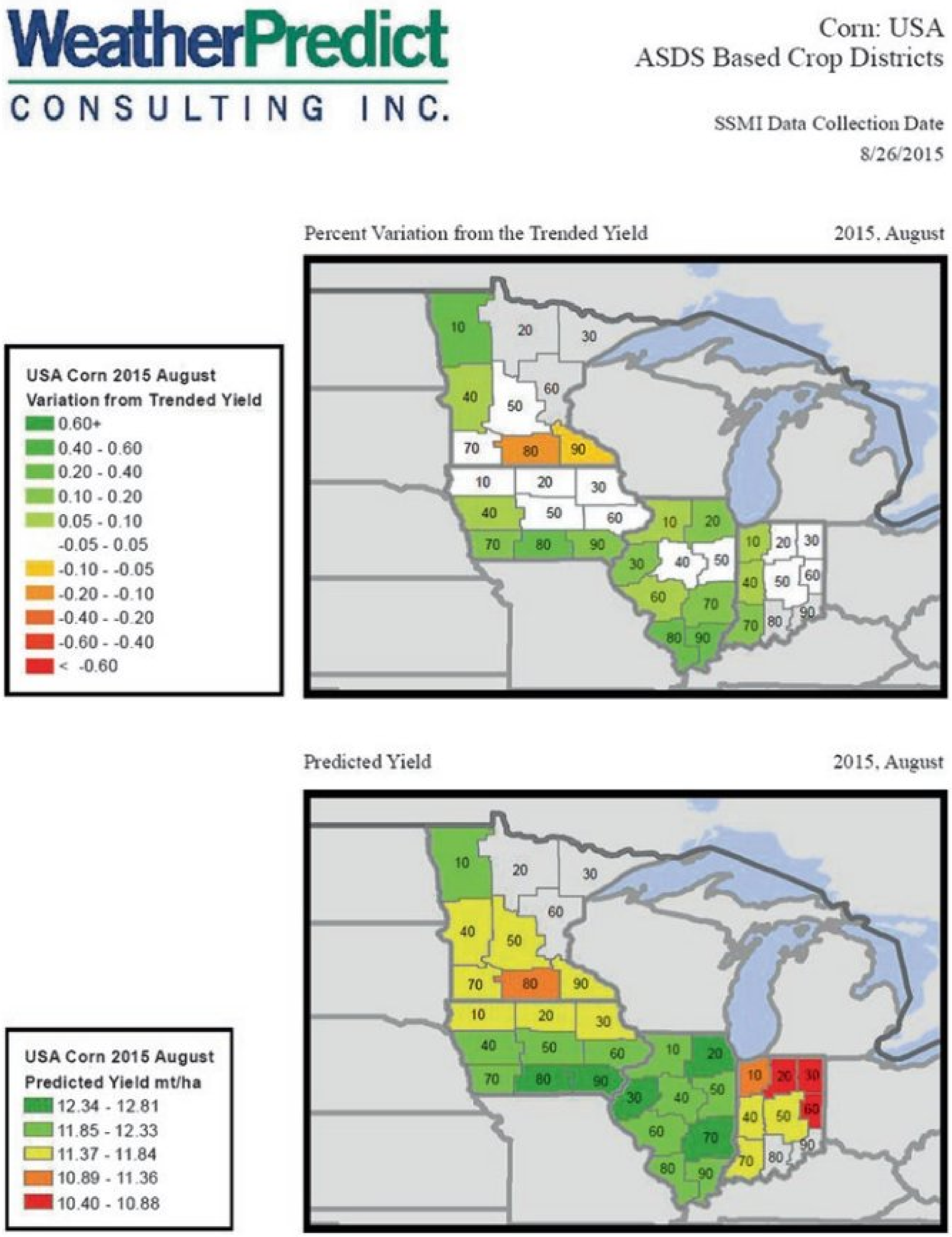

Fig. 3 (**a**) The percentage departure from the expected (trended) yield. (**b**) The predicted yield in Mt/ha. Note: Zero departures are *white*, and the departures are more amplified the color gets darker towards *red* (*below*) expected, or *green* (*above*) expected yields. They are displayed percentages from the expected value

models. August was chosen, as it provides an early warning to projected yield, as the crop has already entered seed-pod filling.

Generally, the predictions in this report range from average to above average yields for the primary growing regions in the United States. The exceptions are in southeastern Minnesota, where predictions are generally below the expected value. Yields, which have the greatest deviation above the expected values, include much of Illinois and southern Iowa. These areas had near average wetness and slightly below average temperatures, thereby promoting healthy growing conditions during the corn's development. The cooler than average temperatures allowed many areas with some moisture deficit to achieve near average yields, since the cool temperatures limited the moisture stress in the crop. Figure 3b displays the predicted yield as metric tons per hectare. The area with the highest yields occurs in locations where corn tends to produce some of the best yields in the world, and these areas also had better than aveage growing conditions. Note that the low yields in northern Indiana (where yields are near the expected value) indictate that growing conditions are generally inferior, compared to some the neighboring crop districts.

Figure 4 shows the wetness and temperature anomalies, which are used to predict corn yields for the center of the USA growing area. Predictions include data from May, June, July, August, the plot in fig. 4 displays the anomalies for July, which is the most important period in the determination of the yield. August is the time when seed pod filling occurs, after reproduction, it is the most critical period in the development of corn yield.

The above-average temperatures in July across areas of Iowa and most of Minnesota introduce heat stress, which reduces potential yield. Fortunately, there was ample moisture across most of the area, so the negative impact of excessive heat is nominal, in terms of yield reduction. More soil mositure is available in portions of Indiana and Illinois, and these areas are the regions with better than expected yields.

The parameters of the predictive model along with its calculation of yield are presented in Table 1. These values are presented by crop district for the state of Iowa. The location was chosen since it is the most important agricultural state for the production of corn. The slope for the trend of corn yields over the period of record is 0.16 (shared across the state), which means that the average annual increase in yield, due to improved seed stock and agricultural practices is 0.16 metric tons/ha/yr. The intercept for each crop district is unique, since some crop districts produce higher yields than others. The predicted yield is the model derived yield, in metric tons per hectare, for each crop district, based upon its wetness and temperature anomalies throughout the growing season to August 2015. The trended (expected) yield value is based on the 2015 crop season. The last column on the right is the percent variation from the expected yield, the parentheses means the value is negative.

Figure 5 illustrates that some crop districts are slightly below the expected value in terms of yield. However, the majority of the crop districts had higher than expected yield. Therefore, at the end of August the state of Iowa as a whole is predicted to have higher than expected yield. At this time of the growing season the seedpods are approaching maturity, and they provide a reliable measurement of the final yield.

The regression equation and statistical significance of each predictor variable in the model are presented in Table 2. The adjusted R^2 for the model is 0.60 with an F-statistic of 28.46. The model has 211 degrees of freedom. The predictive variables

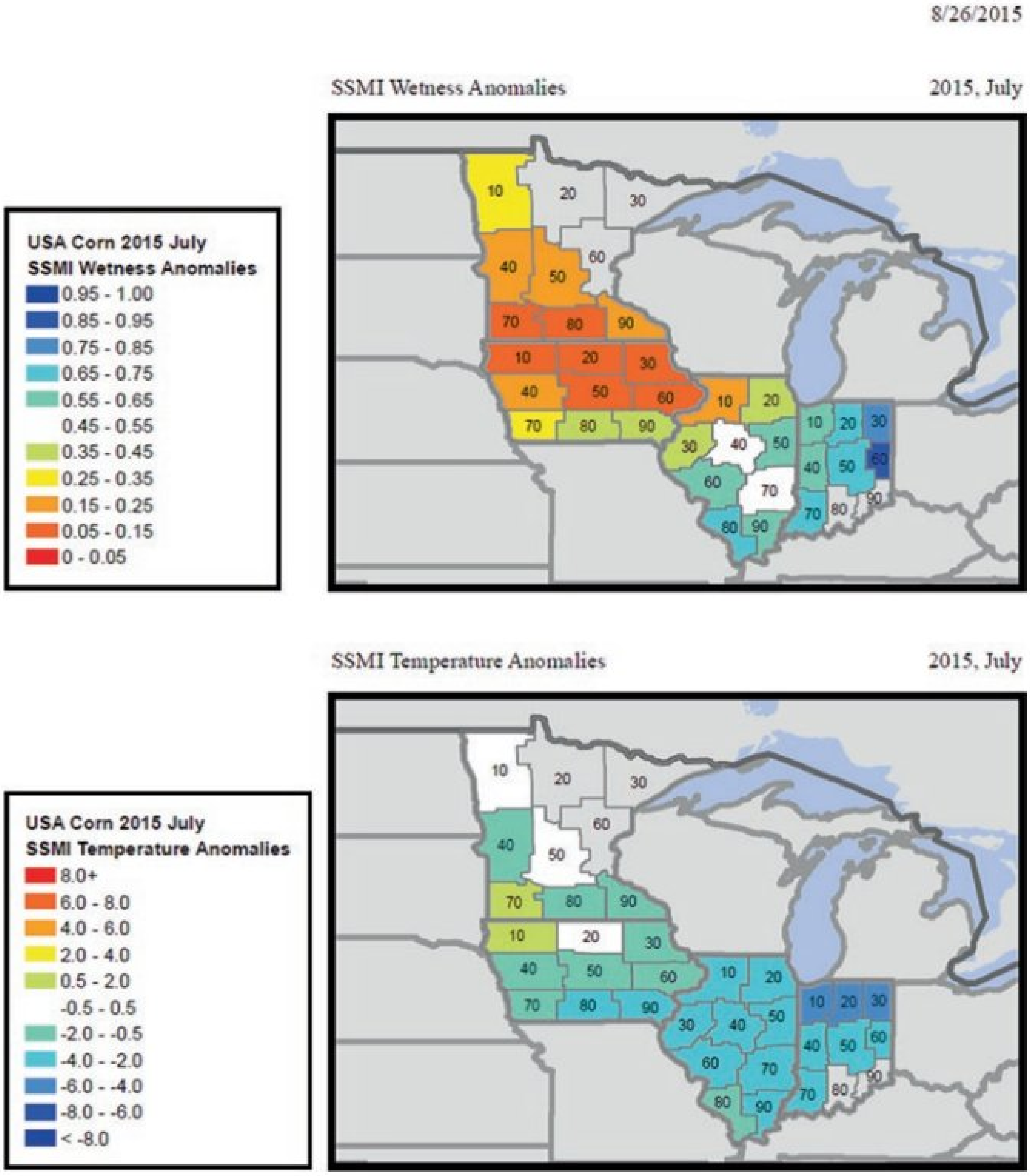

Fig. 4 July values are presented by crop districts: (**a**) Surface wetness anomalies are displayed by color, where shades towards *blue* (*red*) are increasingly *above* (*below*) the expected surface wetness value (see text for more details). (**b**) Surface temperature anomalies are displayed by color, where shades towards *blue* (*red*) are increasingly *below* (*above*) the expected surface temperature

are temperature and wetness anomalies from May, June, July and August. Also, the interaction of temperature and wetness is included as an independent variable in the model. The negative coefficients are portrayed in red and are inside parentheses. Predictive variables that are significant at the 0.90 confidence level are checked in the right-hand column. The most important variables in the model are the interaction of temperature and wetness in June and July, and the temperature in August. These three variables are all significant above the 99 percent confident interval.[2]

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[2] The interactions of temperature and wetness for June and July are two of the strongest predictor variables in the model.

Table 1 Regression-model derived parameters for Iowa

Corn						
United States, Iowa						
Percent variation from trended yield						
Crop districts, ASDS based						
SSMI collection data date 8/26/2015						
	GeoID	**Slope**	**Intercept**	**Pred yield**	**Trend yield**	
Admin region	Crop district	mt/ha	mt/ha	mt/ha	mt/ha	**Percent variation from trended**
Buena Vista	19_10	0.16	7.53	11.45	12.05	(0.05)
Butler	19_20	0.16	7.46	11.48	11.98	(0.04)
Allamakee	19_30	0.16	7.26	11.53	11.78	(0.02)
Audubon	19_40	0.16	7.10	12.27	11.62	0.06
Boone	19_50	0.16	7.51	12.19	12.03	0.01
Benton	19_60	0.16	7.22	12.29	11.75	0.05
Adair	19_70	0.16	6.54	12.28	11.06	0.11
Appanoose	19_80	0.16	5.69	12.81	10.21	0.25
Davis	19_90	0.16	6.45	12.74	10.97	0.16

Identifies the slope and intercept for the linear trend in yield derived by the USDA yield values from 1988 to 2014

Note: The three columns to the right are predicted yield derived from the wetness and temperature anomalies, trended (expected) yield, and the column on the right is the ratio of the predicted/trended yield for August 2015 (parenthesis means the values are negative).

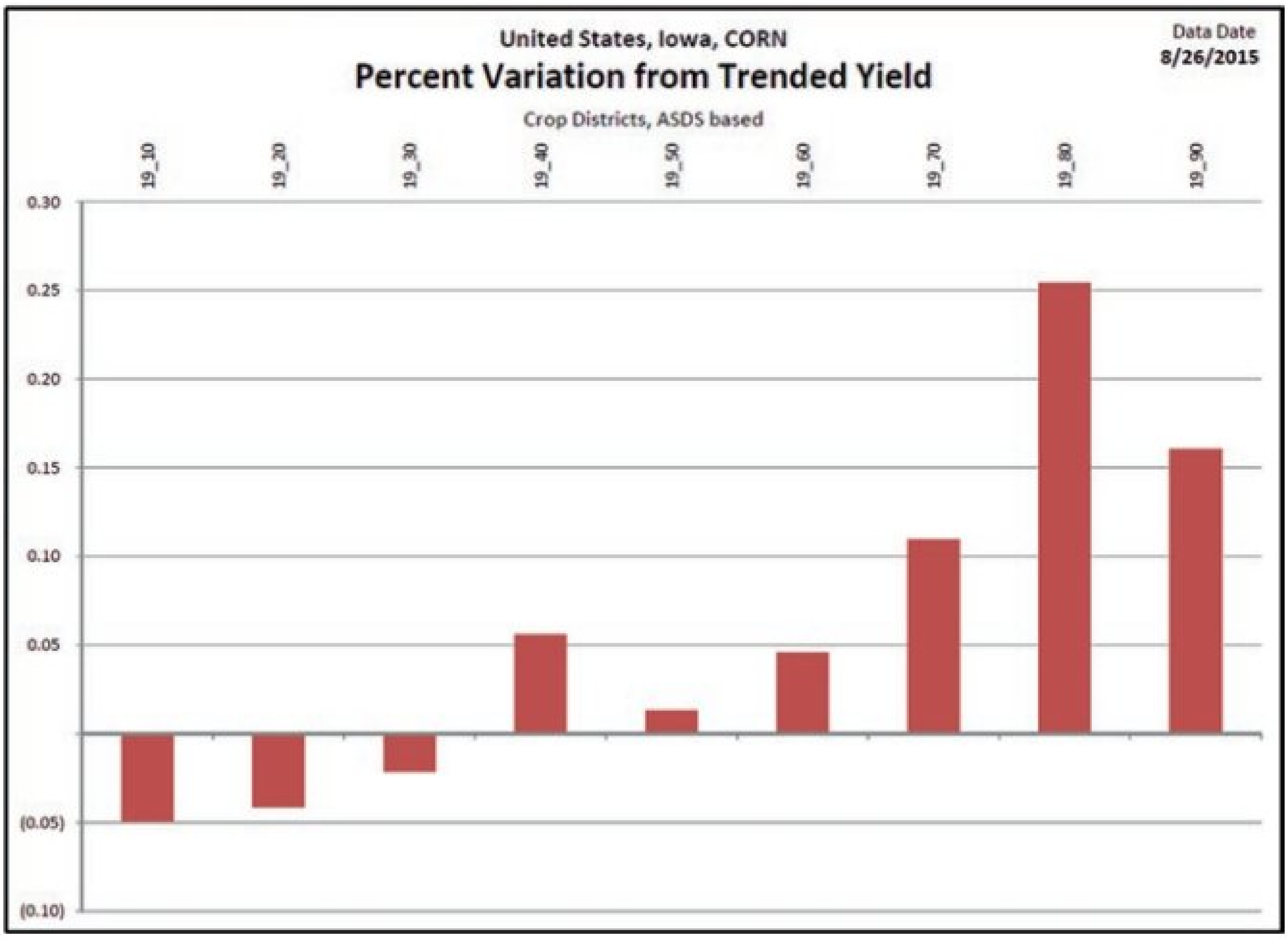

Fig. 5 Graphical representation of the variation from trended yield, in Iowa plot is conveyed by crop district in the state

Table 2 Model coefficients and significance values

Corn			
United States, lowa			
Statistical model output			
Crop districts, ASDS based			
Data date 8/26/2015			
# observations	225	R-squared	0.62
# variables	13	Adjusted R-squared	0.60
Degrees of freedom	211	F-Statistic	28.46
Variables	**Coefficients() negative values**	**Significance (in percent probability)**	**Significance @ 90% confidence**
Constant	13.28	0.00	×
Temp May	0.05	0.01	×
Temp Jun	0.01	0.69	
Temp Jul	(0.05)	0.03	×
Temp Aug	(0.17)	0.00	×
Wet May	(0.19)	0.58	
Wet Jun	(1.06)	0.00	×
Wet Jul	(0.57)	0.24	
Wet Aug	0.11	0.78	
Interact May	(0.00)	0.10	
Interact Jun	(0.02)	0.00	×
Interact Jul	(0.02)	0.00	×
Interact Aug	(0.01)	0.10	

The degrees of freedom in the model, along with its predictive skill, regression coefficients, their significance level for each predictor variable Negative coefficients are in parenthesis

Finally, a scatterplot of the wetness and temperature anomalies for the months of July and August at the crop district level is presented (Fig. 6). Note that in the month of July the majority of Iowa had slightly below normal temperatures, while wetness values were drier than normal during the month. The lack of heat stress during reproduction was for yields. August continued to bring drier than average conditions to the majority of the state, while near average temperatures helped minimize soil moisture stress. Therefore yields predictions were near-normal. The forecast generally remained the same between the end of July and the end of August, since July is the most important month for yield prediction. Although there were changes in field conditions across a few crops districts during the August, the addional information in August improves the model skill as the crop reached maturity.

3.2 *Monitoring River Flow*

Quantitative and indepenedent measurements of river flow levels are essential for water rights and planned allocations. Moreover, reliable and independent measurements of available water resources are required for mitigation strategies and

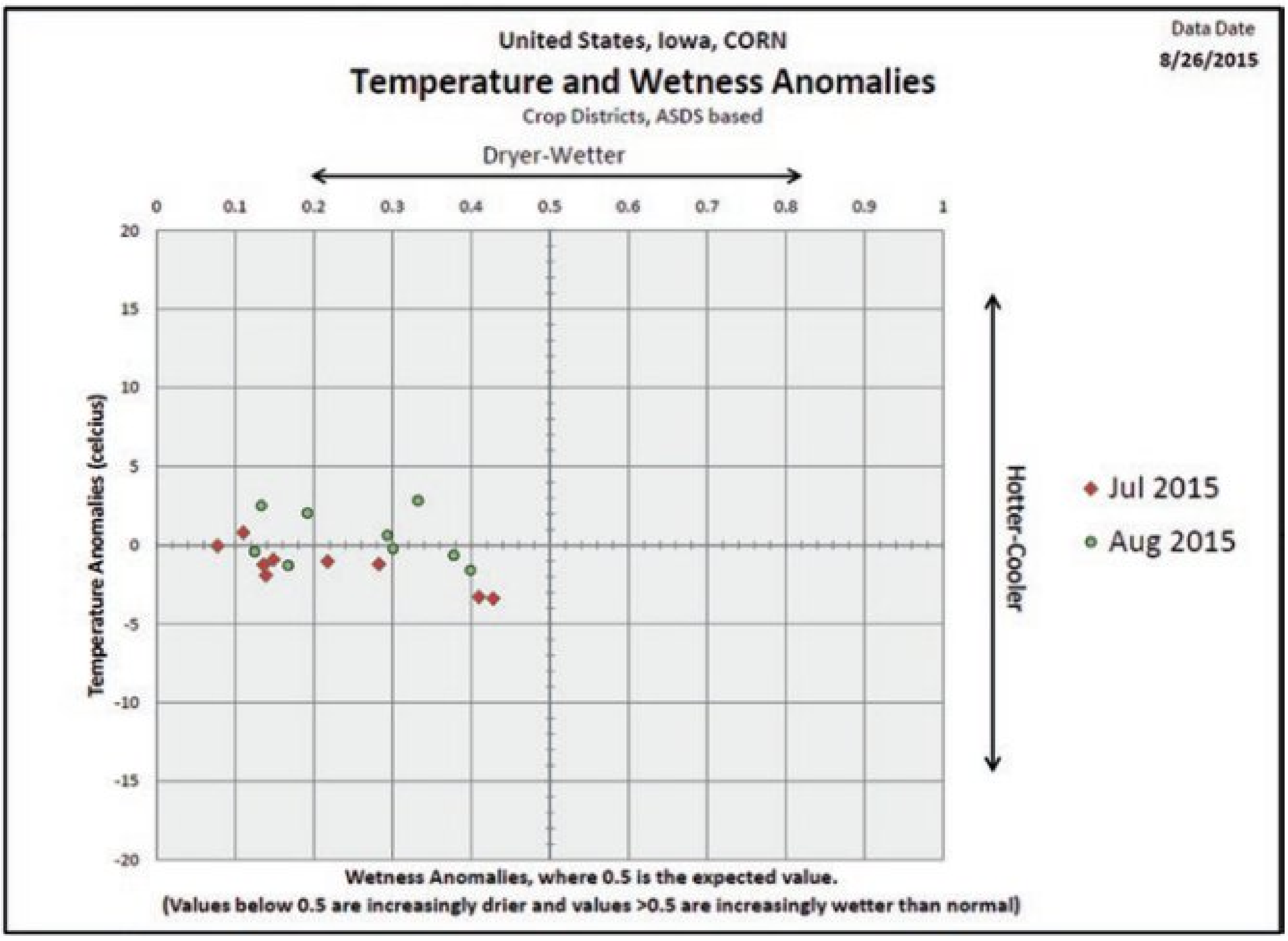

Fig. 6 Scatter plot of wetness and temperature anomalies by crop district for the months of July and August. Note: *Top left* quadrant is above temperature and below wetness, *bottom left* is below both temperature and wetness, *top right* is above both temperature and wetness, and *bottom right* is below temperature and above wetness

insurance compensation, which are a fundamental component of an effective treaty (Dinar et al. 2010) that allows proper planning and allocation of the basin water to various water consuming activities. Also, independent monitoring of flow measurements is required to implement an effective treaty, which is based on triggers, response and compensation, or to operate reservoirs used for irrigation projects. Therefore, high quality flow data are a necessary component of effective treaty stipulations and institutional mechanisms (Dinar et al. 2015), as well as infrastructure for reservoirs that can deal with future challenges. Real time data can also provide policy makers and researchers with the ability to predict extreme weather events, and cooperatively address economic impacts on existing projects. In addition, models can increase institutional capacity by providing timely (near real time) flow information to build climate resilience and effective sharing and allocation of limited water resources.

Considering the challenges to estimate flow where standard measurements are not available, we demonstrate a simple, yet robust model to predict both present and future flow measurements, using the wetness product in two basins: Zambezi and Mekong. The period of record for calibration of the models is from historic river gauge values, and these flow values are regressed on the BWI values (the predictor of flow). In order to keep the equation as simple as possible, yet robust, the regression is based on one variable and tested in two basins of very different climatology's, topography's, land use patterns and annual water supply cycles. An important consideration between the gauge and BWI values is a lagged relationship between water accumulating near the surface and detected downstream at the gauge. The lag between the water input upstream and the detection of changes in flow downtstream is based on numerous empirical observations and theory that flow models are more accurate when they include the prior month(s) due to the time lapse for the water accumulate into the major stem of the river (Demirel et al. 2013). The number of prior months used in the predictions of flows is directly related to the size of the basin, the influence of snow melt and its topography. Therefore, a lagged term is included in Equation 2, where $Q_{m(BWI)}$ is the discharge at a station for month m While n is the number of previous month(s) averaged together with the concurrent month BWI value.

$$Q_{m(BWI)} = g\left(d\right) \tag{2}$$

where $d = \frac{\sum_{i=0}^{n} BWI_{m-n}}{n}$.

Table 3 lists model statistics and parameters for the two river basins. The number of month(s) lagged prior to the gauge observations is included, along with the parameters of the regression model. Our goal is to define a simple and robust prediction from one variable and explore the utility of the predictor in areas of society that could benefit from the models.

The Zambezi model flow signature is clearly curved (Fig. 7a); it has a quadratic structure of high wetness values and extremely high flow. High values display considerable heteroscedasticity (from the studentized Breusch-Pagan test), which implies that numerous factors impact the high rate of flow past the gauge. In contrast, low BWI values (less than 1) contain a high confidence that the flow will be near the base flow. These results compared favorably to model prediction for the Zambezi presented by Winsemius et al. (2006), whose predictions were based on a more complex model. As a result, the BWI can be a quantitative indicator for periods and frequencies of flow associated with limited water – of particular relevance to obligations and commitments agreed upon in international water treaties.

Table 3 Parameters from Zambezi, Mekong predictive river flow models

Model	Zambezi (BWI)	Zambezi (precip)	Mekong (BWI)	Mekong (precip)
Linear term	−420.2	71.9	303.8	75.9
Quadratic term	748.6	0.78	886.6	0.297
Months lagged	2	2	2	2
month observation	148	198	44	44
Predictive skill (R2)	0.89	0.52	0.95	0.97
Residuals	485	1020	645	523

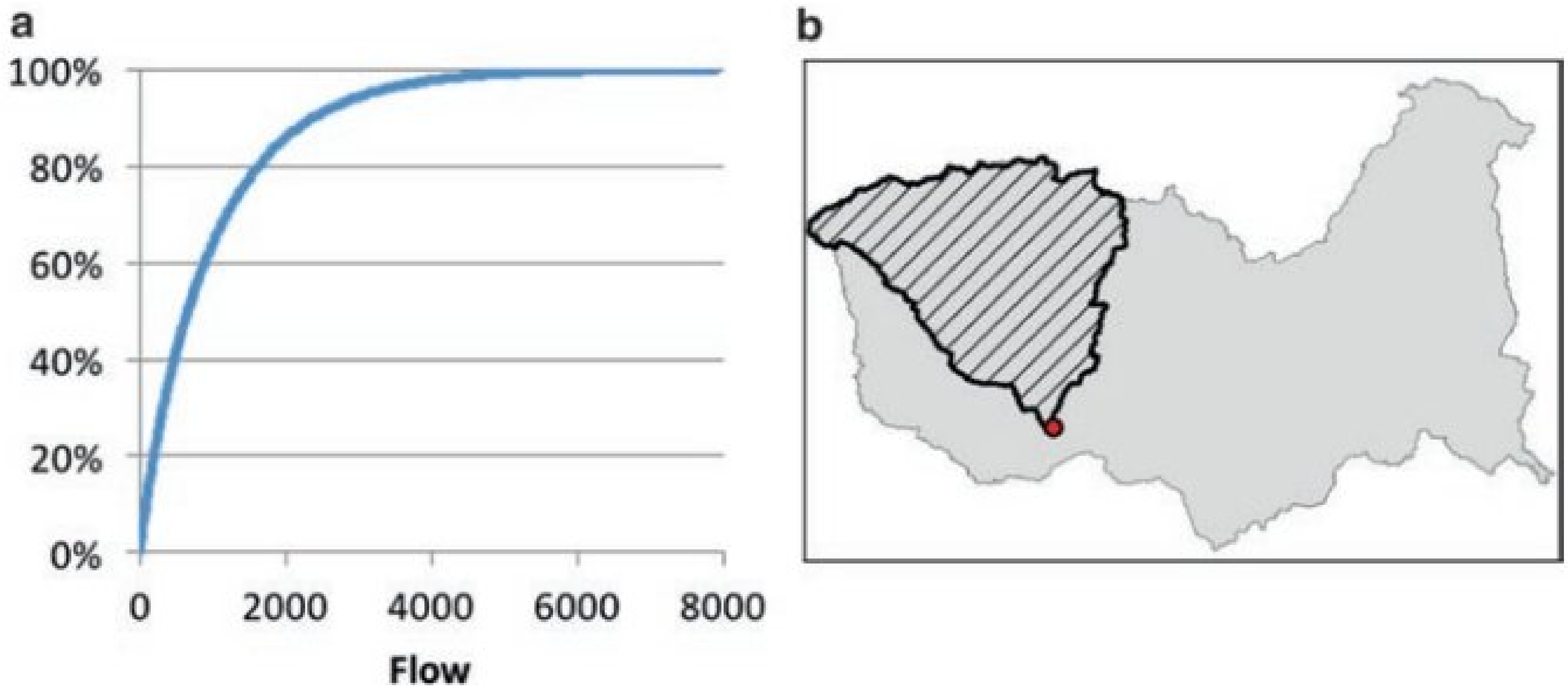

Fig. 7 (**a**) Cumulative distribution of flow using a gamma distribution (percent. y-axis) and flow (m^3/s per month. x-axis) of the Zambezi river basin sample area; (**b**) Map of Zambezi basin (*grey*) with the selected gauge data (point), international border (line) and respective catchment (hatched) used in the model

The lower bound of predicted flow is 288 m^3/s (BWI = 1.0) occurs approximately 28% of the time. Therefore, for the Zambezi River at the Katima Mulilo station, approximately 28% of the time the flow is less than 288 m^3/s averaged over the 3 months. The area feeding water to the gauge is defined in Fig. 7b.

Since the SSM/I instrument is currently operational, it is possible to use the fitted model to predict recent runoff from monthly wetness values, based on the calibration period. Due to the accuracy and significance of the models, we chose to explore the ability of the BWI to predict seasonality, low flow (e.g. droughts), and high flow events (e.g. floods). This analysis was used to explore the utility of the model in *serving as an early warning indicator.*

With regards to the Zambezi, the BWI model identified and predicted a flood in 2010, which according to the model is higher than any previous flood over the period of the SSMI record (Fig. 8). In April 2010, there is a pattern of large positive surface wetness anomalies in Western Zambia (Fig. 9). This broad pattern of purple indicates that the area was extremely wet conditions. This extreme event occurred across a large section of the basin. In rare instances, when there is an extreme flood on the Zambezi, due to heavy rainfall on the highlands in Angola and Zambia, the flow can actually accumulate at the Mambova fault. During this instance, the river expands over the flat floodplain behind the fault until the waters meet the channel cut by the Chobe River in the south. During this extreme flood, the accumulation of water from the Zambezi River overcomes the Chobe River, and water begins to flow upstream on the Chobe, flowing into Lake Liambezi. At the height of the flood, water flowed directly into Lake Liambezi from the Zambezi River through the Bukalo Channel on May 8, 2010 (NASA 2010), which is the same time the BWI predicted the highest flow over the period of record.

Next is discussed the Mekong model, which is presented in Table 3. The section of the river basin that feeds the Mekong gauge station is presented in Fig. 10b. The best explanatory model has a non-linear relation. The Mekong models also used a

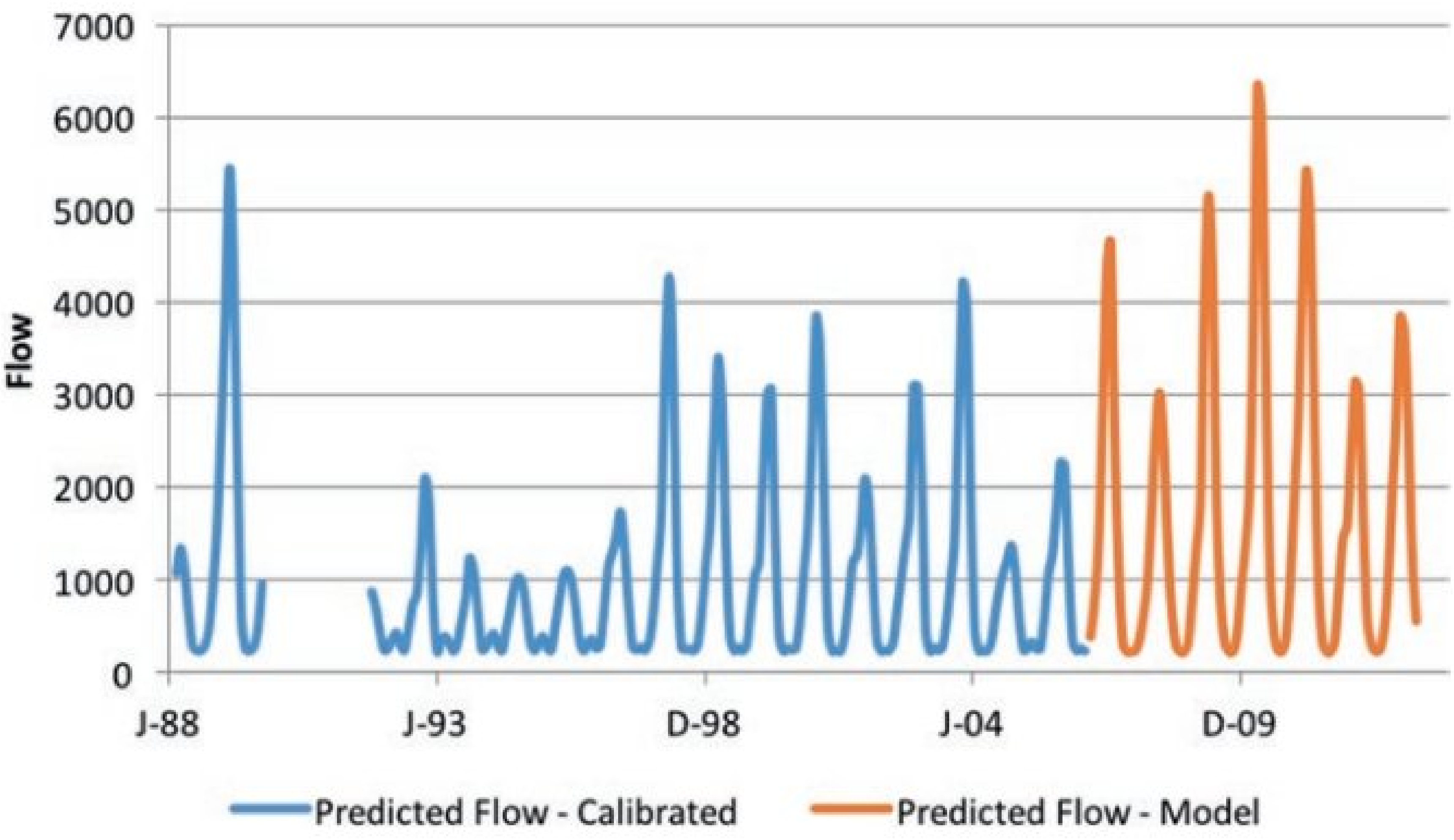

Fig. 8 The Zambezi values of runoff (m³/s per month, y-axis) and time (x-axis, January 1988 through July 2013). The time series displays seasonality and interanual variability over the predicted (calibration) period in red (*blue*). The highest flow occurred in April/May 2010. Missing values are due to the lack of reliable SSM/I data

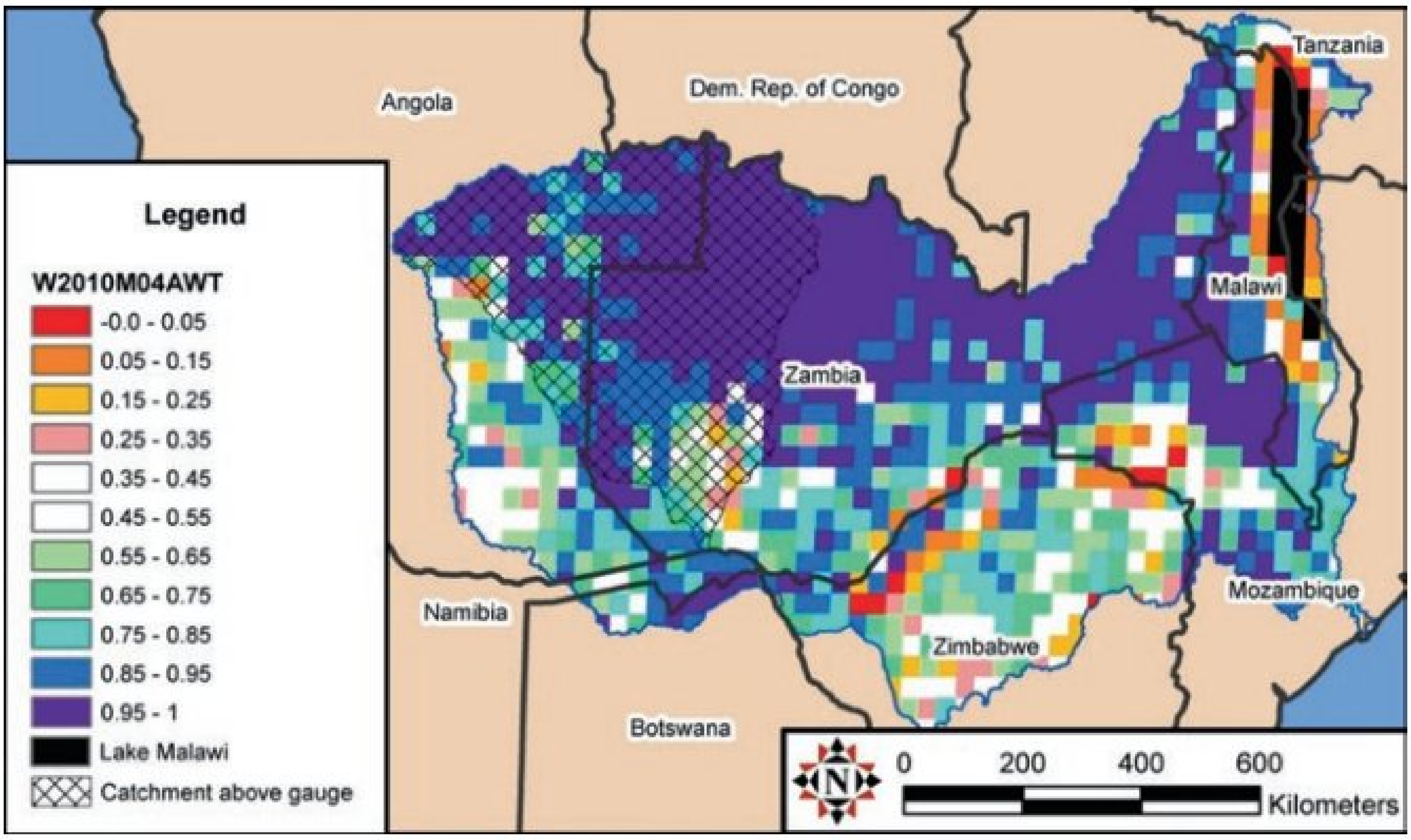

Fig. 9 Surface wetness Values for a section of the Zambezi River: April 2010, where 0.00–0.05 (*red*) means that less than 5% of the time is it this dry, 0.45–0.55 (*white*) is the expected normal soil moisture, and 0.95–1.0 (*purple*) means less than 5% of the time is it this wet

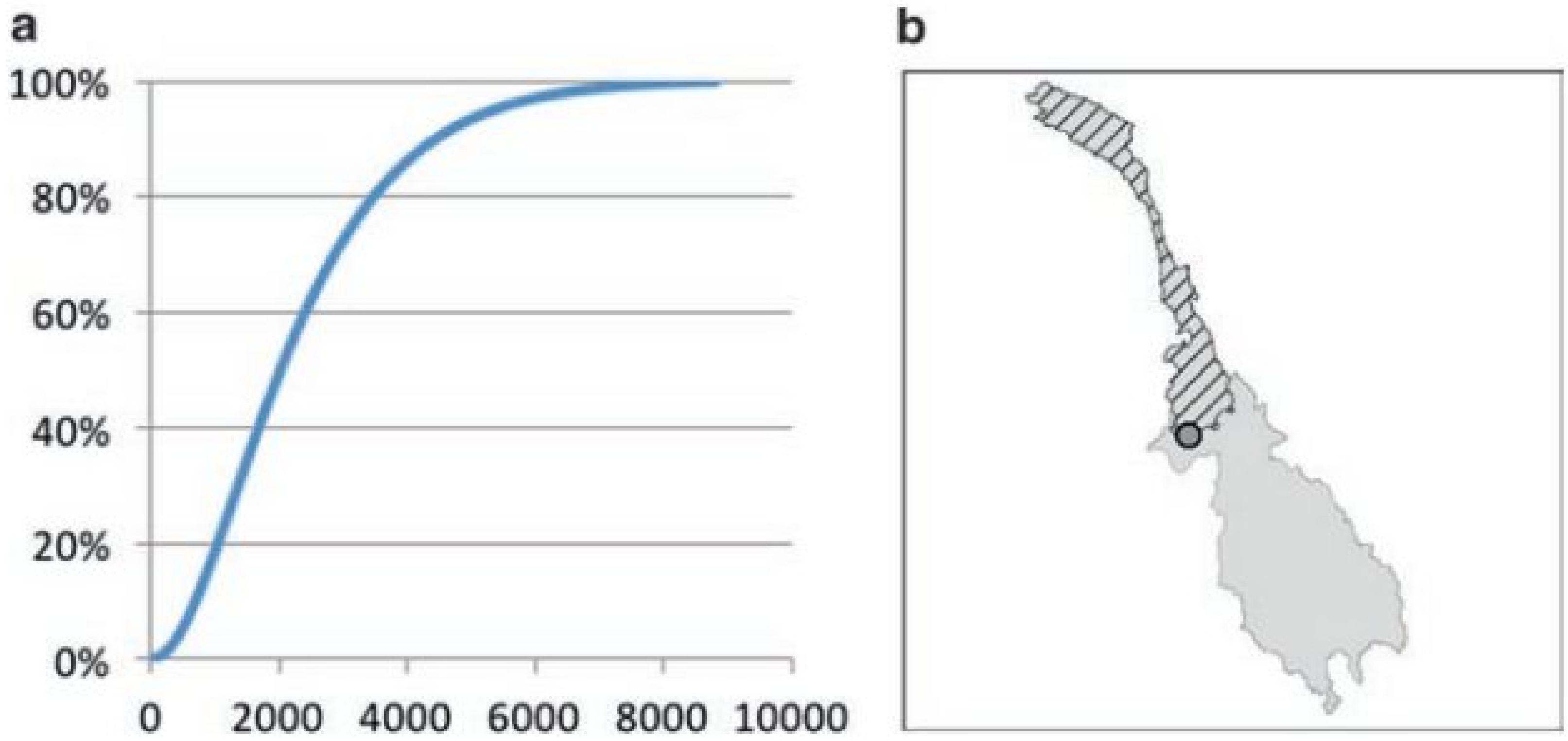

Fig. 10 (**a**) Cumulative distribution of flow using a gamma distribution (percent. y-axis) and flow (m^3/s per month. x-axis) of the Mekong river basin sample area. (**b**) Map of Mekong basin (*grey*) with the selected gauge data (point) and respective catchment (hatched)

quadratic form. It also implies that predicted flow below 1215 m^3/s (BWI = 1.0) occurs less than 25% of the time. There is a limited period of calibration data, and some concern about the accuracy of the model. Therefore, an evaluation of the skill during the predictive preiod will demonstarte the robustness of this approach to monitor flow from the BWI data.

The Mekong river model captures the seasonal hydrologic variation (Fig. 11). The peak flows typically happen in September (end of the monsoon season), while typical low flow is in February. The calibration period ended in 1993, while the model predicted extremely high flow in September of 1995. We evlauated the accuracy of this predictions with meta data, since guage data was unavailable. Research shows that 1995 brought an extreme flood, which was predicted by the BWI. At this time over 100,000 ha of the Vientiane Plain was under more than a half-meter of water for up to 8 weeks. In human terms, the 1995 flood affected 153,398 people in the Vientiane Plain (out of a total population of 653,013 persons), 26,603 households, or 427 villages (FAO 1999). Importantly, we found that the BWI predictive model was robust, even when derived from the limited calibration period. None-theless, it captured this extreme event and its magnitude. Moreover, the BWI provided lead-time to the crest of the event, allowing a valuable opportunity to implement mitigation strategies. This result promotes confidence in applying the BWI to other basins where flow data is limited, which is a considerable number of the world's river.

3.3 River Basin Management: The Case of the Mekong

In locations where irrigation is a major component of agricultural production, economic planning around limited water resources is critical to the success of Climate Smart Agriculture. Specifically, it applies to allocation of river water to promote

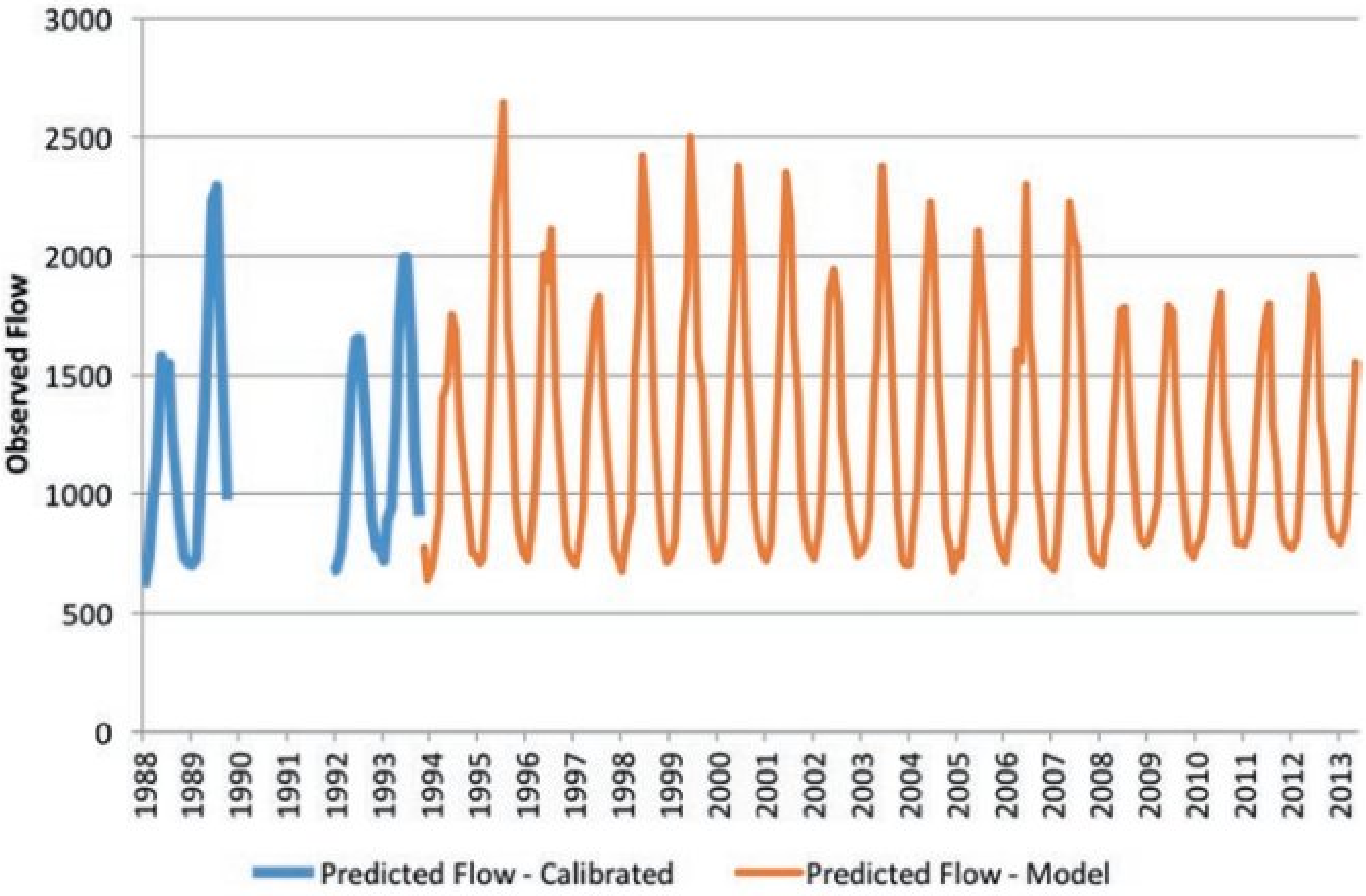

Fig. 11 The Mekong values of runoff (m^3/s per month, y-axis) and time (January 1988 through July 2013) display seasonality and the interannual variability over the calibration (predicted) in blue (red) period of the time series. Missing values are due to the lack of reliable SSM/I data

resilience to climate variability and optimize water allocation for economic growth. We provide a modified version of the empirical model used in Houba et al. (2013). The range of flow probabilities as measured by the BWI and at the gauging station Chiang Saen in Thailand are presented. These probabilities are used to calculate the expected value of basin benefits under various climatic scenarios. While the application of the BWI is demonstrated with the Mekong River Basin, we argue that it is a very simple process to apply the BWI to assist policy guidance in any of the river basins around the world, due to the fact that the main information needed for the analysis comes from satellite-based data, which is readily available. This application can benefit river basin planning, economic opportunities, resource management, and agricultural resilience.

3.3.1 Description of the Model

The model is based on a simplified hydrological structure of the basin, where water flows from China, hereafter noted as the Upper Mekong Basin (UMB) to the Lower Mekong Basin (LMB) and its tributaries, which originate in Thailand, Laos, Cambodia, and Vietnam, before the river enters the Delta (estuary), as seen in Fig. 12.

Basin-wide water availability is determined by water arriving from the UMB, and precipitation received in tributaries of the LMB. Water uses are aggregated in each sub region of the model into (1) industry and households, (2) hydropower

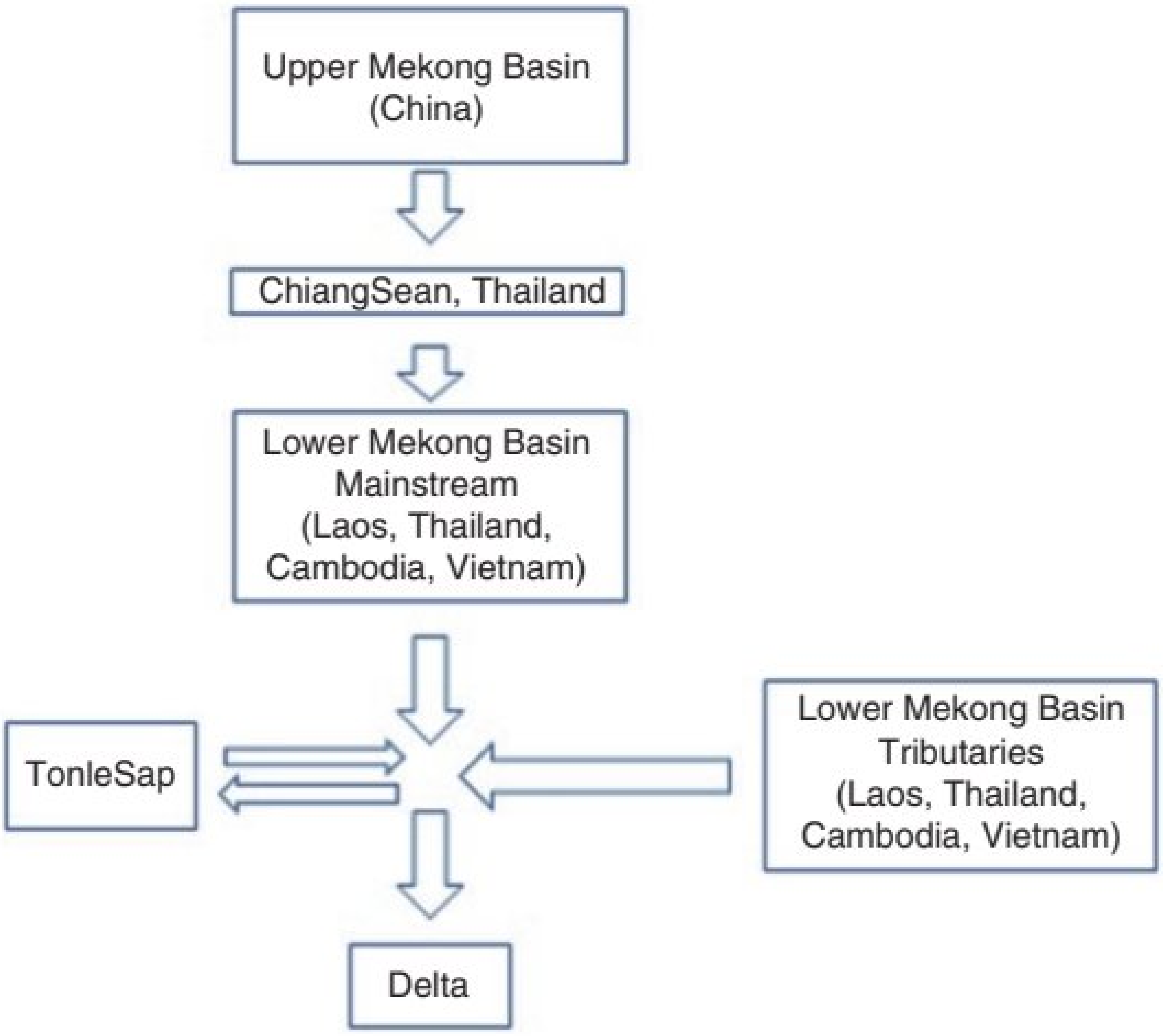

Fig. 12 Simple representation of the Mekong river basin used in our model (Modified from Houba et al. 2013). Note: We exclude Burma (Myanmar) from the analysis because it has a negligible share of water and land in the basin

generation, (3) irrigated agriculture, and (4) fisheries (Table 4). Water quality is measured in terms of salinity in Houba et al. (2013). In this paper we assume that salinity impacts fishery and irrigated agriculture. Hydropower generation is considered to be an in-flow user, while providing economic opportunities and growth. Moreover, water entering the first reservoir of a cascade can be reused and stored, over time, in all downstream reservoirs, which expanding capacity for economic growth along the river.

The model is calibrated on flow data from 2010 and it is static with an annual setup, represented by two seasons' dynamics (wet and dry) across the entire basin. All modifications introduced in this paper comply with the original calibration. The water inflow for the mainstream of the LMB consists solely of the outflow received from China. Reservoirs/dams are filled in the wet season and the water is used during the dry season mainly for irrigation. During the wet season the Mekong water in UMB (China) can be used for industrial and household activities, fish production, storage for use in the dry season, and non-consumptive hydropower generation. Moreover, the wet season water supplies dry season irrigation for Climate Smart Agriculture. Moreover, effectively monitored outflow from mainstream UMB and tributary dams can promote inundations of wetlands in the delta. This nurtures fisheries production and flushes salinity from the estuary (Delta), which improves water quality and irrigation supplies.

Table 4 Water balances and use by sectors (km^3/year) for mean flows at UMB and LMB tributaries

Variable	UMB wet season	UMB dry season	LMB wet season	LMB dry season
Inflow water	66.737	9.534	375.920	53.703
River flow from upstream			60.522	7.151
Water availability	66.737	9.534	436.442	60.854
Stored water total[a]	5.474		12.888	
H&I water use	0.741	0.529	1.895	1.352
Outflow water from dams	60.522	13.565	421.659	69.735
Irrigation		6.414		6.579
River flow to Tonle Sap			86.950	−86.950
River flow to downstream/estuaries	60.522	7.151	334.709	150.107
Hydropower water total[b]	69.226	74.912	60.003	42.860

Source: Houba et al. (2013)

[a] Water is stored on main river in UMB and on tributaries in LMB

[b] Hydropower is produced on main river in UMB and on tributaries in LMB

Following Houba et al. (2013) the benefit, cost and loss functions in the model are quadratic, with the benefit function being concave (same as the flow parameters in the BWI model) and the cost and loss functions being convex to the origin. The volume of water that enters the Tonle Sap and then flows out into the Delta wetlands is a linear function of the river flow. Benefit functions were used for industry and households, hydropower generation, irrigated agriculture, and fisheries. The value function of the Tonle Sap and Delta/Wetlands assumes that all fishery production concentrates in that lake and surrounding wetlands. Salinity losses are modeled only in the LMB agricultural sector.

3.3.2 Applying the BWI to the Mekong Economic Model

A regression equation calibrates the BWI on gauge data from the UMB at Chiang Saen. The upper and lower basins have appreciably different geographies, sizes, and rainfall. Nonetheless, we applied the upstream hydrological model to the lower basin. Our assumption in doing so is that the BWI signal is designed to detect liquid water from all sources, and is defined as the percentage of the surface that is liquid water near the surface. Therefore, we explore the robustness of the model to detect that amount of water moving through the lower basin. Our hypothesis is that BWI values are a robust signal and the model parameters could effectively transcend different geographies.

There was the possibility of shifting the intercept, since the lower basin is appreciably larger, and therefore its base flow should be higher. However, we wanted to minimize any tuning, in order to test the robustness of the model. The only change is the lag was reduced from 2 to 1 month, to allow for better integration (time to flow) from the upper basin into the lower basin. This, in turn, would allow us to model the flow as one kinematic wave based on the speed of flow.

In order to calculate the magnitude of water moving through the entire basin, the upper and lower basins were weighed in terms of their area (the large lower basin is a much larger area, and therefore has higher weights). This allowed us to integrate the upper and lower basins into one combined flow. Since the upper basin has a two-month lag, the first 2 months of 1988 and 1992 were set to be missing. A simple interpolation technique could easily and effectively be applied, since the beginning of the year is not a critical period of flow, however we did not apply it in order to minimize assumptions.

The average flow was derived from the BWI values and the model parameters over the period of record, in terms of cubic meters/second. To keep our economic optimization comparable with previous work Houba et al. 2013, we express water in cubic kilometers per year rather than in cubic meters per second (1 m^3/s = 0.031556926 km^3/year). The mean annual flow over the period of record derived by the BWI for the UMB and LMB is 424 km^3, which is reasonably close to the independent assessments of annual mean flow on the Mekong, which range from 410 (Houba et al. 2013) to 475 (Mekong Water Commission 2009).

We were very encouraged by the fact that the flow numbers derived through the BWI wetness values were congruent with the expected flow values. Equally important, the monitored variation of flow from month to month, and year to year was accurately captured by the BWI values. For example, the major flood of of 1995 and smaller flood of 2000 was also predicted by the BWI, providing a one-month lead-time to the magnitude of the flood, allowing time to mitigate its consequences.

We performed a similar analysis using precipitation inputs to predict mean annual flow for the Mekong. Specifically, we used the flow model parameters derived from the upper basin and applied them to the LMB, in order to determine integrated flow for the River as a whole. The calculated flow based on rainfall is 359, while the BWI provided a value of 424 km^3/year (i.e. the BWI value is much closer to the consensus of the mean annual flow). This result was surprising; since the precipitation model had a slightly better explanatory power of flow in the upper basin, see Blankespoor et al. 2012. We interpreted this finding as demonstrating the robustness of the wetness index, and the ability to apply the model in areas outside of the region where they are calibrated. Consequently, we use the BWI flow predictions to enhance CSA, climate resilience, and calculate return periods of extreme events (Table 5).

3.3.3 Results of the Economic Model

We ran four scenarios, following the pairs (a_i; b_i, i= 1,…,4) of flow values from Table 5, which correspond to distribution of the flow in both the UMB and the LMB tributaries. As can be seen from Table 5, the distribution of the LMB tributaries flow is much more skewed towards lower values (drought) than the flow of the UMB. Table 6 presents the net welfare in each region for various distributions of the flow as obtained from the basin optimization model we run.

Table 5 Flow data in the UMB and LMB as calculated by the BWI

Description	km^3/year	m^3/sec	Cumulative probability	Probability
a. Flow at Chiang Saen (UMB coming from China)				
a1: Mean – 1 SD	27.863	882	0.117	0.117
a2: Mean	76.271	2416	0.588	0.471
a3: Mean + 1 SD	124.679	3950	0.862	0.274
a4: Mean + 2 SDs	173.087	5484	0.961	0.099
b. Flow of LMB tributaries				
b1: Mean – 1 SD	345.536	10,949	0.414	0.414
b2: Mean	429.623	13,614	0.576	0.162
b3: Mean + 1 SD	513.710	16,278	0.710	0.134
b4: Mean + 2 SD	597.797	18,943	0.809	0.099

Table 6 Net benefit calculations for various flow values in the Mekong basin (billion $)

	Mean flow – 1 SD		Mean flow		Mean flow +1 SD		Mean flow +2 SD	
	UMB	LMB	UMB	LMB	UMB	LMB	UMB	LMB
km^3/year	27.863	345.536	76.271	429.623	124.679	513.710	173.087	597.797
Net welfare created	2.376	3.222	2.656	6.663	2.544	6.445	2.313	6.336
Aggregated economic value	2.376	6.355	2.656	6.663	2.544	6.445	2.313	6.336
Econ value households and industry	0.408	1.957	0.408	1.957	0.408	1.957	0.408	1.957
Econ value fishery	0.128	2.772	0.241	2.728	0.167	2.077	0.082	1.109
Econ value irrigation	1.193	1.421	1.193	1.772	1.193	2.206	1.193	3.065
Econ value of hydro in main	0.647		0.815		0.776		0.629	
Econ value of hydro in tributaries		0.205		0.206		0.206		0.206
Aggregated economic costs		3.133		0.000				
Costs saltwater intrusion		3.133		0.000				

Source: Authors' calculations

Note: *SD* standard deviation, *UMB* upper Mekong basin, *LMB* lower Mekong basin

As is apparent from Table 6, the net welfare generated in the UMB is \$2.656 billion and that of the LMB is \$6.663 billion, annually. Of the net welfare produced annually in the UMB, hydropower comprises 31%, irrigation 45%, fisheries 9% and households and industry 15%. For the LMB the values are 3%, 27%, 41%, and 30%, respectively. Table 6 also suggests that the damage from salinity due to seawater intrusion in the LMB is 0 for mean flow or above mean flow runs. However, losses of \$3.133 billion are encountered in the LMB in the case of the below mean flow run. It appears that the LMB is much more sensitive to flow fluctuations than the UMB. This is also apparent from Fig. 13, which summarizes the results in aggregate terms for different flow distributions by the Mekong regions. Both high and low levels of flow have a negative impact on net welfare of the basin.

Using the probabilities in Table 5 and the net benefits in Fig. 13 the expected total basin net benefit value at \$6.359 billion at one standard deviation below mean flow. This figure represents only 68% of the basin-wide net benefits (\$9.313 billion) that was estimated under the mean flow. Having the flow distribution information (as provided by the BWI) allows the basin riparians to reconsider arrangements that will secure their economies rather than face significant losses under extreme flow situations. Having probabilities assigned to the various flow values allows a cost-benefit analysis by policy makers who consider their interventions. The information can be used directly in Climate Smart Agriculture to promote cooperation for efficient and equable water use in agriculture, as well as serve as a quantitative measure to implement early warning strategies to mitigate the losses from limited water supplies.

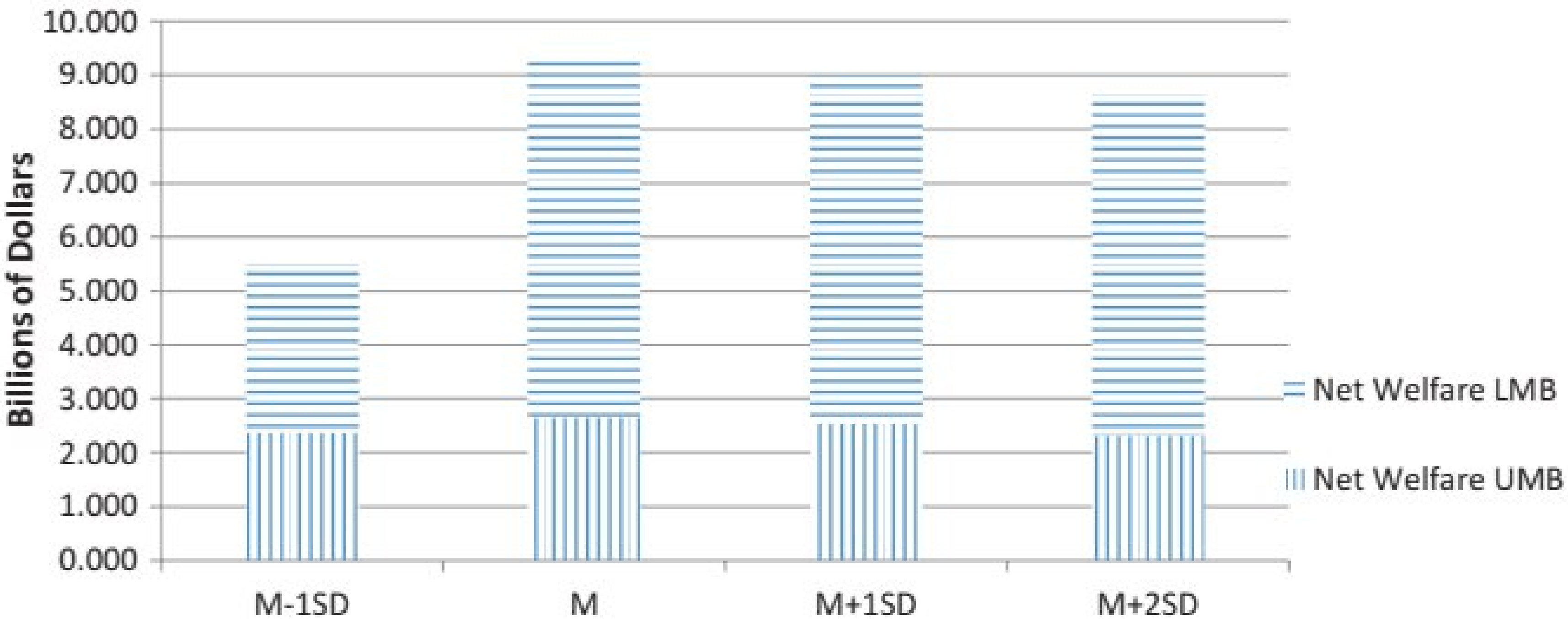

Fig. 13 Net benefits in the Mekong basin as a function of flow distribution. *M* mean, *SD* standard deviation

4 Concluding Discussion

This chapter demonstrates several applications of the satellite derived surface wetness and temperature data to promote CSA. First, the early detection of growing conditions and predicting the availability of food directly improves climate resilience and food security. Second, insurance (risk management) programs can use the indexes in triggers for a quick release of catastrophic bonds to farmers adversely impacted by the weather in order to mitigate the impact of crop failure. Third, these tools provide information to educate farmers about the viable yields from various crops under current and changing climatic conditions. Fourth, an early warning system distributed across the globe can help identify and expedite the exportation of food supplies from areas where they are in excess into areas where a deficiency is likely to occur.

The BWI has skill to predict river flows in several geographies and locations around the world, where it captured the integration of rainfall, melting snow cover, the change in wetland areas in a quantitative measure of river flow. It also provides a quantitative measurement that is independent of local governmental reports.We realize that more sophisticated models can generate more accurate calculations of flow. However these models require detailed parameterizations and assumptions, which means they are difficult to run and maintain, and they must be trained for each basin. Whereas the approach taken in this study is a simple, yet robust variable that has expanded application and portability to other basins and periods of time beyond the calibration time and location. This expands the accuracy and utility of the product for CSA.

In terms of adding new variables to interact with the wetness and temperature products, the Normalized Difference Vegetative index (NDVI) is a natural complement, since it is a direct measurement of canopy greenness. The three products together can be used as a superior signal of crop conditions and potential yields. The CSA will benefit directly by improving near real time monitoring capacity. In this situation the synergy between the three observations can create a superior tool for crop yield predictions, insurance triggers, trends and return period of extreme events, all of which improve climate resilience.

In order to maximize the skill of crop prediction models, it is essential to calibrate the models with reliable yield data from at least 10 years and preferably 20–25 years. Most countries collect field data and calculate yields, however the spatial resolutions of the values can range from county (districts) to province (states, oblast), all the way to country-wide estimates. Since these yield values are always best guesses, CSA needs independent, objective and transparent tools to assess the food production at the regional level in across the globe in near real time. This is a particularly important requirement, since many countries do not release their best estimates; instead the data they do release is manipulated data for national security, political and economic reasons. Consequently, models based on these yield data lack both skill and confidence in their predictions. One approach is to use analogues from areas that grow the same crop and share similar climate, soils, and irrigation practices. In this case, the models developed in the analogue region can be applied to the target area.

Another application to the CSA is using the indexes and predictions as triggers to release catastrophic bonds to farmers having substantial crop failure. There are several advantages to index-based insurance that support CSA.

1. The cost of the premium is substantially lower than the traditional indemnification insurance programs, since no adjuster or field survey are required.
2. The funds are released in near real time, mitigate the impact of the financial losses of the harvest.
3. It is an objective program that can be readily underwritten by numerous sources, thereby the distribution of the losses through various government and financial institutions, reducing exposure to a particular organization. Insurance based on a composite of indexes (used as triggers) has been tried with some success. However, one of the major obstacles is confidence in the triggers by both the insurance companies and the farmers. One intention of the study is to support the CSA's ability to identify reliable and easy to apply triggers in the crop insurance industry.

The value of the wetness index for monitoring and predicting river flow is multifold.

1. Improved knowleddge on the distribution of water resources and the probability of various levels of water for agriculture, commercial, industrial and human consumption is critical to sustainability and development strategies.
2. Mitigate the impact of flood and drought with a reliable early warning system, which provides valuable lead-time about upcoming extreme events.
3. Provide a reliable and objective source of information about the available water resources, in planning and promoting water sharing between riparian states .
4. Use objective measurements to establish an insurance program that protects sectors of society against extreme events, and provides financial compensations for mitigating impacts on infrastructure and society's welfare.

We introduced a model to demonstrate how to qunatify the value on water resources in various sectors of society. The model broke the impacts across the agriculture, fishing, commercial and human consumption. Ther are many benefits to use the BWI to quantify these relationships, in terms of social and economic costs/benefits related to water resource management and mitigation strageties against extreme events. This chapter demonstrates the application of both the wetness and temperature data for monitoring growing conditions and predicting yields, which directly support CSA around the world. We plan to integrate these products with various datasets, such as in situ surface temperature, the greenness index, and soil moisture data, in order to expand their complementary value and utility. We are excited about collaborating with organizations that would like to apply these products in various sectors. Since the data is global and has more than 25 years of observations, we believe that the potential for application is vast and look forward to developing that potential in many areas. The goal is to assist the CSA by applying these products to support resource management, food security, climate resilience, as well as mitigate the adverse impacts of extreme events.

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Early Warning Techniques for Local Climate Resilience: Smallholder Rice in Lao PDR

Drew Behnke, Sam Heft-Neal, and David Roland-Holst

Abstract As part of the Regional Rice Initiative Pilot Project, UNFAO has committed resources to support policy dialog and decision capacity related to climate change adaptation and mitigation in agriculture, with particular attention to food security and the rice sector in Asia and the Pacific. This initiative includes sponsorship of research to deliver information and knowledge products for policy makers to better manage climate risks to the rice sector and identify adaptation needs for the rice sector in Lao PDR. In the following pages, we report on progress of one component of this activity, econometric estimation of long term impacts that climate change can be expected to have on rice yields. The work reported here is preliminary and should not in its current form be used as a basis for policy.

1 Introduction

The report presents a new approach to estimating how climate conditions affect rice production in Lao PDR and modeling the associated potential future impacts of climate change in the rice sector. To conduct our analysis, we use advanced econometric models to estimate the historical relationship between observed rice yields and weather inputs. We then downscale projections from leading climate models to evaluate potential future climate conditions in Lao PDR and implement the econometric models to estimate rice yields under these climate scenarios.

The organization of this report is as follows. First, we provide background and review weather and rice production conditions in Lao PDR as well as summarize the role of weather inputs in rice yields. In addition to average weather conditions,

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special attention is devoted to extreme events such as floods and droughts that can play disruptive roles in rice production. Next we review methodologies used in the literature and discuss the statistical approach employed here in order to estimate the relationship between weather and observed rice yields. Again, we include both average weather and measures of natural disasters in our analysis. Finally, we provide an overview of climate models and apply climate projections to our statistical models of rice yields in order to evaluate potential impacts of climate change on rice yields in Lao PDR.

2 Background

The following section provides an overview of rice growing conditions in Lao PDR. Weather inputs, the occurrence of extreme events, and rice production systems are all discussed in order to provide context for the subsequent analysis.

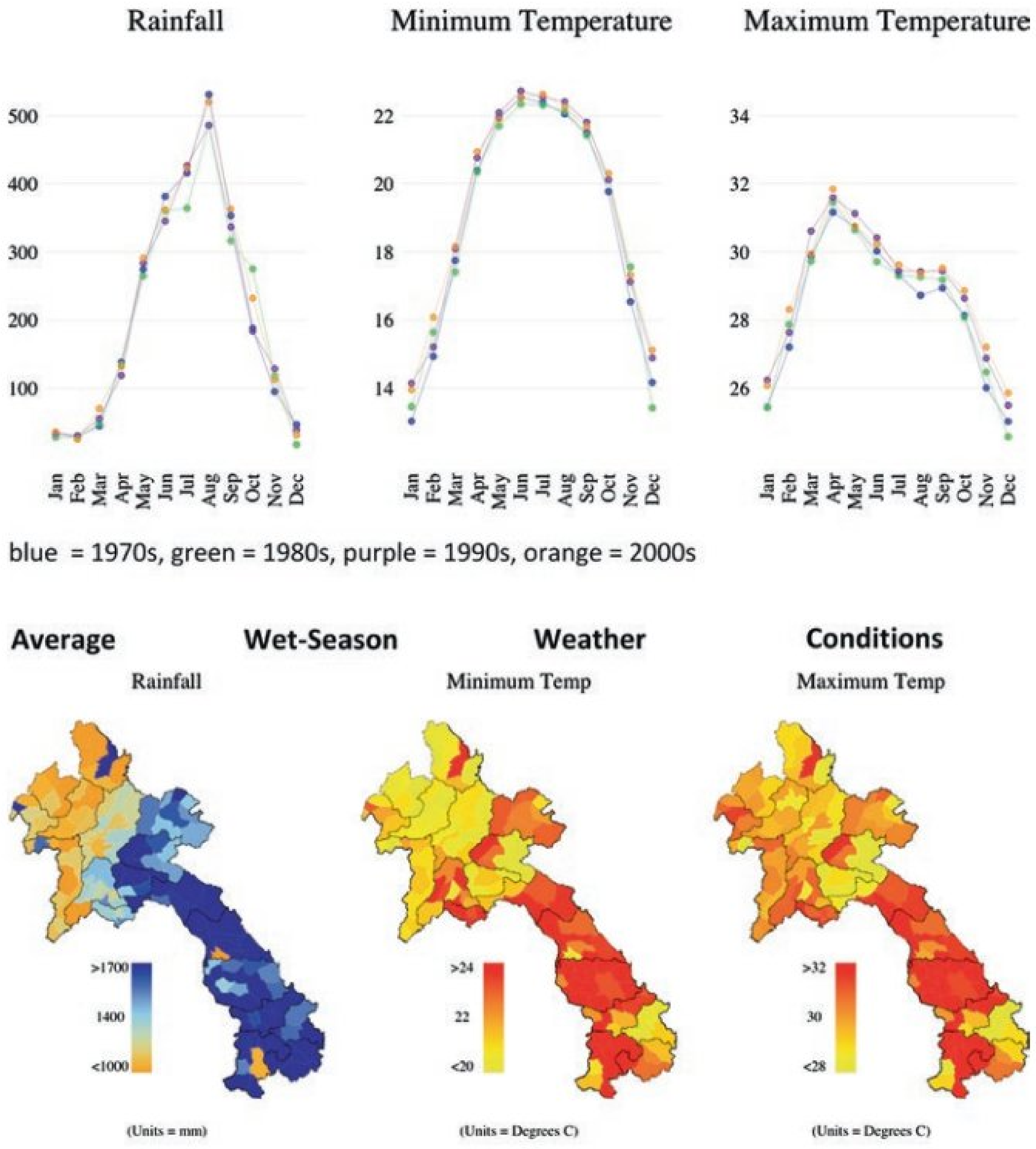
2.1 Overview of Climate Conditions

Total rainfall during the rice-growing season in Lao PDR ranges from about 100–170 cm. However, year-to-year rainfall is highly variable. Moreover, even years with identical levels of total rainfall can have very different growing conditions depending on the pattern of rainfall arrival. Monthly rainfall generally rises each month from the beginning of the growing season until it peaks in August and then decreases thereafter as illustrated in Fig. 1 (both panels).

There is also significant variation in growing season temperatures across Lao PDR. Figure 1 shows the geographical distribution of growing season conditions across space and time. Average minimum (nighttime) temperatures during the growing season range from approximately 20–24 °C, while average maximum (daytime) temperatures range from 28–32 °C. It should be noted however, that these averages mask much of the underlying variability in temperature. For example, average temperature varies across the growing season, where the beginning of the season is typically several degrees hotter than the end of the growing season. Moreover, daily maximum temperatures can exceed 40 °C. Extreme heat, particularly if sustained over several days, puts additional stress on rice growth and may cause large damages (Wassmann et al. 2009b).

2.2 Extreme Events

While average climate conditions play an important role in average rice yields, extreme events can cause large impacts that may not be captured by seasonal averages. For example, a year with early season drought and late season floods may

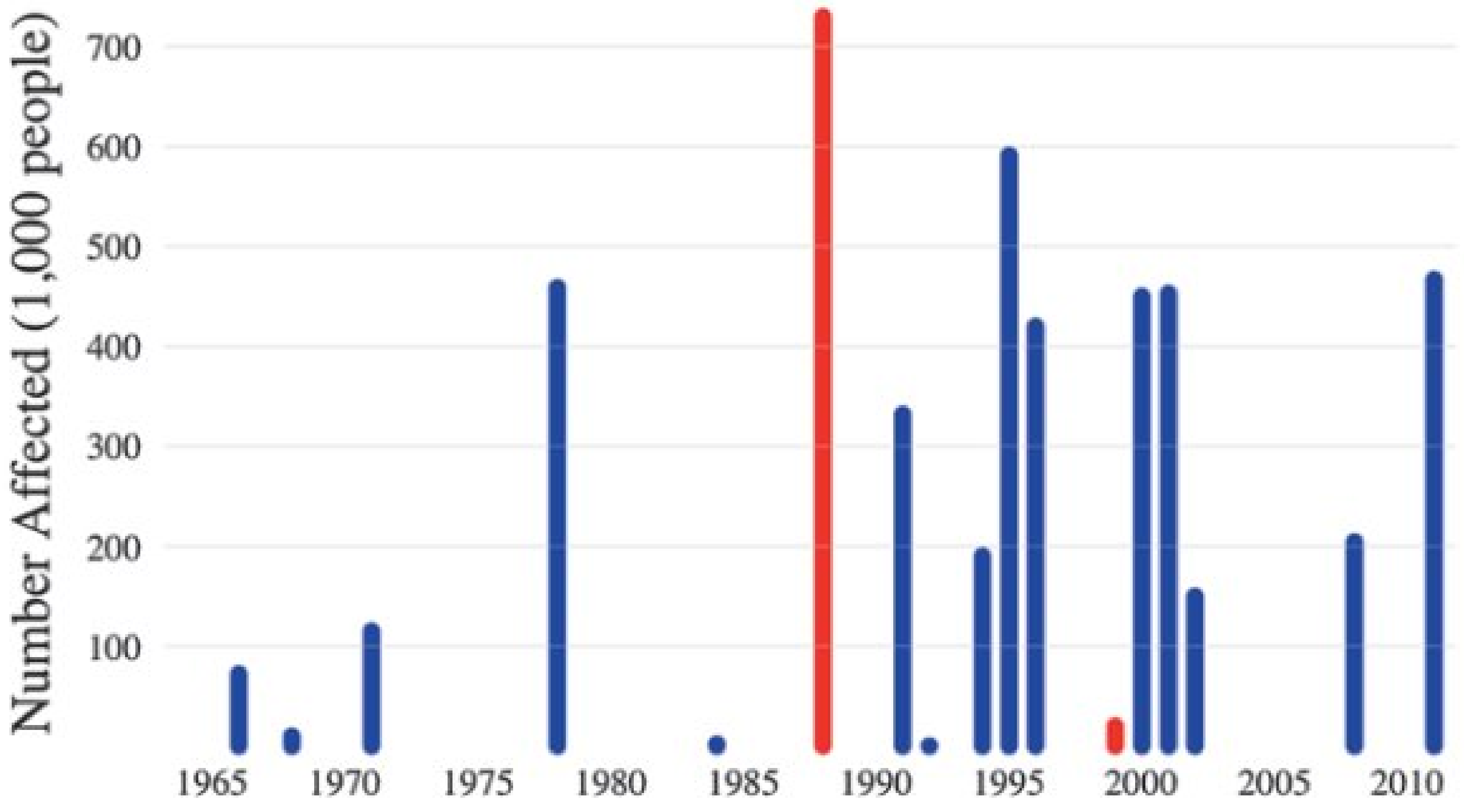


Source: CRU (see section 2.2)

Fig. 1 Decadal changes in seasonal weather conditions (two panels)

record normal growing season rainfall totals while resulting in significant crop damage. Furthermore, rather than contributing to lower annual yields, extreme events may cause the rice planted area to be damaged, resulting in significant loss of the planted crop, which can be devastating to farmer livelihoods. In order to address this important facet of the climate-rice production relationship, we incorporate effects of both average climate and extreme extreme weather events on rice yields.

The majority of rice production in Lao PDR is rain-fed and consequently droughts pose a serious threat. In addition to water shortage, flooding is also a common danger to Lao and other Southeast Asian rice production. In fact, regular



Source: EMDAT database (www.emdat.be)

Fig. 2 Population affected by major flood or drought events in Lao PDR. *Blue* represents floods and *red* represents droughts. Note that regional floods and droughts are not included in the figure. Consequently, the figure represents only the largest scale events that have been recorded in this international database of natural disasters

seasonal flooding from the Mekong River is often a greater threat to the central region rice production than water shortages (Schiller et al. 2001).

The toll from extreme flooding and droughts can be significant. Figure 2 displays the estimated number of people affected by major floods and droughts in Lao PDR as recorded in the international natural disaster database EMDAT.[1] This database provides statistics for the number of people affected by particular large-scale extreme weather events. It should be noted that smaller regional scale events are not recorded in the database and thus not included in the figure. It should also be noted that many of the people affected by these disasters may not be farmers. That being said, farmers are particularly vulnerable to droughts and floods because their livelihoods can be negatively affected. Nonetheless, the EMDAT database provides insight into the potential magnitude of these effects. According to the database, there have been six floods in the last 20 years that affected at least 300,000 people in Lao PDR. Major droughts, although less common than floods, can also exact large damages. In fact, the biggest event in the database is a late 1980s drought that affected more than 700,000 people in Lao PDR.

To address the shortcomings of the EMDAT data we consider the direct impact of flooding and droughts on rice yields in subsequent sections. The data that we use in our analysis, which comes from the Department of Agriculture and is described further in Section 4, is more precise and includes annual damaged rice area for each district that resulted from drought, floods, or pests (Fig. 3).

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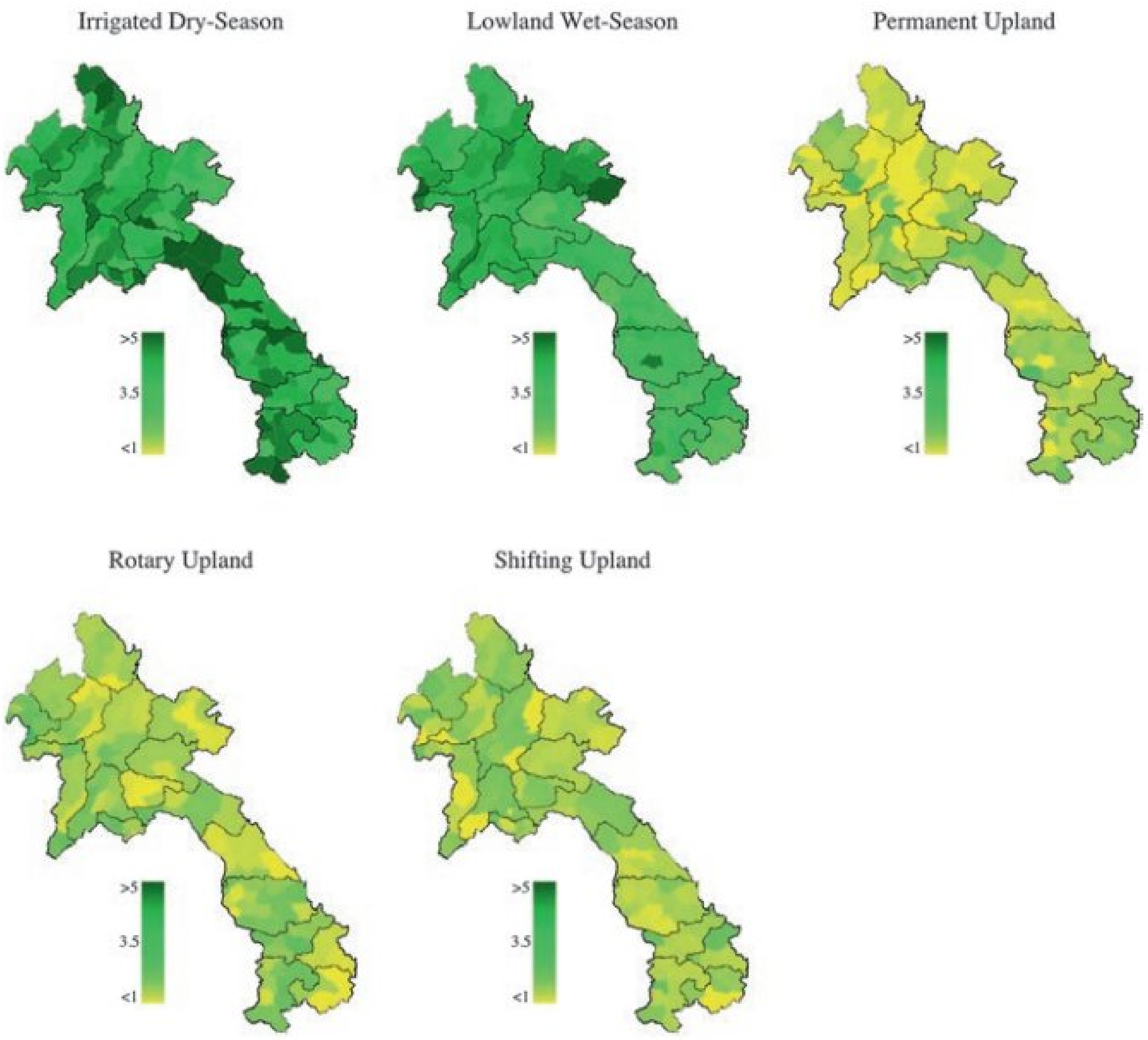
[1] Available online at www.emdat.be.



Source: Crop Statistics Yearbook (DOA, Lao PDR)

Fig. 3 Average rice yields. Maps show average rice yields by rice production system. Data cover the period 2006–2012

2.3 Rice Production

As a culturally significant, staple food crop, rice has an important role in the economy of Lao PDR. Because of this, the rice production sector has been the focus of various political policies in order to increase production and maintain food security. As a result, Lao PDR has undergone significant transitions in the sector over the past several decades, moving from a net rice importer in the 1970s and 1980s, to a stable and increasing surplus over the last decade.

The introduction of improved seed varieties in the 1970s as well as loosening of price controls in the early 1980s led to some production increases, but the majority of growth occurred in the 1990s. Over the last 20 years, rice production has more than doubled to reach nearly 3.5 million tones of paddy in 2012 (DOA 2012). This represents an average of 5.1% annual growth, which is one of the highest in the region over this time period. This high growth can be attributed both to the yield improvements (from new, improved seed varieties and increased use of fertilizer) as well as land expansion. Growth from land expansion over the previous two decades can be explained by the steady increase in lowland, rain fed production systems as well as a rapid increase in dry season irrigated production. Concurrently, the lower yield, upland rice production system saw total area steadily fall. Regionally, much of this growth was concentrated in the central plain provinces of Savannakhet, Khammuane, Vientiane, and the Vientiane Municipality as well as the southern province of Saravan. In total, these five provinces comprised 70% of the total increase in rice production between 1995 and 2010 (MAF 2012).

2.3.1 Production Systems

Rice production systems can be categorized into one of five different categories: lowland wet-season, lowland irrigated dry-season, upland permanent, upland rotary, and upland shifting.

Lowland Wet-Season Lowland wet-season is responsible for the majority of production, representing 79% of the total yield in 2012. This production system is most common in the central and southern regions of the country with 83% of total yields coming from these areas (DOA 2012). Lowland wet-season production has relatively high yields compared to other production systems with an average of 3.91 tons per ha in 2012. Given the comparatively high yields, and ubiquity of production along the populated Mekong River Valley, lowland wet-season will remain the most important ecosystem for rice cultivation in the foreseeable future.

That being said, lowland wet-season production faces a variety of production constraints. First and foremost, is the constraint from climatic variability, as the production system is reliant on weather inputs for the production process. Rainfall is identified as a particular concern among farmers, as the rainfall pattern can vary from year-to-year, resulting in large fluctuations in production. Furthermore, the permeable nature of the sandy soils that prevail in much of the Mekong River Valley means drought is common occurrence. Temperature is of course an issue as well, as extreme temperature events are known to be harmful to rice production and the random nature of such events means farmers and unable to anticipate temperature shocks (Schiller et al. 2001).

Related to climatic variability, is the problem of insect pests that are rated by farmers as being among the top three production constraints. The relationship between pests, climatic variability, and production is not clearly understood, although it is understood that pests are believed to significantly impact yields and climate plausibly affects the prevalence of pests (Schiller et al. 2001).

Irrigated Dry-Season Dry-season production occurs under irrigated conditions only. During the 1990s, the irrigated dry-season production system saw a rapid increase in production as part of the official national policy to support the continued development of small-scale irrigation schemes. The expansion of the irrigated system was promoted in order to increase national rice production, while at the same time reducing the year-to-year variability associated with wet-season production. Over the 2011–2012 dry-season growing season planted area totaled 108,000 ha representing approximately 11% of the national crop. Although this is a large increase from the 13,000 ha planted in 1992–1993, it represents only a modest increase from the 87,000 ha planted in 1998–1999. Furthermore, there is a large disparity from the MAF's projected goal of 180,000 ha of production by 2005 (DOA 2012; Schiller et al. 2001).

Due to the intensive nature of irrigated production, the majority of production is concentrated in a few provinces that can support this system. The central region is home to nearly 68% of the total irrigated dry-season planted area, with production being highly concentrated in the Vientiane Capital and Savannakhet (19% and 29% of total area planted respectively). Yields are the highest in this production system with 4.72 tons per ha on average over the 2011–2012 season (DOA 2012). This is unsurprising as the adoption of improved rice production technology is highest in the irrigated areas both as a combination of better extension services and higher farm incomes.

In regards to production constraints, temperature likely plays a larger role for the irrigated production system, as dry-season temperatures are initially cool before dramatically increasing toward the end of the season. Especially of concern are low temperatures in the north where temperatures can fall below 5 °C. In southern and central Lao PDR, the high temperatures during March and April that can coincide with flowering and grain filling are of primary concern (Schiller et al. 2001).

Upland Upland rice cultivation in Lao PDR is split between three production categories; permanent, rotary, and shifting. Estimates vary about the size of these systems, as they are predominantly located in the remote, mountainous northern and eastern regions of the country. Furthermore, due to remote nature of these systems accurate yield measurements are next to impossible. Often upland rice plots are not clearly marked and typically grow in combination with forest trees and other crops. Furthermore, much of the production is in remote areas with limited to no road access and inadequate resources and staff to accurately record yields.

That being said, some estimates for upland production do exist. In the early 1990s it was estimated that 2.1 million ha (or 8.8% of the national territory) was being used for slash-and-burn cultivation (Schiller et al. 2001). By 2000, it was estimated that about one third of the population still relied on shifting cultivation systems, covering about 13% of the of the total land area of the country (ADB 2006). In regards to rice production only, official data reports there was 119,000 ha of upland rice planted in 2012 representing approximately 12% of the total planted area of rice. Of this, approximately 47% was classified as a permanent upland system (DOA 2012). Furthermore, the DOA reports data on two types of slash-and-burn systems referring to them as either "rotary" or "shifting," but has no explicit information on the differences between these systems.

Much like other production systems, there is a strong regional trend in the upland production system. The northern provinces accounted for over 73% of the total area planted, with Luangprabang responsible for 18% of the total area alone. Yields are low in the upland system and relatively much lower than the other production types with an average yield of 1.8 ton per ha (DOA 2012).

In regards to production constraints, the upland production system has both similar and unique limitations to production. Climatic variability is again a major concern, as farmers must rely on the weather for inputs into production. However, biotic constraints are a much larger concern for the upland system than others. Weeds and rodents were highlighted as the two largest limitations to production for upland farmers (Schiller et al. 2001). Additionally land pressure and pressure for the government have limited production. Traditionally, farmers would clear the forest with fire and after growing rice for a year or two, land would be left to fallow for 10–20 years before returning. However, increased population pressure and land-use restrictions have led to a reduction in fallow periods to as short as 3 years (ADB 2006). Without the necessary time for the land to restore fertility, production is adversely impacted and furthermore such a system is unsustainable ecologically.

2.3.2 Irrigation

As previously discussed, irrigation in Lao PDR increased dramatically during the mid-1990s and early-2000s under the government's official policy to expand coverage. During this time, large investments were made to install high-capacity pumps along the Mekong River and its tributaries to expand small-scale irrigation opportunities for smallholders. As a result of the government's expansion efforts, irrigated area increased from about 12,000 ha in 1990 to 87,000 in 1999, representing a seven-fold increase (Pandey 2001). Growth was even more rapid in the early 2000s, eventually reaching peak coverage of over 500,000 ha in 2006 before declining slightly to the current 400,000 ha of coverage in 2012 (DOA 2012).

2.4 The Physiological Relationship Between Rice and Weather Inputs

2.4.1 The Role of Water

Rice production, more than most crops, is highly dependent on water availability, both in terms of quantity and timing of application. At some points during the growing season rainfall is highly beneficial, while at other times during the season it can be harmful. Too much or too little rainfall at any stage of rice growth can cause partial or total crop failure (Belder et al. 2004). Excessive water can lead to partial submergence of the rice plant, which reduces yields. In one experiment, Yoshida (1981) reports that 50% of plant submergence during any of the growth phases led to a 30–50% reduction in yields. However, while excessive water damages rice crops, drought is widely recognized as the primary constraint for rain-fed rice production (Bouman et al. 2005, 2007). Insufficient water causes plant mortality and a wide range of stresses that can lead to spikelet sterility, incomplete grain filling, stunting (Yoshida 1981), delayed heading (Homma et al. 2004), and other adverse yield effects.

Prior to planting, water is also important for rice production as an input to field preparation. In rain-fed production systems, insufficient early rainfall can force farmers to delay planting. Although data in Lao PDR are not available, Sawano et al. (2008) studied the relationship between rainfall and planting dates in rain-fed areas of northeast Thailand, an area that is geographically similar to the central plains of Lao PDR. The authors concluded that, depending on field-level water availability from rainfall, planting dates were locally distributed over an approximately two-month period, while local harvesting took place around the same time everywhere. The implication is obvious – delayed planting from insufficient early season water resources can significantly shorten the growing season and thus reduce output. It remains unclear why farmers who delayed planting did not delay harvest. While the authors did not offer any conclusive answers for this question, they suggested that farmers may not want to delay harvesting in order to prevent interference with subsequent growing seasons, marketing considerations, and other farm and nonfarm activities.

2.4.2 The Role of Temperature

Sunlight is another essential input into rice production – rice plants require solar radiation for photosynthesis and heat to promote tissue growth. There are a number of ways to measure energy requirements, the simplest being average temperature. Other related measures include other temperature boundaries (e.g., daily min T, daily max T), agronomic measures such as Growing Degree Days (GDD), and radiation measures.

Generally, extreme highs and lows are of concern to crop growth. However, at the range of temperatures experienced by rice growers in Lao PDR, extreme lows are unlikely to harm rice growth, but extreme highs are a greater threat.[2] Extreme high temperatures hurt plant growth because it causes heat stress, which delays the growth process (Yoshida 1981; Wassmann et al. 2009b). Furthermore, researchers have highlighted the difference between extreme high nighttime (minimum) temperatures and extreme high daytime (maximum) temperatures. The respiration process appears to make rice plants particularly sensitive to nighttime temperature (Yin et al. 1996). Several studies have highlighted nighttime temperatures as a driving factor of rice growth, where elevated minimum nighttime temperatures greatly reduce rice yields (Yin et al. 1996; Peng et al. 2004; Welch et al. 2010). Using a laboratory experiment to artificially manipulate temperatures, Yin et al. (1996) demonstrate that a one-degree increase in nighttime temperature has a large negative

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[2] Both daytime (daily maximum) and night-time (daily minimum) extreme highs are potentially harmful to rice yields.

effect on rice yields whereas a one-degree increase in daytime temperature has a slightly positive effect. In fact, across most observed ranges of maximum temperatures, higher daytime temperatures have generally been found to positively affect rice growth (Peng et al. 2004; Welch et al. 2010), however, as temperatures continue to rise, they eventually become harmful. The threshold where maximum daytime temperatures become detrimental to rice growth depends largely on genotype and local growing conditions (including e.g., soils and water availability). For example, depending on genotype and field conditions, Wassmann et al. (2009a) estimated an average cutoff for maximum temperature of 31 °C, beyond which "growth and productivity (yield) rapidly decrease". However, these estimates come from experimental rather than field results, which may not be representative of adaptive, farmer-managed fields where some precautions may be taken when temperatures become potentially harmful. Consequently, if we believe that farmers can effectively ameliorate the effects of extreme temperature through management practices, or through use of local varieties selected for heat resistance qualities, then we might expect observed field data to exhibit higher thresholds.

3 Analysis I: Estimating the Relationship Between Rice and Climate Change

This section constitutes the first part of our analysis, where we estimate the relationship between observed historical rice yields and weather conditions in Lao PDR. The following section will use the observed relationship to project yields under potential future climate scenarios. In this we first describe the data and methods used, then describe our primary results. Full model results are presented in tables in the appendix.

3.1 Methods

Climate change is a long run phenomenon and it is difficult to distinguish historical climate change from short to medium run weather cycles. In order to estimate potential climate change impacts on agriculture, researchers often estimate the short-term relationship between weather inputs and yields and then apply this relationship over the range of future conditions predicted by climate models. While this approach is imperfect[3], it allows us to provide an approximate estimate of future climate impacts.

In general, two approaches have been taken to characterize the relationship between weather inputs and rice yields. First, in agronomic studies, usually involv-

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[3] One needs to be particularly careful about extrapolating current relationships to future unexperienced ranges of climate conditions.

ing laboratory or experimental fields, rice plants are placed under different types of environmental stresses and physiological responses are measured (e.g., Borrell et al. 1997; Homma et al. 2004; Yin et al. 1996). An extension of this approach is to use field data to calibrate crop models that simulate the physiological growth process. Perturbing the inputs in these models can in turn generate predictions of crop growth under potential future climate conditions.

The second approach, which we take here, applies statistical models using plausibly random variations in weather to estimate the effects of weather conditions on observed rice yields. We exploit the presumably random year-to-year variation in temperature and precipitation to estimate whether rice yields are higher or lower in years that are warmer and wetter. With the relationship firmly established, we then use climate projections to model how climate change will affect yields.

In a controlled lab experiment, scientists repeatedly carry out procedures that are identical except for one factor of interest, which is manually manipulated in order to measure the causal impact of said factor on the outcome. As with many social science settings, this type of experiment is not possible for the Lao PDR rice sector. Thus we rely on existing data to demonstrate the impact of historical weather realizations on yields and model the impacts of climate change once this relationship has been established. It should be noted that overall yields have increased over the study period due in large part to technological advances. Consequently, our estimates represent losses with respect to the counterfactual scenario of no climate change. Losses due to climate change do not imply that the yield trends are downward sloping, only that yields have been, and will continue to be, lower in the face of climate change than they would be otherwise. This distinction does not change the fact that climate change has potential to have strongly negative impacts on the rice sector in Lao PDR.

Typically, statistical studies use average growing season (or sub-season) conditions, to represent the weather inputs in the production function. The simplest approach estimates yields (calculated as *log(yield)*) as a function of mean temperature, mean precipitation, and their squares. However, several studies have emphasized the differential effects of minimum and maximum temperature (Yin et al. 1996; Peng et al. 2004; Welch et al. 2010), the importance of including radiation (Sheehy et al. 2006; Welch et al. 2010), and the differential effects across phases of the growing season (Welch et al. 2010). In addition, there has been extensive research on water requirements for rice production in irrigated (Bouman et al. 2005, 2007) or rain-fed settings (Xu and Mackill 1996; Sharma et al. 1994; Wade et al. 1999).

Our goal is to provide a localized analysis for Lao PDR. In order to do so, we seek to incorporate the main methods and findings from these disparate sources into statistical models that estimate the impact of climate on rice types grown particularly in Lao PDR. This analysis, in turn, will be used to inform policy prescriptions and identify the production systems and rice growing areas that are most vulnerable to adverse changes in growing conditions.

3.1.1 Average Weather Models

We begin with an approach of estimating the effects of climate on rice yields using a panel regression with a single growing season metric for each weather covariate (average min T, max T, and precipitation across the growing season). Using average seasonal conditions, we estimate a linear model for each rice production system. These are later used to predict yields under various climate scenarios.

Here, we present a variation of the panel fixed effects (FE) model. This model is an accepted and commonly applied model in the literature (see e.g. Lobell and Burke 2010). Panel data contains repeated observations of the same units over time. In this case we repeatedly observe district rice outcomes. Panel data allows the use of fixed effects, which control for a variety of observations that are unobserved. By conditioning on fixed effects, county specific deviations in weather from the county averages are used to identify the effect of weather on yields. Specifically we chose to control for district and year fixed effects. District fixed effects control for any unobservable characteristic that varies across district but is constant over time. This accounts for important differences across districts such as soil conditions or areas with a higher prevalence of intensive production systems. Year fixed effects control for any unobservable characteristic that varies across years but is constant across all districts. This includes national time trends such as improved technology (irrigation, fertilizer use, or the introduction of improved seed varieties for example).

Within this framework there are a number of choices/assumptions to be made. In each case, there is a tradeoff between controlling for unobserved factors and observing enough variation in the data to be able to make econometric estimations. In reality, we know that there are many factors that affect crop yields, including soil quality, technology, agrochemicals, endogenous behavior, etc. Here, we are only considering the impact of weather, while the other factors are unobserved by us. Thus we are trying to estimate the disaggregated yield impact of weather holding constant other explanatory variables. If district-level time-series data were available on other factors such as agricultural investment, fertilizer use, or pesticides, then we could include these explanatory variables in our model. However, to our knowledge these data do not exist at the required resolution. Fortunately, the fixed effects model attempts to control for these unobserved factors, so that we can still produce unbiased estimates of climate effects. In other words, we can control for a variety of unobserved characteristics but cannot estimate them in our model. We are not attempting to explain every factor that affects yields, but merely to identify the effect of temperature and rainfall. Given our interest is ultimately how yields will change in the face of new climate conditions this does not affect our analysis.

The following reduced form model is our primary empirical specification. In our ideal specification we would have a vector of controls for the other factors that affect yields that we have previously discussed. This would include characteristics such as fertilizer use, pesticide use, soil quality, etc. However, data of this quality does not exist in Lao PDR, which is why we rely on fixed effects.

Equation 1: Panel Model of Average Weather Effects

$$\log\left(\mathrm{Y}_{dt}\right)=\gamma_{\mathrm{d}}+\theta_{\mathrm{t}}+\beta_1\mathrm{MinT}_{\mathrm{dt}}+\beta_2\mathrm{MaxT}_{\mathrm{dt}}+\beta_3\mathrm{P}+\varepsilon_{\mathrm{dt}} \tag{1}$$

Y_{dt} is yield for district d in year t. The model includes district fixed effects γ_{d} and year fixed effects θ_{t}. $\beta_{1\text{–}3}$ represent the coefficients on our weather variables

One of the fundamental assumptions we have to make is that individual specific time series variation is a valid source of variation for identifying causal effects. In other words, our model assumes that, for each district, weather variation from year-to-year is random. It is obviously not true that weather is random over space (i.e., we expect that some parts of the country to get more rain than other parts every year) but we argue that it is reasonable to assume that deviations from local averages in one year are unrelated to deviations from local averages in the next year.

The modeling approach in equation 1 makes the strong assumption that the effect of weather on yields is the same over different ranges. For example, the linear model assumes an increase in maximum temperature from 29 to 30 has the same effect as an increase from 33 to 34. This is a very strong assumption and other researchers (Schlenker and Roberts 2009) have found a nonlinear relationship between temperature and yields. Therefore, to add robustness to our analysis we also consider a non-linear model as seen in equation 2. This model adds square terms for the climate variables used in equation 1, which allows us to consider if there is a threshold at which the relationship between weather and yields changes. Ideally, we would like to estimate a piece-wise linear model that estimates different slopes over different ranges of covariates. However, given our limited number of observations, a piece-wise model is not advised as it will increase the number of covariates and reduce the necessary power for statistical inference.

Equation 2: Panel Model of Average Weather Effects

$$\log\left(\mathrm{Y}_{dt}\right)=\gamma_{\mathrm{d}}+\theta_{\mathrm{t}}+\beta_1\mathrm{MinT}_{\mathrm{dt}}+\beta_2\mathrm{MinT}^2{}_{\mathrm{dt}}+\beta_3\mathrm{MaxT}_{\mathrm{dt}}+\beta_4\mathrm{MaxT}^2{}_{\mathrm{dt}}+\beta_5\mathrm{P}+\varepsilon_{\mathbf{dt}} \tag{2}$$

Y_{dt} is yield for district d in year t. The model includes district fixed effects γ_{d} and year fixed effects θ_{t}. $\beta_{1\text{–}5}$ represent the coefficients on our weather variables

3.1.2 Modeling Extreme Events

In addition to modeling the effects of average weather conditions on average rice yields, we can model the effects of drought and floods on rice losses with the same methodology. In equation 2, L_{dt} represents rice losses[4] and $\mathrm{Dr}_{\mathrm{dt}}$ measures drought severity in district *d* and year *t*. Since our yield measures are annual, drought and

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[4] Planted area that could not be harvested.

flood measures need to be aggregated annually. We will experiment with different aggregation methods.

Equation 3: Panel Model of Extreme Event Effects

$$\log\left(\mathrm{L}_{\mathrm{dt}}\right) = \gamma_{\mathrm{d}} + \theta_t + \beta_1 \mathrm{Dr}_{\mathrm{dt}} + \beta_2 \mathbf{X}_{\mathrm{dt}} + \varepsilon_{\mathrm{dt}} \tag{3}$$

Y_{pt} is yield for district d in year t. The model includes province fixed effects γ_{d} and year fixed effects θ_{t}. β_1 represents the coefficients on our drought measure. X_{dt} are other controls.

3.2 Data

3.2.1 Rice Yields

Our rice yield data for Lao PDR come from the "Crop Statistics Year Book" published by the Department of Agriculture (DOA) within the Ministry of Agriculture and Forestry (MAF). These reports contain a wide variety of detailed crop production data at the district level and have been published annually since 2005. Unfortunately, rice production data before 2005 in Lao PDR is limited to province level aggregates that are of little use to our analysis, and district level rice production data is only available from 2005 through 2011. Although our panel is limited, it represents the most accurate and detailed rice production data in existence for this country. Rice production data is split between the five distinct production systems used in Lao PDR and these contain a variety of important statistics useful to our analysis. The variables in the data include planted area, harvested area, yield, and damaged area by source (drought, flood, etc).

3.2.2 Weather Conditions

It is inherently difficult to measure weather over space. Weather is observed at individual weather stations, and ideally want to have weather stations collecting data every few meters in order to capture variation in conditions over space. Of course, managing so many weather stations is impractical, and instead observed values are interpolated over locations in between weather stations. There are many different forms of weather data sets that have carried out this interpolation over different spatial and temporal resolutions. Each data set has its own advantages and drawbacks. Here we carry out our analysis with two separate weather data sets, known by the acronyms CRU and APHRODITE, described below. CRU data provide more weather variables (i.e., MIN, MAX) but at a lower temporal and spatial resolution. By including two completely different weather data sets we decrease the likelihood that our results will rely on the peculiarities of a particular data set.

The first weather data come from the Climatic Research Unit (CRU) at the University of East Anglia. The research group produces several global data products that include *monthly average* minimum (nighttime) temperature, maximum (daytime) temperature, mean temperature, and *monthly total* rainfall. We utilize the high-resolution gridded data sets[5] that have a resolution of 0.5 × 0.5 degrees globally. This translates to approximately 55 × 55 km at the equator. Each Lao PDR district is overlapped on the grid and area weighted averages are calculated in order to estimate monthly weather conditions for each district over the sample period.

The second data set, APHRODITE[6], is described by Yatagai et al. (2012). Researchers in Japan utilized a high density cluster of proprietary station data in order to create a high-resolution data set that includes daily average temperature and daily rainfall at a resolution of 0.05 × 0.05 degrees (~5 × 5 km). Although daily temperatures are useful, this data set does not contain minimum and maximum temperature information, and covers only Asia.

3.2.3 Extreme Events

Droughts

Although difficult to measure from seasonal rainfall and temperature data, researchers have begun to use remote sensing data from satellites to estimate drought severity. In the present analysis, we utilize a new measure developed by Mu et al. (2013) called the Drought Severity Index (DSI). Mu and colleagues produce global DSI measures from satellite data covering the globe averaged over eight day periods from 2000 through 2011 at a resolution of 0.05 × 0.05 degrees (~5.5 × 5.5 km). In theory, DSI values range from negative infinity to positive infinity, however, in practice most values are clustered around zero. Negative DSI values signify drier-than-normal conditions while positive values signify wetter than normal conditions. A zero value for DSI implies normal conditions. While it is an imperfect measure, DSI allows us to estimate district level drought severity across the rice-growing season and therefore estimate the effects of droughts on rice losses. Moreover, the drought patterns suggested by the DSI appear to be consistent with precipitation patterns observed in other data sets.

Floods

Like droughts, measuring flood extent is a practical difficulty that we address by using remotely sensed satellite data processed to estimate standing water extent. As far as the authors know, there are no available global remotely sensed flood measures. Consequently, as a second best option, we utilize DSI as a flood measure

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[5] http://www.cru.uea.ac.uk/data.

[6] http://www.chikyu.ac.jp/precip/products/index.html.

where large positive values for DSI imply flooding. The developers of DSI note that flood measurement is a potential extension of DSI, but also caution that DSI has not been fully evaluated as a flood measure. Consequently, we proceed with caution using the best available flood measures to estimate the impact of flooding on rice production.

3.2.4 Data Limitations

There are significant constraints on data availability (and, inevitably, quality) for Lao PDR. First and foremost, detailed rice production statistics have only begun to be collected in recent years. Therefore, although we have a more than 40-year panel for weather, our analysis is limited given extreme constraints on availability of rice production statistics. For example, the small number of observations makes it difficult for us to detect non-linearities in the weather-rice relationship. That being said, the DOA has done an excellent job of identifying the data shortcomings, and there appears to be a serious effort underway to improve data availability across the country. Therefore, we believe that despite having a limited panel, this represents the single best quality data currently available.

We have also been unable to locate other data that would have improved our analysis. We hoped, for example, to obtain rice crop calendar information on the length of growing period for each district in the country, but no data like this currently exists. The closest data of use came from the National Agricultural and Forestry Research Institute (NAFRI), which had crop calendar information for just a single province, based on their own recent field study. Although this is of value, we do not incorporate into this analysis as we model yields for the entire country, which has diverse geographical regions and growing climates. Another potential area of further exploration we hoped to explore was the affect of changes on rice yields on different socio-economic variables. In order to examine this however, we would need access to the Lao Expenditure and Consumption Survey (LECS), which has been conducted every five years since 1997/98.

Given the serious data concerns over the quality of upland rice production data we chose to omit upland production from our analysis. Data collection in Lao PDR suffer from imperfect systems and data collection is often a highly political issue. Reliable data on yields at the district level require a dedicated support staff and systems in place to ensure accurate reporting. Furthermore, upland production faces a variety of constraints that severely limit the accuracy of data collection. Considering these issues, we instead focus our analysis on lowland systems where data quality is believed to be much higher.

3.3 Results

Consistent with previous statistical studies (e.g., Peng et al. 2004; Welch et al. 2010), the **preliminary** results of our linear fixed-effects regression model of average weather (equation 1) suggest that elevated minimum nighttime temperatures[7] are highly damaging to rice yields as seen in Table 1. With regards to different production systems we find these trends are largely similar, although varying in their severity and significance. For lowland rain-fed production we find that that a 1-degree rise in the nighttime temperature reduces rice yields by 4.6% holding all else constant. Although this result is not statistically significant at conventional levels it is consistent with results from previous studies that suggest an increase in average nighttime temperature leads to reduction in yields. Given the limited amount of data and associated low statistical power, non-significant effects are unsurprising. Looking at daytime temperatures, we find that a 1-degree rise in temperature increase yields by 11.8% holding all else constant, and these effects are significant at the 10% level. Based on this evidence, this might suggest that increasing temperatures could have an overall positive impact on rice yields for the most important and common rice production system in the country. Furthermore, we find statistically significant evidence that increases in precipitation increase yields, although the effect is very small. We show that increasing precipitation by 1 cm over the growing season increases yields by approximately 0.1% holding all else constant.

We find that changes in temperature appear to have no effect on yields for irrigated dry season production. This might be suggestive of the fact that irrigated

Table 1 Impact of weather on log rice yields, district level, 2006–2011

	(1)	(2)
	Dry season	Wet season
Min temperature	0.045	−0.046
	(0.028)	(0.038)
Max temperature	−0.013	0.118*
	(0.053)	(0.066)
Precipitation	−0.001**	0.001***
	(0.000)	(0.000)
Mean log-yield	1.530	1.277
No obs	578	683
R^2	0.691	0.732

Standard errors in parentheses
Significance levels indicated by *0.1, **0.01, ***0.05

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[7] For the purpose of this study, minimum nighttime temperature is defined as the lowest temperature recorded by weather stations at night. Some stations record several observations per night while other stations record a single nighttime observation.

Table 2 Non-linear impact of weather on log rice yields, district level, 2006–2011

	(1) Dry season	(2) Wet season
Min temperature	−0.099	1.007^{*}
	(0.481)	(0.427)
Min temperature square	0.003	-0.024^{*}
	(0.010)	(0.010)
Max temperature	0.249	−0.490
	(0.692)	(0.358)
Max temperature square	−0.004	0.010^{**}
	(0.011)	(0.005)
Precipitation	-0.000^{***}	0.000^{*}
	(0.000)	(0.000)
Mean log-yield	1.530	1.277
No obs	578	683
R^2	0.691	0.739

Significance levels indicated by *0.05, **0.1, ***0.01

production systems are typically market oriented, intensive systems, and thus farmers are better able to withstand extreme temperature events. However, we find there is a small effect that increased precipitation decreases yields in the dry season.

In regards to the non-linear approach modeled in eq. 2, we find some evidence that there is a non-linear relationship between temperature and yields as seen in Table 2. For lowland rain-fed production, we find that elevated nighttime temperatures improve yields up to approximately 21 °C, after which increased nighttime temperatures reduce yields. Given that the average minimum temperature across our sample is greater than 21 °C, we see the large negative effect in Table 1. For daytime temperatures we find weak evidence of the opposite effect. The results in Table 2 suggest that elevated daytime temperatures decrease yields until approximately 24.5 °C, after which they have a positive effect. Once again, average daytime temperatures are above 24.5 °C, which adds robustness to the effect we find in Table 1.

3.3.1 Evaluating the Model

While the results are broadly consistent with previous studies (i.e., negative coefficients on minimum temperature, positive coefficients on maximum temperature), limited data sources mean that our analysis may lack sufficient power to precisely identify these effects. Consequently, many of the coefficients are not statistically significant. The R^2 and adjusted R^2 are generally similar to studies carried out in other settings, if not slightly lower here.

As a robustness check, we also estimated Equation 1 for provincial level rice yields from 1990 through 2008 as seen in Table 4. These data represent all rice types across all growing seasons and comes from the IRRI World Rice Statistics database.

Table 3 Rice area, production, and yield (2012)

Region/province	Area (% of total)	Production (% of total)	Yield
A. Northern	**21.55**	**18.91**	**3.26**
Phongsaly	1.98	1.50	2.81
Luangnamtha	1.78	1.78	3.7
Oudomxay	2.62	2.21	3.13
Bokeo	2.76	2.70	3.63
Luangprabang	3.91	2.63	2.51
Huaphanh	3.21	2.83	3.28
Xayabury	5.28	5.27	3.7
B. Central	**52.63**	**54.18**	**3.85**
Vientiane Municipality	8.14	9.82	4.49
Xiengkhouang	3.16	3.04	3.58
Vientiane	7.10	7.76	4.12
Borikhamxay	4.69	4.60	3.79
Khammuane	7.61	7.30	3.56
Savannakhet	21.92	21.66	3.67
Xaysomboun	25.82	26.92	3.91
C. Southern	**9.32**	**8.74**	**3.51**
Saravan	1.18	1.09	3.43
Sekong	12.74	15.07	4.45
Chmpasack	2.58	2.02	2.91
Attapeu	21.55	18.91	3.26

Source: DOA 2012

Table 4 Impact of weather on log rice yields, province level, 1990–2008

	(1)
Min temperature	−0.074*
	(0.032)
Max temperature	0.052**
	(0.025)
Precipitation	0.000**
	(0.000)
Mean log-yield	7.89
No obs	337
R^2	0.854
Adjusted R^2	0.836

Significance levels indicated by *0.01, **0.05, ***0.1
Standard errors in parentheses

The results are displayed in the appendix. With the IRRI provincial data, all coefficients are found to be statistically significant and the R^2 values are significantly higher. This exercise suggests that a longer time series may provide more power to estimate these relationships relative to a larger cross-section.

4 Analysis II: Projecting Future Rice Production Under Climate Change

4.1 Climate Projections

The Intergovernmental Panel on Climate Change (IPCC 2007a) predicts that Southeast Asia will experience warmer temperatures, increased frequency of heavy precipitation, increased droughts, and lower annual levels of rainfall in the next century. Changes in the climate are most likely to affect Lao rice yields through harmful extreme temperatures, reduction in water availability from lower levels of rainfall, and a reduced growth period attributed to higher temperatures and radiation levels. Rice in Lao PDR is presently grown at the upper end of the optimal temperature range for rice production. This suggests that Lao rice production is likely to be harmed if future temperatures rise as expected (Wassmann et al. 2009b).

On a global scale, researchers estimate that minimum temperatures have risen faster than maximum temperatures over the last century. Easterling et al. (1997) dissects the trend of increasing diurnal temperatures and attributes it to increased CO_2 concentration in the atmosphere. However, in our data set we observe maximum temperatures *rising faster* than minimum temperatures in the last 30 years. For more detailed predictions of future conditions we turn to the Global Climate Models (GCM) published by the IPCC.

Overview of Global Climate Models (GCMs) GCM[8] are mathematical models used to simulate the dynamics of the climate system including the interactions of atmosphere, oceans, land surface, and ice. They take into account the physical components of weather systems and use these relationships to model future climate conditions. While there are high levels of uncertainty involved in GCMs, these models can help provide insights into future climate scenarios.

The IPCC serves as a central organization for research groups around the world to submit their models. Each research group must choose an approach to modeling physical climate interactions, spatial and time resolutions, and future economic conditions, among other things. Variation in model choice can result in a wide variety of predictions. Fortunately, the IPCC has attempted to standardize economic/emissions scenarios in order to increase comparability across models. However, while these scenarios limit the choices that modelers are faced with, there are still many assumptions to be made about how to model future climate. Differences in these choices result in a still wide variation in predictions across models, even within economic scenarios.

In order to improve comparison across GCMs from different research groups across the world, the IPCC publishes baseline greenhouse gas emissions scenarios, the most recent of which is called the Special Report on Emissions Scenarios (SRES), for all groups to utilize. Here we use three of the baseline scenarios established in the IPCC Fourth Assessment Report (AR4), published in 2007 (IPCC 2007b).

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[8] Also referred to as Global Circulation Models with the same acronym.

The B1 scenario depicts increased emphasis on global solutions to economic, social, and environmental stability, but without additional climate initiatives. It assumes rapid global economic growth, but with changes toward a service and information economy with a population rising to 9 billion in 2050 and then declining thereafter. Clean and resource efficient technologies are introduced limiting future emissions. This scenario estimates an increase in global mean temperatures of 1.1–2.9 °C by 2100.

The A1B scenario also assumes global economic growth and a more homogenous future world but with less global emphasis on the information and service economy. Instead, it assumes a continuation of current economic activities, but with more efficient technologies and a balanced emphasis on all energy sources. It assumes similar population increase to 2050, followed by a decline in global birth rates. This scenario predicts, on average, a 2–6 °C warming of global temperatures by 2100.

The A2 scenario depicts a more heterogeneous world with uneven global economic develop and an emphasis on self-reliance and preservation of local identities. Fertility patterns across regions converge slowly, resulting in a continuous increase in global population. Economic development is regionally fragmented and there is less global cooperation. This scenario predicts a global increase in temperature of 2–5.4 °C by 2100.

4.1.1 Selecting GCM Models

It is unclear whether any one model is more ‘valid’ than others (Burke et al. 2015). However, some argue that models have different strengths and weaknesses and should thus be carefully selected for specific applications (e.g. Knutti et al. 2010). While many studies choose one (or a few) models, and make predictions based on those scenarios, it is unclear how one would select the ‘best’ model. To add to these difficulties, different models offer widely different future predictions of climate conditions. Consequently, predicted future yields will depend highly on which GCM is utilized to forecast future climate conditions. For the time being, we follow the recommendations made by Burke et al. (2015) and include as many models as possible with equal weights on the outcome predicted by each model. Our reasoning is that policy recommendations should be informed on the range of possibilities. However, by using many models the range of predicted outcomes can vary widely. Nonetheless, we argue that the alternative of counting on the predictions of one model underrepresents the uncertainty involved in predicting effects of future climate change, and that it would be unwise to make policy recommendations based on a single model. Instead, we incorporate predictions from the 14 models that offer predictions for our variables of interest (min temperature, max temperature, precipitation) under three economic scenarios (A1B, A2, B1). In total, we therefore have 42 future climate scenarios, one for each model-scenario pair, each of which can be evaluated for a range of time frames. Finally, we can calculate the yield outcomes under each of these scenarios and the median outcomes for each economic scenario represent our estimates for future yields assuming low, medium, or high emissions in the future.

4.1.2 Downscaling Methods

For each model-scenario combination we first calculate the model estimated monthly average weather conditions (min/mean/max temperature and precipitation) over the previous decade (2000–2010) for each district. We do this by matching each district to the four closest GCM grid cells and then weighting each GCM cell by the inverse distance of the center of the GCM cell to the center of the district where weights are forced to sum to 1. This provides us with a historical standard by which to measure future projections. Next, future period monthly averages are calculated for each decade up to 2050. Future average monthly conditions are then related back to the GCM estimated historical conditions for the 2000–2010 period to provide predicted climate change. Temperature changes are calculated as an absolute degree change in monthly averages while precipitation change is calculated as percentage change in average millimeters of rainfall per month.

Once we have estimated future changes in absolute (temperature), or percentage absolute (precipitation) terms, we add the predicted changes to the estimated historical data for each district, with changes separated by month. Once we have calculated historical conditions under climate change, we use our model to predict yields under the climate change weather conditions.

This process is repeated for all 42 model-scenario combinations (14 models, 3 scenarios) and the median outcomes are reported as the predicted yield changes under climate change for each decade. Although computationally tedious, incorporating 14 models provides a more representative range of possible future climate conditions, and of the high levels of uncertainty associated with predicting future climate. This issue is discussed in detail below.

4.1.3 Climate Projections for Lao PDR

Time-series of the climate projections for Lao PDR are displayed in Fig. 4. On average, growing season temperatures are predicted to increase approximately 1 °C by 2050 while growing season rainfall is expected to slightly decrease. However, some GCMs predict an increase in growing season rainfall over this period.

4.2 Yield Projections

4.2.1 Methods

In order to evaluate potential climate risk to rice production, we use our rice models to predict yields under future climate scenarios. Due to the resolution of our data, we are able to predict yields at the district level. We estimate future yields by using our estimated statistical model to predict yields at the values of weather variables

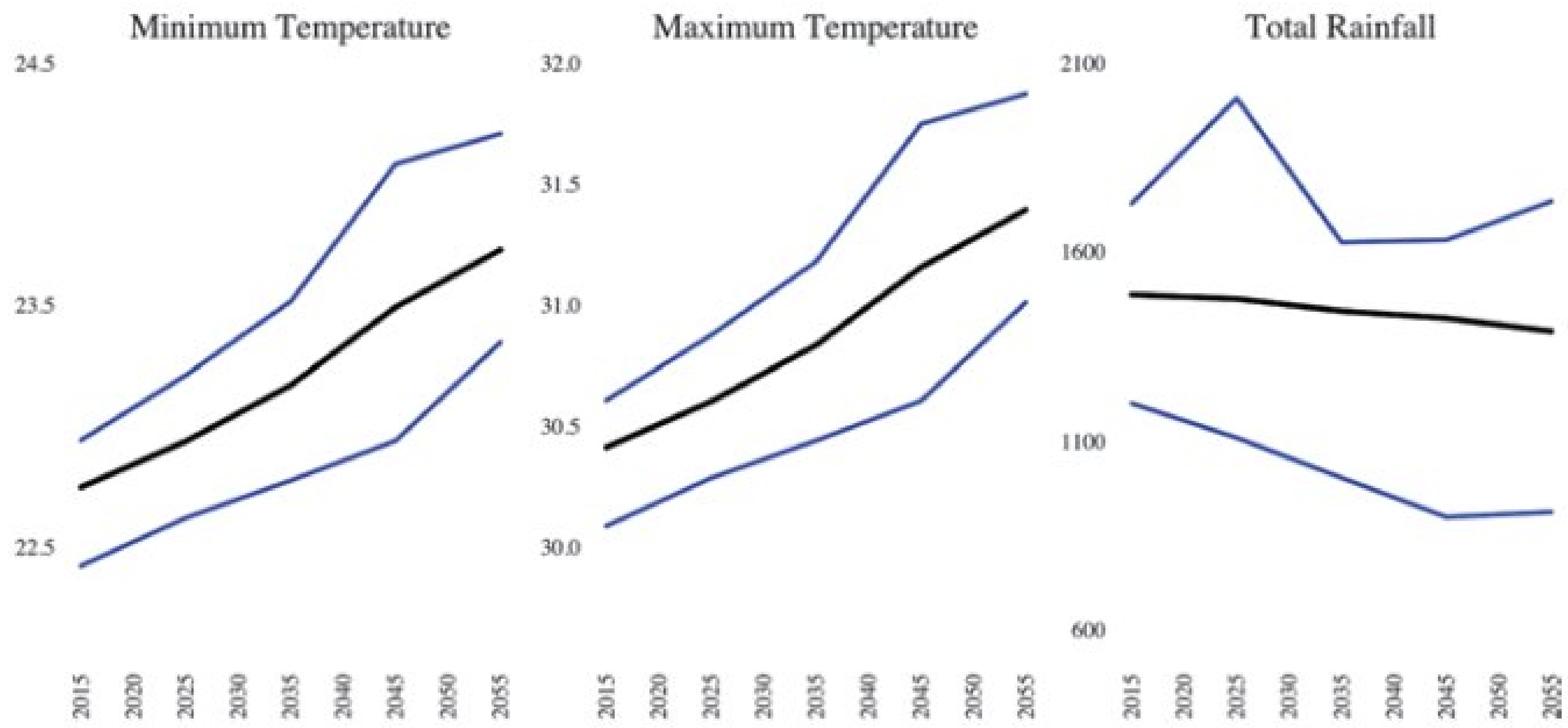

Fig. 4 Forecast climate conditions across 14 GCMs. Average growing season climate conditions forecast up to 2055. The *black* line represents the median value across 14 GCMs. The *blue* lines represent the minimum and maximum values across GCMs

predicted by the climate model. In order to remain consistent, we use the same approach to estimate yields over the study period (i.e., the 2000s) and then calculate yield changes relative to this baseline.

Quantifying Uncertainty with Yield Projections There are two primary types of uncertainty associated with making yield-climate projections. First, there is uncertainty associated with our statistical models. Our models are linear approximations of the yield-weather relationship and thus are best suited to predict how yields respond to perturbations in weather variables only over the observed range of conditions. Fortunately, this type of uncertainty is quantifiable through standard errors and other measures such as Root Mean Squared-Error calculated by using our model to predict observed yields. The second type of uncertainty arises from unpredictability of future climate conditions. GCMs attempt to predict future conditions, however, the uncertainty associated with these predictions far exceeds the statistical uncertainties discussed above. In fact, simulations have shown that uncertainty arising from climate projections outweighs statistical uncertainty by several orders of magnitude (Burke et al. 2015). Quantifying model uncertainty is less straightforward. Here we follow the approach suggested in Burke et al. (2015) and use variation across yield projections utilizing different climate models to provide a measure of climate uncertainty.

4.2.2 Results

Figure 9 (see Appendix) displays the **preliminary** median yield projection across climate models using the statistical model described in equation 1 discussed above. Figure 9, panel 2 shows the time series of the yield changes. Yield changes are

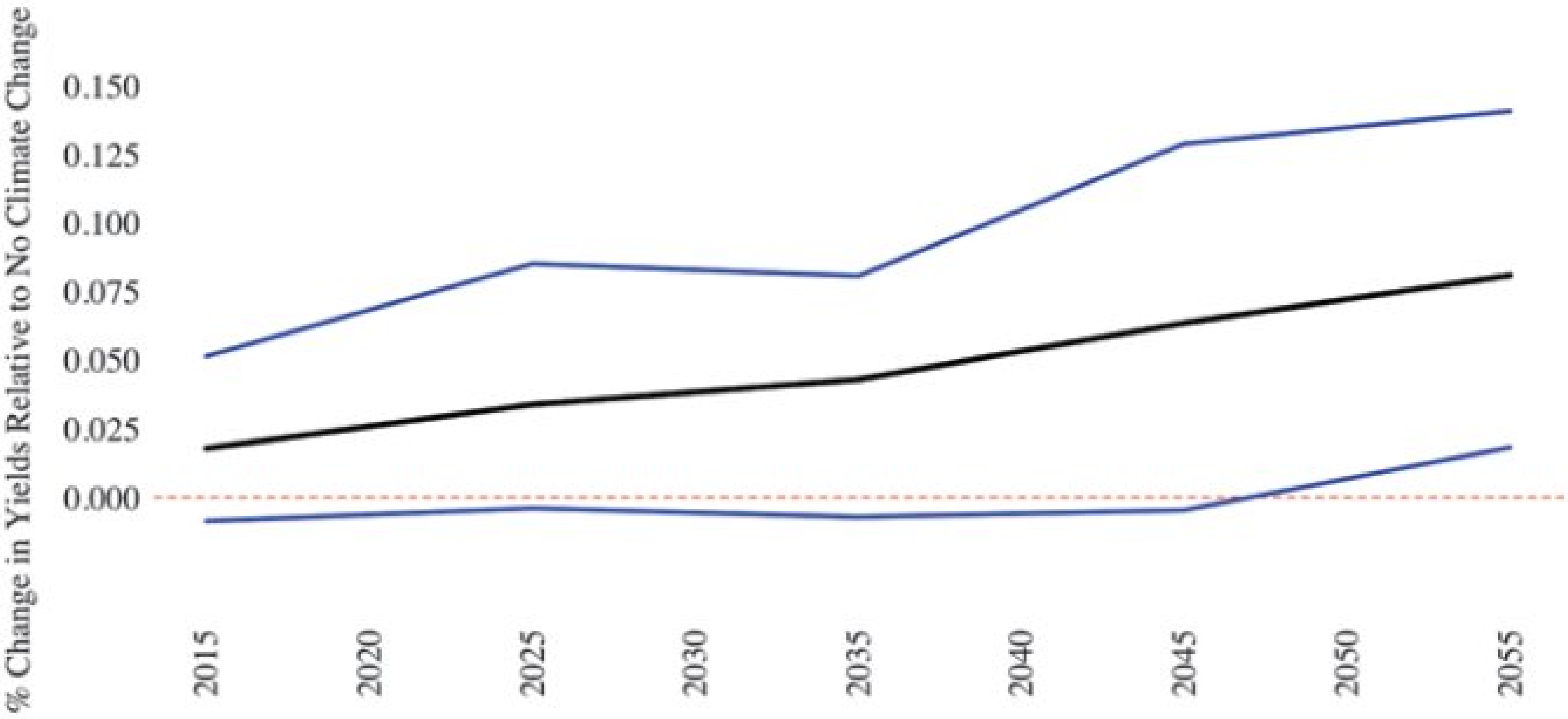

Fig. 5 Time series of forecasted yield impacts (lowland wet rice). *Blue* lines represent minimum and maximum predicted yields across 14 climate models. *Black* line represents the median predicted yield change across models. Baseline scenario is that yield trends continue on their current path but temperatures and rainfall patterns continue to follow historical averages

measured relative to a baseline scenario where yields continue on their historical upward trends but where climate conditions continue to vary around their historical averages. The climate scenarios assume the same current yield trends but with changes in climate predicted by GCMs. Because maximum temperature is found to be strongly positively related to higher yields, future yields are predicted to be higher, on average, under climate change. This is likely a result of insufficient observations needed to estimate the historical relationship accurately. Here we find the benefits from rising maximum temperatures outweigh the negatives from rising minimum temperature. In other cases we have found the opposite to be true (Fig. 5).

5 Summary and Outlook

Given the extremely limited nature of data in Lao PDR we are hesitant to offer any precise policy recommendations. Our results come from a 6-year panel, which cannot be considered an entirely accurate representation of the historical relationship between climatic variables and yields. This is echoed in our results as we find only three significant effects across all specifications. Moreover, it should also be noted that our results rely on historical data and thus model accuracy is tied to (unobservable) data quality.

In regards to wet season production, we find that a 1-degree increase in daytime temperatures holding all else equal causes an 11.8% increase in yield. This would suggest that higher daytime temperatures as a result of climate change would in fact be beneficial for rice production in Lao PDR. Furthermore, given that Lao PDR has achieved self-sufficiency in rice production in recent years it appears that the impact of climate change on food security does not appear to be a major concern. Although the country appears to have met self-sufficiency at the national level, it is certainly clear that not all households are able to meet rice consumption requirements. According to some estimates, about 30% of the population has insufficient food for more than 6 months of the year. However, much of this deficiency is in the northern and eastern mountainous areas, while the Mekong River valley is an area of surplus (ADB 2006). Thus, based on our projections, yields in the Mekong River valley will increase as a result of climate change surpluses will be further extended. In regards to policy, marketing of the surplus will be the key policy challenge. According to the LECS only 8% of all rice produced is sold, and thus extending both domestic and international trade should be made a priority.

Of more concern are the individuals located in the mountainous regions of the country that rely on upland production systems. Our results suggest there is a high level of uncertainty between temperature and yields. For example, we find that an increase of 1 degree in average daytime temperature causes a 38% increase in yields, while an increase of 1 degree in average nighttime temperature causes a 30% reduction in yields. These large shocks can be incredibly damaging as individuals engaged in this production system are the most likely to be unable to reach self-sufficiency. Therefore, it appears that one clear policy option would be strategies to reduce variability. Crop diversification is one potential option, although our analysis does not consider other crops so we cannot comment wither there is less variability. Insurance mechanisms that protect against shocks are likely the best option. However, extending any type of insurance to individuals in such remote locations will likely be of extreme difficulty.

We also want to add the caveat that data from upland production systems are likely the most inaccurate. Due to the extremely remote nature of these systems the validity of the data should certainly be taken with a grain of salt. Furthermore, we would like to highlight the limited sample size and subsequent limited power of our results for the upland systems. Thus we offer these recommendations with reservations.

6 Conclusions and Extensions

This report adds support to the growing literature estimating the impacts of weather and climate change on rice production. We focus our analysis in Lao PDR, a country whose economy relies on the production of rice, but has had received little analysis on how climate change will impact the sector. This represents a crucial gap in the literature, as rice is instrumental to the Lao economy and will undoubtedly face challenges from climate change.

We use advanced econometric models to first estimate the historical relationship between observed rice yields and climatic variables. With this relationship established, we then downscale projections from the leading climate models to forecast the impact on rice yields under these climate scenarios. Our results are consistent with previous work in the region, as we find weak evidence that elevated minimum nighttime temperatures are highly damaging to rice yields. Conversely, we find support that elevated maximum daytime temperatures increase yields. Overall the size of the impact and statistical significance is larger for increased maximum temperatures, suggesting that elevated temperatures might have a net positive impact on rice yields in Lao PDR. Turning next to forecasting, our projections confirm this intuition, as future yields are predicted to be higher, on average, under climate change.

We offer some major caveats to these findings. First, our results are not significant at traditional levels although this not surprising given our limited panel. Our results come from a 6-year panel, which cannot be considered an entirely accurate representation of the historical relationship between climatic variables and yields. Second, there are major data quality issues surrounding rice yields. Although data quality is improving rapidly in Lao PRD, high-resolution rice yield data is only recently available, and is of unknown quality. Given our results rely on this historical data, our model accuracy is tied to the quality of the data. That being said, our results are in line with previous work in the region and serve as a useful preliminary first step to modeling how climate change will impact rice yields in Lao PDR. Over time as data quality improves, these results can be easily replicated to strengthen the analysis.

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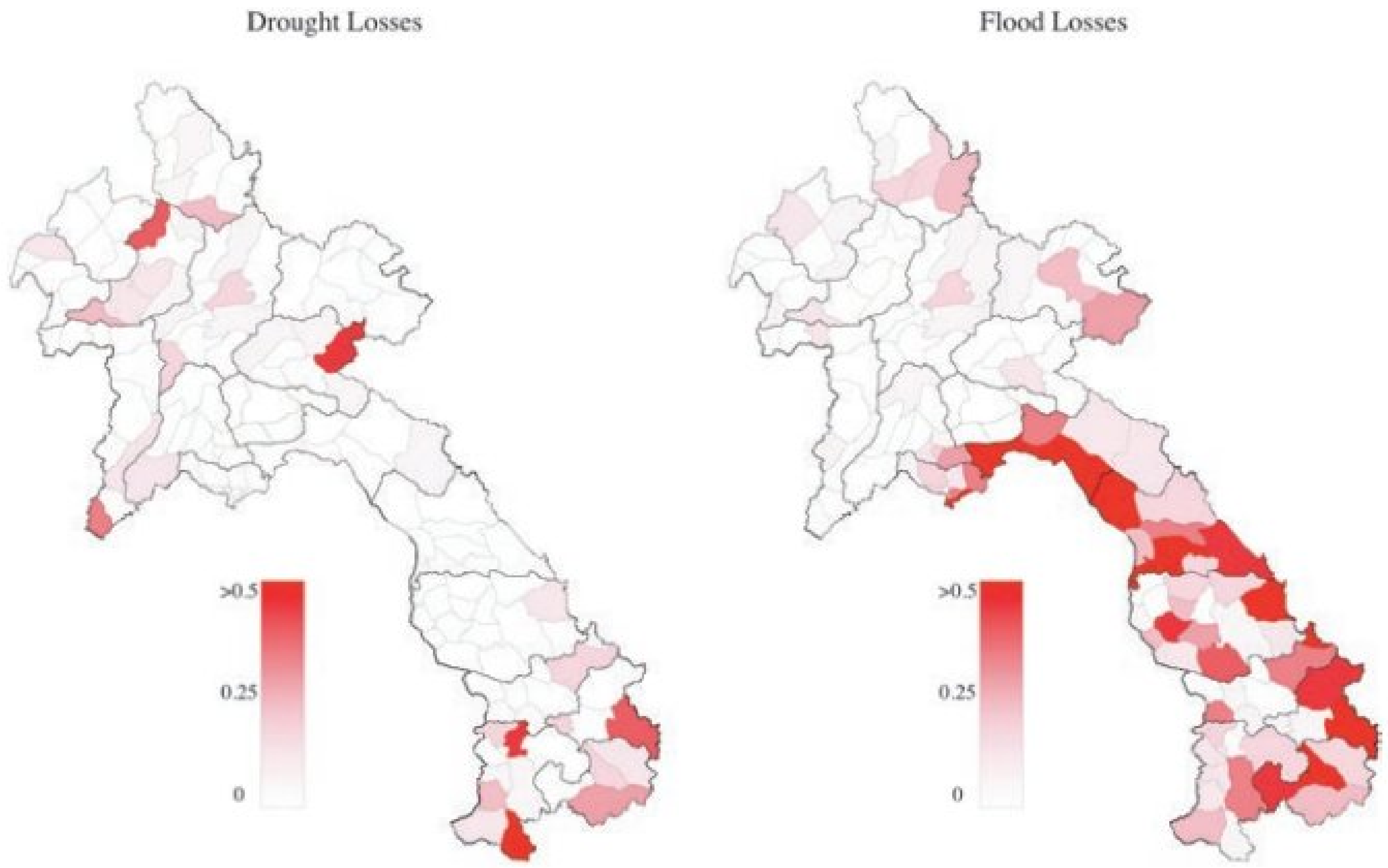
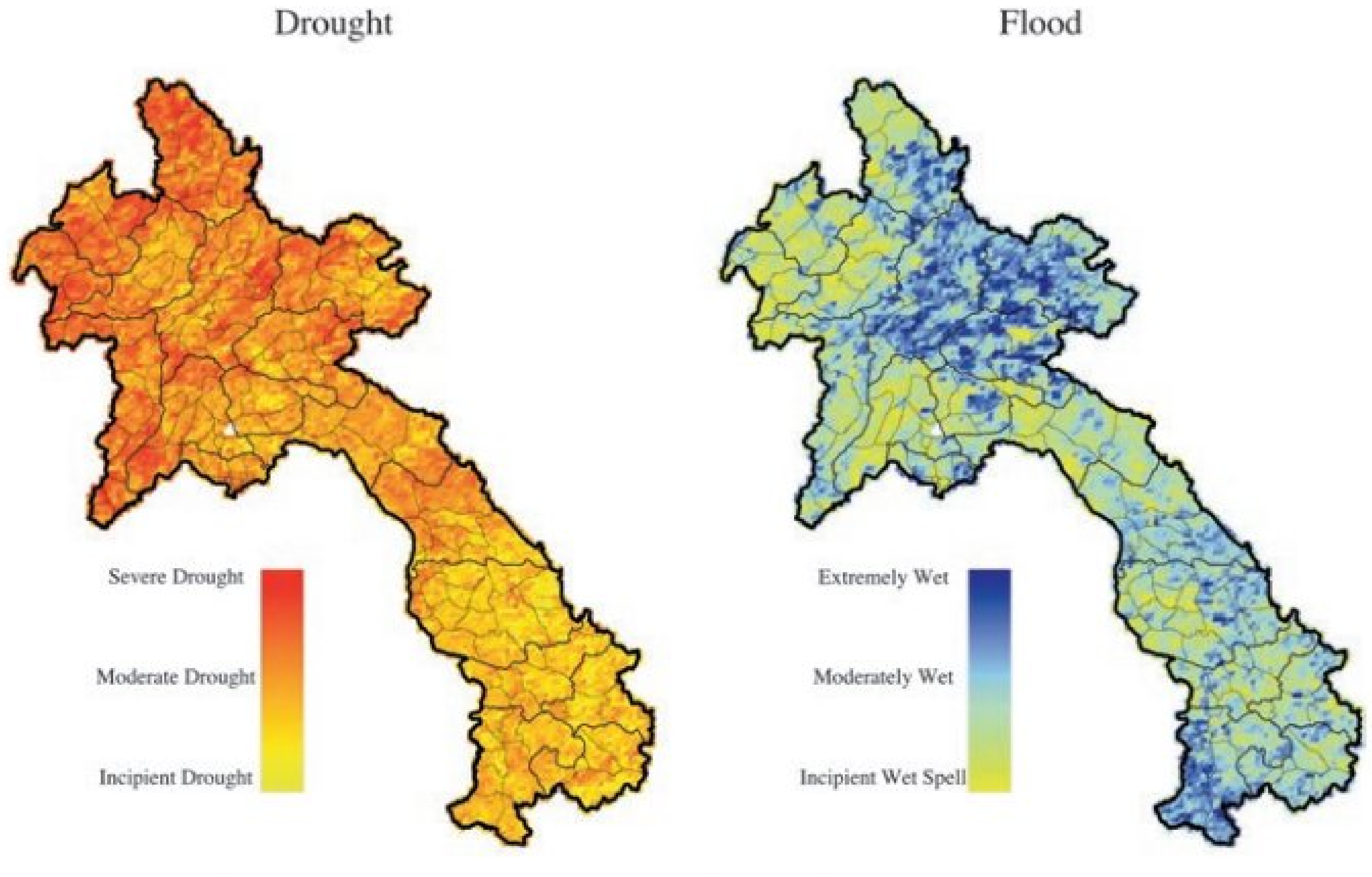
Appendix – Rice Yield Regression Model Results (Figs. 6, 7, 8, and 9)



Source: Crop Statistics Yearbook (DOA, Lao PDR)

Fig. 6 Largest rice area losses 2006–2012 by cause. Maps show the maximum wet-season lowland rice area lost from flood or drought in any year over the study period 2006–2012. The figure illustrates that over the seven-year study period a majority of districts experienced some losses from floods or droughts. Flood losses were more common and tended be to more severe with some districts reporting 100% losses in bad a flood year



Source: Drought Severity Index (DSI) described in Mu et al (2013)

Fig. 7 Most extreme growing-season weather conditions 2006–2012. Maps show the most extreme dry and wet conditions experienced during the rice-growing season over the study period. Categories correspond to the qualitative categories described in Mu et al.

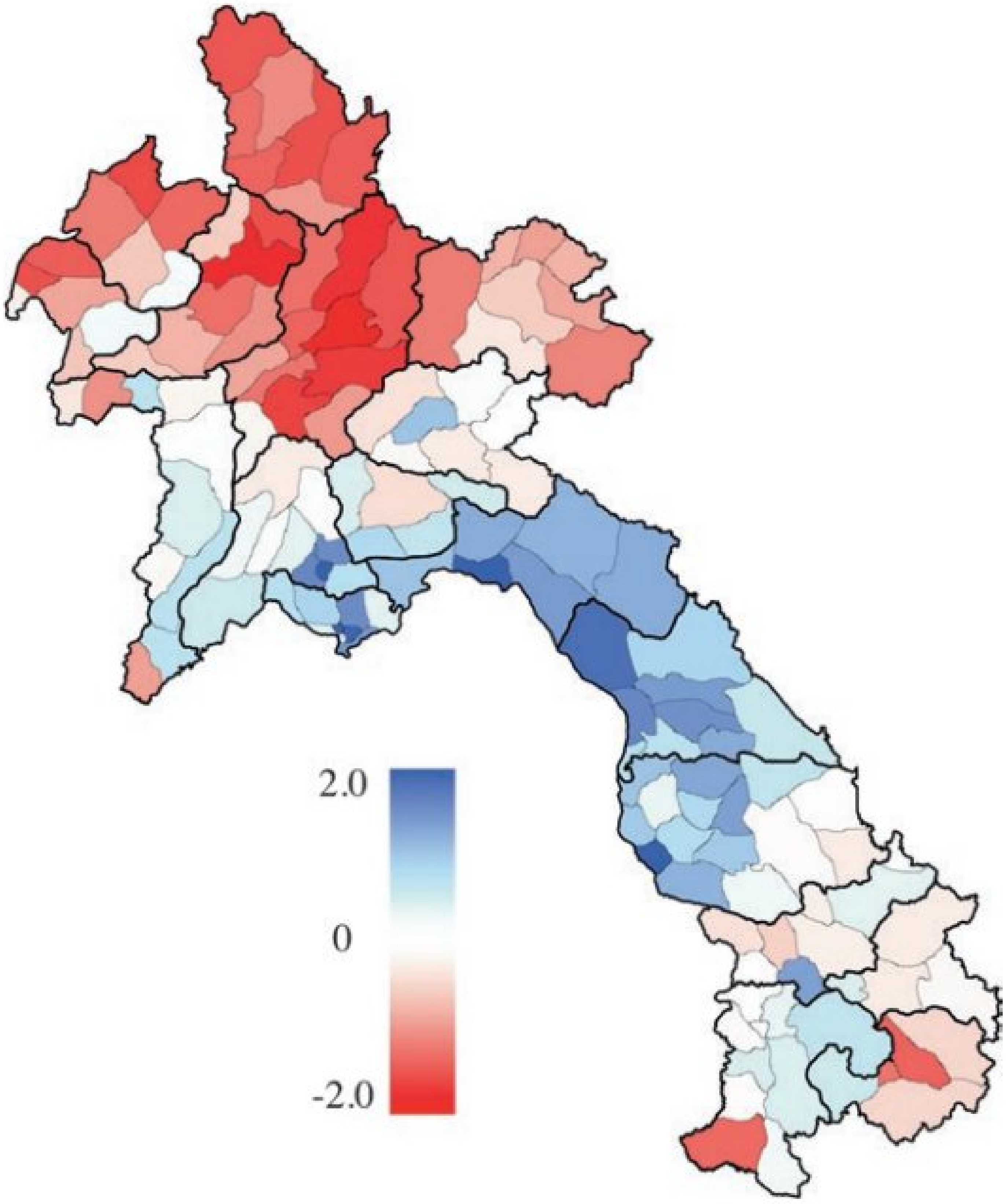


Fig. 8 Average Drought Severity Index (DSI) for rainy season 2004. Average area-weighted DSI values for Lao PDR districts. Blue represents greater than normal and red represents less than normal water levels. This figure is meant to provide an illustration of the data source described in Mu et al. (2013). Data are averaged over rainy season in 2004. Note that the DSI map is roughly an inverse of the precipitation map in Fig. 1

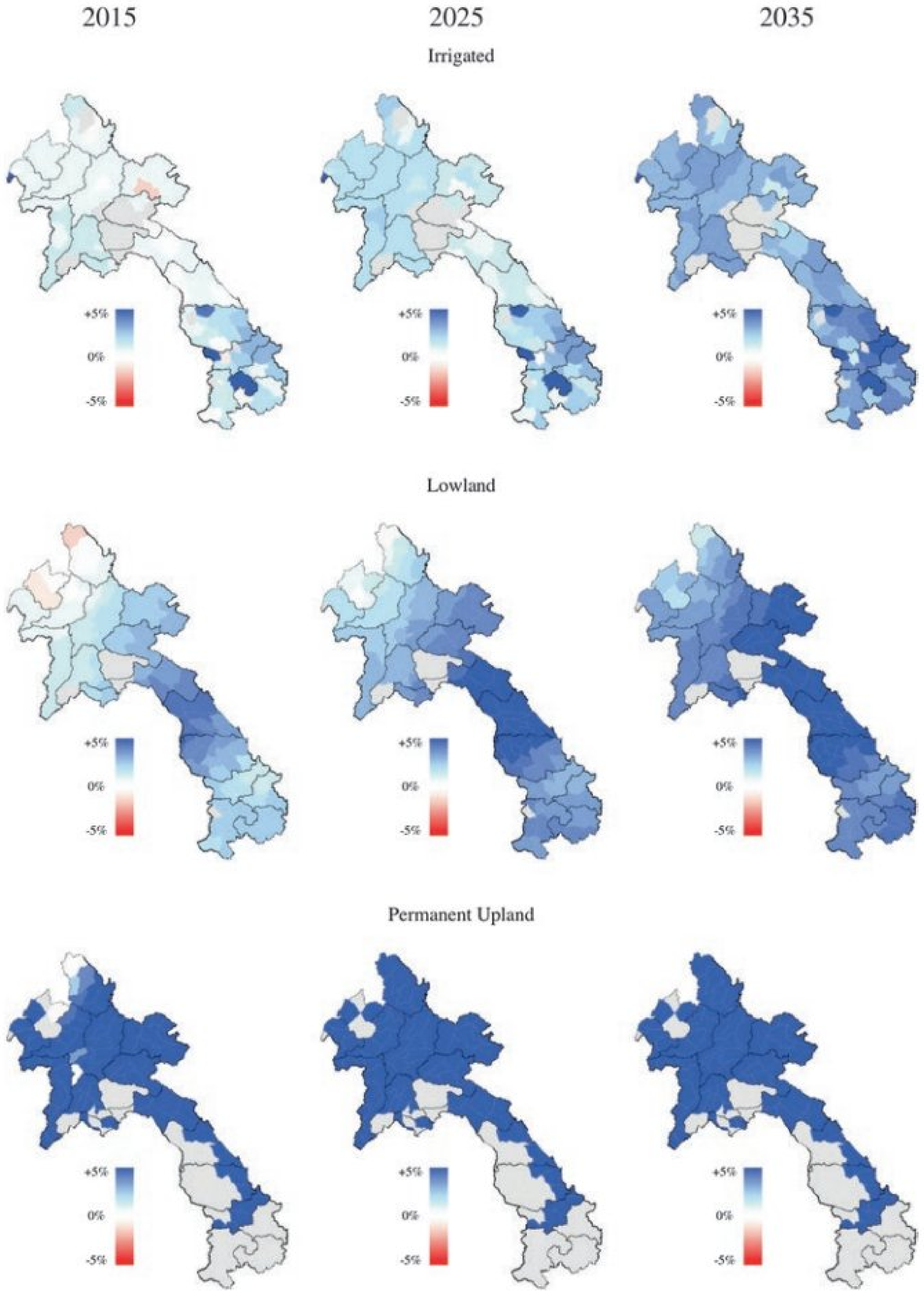


Fig. 9 Preliminary projected yield changes 2015–2035

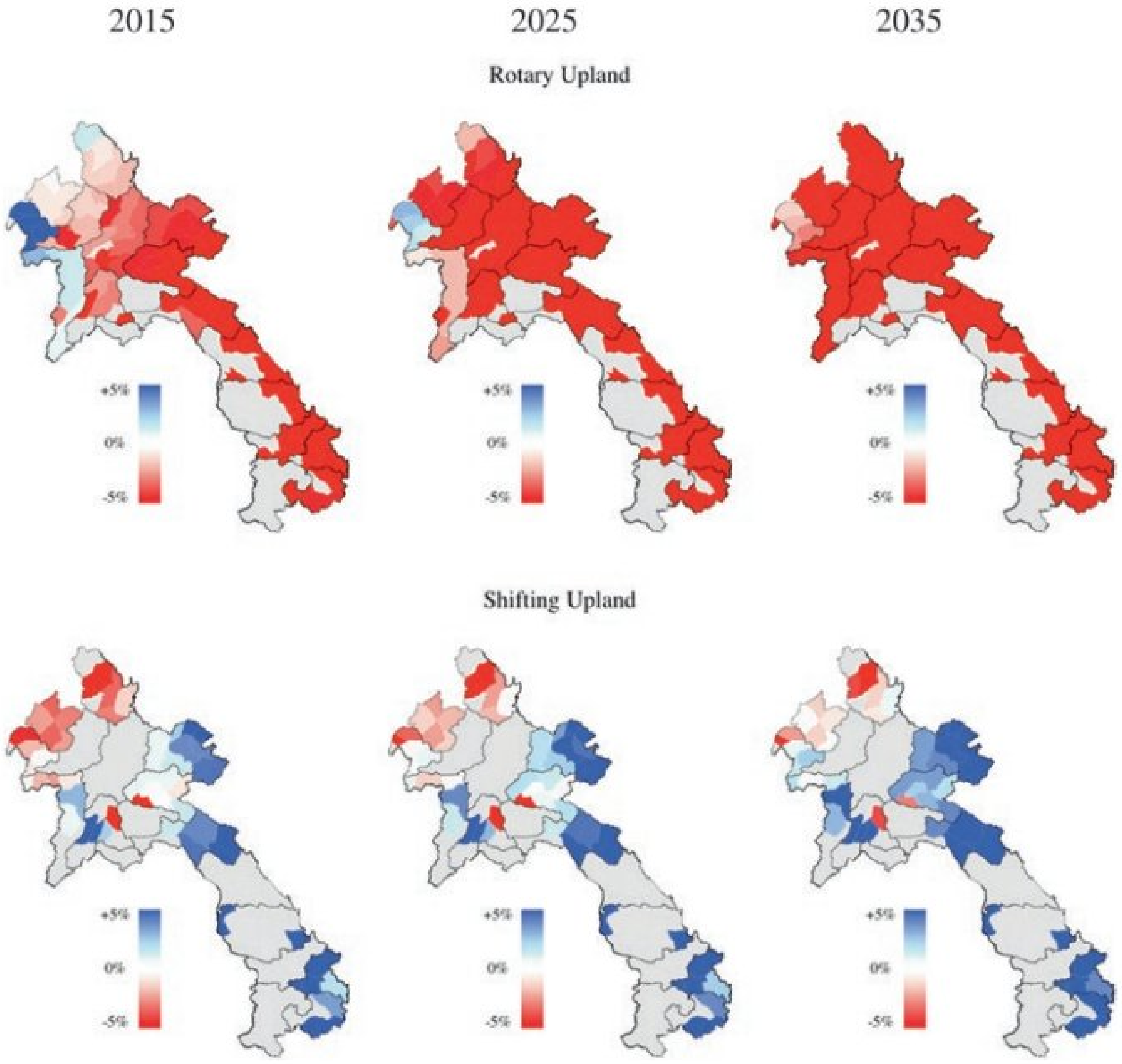


Fig. 9 (continued)

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Farmers' Perceptions of and Adaptations to Climate Change in Southeast Asia: The Case Study from Thailand and Vietnam

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Abstract The perceptions of climate change and adaptation choices made by farmers are important considerations in the design of adaptation strategies by policy makers and agricultural extension services. This paper seeks to determine these perceptions and choices by farmers in already poor environmental regions of Thailand and Vietnam especially vulnerable to climate change. Overall findings were that farmers do perceive climate change, but describe it in quite distinct ways and that location influences how farmers recognize climate change. Our 2007 and 2013 surveys show that farmers are adapting, but it is difficult to determine if specific practices are "climate smart". Further, adaptation measures are informed by perception and, at least in the case of Vietnam, perceptions are shaped by the respondent's characteristics, location variables and recent climate related shocks. Finally, the three climate variables of rainfall, temperature, and wind are the most important factors in explaining specific adaptation measures chosen by farmers. Farmer participation is an essential part of public actions designed to allow adaptation to climate change. Our research can also contribute to understanding farmer constraints and tailoring good overall strategies to the local heterogeneity of vulnerable locations.

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1 Introduction

As established by the Intergovernmental Panel on Climate Change (IPCC 2014), climate change is affecting Southeast Asia through increasing average temperatures, sea level rise and changes in precipitation, although trends differ strongly across the region. Countries in Southeast Asia are especially vulnerable to the downside effects of global climate change because of (i) their long coastlines, (ii) high concentration of human and economic activities in coastal areas, (iii) large and growing populations, and (iv) the importance of agriculture as a source of employment and income (ADB 2009). Climate change can have especially negative consequences for agricultural productivity and food security (Iglesias et al. 2011). In Thailand, Boonpragob (2005) found that between 1991 and 2002 the country's agriculture experienced crop yield losses worth some 50 billion Thai Baht (approximately 1.3 billion EURO). In Vietnam, which ranks among the top five countries most affected by rising sea levels (Dasgupta et al. 2007), the impact of extreme weather has led to the damage of rice fields by frequent flooding, for example in the Red River Delta, Central Region, and the Mekong Delta. At the same time, rice areas affected by droughts doubled from some 77,000 ha in 1979–1983 to over 175,000 ha in 1994–1998 (Cuong 2008).

To reduce their vulnerability to the negative effects of climate change, farmers must adapt (Gbetibouo 2009). Adaptation measures should be both technically appropriate and economically feasible. In agriculture, adaptations to climate change will require new technologies and investments. Farmers may have to adopt new crop varieties and new livestock breeds, change their cropping systems and invest in new soil and water conservation methods.

In this paper, we explore climate change in Thailand and Vietnam from the perspective of households living in less favored rural areas who are especially vulnerable to the effects of climate change. We focus on three provinces in Northeast Thailand and three provinces in the Central Highlands and North Central Coast of Vietnam. The study makes use of a database of some 4000 households in these two countries collected as an ongoing research project since 2007 entitled "Impact of Shocks on the Vulnerability to Poverty: Consequences for Development of Emerging Southeast Asian Economies" (DFG FOR 756). We mainly use the 2013 survey as it contained a module on climate change. In addition, the survey included questions on household member characteristics, assets, income and consumption, past shock experience, expected risks and individual risk attitudes.

We aim to answer the following questions:

1. What climate-related shocks did farm households experience, what observations did they make about changes in climate over time and what indicators did they use to describe climate change?
2. What determines the farmers' perceptions of climate change and their decision to adjust agricultural production in response to the effects of perceived climate change?
3. What explains the choice of agricultural adaptation measures by farm households?

The answers to these questions are important for the design of policies and projects aimed to help farmers living in poor environments to adapt to climate change. The participation of farm households in public actions aiming to mitigate or adapt to the impacts of climate change depends on the willingness of these households to participate. Our research can also contribute to the interpretation of the results of climate change models that may have a good overall geographic perspective but may miss the heterogeneity that exists at local levels.

The paper proceeds as follows: Section 2 presents the theoretical background for the determinants of individual climate change perceptions and adaptation behavior. Section 3 describes data collection and Section 4 describes the methodology. Section 5 reports some descriptive results as background information. Section 6 discusses results of our models. Finally, in Section 7, summary and policy conclusions are submitted.

2 Theoretical Background

In principle farmers' adaptation to climate change can be modeled using the framework of technology adoption. Generally adoption of technologies depends on a number of factors such as financial incentives, access to extension services and markets but also perceptions and behavior. There is, however, a difference between conventional technology adoption and climate adaptation. While adoption of new technologies mostly aims at increasing profits, adjustments to climate change are often undertaken to reduce risks and to minimize future losses, both of which are directly affected by perceptions of current and future change. It is therefore necessary to incorporate farmers' perception of climate change in an adoption model (Maddison 2007).

Weber (2010) found that people's perception of climate change both in terms of its existence and extent are shaped by learning from personal experience and by making use of statistical information. The formation of perceptions depends on the trust that people attribute to climate scientists and their social amplifiers. Perceptions, however, are only meaningful when they can be linked to actual adaptation measures (Reilly and Schimmelpfennig 1999).

Theoretical insights about the relationship between risk perception and the adoption of risk management actions can be gained from the psychology and economics literature. The psychology literature (e.g. Fuster 2002) refers to the *perception-action cycle*, where people prepare themselves for perceived future outcomes, including the perceived seriousness of potential outcomes. From the economics literature, we can learn that it is necessary to distinguish between gain and loss domain (Kahneman et al. 1990). Tversky and Kahneman (1992) have shown people tend to weigh potential losses higher than potential gains.

Traditionally, adoption decisions have been analyzed in a utility maximization framework with profit as the primary motive (Greene 2003; Norris and Batie 1987). Accordingly, a technology is adopted when the perceived utility or net profit from adoption is significantly larger than not adopting it. The adoption decision is subject to a set of exogenous variables such as household characteristics, socioeconomic and physical factors (Feder et al. 1985). More recent models of climate change adaptations have been developed for African countries (Maddison 2007; Deressa et al. 2008; Gbetibouo 2009). These models incorporated climate change perceptions as explanatory variable. We follow this approach to model the factors that influence climate change perceptions and related adaptation measures as well as to explain specific climate change adaptation measures.

3 Study Regions and Data

We focus on the 2900 households from the DFG FOR 756 that are engaged in agricultural production because we are interested in the connection between climate change perception and consequences for agriculture. In Thailand, the provinces are Buri Ram, Nakhon Phanom and Ubon Ratchathani located in the Northeastern region of the country. In Vietnam, the provinces are Ha Tinh and Thua Thien Hue located in the North Central Coast region and Dak Lak situated in the Central Highlands. All six provinces are dominantly agricultural areas albeit with a large degree of heterogeneity in development potential. The provinces are bordering neighboring Laos and/or Cambodia. The choice of the provinces was motivated by the assumption that people in rural and geographically remote regions are more vulnerable than people in urban and central regions. Furthermore, these provinces belong to the poorer environments with less developed infrastructure in agriculture and a high potential for climate-related shocks and thus are more likely to be affected by climate change (Waibel et al. 2013).

The survey instruments comprise of a village head and a household questionnaires. The village head questionnaire contains information on the physical and social infrastructure of the village. The household questionnaire has a detailed shock section that included questions about past climate-related shock experience and details about shock severity in terms of income and asset loss (using a 4 point ordinal scale).[1] A special module on climate change was included where respondents were asked whether or not they had perceived a change in climate in the time that they had lived in their location. Respondents were also asked how they thought that changes in climate is affecting their agriculture (e.g. lower yield, more crop failure) and what measures they had taken to adapt to climate change (e.g. change crop varieties, invest more in irrigation, planting trees, etc.). Part of the household questionnaire was a simple risk item that measures respondents' general attitude towards risk on an 11 point Likert scale following Dohmen et al. (2011) and Hardeweg et al. (2013).

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[1] 0 = no impact, 1 = low impact, 2 = medium impact, 3 = high impact.

4 Empirical Strategy

We address question 1 through a descriptive analysis of the household survey data, and question 2 by employing an econometric model (model 1) that allows us to establish a link between climate change perceptions and adaptation decisions. Question 3 is addressed through a second model (model 2).

The first model is a two-stage procedure. In the first stage, perception of climate change is specified as the outcome variable. In the second stage, adaptation is the outcome variable for respondents who reported awareness of climate change. Accordingly, households in the second stage are non-randomly selected from the entire sample.

To deal with potential selection bias, a Heckman's selection probit model was specified. We consider a random sample of *i* observations. Equations for individual *i* are:

$$Y_{1j} = X_{1j}\beta_1 + U_{1i} \tag{1a}$$

$$Y_{2i} = X_{2i}\beta_2 + U_{2i} \tag{1b}$$

where X_{ji} is a $1 \times K_j$ vector of regressors, β_j is a $K_j \times 1$ vector of parameters, and

$$E\left(U_{ij}\right) = 0, E\left(U_{ji}U_{j'j''}\right) = \sigma_{jj'}, i = i'' \text{ and } E\left(U_{ji}U_{j'j''}\right) = 0, i \neq i''$$

Suppose that Y_{1i} is observed only if $Y_{2i} \geq 0$. In the case of independence between U_{1i} and U_{2i} or $E\left(U_{ji}U_{j'j''}\right) = 0$ so that the data available on Y_{1i} are missing randomly, the regression function for the selected subsample is the same as the population regression function. In the general case where $E\left(U_{ji}U_{j'j''}\right) = \sigma_{jj'}$, least squares estimators yield biased results. Thus, the Heckman selection model as a solution in providing consistent, efficient estimates in the following way:

$$E\left(Y_{1i} | X_{1i}, Y_{2i} \geq 0\right) = X_{1i}\beta_1 + \frac{\sigma_{12}}{\left(\sigma_{22}\right)^{1/2}}\lambda_i \tag{1c}$$

$$E\left(Y_{2i} | X_{2i}, Y_{2i} \geq 0\right) = X_{2i}\beta_2 + \frac{\sigma_{22}}{\left(\sigma_{22}\right)^{1/2}}\lambda_i \tag{1d}$$

where $\lambda_i = \frac{\phi\left(Z_i\right)}{1 - \Phi\left(Z_i\right)}$ and $Z_i = -\frac{X_{2i}\beta_2}{\left(\sigma_{22}\right)^{1/2}}$ with ϕ and Φ are, respectively, the density and distribution function for a standard normal variable (Heckman 1979).

In our analysis, Y_{1i} is a binary variable specifying whether or not household *i* adapts their agricultural activities to climate change. Y_{2i} is a binary variable taking on the value unity if respondent of household *i* perceived climate change and zero otherwise. X_{1i} is a vector of explanatory variables for the outcome Equation (1a).

X_{2i} is a vector of explanatory variables for the selection Equation (1b). It is not absolutely necessary to have the exclusion restriction in the Heckman selection model (Wooldridge 2009) and in some cases the vectors of explanatory variables for selection equation and outcome equation are even identical (Puhani 2000). Thus, the justification for inclusion of variables for X_{1i} and X_{2i} is merely based on the expected effect of these variables on the dependent variables Y_{1i} and Y_{2i} respectively.

X_{1i} includes household head characteristics (age, education, gender, membership of socio-political organization), household characteristic (agricultural member ratio, farm size, income, risk attitude and ethnicity in the model for Vietnam), and distance to district town and province dummies.

Based on the study of Gbetibouo (2009), there is no agreement in the adoption literature on the effect of age of household head. Age can be found to have negative influence on the adoption decision of new technologies because older farmers are more risk-averse than younger farmers and thus have a lesser likelihood of adopting. It is also possible however that older farmers have more farming experiences enabling them to better judge the merits of new technology.

Education is believed to increase the probability of accessing information (Norris and Batie 1987). Evidence from previous studies shows a positive influence of household head's education on the decision to adapt to climate change (Deressa et al. 2008; Maddison 2007). Therefore, we expect that education level of household head is positively related with adaptations to climate change.

We expect that male household heads are more likely to gain information on new technologies and are more likely to be risk takers (Asfaw and Admassie 2004). Therefore, the likelihood of male-headed households to adapt to climate change is believed to be higher than that of female-headed households.

Membership in a social-political organization is hypothesized to have a positive effect on the adaptation decision. It is considered as one kind of social capital of the farmers and as a member of such organization, household heads may have more opportunities to learn new agricultural practices than other members.

Household characteristics used in explaining the adaptation decision include agricultural member ratio, farm size, income and risk attitude. Agricultural member ratio is defined as the ratio between number of household members aged from 15 to 64 engaged in its own agricultural production and the total number of household members in that age range. This ratio is expected to positively influence the decision to adapt to climate change. This enables household to accomplish various agricultural tasks even at peak times. This hypothesis is based on the study of Croppenstedt et al. (2003) revealing that larger amount of labor increases the household's probability of adopting agricultural technology and using it more intensively.

The effect of farm size on the adaptation to climate change is ambiguous. Gbetibouo (2009) found a positive relationship between farm size and the adaptation to climate change. The author also argued that adoption of an innovation tends to take place earlier on larger farms than on smaller farms. On the contrary, farm size showed a negative effect on the adaptation decision in the study Deressa et al. (2008) which is perhaps due to plot level heterogeneity.

We hypothesize that households with higher income will be more likely to undertake adaptation measures. Similarly, if household has larger capital endowment, it has a better possibility to invest (e.g. Franzel 1999). We further hypothesize that in households where the respondent (household head) expresses a lower degree of risk aversion she is more likely to undertake adaption measures.

In the model for Vietnam, we included ethnicity as a binary variable taking on the value 1 if household is the majority Kinh and 0 if household belongs to any of the many ethnic minorities. We expect that ethnic minorities are less likely to invest in climate change related adaptation measures due to their living in the remote areas and villages less endowed with infrastructure (Hung et al. 2010).

To capture the effect of remoteness for all households we added the variable "Distance to district town" from the village head questionnaire. Here we expect a negative relationship with climate change adaptation. Finally, we added province dummy variables to capture other differences among the study regions.

In the selection Equation (1b), we use the respondent characteristics including age, education, gender and membership of socio-political organization as the independent variables. This is because the adaptation decision is made by the household head but the perception of climate change is given by the respondent of that household who in most cases is the household head. Age, a proxy of farming experience, is supposed to have a positive effect on the farmers' awareness. We expect that more experienced farmers are more likely to observe changes in climate over time. Likewise, better educated farmers are believed to have more access to information on climate change (Deressa et al. 2008). Household size is assumed to have a positive effect as the chance to obtain information increases with the number of household members and the same mechanism we assume for income (Deressa et al. 2008).

One important household characteristic included as an explanatory variable in the selection equation is the climate-related shock experience. This variable is computed by summing up the severity scores multiplied by the frequencies of all climatic events, namely drought, floods, storm and soil erosion experienced by a household in the reference period. We expect that more experience with negative climate-related shocks in the past increases the probability that a respondent is aware of climate change.

The inclusion of the ethnicity variable in the model for Vietnam is based on the same arguments as in Equation 1a. We expect that the Kinh majority is more likely to be aware of climate change. Likewise, we have added province dummy variables. In order to control for country heterogeneity we estimate models for Thailand and Vietnam separately.

In order to further explore the type of adaptation measures undertaken by farmers, we formulated a multinomial logit model (MNL) to assess the drives for four categories of adaptation measures, while not undertaking any adaptation was treated as the base category as follows:

$$\Pr\left(Y_i = j\right) = \frac{\exp\left(x\beta_j\right)}{\sum_{k=1}^{J} \exp\left(x\beta_k\right)} \tag{2}$$

where the dependent variable Y denotes adaptation categories taking on value $j = \{0,1,2,\ldots J\}$ and x is a vector of regressors (Greene 2003).

In our study, the adaptation categories include the following:

- 0 = No adaptation
- 1 = Crop diversification
- 2 = Chemical input management
- 3 = Water management
- 4 = Planting trees

The explanatory variables x include different household head characteristics (i.e. age, education, gender, membership of socio-political organization), household characteristic (agricultural member ratio, farm size, income, risk attitude and ethnicity (only in model for Vietnam)), distance to district town and province dummies. The justification of these variables and their expected direction of influence are assumed to be identical with those in Equation 1a.

In addition, however, we include the respondent's perceptions of changes in climate-related parameters like rainfall, temperature and wind as these perceptions may influence the choice of adaptation measures in different ways. The multinomial logit model makes the assumption of *independence of irrelevant alternatives* (IIA) (Long and Freese 2006). We use the Hausman test to verify this assumption.

5 Descriptive Results

In the shock section of the survey, households were asked for the four most frequent types of climate-related shocks (i.e. droughts, floods, storms and soil erosion) experienced during the past 3 years (2010–2013). Table 1a reports these results for Thailand and Table 1b for Vietnam. As shown in Table 1a, drought was the major climate-related shock event reported with a considerable variation across the three provinces in Thailand. The province of Buri Ram was most affected. Flood was reported by over 10% of households in two provinces while storms and soil erosion was reported by only few households. Average frequency of climate events was little over one event

Table 1a Climate-related shocks experienced by farmers by province in Thailand

Type of climate-related shocks	% of households reported			Average frequency			Average severity		
	Buri Ram	Ubon Ratchathani	Nakhon Phanom	Buri Ram	Ubon Ratchathani	Nakhon Phanom	Buri Ram	Ubon Ratchathani	Nakhon Phanom
Drought	58.57	21.27	16.84	1.00	1.00	1.08	2.49	2.43	2.39
Flood	6.96	11.21	13.68	1.02	1.00	1.05	2.37	2.51	2.63
Storm	4.41	1.21	3.16	1.00	1.00	1.00	2.54	2.00	1.78
Soil erosion	0.34	0.91	0.00	1.00	1.00	–	2.00	2.50	–

Source: DFG Household survey 2013

Table 1b Climate-related shocks experienced by farmers by province in Vietnam

Type of climate-related shocks	% of households reported			Average frequency			Average severity		
	Ha Tinh	Thua Thien Hue	Dak Lak	Ha Tinh	Thua Thien Hue	Dak Lak	Ha Tinh	Thua Thien Hue	Dak Lak
Drought	13.23	14.37	47.48	1.00	1.00	1.04	2.37	2.58	2.65
Flood	36.38	13.97	3.47	1.03	1.03	1.00	2.55	2.60	2.59
Storm	8.56	8.58	0.79	1.00	1.00	1.00	2.43	2.51	1.80
Soil erosion	0.58	3.19	0.47	1.67	1.00	1.00	3.00	2.38	2.67

Source: DFG Household survey 2013

and quite consistent across the provinces. The same can be said for perceived severity which is mostly around 2.5 on average on scale from 0 to 3. This severity score implies that climatic extreme events affected farm households quite critically according to their subjective assessment. Overall, among the three provinces in Thailand, Buri Ram province located in the eastern part of the country and on the border with Cambodia had the highest degree of climate-related shocks reported.

From Table 1b it can be derived that results vary considerable across the three provinces in Vietnam. In the land locked province of Dak Lak where coffee is a major crop drought was reported by almost half of the households and storm was reported by just few households. On the other hand in Ha Tinh, the province located in the central coastal region with exposure to the sea, more households reported floods. Drought, flood and storm were reported with quite similar rates of households in Thua Thien Hue. This is also the province where soil erosion was most experienced. Frequency of events was similar to Thailand with the exception of soil erosion in Ha Tinh, which can be explained by the mountainous terrain where some of the sample households are located. This observation is also reflected in the perceived severity which is higher than for the other categories. Overall, severity is somewhat higher in the Vietnamese provinces compared to the provinces in Thailand. This seems reasonable as Vietnam is generally more severely affected by the climate change.

In the climate change module, we asked respondents whether or not they perceived changes in climate in general and changes in rainfall, temperature and wind in particular during the time they resided in the area. In Table 2, the different variants of climate change for the three climate categories are reported.

Overall, the vast majority of respondents in all six provinces in the two countries have recognized changes in climate and changes in rainfall and temperature were more frequently reported than changes in wind. Results do not differ much between the two countries although variation between provinces remains high.

Changes in rainfall patterns were described differently between provinces and countries. For example, in two provinces of Thailand respondents observed the length of the dry season to have increased while in Vietnam lower total rainfall was more noted. However, in Vietnam households perceived rainfall variability to increase. Differences among provinces in both countries may show the difference of their geographic conditions.

Table 2 Climate change perceptions of farmers in Thailand and Vietnam by province, percentage of households reported

	Thailand			Vietnam		
Observations	Buri Ram	Ubon Ratchathani	Nakhon Phanom	Ha Tinh	Thua Thien Hue	Dak Lak
Climate in general	**94.57**	**90.61**	**74.74**	**81.52**	**82.04**	**90.69**
Rainfall	**94.51**	**88.79**	**68.98**	**78.30**	**80.40**	**89.19**
Less rain in the whole year	40.08	24.26	11.63	25.95	42.44	46.09
Less rain early in the season	23.26	16.70	14.68	2.12	15.12	13.80
Dry season becomes longer	49.15	38.33	16.90	19.42	24.69	28.02
Rain becomes more erratic	16.43	33.18	9.97	30.35	19.91	37.13
Fewer rainy days	15.11	12.70	4.99	12.75	21.45	29.87
Temperature	**94.41**	**90.27**	**72.85**	**76.93**	**77.16**	**86.77**
Getting hotter in summer	86.86	87.64	55.68	55.08	61.57	63.02
Cool season is shorter	35.35	41.53	15.24	20.49	28.24	9.96
More extreme temperature	18.00	37.64	20.20	57.21	45.22	54.91
More heat days	59.53	62.36	17.45	23.07	52.47	56.19
Wind	**80.81**	**67.39**	**54.85**	**34.14**	**27.93**	**37.84**
Wind speed higher	71.62	60.18	46.54	21.4	19.60	32.43
More frequent storms	31.14	34.67	16.62	8.65	8.80	1.71
Wind direction changes	24.54	31.01	12.19	13.51	13.73	11.52

Source: DFG Household survey 2013

Temperature results generally follow those of rainfall. However, there is more agreement on the description of the type of temperature changes with most respondents observing higher summer temperatures. Both in Thailand and Vietnam over half the respondents in two provinces said that extreme temperatures have increased.

Changes in wind were less frequently mentioned especially in Vietnam while in the province of Buri Ram 80% of the respondents specified a higher wind speed as major change and 30% reported more frequent storms which was confirmed by respondents from the province of Ubon Ratchathani.

Comparing farmer observations with existing literatures supports the notion that their subjective perceptions match scientific data. This confirms findings from South Africa that farmers' perceptions of climate change are in line with the climatic data records (Gbetibouo 2009). Meteorological data from Thailand confirm that rainfall in Thailand decreased in the past three to five decades compared to the first half of

Table 3 Effects of climate change on crop production and farmers' adaptation measures by province, percentage of households reported

	Thailand			Vietnam		
	Buri Ram	Ubon Rathchathani	Nakhon Phanom	Ha Tinh	Thua Thien Hue	Dak Lak
Effects on crop production	**81.66**	**68.48**	**44.91**	**71.21**	**64.47**	**84.07**
Lower yields	61.89	47.48	32.41	45.83	41.82	63.87
More crop failures	25.23	27.69	9.97	28.83	17.75	32.72
More pests	15.77	12.47	1.94	29.29	26.70	21.62
More drought stress	35.35	23.46	7.20	10.77	15.74	34.99
Adaptation measures	**29.54**	**32.42**	**11.23**	**45.53**	**31.14**	**44.95**
Crop diversification	19.69	21.82	6.67	13.62	11.38	20.82
Chemical input management	12.05	11.52	4.56	22.96	21.76	11.04
Water management	3.40	9.42	0.70	7.39	6.39	22.40
Planting trees	1.87	2.88	0.35	0.39	1.60	0.47
Others	0.00	0.30	0.00	11.09	1.80	2.05

Source: DFG Household Survey 2013

the last century. Also climate models predicted that precipitation will shift from the north to the south (Boonyawat and Chiwanno 2007). Based on climate data generated by a global circulation model temperature in Thailand projected to increase 2° C–4 °C by the end of the century (ADB 2009). Jesdapipat (2008) stated that storms in Thailand have become more intense which is consistent with the subjective perceptions of respondents in our sample.

In Vietnam it has been predicted that most regions will experience an increase in temperature of 2° C–4 °C by the end of the century (Cuong 2008). The same author also found that in most areas of Vietnam, overall rainfall intensity has increased considerably while monthly rainfall has decreased between the months of July and August, but has increased between September and November. It is also expected that the Southern part of Vietnam will become drier.

In Table 3, we illustrate the perceived impact of climate change by farmers on the performance of agriculture, in particular in crop production and their adaptation measures. It is striking that in all six provinces of the two countries a considerable share of households reports a decline in yields. The highest shares with over 60% of households reporting are in Buri Ram and Dak Lak, both provinces with a strong agricultural potential. In these two provinces the occurrence of drought stress was most frequent which is quite consistent with their observations on the change in climate generally and in rainfall reported in Table 2.

In spite of the high share of households who report an impact on crop production only between one fourth and two fifth undertake adaptation measures. This kind of discrepancy has also been observed in a study of farmers in Ethiopia

(Deressa et al. 2008). Adaptation measures include for example growing more (drought resistant) varieties, widening the crop portfolio, spraying more pesticides and applying more fertilizer. Although responses considerably vary by country and by province reflecting differences in agricultural systems, changes in crops and crops varieties and in the amount of chemical input used are the two dominant adaptation measures. In the province of Dak Lak, investment in irrigation was reported by over one fifth of households which is distinctively higher than in all other provinces. Here results are consistent with the perception of more droughts which however is not the case for the province of Buri Ram where 35.35% farmers reported drought stress but only 3.40% take a particular water management method.

In summary, what we can derive from the survey on subjective climate change perceptions is that there is a strong geographic effect of the perceived impacts of climate change. The fact that there is a fairly good congruence between the perceived effects of climate change and adaptations suggesting that farmers are well aware of climate change although the ratio of adaptations to perceptions is in the order of 1:3 only.

In Table 4, we have made use of the 2007 survey and compared farm management parameters related the use chemical inputs, irrigation practices and tools and tree plantation which can serve as proxy parameters for actual adjustment to climate change with the 2013 survey data. It shows that changes can be observed with more cases significant in Vietnam. While no causality to climate change perception can be established here and other factors can also play a role, results are consistent with respondents' climate change perceptions. For example, planting of trees has increased significantly in both countries.

Summarizing the results of the descriptive analysis suggests that farmers in poor and vulnerable environments in Thailand and Vietnam did experience climate-related shocks which on average are perceived as moderately severe. However, variation across locations exists. Furthermore, farmers are well aware of climate change and can describe the process by a range of indicators like "cool season getting shorter" or "rain become more erratic". These criteria differ from those used by scientists in climate models but they seem to correspond well with such findings.

Table 4 Farm management practices in 2007 and 2013 across all provinces in Thailand and Vietnam

	Thailand			Vietnam		
Parameter	2007	2013	p-value	2007	2013	p-value
Chemical input (PPP$)	35.41	55.45	0.02	118.36	93.83	0.02
Irrigation tools (unit)	1.89	1.73	0.63	0.90	2.29	0.00
Newly-bought irrigation tools (unit)	0	0.030	0.00	0	0.004	0.08
Share of irrigated plots (%)	13.98	7.71	0.00	50.64	71.31	0.00
Share of tree areas (%)	4.91	8.09	0.00	23.84	34.19	0.00
Share of trees out of crop types (%)	5.95	10.37	0.00	20.58	30.21	0.00

Source: DFG Household Survey 2007–2013

Also, farmers recognize that climate change has caused negative impacts on their agricultural production. Nevertheless, adaptation actions in response to the perceived downside effects are still few. This underlines the hypotheses established in Section 2 of the paper that perceptions are an important driver for adaptation decisions that aim at reducing risks and losses. In the next section the perception-adoption link will be explored further by means of econometric analysis.

6 Results of Econometric Analysis

With our first model we test the hypothesis that farmers' perception of climate change can be linked to the likelihood of farmer's respective adaption measures. Our two-step Heckman probit model shows a significant lambda for both Thailand and Vietnam dataset indicating the existence of sampling bias (Tables 5a and 5b). The perception model for Vietnam mostly shows the expected signs of the explanatory variables. Education and gender show positive and significant signs (Table 5a). In other words, better educated and male respondents are more likely to recognize climate change. Climate-related shock experience significantly increases the likelihood of respondents recognizing climate change suggesting that short term experience can shape perceptions for long term trends. Differences in province partly reflect the findings of the descriptive statistics. Relative to the base province of Ha Tinh, respondents in Dak Lak are significantly more likely to perceive climate change. This result is consistent with those presented in Tables 1b and 2 with increasing temperatures and an increase in droughts.

The outcome equation with the implementation of adaptation measures as the dependent variable also shows better statistical quality for Vietnam. Age of household head is negatively related to the likelihood of adaptation measures. It is plausible that older farmers are less likely to change their farming system in response to perceived climate change. Gender was significant suggesting that male household heads are more likely to implement adaptation measures which is consistent with the findings of Asfaw and Admassie (2004). As expected, membership in a socio-political organization has a positive influence on adaption measures. Likewise, the share of household members engaged in agriculture and ethnicity of household are positively correlated with likelihood of adaptation.

As shown in Table 5b, the perception model for Thailand overall performed poorly in terms of statistical tests. However, the climate-related shock variable was significant and the significant coefficients of the province dummy variables for Buri Ram (positive) and Nakhon Phanom (negative) were consistent with observations presented in Tables 1a and 2.

Similar to the selection equation, the adaptation model for Thailand showed poor explanatory power and the only significant variable (aside from a province dummy) was the respondent's individual attitude towards risk. The coefficient of risk attitude

Table 5a Perceptions of and adaptations to climate change by farm households in Vietnam, two-stage Heckman selection model

	Adaptation equation	Selection equation
Explanatory variables	Coefficients	Coefficients
Household head characteristics		
Age (Years)	**−0.004*****	
	(−2.71)	
Education (Years of schooling)	−0.001	
	(−0.26)	
Gender (1 = Male, 0 = Female)	0.058	
	(1.47)	
Member of socio-political organization (1 = Yes, 0 = No)	**0.090**** **(2.56)**	
Respondent characteristics[a]		
Age (Years)		0.005
		(1.45)
Education (Years of schooling)		**0.027****
		(2.31)
Gender (1 = Male, 0 = Female)		**0.211****
		(2.56)
Member of socio-political organization (1 = Yes, 0 = No)		0.035 (0.34)
Household characteristics		
Agricultural member ratio	**0.227*****	
	(4.32)	
Log of farm size (ha)	**0.029****	
	(2.10)	
Household size		0.022
		(0.83)
Log of income (PPP$)	**0.029***	0.036
	(1.72)	(0.84)
Ethnicity (1 = Kinh, 0 = Minorities)	**0.095****	−0.113
	(2.25)	(−0.97)
Climate-related shock experience (Ordinal score)		**0.061**** **(2.44)**
Risk attitude (Likert scale)	−0.002 (−0.29)	
Village characteristics		
Log of distance to district town (Km)	−0.016 (−0.80)	**0.089*** **(1.81)**
Province dummies		
Thua Thien Hue	**−0.127*****	0.087
	(−2.96)	(0.80)
Dak Lak	**−0.107****	**0.405*****

(continued)

Table 5a (continued)

Explanatory variables	Adaptation equation Coefficients	Selection equation Coefficients
	(−2.03)	**(3.45)**
Intercept	**0.408***	−0.219
	(1.80)	(−0.52)
Mills		
Lambda	**−0.487****	
	(−1.97)	
rho	−0.87	
Total observations	1529	
Wald chi2	77.86	
Prob > chi2	0.000	

Source: Authors' own calculation

Note: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$, z statistics in parentheses

[a]We tried to use the household head characteristics instead of respondent characteristics in the perception equation but the results are as not good as results in Tables 5a and 5b

shows that the higher the degree of risk-seeking, the higher the likelihood that a household adapts to climate change. While farmers in Buri Ram perceive a higher degree of climate change compared to the reference province of Ubon Ratchathani, fewer farmers undertake adaptation measures. Against this background the negative coefficient for the province dummy is surprising. However, this suggests that other factors such as poorer quality extension services or less attention given by other public institutions to the climate change phenomenon may cause this result.

To investigate the determinants for choosing different adaptation measures, we use a multinomial logit model for four groups of adaptations and "no adaptation" is the base category. The Hausman test for the validity of the *independence of the irrelevant alternatives* (IIA) was insignificant for both Thailand and Vietnam. This suggests that the multinomial logit model is an appropriate specification for modelling the choice of adaptation measures to climate change of farmers. The estimated coefficients along with the standard errors are presented in Table 6a for Vietnam and in Table 6b for Thailand.

In the model for Vietnam, the signs of the explanatory variables are largely consistent with the results of the outcome equation in the Heckman model (Table 5a). For all adaptation measures except for "planting trees" household head' age has a significant and negative signs which is consistent with expectations as older household heads are likely to stick to their traditional practices in spite of recognizing changes in climate conditions. On the other hand, changing water management practices is positively correlated with membership in a socio-political organization. This is plausible as water management in rural Vietnam is a collective action and usually requires good relationships with village authorities namely the people's

Table 5b Perceptions of and adaptations to climate change by farm households in Thailand, two-stage Heckman selection model

	Adaptation equation	Selection equation
Explanatory variables	Coefficients	Coefficients
Household head characteristics		
Age (Years)	0.001	
	(0.93)	
Education (Years of schooling)	0.006	
	(1.01)	
Gender (1 = Male, 0 = Female)	0.034	
	(0.96)	
Member of socio-political organization (1 = Yes, 0 = No)	−0.032 (−0.44)	
Respondent characteristics		
Age (Years)		−0.004
		(−0.99)
Education (Years of schooling)		0.004
		(0.28)
Gender (1 = Male, 0 = Female)		0.020
		(0.20)
Member of socio-political organization (1 = Yes, 0 = No)		−0.039 (−0.17)
Household characteristics		
Agricultural member ratio	0.030	
	(0.53)	
Log of farm size (ha)	−0.024	
	(−1.32)	
Household size		0.042
		(1.39)
Log of income (PPP$)	0.004	0.036
	(0.23)	(0.77)
Climate-related shock experience (Ordinal score)		**0.090***** **(2.69)**
Risk attitude (Likert scale)	**0.013**** **(2.33)**	
Village characteristics		
Log of distance to district town (Km)	0.037 (1.52)	−0.050 (−0.72)
Province dummies		
Buri Ram	**−0.085***	**0.245****
	(−1.88)	**(2.01)**
Nakhon Phanom	−0.054	**−0.643*****
	(−0.54)	**(−5.51)**
Intercept	0.149	**1.057****

(continued)

Table 5b (continued)

Explanatory variables	Adaptation equation Coefficients	Selection equation Coefficients
	(0.72)	**(2.10)**
Mills		
Lambda	**−0.601***	
	(−1.65)	
rho	−1.00	
Total observations	1361	
Wald chi2	17.21	
Prob > chi2	0.102	

Source: Authors' own calculation
Note: $*p < 0.10$, $**p < 0.05$, $***p < 0.01$, z statistics in parentheses

committee. Among household characteristics it is shown in Table 6a that the higher the share of household members engaged in agriculture, the more likely the households undertake adaptation measures. The respective coefficient is positive and significant for all adaptation measures except for planting trees although the direction of influence is positive. This result is plausible as households whose major livelihood is in agriculture are more likely to actively meet the challenges of climate change. Indeed, the coefficients for all categories (i.e. changing crop diversity, chemical input management, and water management) are positive and highly significant for four categories. Income of households shows a significant and positive influence on adaptation measures "water management" and "planting more trees" which seems plausible as these measures are related to investments. The coefficients for the variables reflecting the perception of the respondent in the three indicators of climate change, i.e. rainfall, temperature and wind all show a positive sign although not all are significant. Consistent results are found for rainfall which is plausible as indeed rainfall is the major driving factor for productivity of agriculture and changing rainfall patterns may warrant adjustments in many agricultural practices. Temperature is significant for planting more trees and changes in crop diversification such as changing crops or crop varieties. The variable for farmer's perception in the change of wind conditions is significant for "crop diversification" and "planting trees" which seems plausible again. Overall, however, it can be argued that farmer's climate change perceptions prompt them to change their farming system. The significance of all climate related coefficients for planting more trees is a strong indicator that farmers recognize the need for climate change adaptation for a variety of reasons.

The ethnicity variable is only significant for water management which underlines again the importance of collective action which often relies on public support. This indicates that households belonging to the Kinh ethnic majority group may be more likely to undertake adaptation measures. Finally, the significant coefficient for the

Table 6a Results of multinomial logit model for the choice of adaptation measures, Vietnam

Explanatory variables	Crop diversification	Chemical input management	Water management	Planting trees
	coef/se	coef/se	coef/se	coef/se
Household head characteristics				
Age (Years)	**−0.015***	**−0.017****	**−0.016***	−0.045
	(0.009)	**(0.008)**	**(0.009)**	(0.031)
Education (Years of schooling)	0.014	0.010	−0.010	0.070
	(0.027)	(0.021)	(0.024)	(0.111)
Gender (1 = Male, 0 = Female)	0.471	0.378	0.332	−0.384
	(0.298)	(0.233)	(0.257)	(0.759)
Member of socio-political organization (1 = Yes, 0 = No)	0.178	0.329	**0.568*****	1.627
	(0.222)	(0.219)	**(0.198)**	(0.990)
Household characteristics				
Agricultural member ratio	**1.250*****	**0.986*****	**0.736****	1.928
	(0.364)	**(0.299)**	**(0.324)**	(1.357)
Log of farm size (ha)	0.061	0.066	**0.214****	0.362
	(0.098)	(0.073)	**(0.084)**	(0.220)
Log of income (PPP$)	**0.219****	0.038	**0.299*****	**0.678*****
	(0.105)	(0.087)	**(0.094)**	**(0.262)**
Rainfall perception (1 = Yes, 0 = No)	**1.607***	**17.775*****	**1.635****	**13.515*****
	(0.977)	**(0.326)**	**(0.798)**	**(0.803)**
Temperature perception (1 = Yes, 0 = No)	0.973	0.631	0.953	**15.283*****
	(0.756)	(0.393)	(0.650)	**(0.581)**
Wind perception (1 = Yes, 0 = No)	**0.736*****	0.080	0.105	**1.800*****
	(0.192)	(0.163)	(0.180)	**(0.697)**
Risk attitude (Likert scale)	0.047	−0.001	0.021	−0.166
	(0.043)	(0.029)	(0.035)	(0.105)
Ethinicity (1 = Kinh, 0 = others)	0.102	0.291	**0.374***	0.714
	(0.255)	(0.237)	**(0.223)**	(0.956)
Village characteristics				
Log of distance to district town (Km)	−0.084	0.021	−0.080	0.340

(continued)

Table 6a (continued)

Explanatory variables	Crop diversification	Chemical input management	Water management	Planting trees
	coef/se	coef/se	coef/se	coef/se
	(0.118)	(0.094)	(0.099)	(0.284)
Province dummies				
Thua Thien Hue	−0.220	−0.137	−0.083	1.687
	(0.292)	(0.211)	(0.293)	(1.044)
Dak Lak	**0.556****	**−1.070*****	**1.203*****	0.398
	(0.262)	**(0.260)**	**(0.240)**	(1.102)
Constant	**−7.200*****	**−20.009*****	**−7.371*****	**−40.993*****
	(1.173)	**(0.901)**	**(1.057)**	**(2.233)**
Base category	**No adaptation**			
Number of observations	1529			
Log likelihood	−1505.473			
LR chi2	**353.08*****			
Pseudo R2	0.136			

Source: Authors' own calculation
Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

province dummy of Dak Lak indicates the importance of irrigation and crop diversification is this land locked region compared to the coastal provinces of Thua Thien Hue and Ha Tinh.

In summary, the model for Vietnam shows satisfactory results. It largely confirms the finding of our first model (binary model 1a) and provides further information on the factors that drive specific adaption measures. The results can provide information for extension services to guide farmers in adopting more climate smart technologies.

The model for Thailand shows less explanatory power than the Vietnam model. Although the coefficients generally have the expected signs, much fewer of them are significant. Interestingly, however, individual attitude towards risk of the respondent pops up in two of the four categories of adaptation measures with a positive and significant coefficient. This is plausible as risk seeking behaviour may make farmers more likely to undertake climate change adaptation measures. This however was not observed in the Vietnam model. On the other hand, the coefficients for the three climate change indicators are quite consistent with the Vietnam model although wind speed seems to be a stronger factor in Thailand in explaining agricultural adjustments to climate change. The negative coefficient for the province dummy variable for Buri Ram is consistent with the binary model but does not match with the climate-related shock experience shown in the descriptive statistics. In summary, while the Thailand model is less satisfactory the main message that climate change perception is a major driver for specific adaption measures in agriculture can be confirmed.

Table 6b Results of multinomial logit model for the choice of adaptation measures, Thailand

Explanatory variables	Crop diversification	Chemical input management	Water management	Planting trees
	coef/se	coef/se	coef/se	coef/se
Household head characteristics				
Age (Years)	0.002	0.002	**0.022****	0.017
	(0.008)	(0.009)	**(0.010)**	(0.019)
Education (Years of schooling)	0.038	−0.005	0.010	**0.176*****
	(0.032)	(0.037)	(0.047)	**(0.054)**
Gender (1 = Male, 0 = Female)	−0.075	0.273	**0.670****	0.447
	(0.200)	(0.252)	**(0.333)**	(0.467)
Member of socio-political organization (1 = Yes, 0 = No)	−0.845	0.358	0.212	−0.924
	(0.552)	(0.403)	(0.465)	(1.003)
Household characteristics				
Agricultural member ratio	0.182	−0.185	0.451	0.348
	(0.344)	(0.372)	(0.446)	(0.511)
Log of farm size (ha)	−0.113	0.050	−0.150	−0.279
	(0.099)	(0.129)	(0.152)	(0.281)
Log of income (PPP$)	0.088	0.036	−0.000	−0.071
	(0.088)	(0.102)	(0.133)	(0.198)
Rainfall perception (1 = Yes, 0 = No)	1.286	**16.749*****	0.944	**14.083*****
	(1.115)	**(0.591)**	(1.025)	**(0.388)**
Temperature perception (1 = Yes, 0 = No)	1.747	−0.447	**15.678*****	**12.952*****
	(1.558)	(0.719)	**(0.709)**	**(0.588)**
Wind perception (1 = Yes, 0 = No)	**0.453****	**0.796*****	0.476	**2.443****
	(0.229)	**(0.304)**	(0.328)	(1.042)
Risk attitude (Likert scale)	**0.085*****	0.046	**0.112****	**−0.160***
	(0.033)	(0.036)	**(0.045)**	**(0.094)**
Village characteristics				
Log of distance to district town (Km)	0.044	**0.434*****	0.044	0.034
	(0.132)	**(0.152)**	(0.181)	(0.198)

(continued)

Table 6b (continued)

Explanatory variables	Crop diversification	Chemical input management	Water management	Planting trees
	coef/se	coef/se	coef/se	coef/se
Province dummies				
Buri Ram	−0.037	0.046	**−1.259*****	**−0.801***
	(0.191)	(0.217)	**(0.318)**	**(0.441)**
Nakhon Phanom	**−0.819*****	−0.523	**−2.441*****	**−2.113****
	(0.314)	(0.365)	**(0.715)**	**(1.043)**
Constant	**−6.382*****	**−20.852*****	**−21.526*****	**−33.101*****
	(1.298)	**(1.214)**	**(1.441)**	**(2.448)**
Base category	**No adaptation**			
Number of observations	1361			
Log likelihood	−1174.558			
LR chi2	**176.10*****			
Adjusted R2	0.089			

Source: Authors' own calculation
Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

7 Summary and Conclusions

Using a comprehensive dataset of farm households in Thailand and Vietnam we have tried to answer three questions. Firstly, we wanted to explore what climate related shocks farm households experience in the more recent past and whether they perceive a change in the longer term climate conditions and what indicators they use to describe climate change. Secondly, what factors influence their climate change perceptions and can their perceptions be linked to their adaptation measures. Thirdly, we wanted to know to what extent the explanatory factors differ for specific climate change adaptation measures.

The answer to the first question is quite clear. The majority of farm households in both countries have experienced recent climate-related shocks and the vast majority does perceive that climate has changed. While the latter fact may not be very surprising our results however point out that farmers have their own way of describing the climate change related phenomenon. We can also see that quite consistent with differences in natural and economic conditions, the geographic location has an influence on how farmers recognize climate change. Furthermore, farmers reported adjustment measures which they are planning to undertake or have already undertaken in response to climate change. We have independently checked this claim by comparing some climate relevant agricultural practices from our 2007 survey with the most recent survey in 2013 and we found quite some differences that suggest that farmers are indeed climate-responsive although we cannot judge to what degree these changes fit the metaphor of "climate-smart".

To answer the second question we used a Heckman model that allows joint estimation of a selection and an outcome equation, separately for the two countries. Based on the results we can confirm that perceptions can be reasonably linked to farmers' decision to undertake adaptation measures. In the model for Vietnam we can show that perceptions are shaped by the respondent's characteristics, location variables and recent climate related shocks. Unfortunately, results for the Thailand model are less convincing. However, the climate-related shock variable is significant and consistent with the results in Vietnam. Similar results were found for the outcome equation where again the Vietnam model was more convincing. The difference could be attributed to the lower awareness among the Thai farmers as shown in the lower number of cases in spite of largely equal initial sample size between the two countries. From an objective point of view, Vietnam is indeed more exposed to climate change due to its geographic location along the South China Sea costal line.

Finally, the answer to the third question is that the factors that drive specific climate change related adaption measures differ among practices, provinces and countries. They are to be found in the characteristics of the respondent and the household head whenever there is a difference between the two. Perhaps the most important factor in explaining specific adaptation measures are the three specific climate variables namely rainfall, temperatures and wind, which are all significantly correlated with tree plantation. While for the other adaptation measures such as crop diversification, varietal change, etc. factors other than climate change may be more important, the clearest connection we find is with trees.

We believe our results can provide important information to policy makers and agricultural extension services who should improve their understanding of the farmers' interpretation of climate change and the constraints that have so far prevented them from undertaking more and better adaption measures. Further studies should take a more in-depth look at those constraints and provide a detailed assessment of the costs and benefits of farmer-based adaption measures.

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U.S. Maize Yield Growth and Countervailing Climate Change Impacts

Ariel Ortiz-Bobea

Abstract Over the past several decades, maize yields in the US Midwest have risen at about 17% per decade as a result of steady technological progress. Although the trend is expected to remain positive, climate change is expected to have an increasing countervailing effect. In this chapter, I compute the yield growth rates necessary to fully offset the potential negative effects of a warming climate. Relying on a statistical model allowing for nonlinear effects of temperature on yield, I find that maize yields would decrease by −4.2, −21.8 and −46.1% *around* the trend, under uniform warming scenarios of 1 °C, 3 °C and 5 °C, respectively. I find that an increase of 6.6%/decade in maize yields is required to fully offset the detrimental effects of a severe but still plausible 3 °C warming in the next three decades. This indicates that future maize yield trends could – all else equal – be substantially curtailed due to the climate change. This case study illustrates how agricultural policy analysts can assess the magnitude of potential climate change impacts relative to historical yield trends to help identify targets for agricultural research.

1 Introduction

Climate change is resulting in shifting rainfall patterns and rising temperatures that will increasingly challenge agricultural producers across the globe, including in temperate regions with high agricultural productivity such as the United States (US) Midwest region. Various statistical studies have found a strong longitudinal relationship between exposure to high temperature (>30 °C) and lower-than-average crop yields (Schlenker and Roberts 2009; Lobell et al. 2011). This historical evidence presages lower yields in the region under a warmer climate relative to a world without climate change.[1] At the same time, Midwest maize yields have risen at about 17% per decade in recent times as a result of steady technological progress. This chapter analyzes the extent to which these secular maize yield trends can help

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[1] Evidence suggests that temperature affects yield by lowering the water supply in rainfed environments (see Lobell et al. 2013).

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offset the projected relative decline of maize yields resulting from a warming climate.[2] This case study illustrates how agricultural policy analysts can assess the magnitude of potential climate change impacts relative to historical yield trends to help identify targets for agricultural research and investments.

The case study is organized as follows. First, I estimate a statistical model of maize yields regressed on weather variables for the US Midwest. The model allows for nonlinear temperature effects on yield following the approach developed by Schlenker and Roberts (2009). This model accounts for distinct effects of temperature exposure to various temperature bins within *each day* of the growing season. The model is based on panel data and exploits the longitudinal covariance of maize yields and weather conditions at the county level. Second, I use the estimated climate sensitivity parameters to developed maize yield change projections under three uniform warming scenarios (1, 3 and 5 °C). Third, I use these projections to answer the following question. What yield growth rate would be necessary to fully offset the projected yield effects under warming scenario? Obviously, the answer depends on the time horizon of the warming, so I explore time frames ranging from one decade to a century. Finally, I discuss the magnitude of potential climate change impacts on maize yields in light of historical yield trends.

The chapter is organized as follows. First, I describe the data sources and provide summary statistics for key variables in the analysis. I also provide an overview of the warming scenarios. In the subsequent section I present the crop statistical model and describe how climate change impact projections are computed. I then present the model results and the associated impacts from a uniform warming and provide a discussion of the findings. I then conclude the chapter.

2 Data Sources and Summary Statistics

The empirical analysis in this chapter relies on agricultural and climate data. The agricultural data was obtained from *Quick Stats,* the US Department of Agriculture's (USDA) online database. This database provides data from historical surveys on county-level agricultural production variables such as acres planted and harvested as well as production. The dependent variable in the study, maize yield, is obtained by dividing total maize production by acres planted. For the 1929–2014 period, this information is complete for 644 counties in 13 Midwest states. This constitutes the set of counties in the study.

The climate data is obtained from the PRISM Climate Group, which provide USDA's official climatological data. The PRISM data is a detailed gridded dataset providing daily measurements of minimum, average and maximum temperature and total precipitation for each 4-by-4 km grid over the entire contiguous US since 1981. Because the data is gridded, it needs to be aggregated to the county level to

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[2] Although crop yield does not directly reflect agricultural productivity, it provides a useful metric that is easily understood by a wide audience interested in agriculture and food security concerns.

Table 1 Summary statistics for select variables

Variable	Min	25th pct.	50th pct.	Mean	75th pct.	Max
Corn yield (bu/acre)	17.0	101.1	123.7	122.2	144.6	210.8
Precipitation (mm)	110	467	558	569	659	1254
Temperature exposure (days)						
	<0 °C	0.00	1.07	2.43	3.24	4.744
	0–5 °C	0.00	4.13	6.14	6.55	8.68
	5–10 °C	3.12	12.25	15.96	15.98	19.68
	10–15 °C	9.42	23.89	28.38	28.38	32.67
	15–20 °C	23.14	38.52	42.29	42.02	45.78
	20–25 °C	24.55	39.06	43.32	43.30	47.69
	25–30 °C	6.27	26.05	30.70	30.88	35.97
	>30 °C	0.01	5.90	11.14	12.66	18.15

Notes: Summary statistics correspond to a balanced panel of 644 counties for the 1981–2014 period. Weather variables are aggregated between April and September of each year. For reference, 100 bu./acre of maize are roughly equivalent to 6.3 t/ha

match the agricultural observations. I perform this aggregation by weighting each PRISM grid by the amount of cropland it contains based on USDA's Cropland Data Layer (CDL). The CDL provides 30-m resolution land cover pixels corresponding to over 100 classes. The weights were based on cropland pixel counts falling within each PRISM data grid and the average of CDL cropland counts for years 2008–2014 were used. Note that temperature exposure to each temperature "bin" or interval is computed by fitting a double sine curve going through the minimum and maximum temperature of each consecutive day for each PRISM grid and subsequently counting the time spent within each degree bin over the growing season in each year. The temperature exposure was then aggregated to county using the aforementioned approach.

Key summary statistics are presented in Table 1 and correspond to a balanced panel of 644 counties over the 1981–2014 study period. This period is confined to years with complete climate data. The table shows maize yields vary considerably, ranging from 17.0 to 210.8 bu./acre. This variation obviously encompasses both cross-sectional (across counties) and longitudinal (within counties) dimensions. There is also a wide range of variation for precipitation over this time period with minimum and maximum levels of 110 and 1254 mm for the April–September period. Following conventional practice, these months correspond were chosen to approximate the maize growing season in the region.

Regarding air temperature, the present study relies on measurements of the temperature distribution across the entire growing season rather than average monthly temperature. In other words, the temperature variables correspond to the time spent within each temperature bin over the April–September period. This approach is arguably better suited to capture exposure to extreme temperatures than monthly average temperatures. Although the statistical analysis makes use of exposure data to each bin ranging from 0 to 36 °C, I only present summary statistics for aggregated

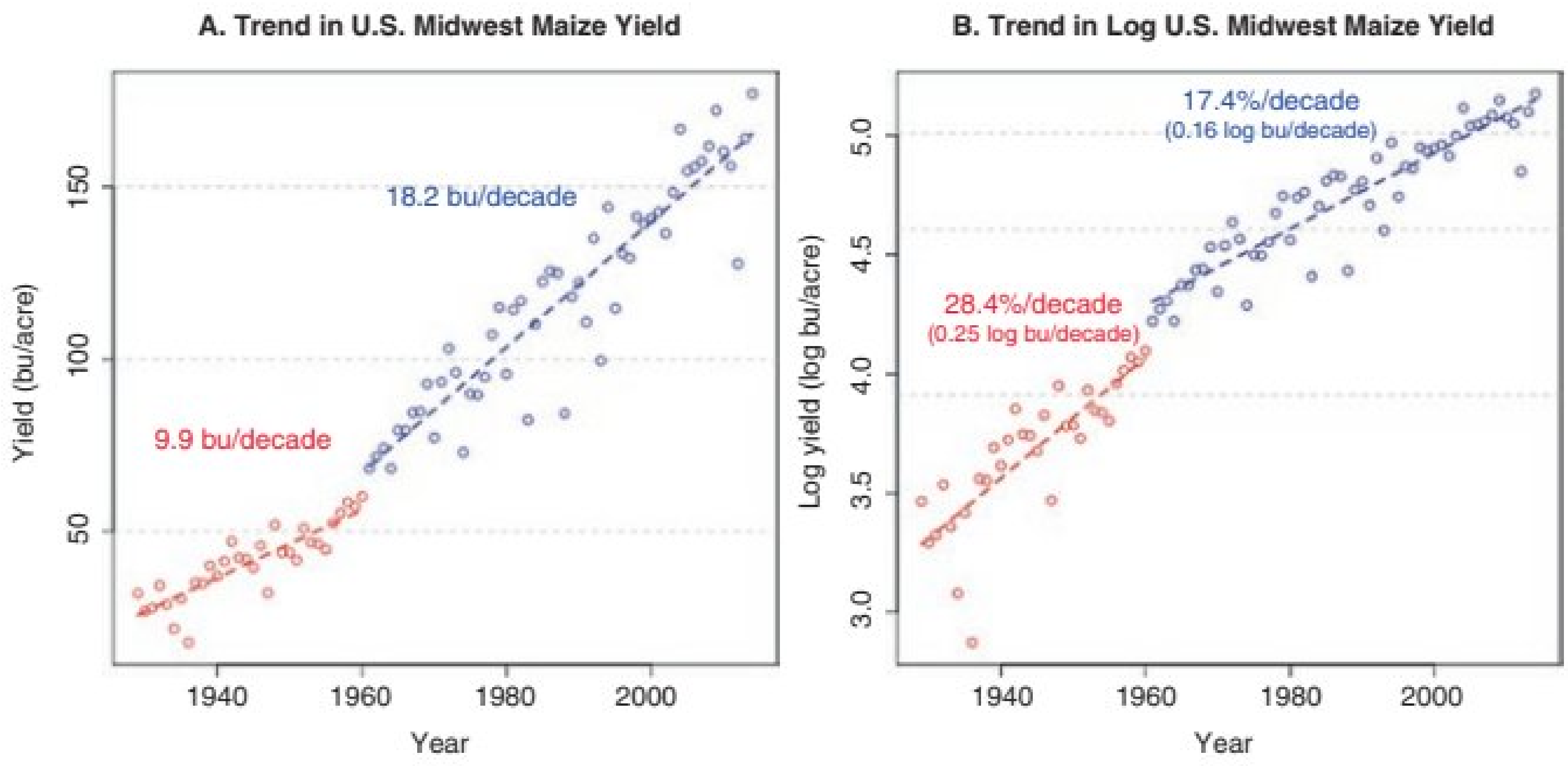

Fig. 1 Corn yield trends in the US Midwest (*Notes:* Observations correspond to acreage-weighted maize yields for each year. The trend lines were fitted assuming a linear trend for years 1929–1960 and 1961–2014. The sample corresponds to a balanced panel of 644 counties across 13 states over the 1929–2014 period)

contiguous bins in Table 1. The table shows that the most frequent temperature range is between 15 and 25 °C, which corresponds to the bins with the highest mean exposures.

In this chapter I seek to compare the potential effects of a warming climate relative to historical yields trends. Figure 1 illustrates the rise in maize yields in the Midwest since 1929. Panel A shows the yield trend has roughly doubled in *absolute* terms between 1929–1960 and 1961–2014. However, this obscures the fact that the *rate* of this trend has slowed down by almost 40% during this period, as shown in panel B.[3] I will refer to these growth rates later on in the analysis. Also, it is worth noting that I do not detect a statistically significant trend in weather variables over the study period (1981–2014). This suggests that these yield trends are mostly a reflection of technological progress and not really of parallel climate trends.

Regarding climate change data, I adopt 3 uniform warming scenarios of 1, 3 and 5 °C with no precipitation change. The reason I focus on temperature rather than precipitation changes is that previous studies (e.g. Lobell et al. 2008; Schlenker and Roberts 2009) have found that temperature changes are the major explanatory factor explaining crop yield fluctuations in the US Midwest (and elsewhere). A possible reason is that high temperatures capture the effect of dry summer spells, which are crucial for maize production, but are not captured by the season-long precipitation variables. Figure 2 provides an overview of the temperature distribution for the baseline climate as well as under the warming scenarios (lower row). The maps illustrate the mean exposure above 30 °C in each county during the growing season. Under the baseline climate, very few counties have mean exposure exceeding 30 days over the April–September period (total of 183 days). However,

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[3] The 1929–1960 period corresponds to the period of hybrid corn varieties adoption across the US.

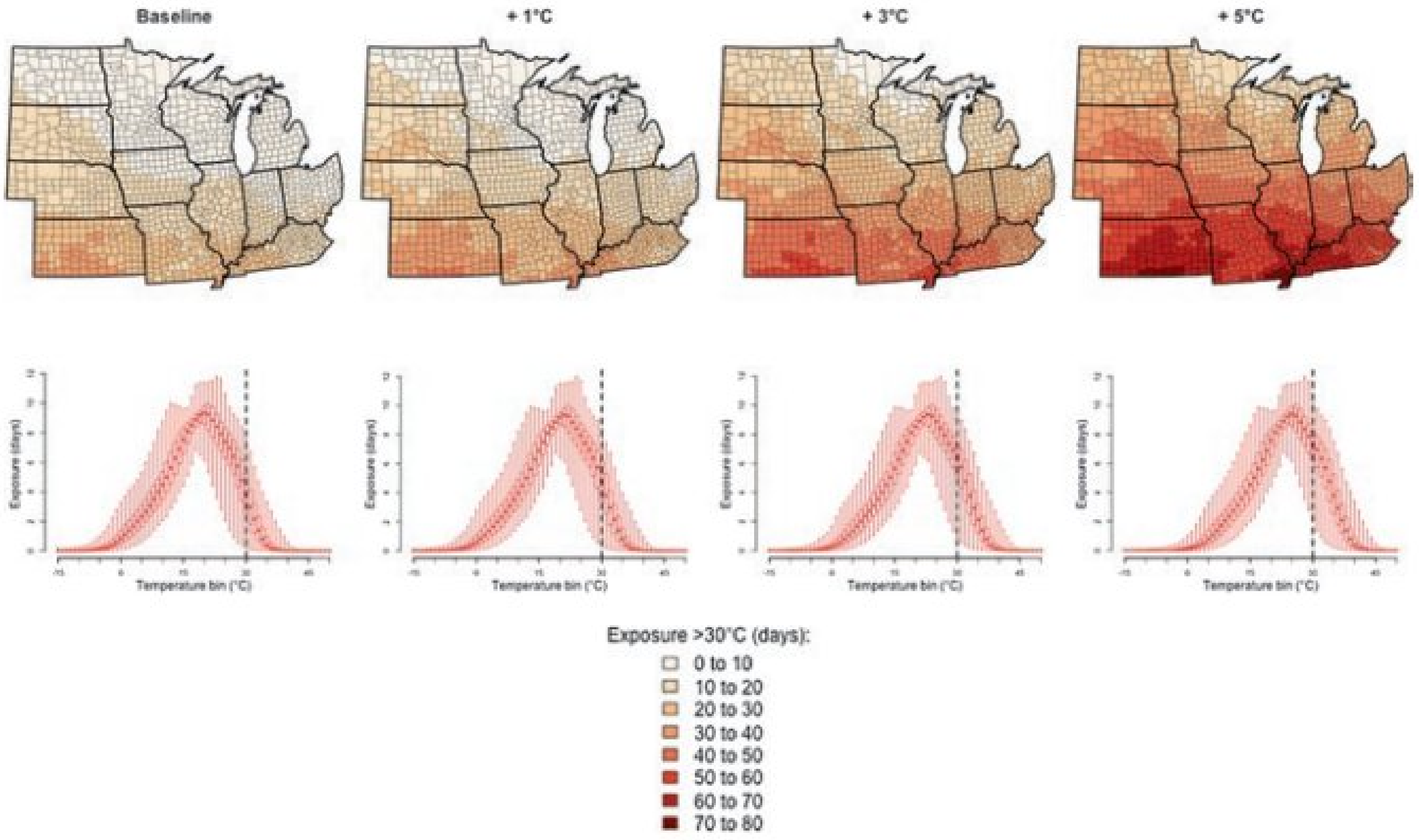

Fig. 2 Exposure to extreme temperature under varying uniform warming scenarios (*Notes:* The upper row shows the yearly mean exposure (in days) to temperatures exceeding 30 °C during the April–September growing season for each county in 13 Midwest states for baseline and 3 uniform warming scenarios. The lower row presents the temperature distribution across the sample for each temperature bin. Each box represents the median and the first and third quantiles of the distribution. The whiskers extent to data extremes. The dotted vertical line indicates the 30 °C threshold for illustrative purposes)

exposure above this threshold substantially increases under the most severe warming scenario. This will have a major effect on the projected yield impacts as we will see shortly.

3 Crop Yield Model and Climate Change Impacts

Crop statistical models have re-emerged as an alternative approach to the traditional biophysical models for assessing the potential impacts of climate change on crop yields. A statistical crop yield model is basically a regression analysis of crop yields on weather variables. Early examples can be traced back to the early part of the last century (Wallace 1920; Hodges 1931). In this chapter, I adopt the approach developed more recently by Schlenker and Roberts (2009). These authors developed an innovative approach that separately estimates the effect of the cumulative exposure (over the growing season) to different temperature bins on crop yield.[4] Mathematically, the nonlinear effect of temperature on yield may be represented by

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[4] This approach assumes that temperature effects on yield are cumulative and substitutable over time. This assumption may be relaxed.

a function of temperature h, denoted $g(h)$. Logged maize yield y_{it} in county i and year t can thus be represented as:

$$y_{it} = \int_{\underline{h}}^{\overline{h}} g(h)\phi_{it}(h)d(h) + p_{it}\delta_1 + p_{it}^2\delta_2 + z_{it}\tau + c_i + \epsilon_{it} \tag{1}$$

where $\phi_{it}(h)$ is the time distribution of temperature for April–September, p_{it} is precipitation, z_{it} is a quadratic time trend and the c_i are county fixed-effects that capture time-invariant factors explaining yields level across counties (e.g. soil quality, etc). However, Eq. (1) cannot be estimated directly because of the integral. To make this model tractable one needs to approximate the integral with a summation over discrete temperature bins:

$$y_{it} = \sum_{h=0}^{36} g(h+0.5)\left[\Phi_{it}(h+1) - \Phi_{it}(h)\right] + p_{it}\delta_1 + p_{it}^2\delta_2 + z_{it}\tau + c_i + \epsilon_{it}$$

where $\Phi_{it}(h+1) - \Phi_{it}(h)$ represents the time spent over the $[h; h+1]$ interval, and $g(h+0.5)$ is a parameter to estimate. However, given the high number of temperature bins, collinearity between exposures to contiguous bins might create noisy estimates. As a result I assume that $g(h)$ is a smooth function over temperature bins which I can approximate with cubic B-spline with 8 degrees of freedom evaluated at each temperature bin. This can be written as:

$$\begin{aligned} y_{it} &= \sum_{h=0}^{36}\sum_{j=1}^{8}\gamma_j B_j(h+0.5)\left[\Phi_{it}(h+1) - \Phi_{it}(h)\right] + p_{it}\delta_1 + p_{it}^2\delta_2 + z_{it}\tau + c_i + \epsilon_{it} \\ y_{it} &= \sum_{h=0}^{36}\underbrace{\sum_{j=1}^{8}\gamma_j B_j(h+0.5)\left[\Phi_{it}(h+1) - \Phi_{it}(h)\right]}_{x_{it,j}} + p_{it}\delta_1 + p_{it}^2\delta_2 + z_{it}\tau + c_i + \epsilon_{it} \end{aligned}$$

where B_j is the jth column of the basis matrix of the natural cubic spline. The model effectively regresses yield on eight temperature variables, $x_{it,j}$. The model is estimated via Least Squares and errors are clustered by county and by year to account for heteroscedasticity and contemporaneous error dependence. Once parameters γ_j are estimated, one can derive the marginal effects of temperature exposure by premultiplying estimated coefficients by the basis matrix. These marginal effects correspond to the marginal effects of each temperature bin on crop yield.

Obtaining climate change projections based on these marginal effects is straightforward and simply requires multiplying the marginal effects for each temperature bin by the change in exposure to each bin under a given warming scenario. The log yield changes can then transformed into percentage changes using well-known formulas.

4 Results and Discussion

4.1 Model Results and Warming Impacts

The main result of the model is the nonlinear effect of temperature on maize yields which is illustrated in Fig. 3. The effects of precipitation are not presented here because the scenarios do not alter the level of precipitation. Exposure to temperatures above 30 °C appear detrimental to maize yields. The response function reflects the fact that years with higher exposure to high temperature tend to be associated with lower than average maize yields in the study region. This is in line with previous findings in the literature.

The lower part of the Fig. 3 represents the baseline temperature distribution across temperature bins. This is somewhat similar to the distribution within bins illustrated in Fig. 2. Again, for the baseline climate, exposure beyond 30 °C is not very common. However, a uniform warming scenario shifts the temperature distribution to the right, which increases the frequency of high temperatures. The anticipated consequence is that maize yields would decrease as exposure to detrimental temperature levels rises.

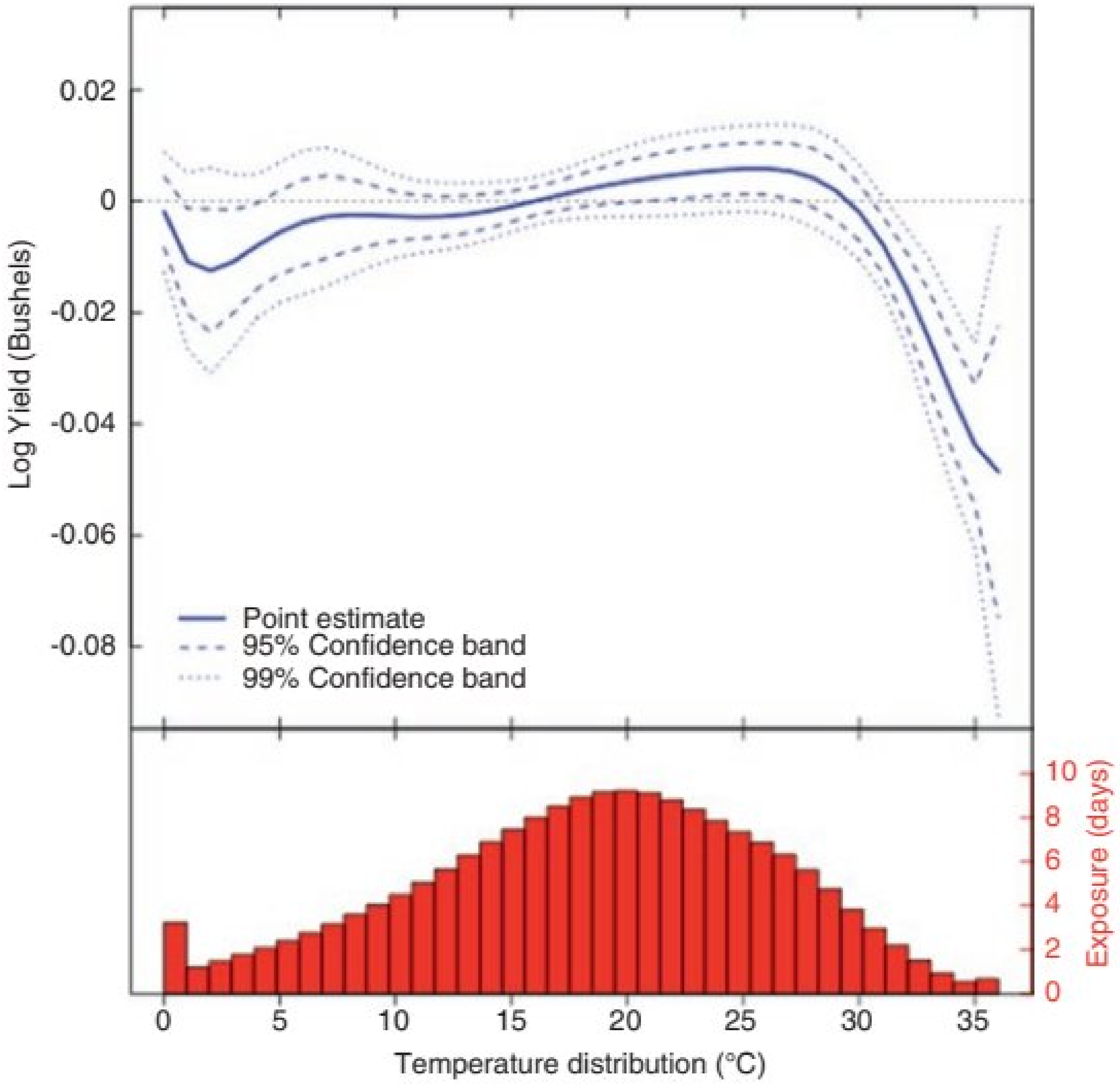

Fig. 3 Nonlinear effects of temperature on maize yields

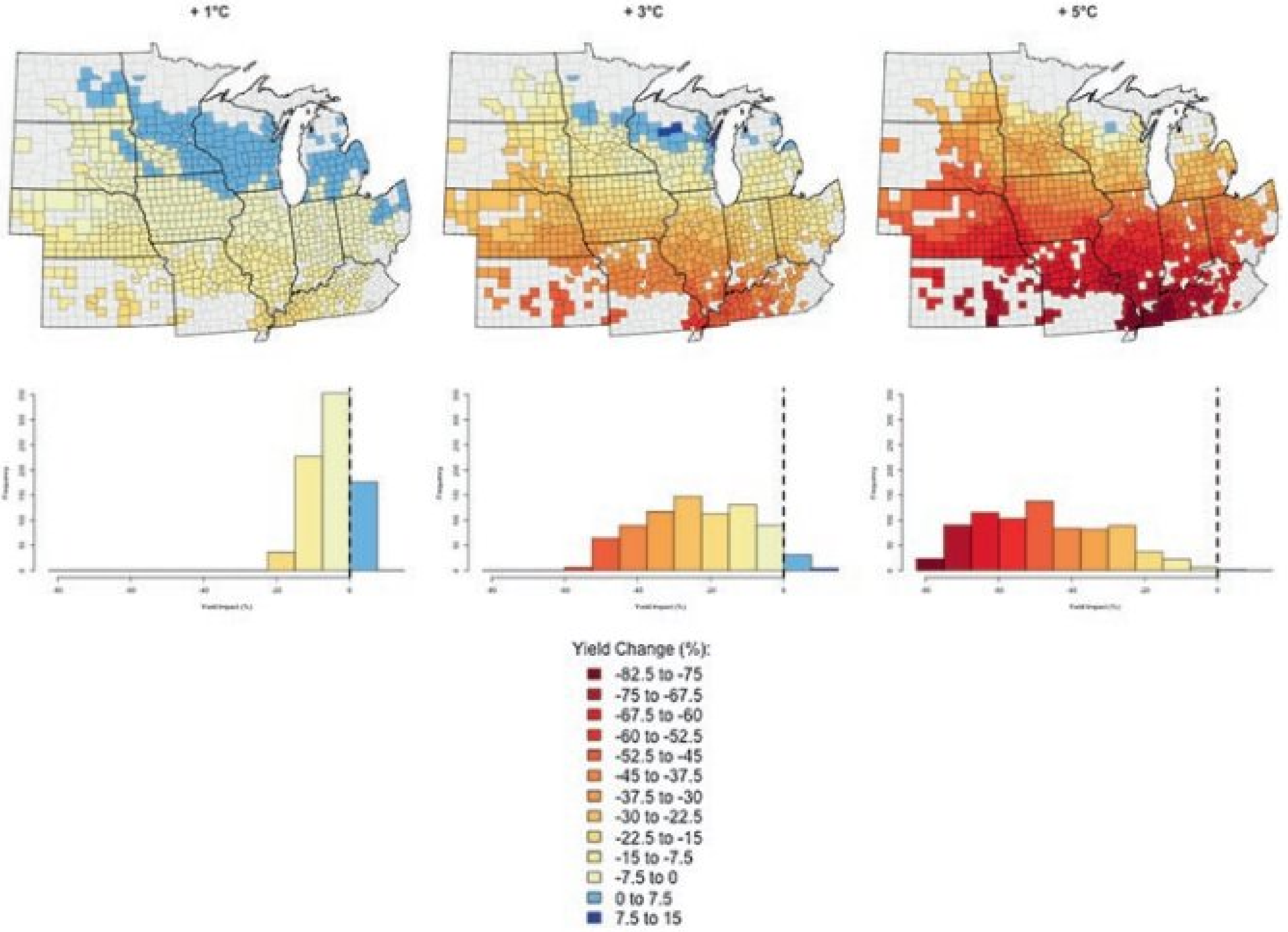

Fig. 4 Maize yield impacts under alternative warming scenarios (*Notes:* The top row represents the projected effect of the corresponding warming scenario for each county in the sample. Grey counties are not in the sample. Some of these effects are not statistically significant when close to zero. The bottom row represents the distributions of these county-level effects)

Figure 4 illustrates the maize yields impacts for all counties in the sample (top row) as well as the distribution of impacts (bottom row) for each warming scenario. Because the statistical model regresses the log yield on weather variables conditional on a time trend, these impacts reflect percentage changes around the yield trend. A warming scenario of 1 °C has a relatively small effect with some northern counties experiencing small positive effects. However, more severe warming scenarios generate increasing crop yield losses. Interestingly, the model predicts rising heterogeneous effects across the sample as illustrated by the higher variance of projected impacts for the most severe warming scenario. The reason is that warming results in a disproportionately higher increase in the frequency of extreme temperatures in region that were warmer in the baseline climate.

The acreage-weighted maize yield impacts for the sample are −4.2%, −21.8% and −46.1% for the 1 °C, 3 °C, and 5 °C warming scenarios, respectively. Again, these impacts are around the trend so they do not represent net effects on yields. These impacts from uniform scenarios, however, do not provide information about their timing or the pace of warming.

4.2 Warming Impacts Against Technological Progress

To provide some context for the magnitude of these yield impacts, I compute the yield growth rate necessary to fully compensate these warming effects. This rate is computed as $r = 1/t\,((y_0 - y_t)/y_0 + 1)$ where t is the time allowed for yield growth (in decades), and $(y_0 - y_t)/y_0$ is the share of acreage-weighted average yields loss in the projected climate relative to the baseline climate ($y_t < y_0$).

I present these rates based on the historical yield sensitivity to temperature in panel A of Table 1. The table naturally shows that in order to compensate the impacts of a warming climate the growth rate in maize yields needs to be higher, the sooner this warming occurs. This explains the higher rates for lower time horizons (upper rows). Obviously, the rate needs to be even higher, to compensate larger damages from a more warming. This explains why higher rates are also found under more severe scenarios. Panel A shows that to compensate for a 3 °C warming within the next 3 decades (mid-century) the maize yield growth rate needs to be 6.56%/decade. This warming scenario approximately corresponds to climate change projections under higher emissions scenarios toward the middle of the century for the continental US. Recall that the recent historical yield trend shown in Fig. 1 is about 17.4%/decade. This is greater than the required growth rate to offset the warming impacts. However, these results show that climate change would have a sizable countervailing impact even if relatively high secular yield growth rates are maintained. More precisely, if the secular trend continues at this historical rate, the net yield growth might be reduced to about $17.4 - 6.6 = 10.8\%$/decade. This is a 38% reduction, which seems considerable.

The previous discussion assumed that only an increase in average yields is considered to counterbalance potential yield losses from a warming climate. However, breeding programs may be designed to reduce the vulnerability of maize yield to extreme conditions. This can be graphically represented as a reduction in the slope of the marginal effect of high temperature on crop yield in Fig. 3. I consider a case in which these marginal effects for temperatures exceeding 30 °C are reduced by half. Projected yield impacts will naturally be lower. Similarly, the required maize yield growth rates need to compensate a warming climate would also be lower. These rates are represented in panel B of Table 1. Indeed, with reduced extreme temperature sensitivity, the offsetting rates could be lower.

Panel C presents the difference between the compensating rates in the case based on historical heat sensitivity and with reduced heat sensitivity. These rates can be interpreted as the "secular yield growth rate equivalent" of an immediate reduction by half in extreme temperature sensitivity. In other words, the comparison of panels A and C provide insights into the tradeoff of combatting projected yield losses from warming by increasing average yield trends or by reducing the sensitivity of yields to extreme conditions. It is clear that the sooner and the more severe the warming is, the more appealing reducing the sensitivity to extreme becomes. Alternatively, if warming is mild or very distant, reducing yield sensitivity to high temperature present relatively small advantages (Table 2).

Table 2 Maize yield growth rate required to fully compensate warming damages

	(A)			(B)			(C)		
Time horizon	Historical sensitivity			Reduced sensitivity			Difference		
(in decades)	+1 °C	+3 °C	+5 °C	+1 °C	+3 °C	+5 °C	+1 °C	+3 °C	+5 °C
1	4.14	19.69	37.90	−0.24	5.88	18.66	4.38	13.81	19.24
2	2.07	9.84	18.95	−0.12	2.94	9.33	2.19	6.90	9.62
3	1.38	6.56	12.63	−0.08	1.96	6.22	1.46	4.60	6.41
4	1.03	4.92	9.47	−0.06	1.47	4.66	1.09	3.45	4.81
5	0.83	3.94	7.58	−0.05	1.18	3.73	0.88	2.76	3.85
6	0.69	3.28	6.32	−0.04	0.98	3.11	0.73	2.30	3.21
7	0.59	2.81	5.41	−0.03	0.84	2.67	0.62	1.97	2.74
8	0.52	2.46	4.74	−0.03	0.74	2.33	0.55	1.72	2.41
9	0.46	2.19	4.21	−0.03	0.65	2.07	0.49	1.54	2.14
10	0.41	1.97	3.79	−0.02	0.59	1.87	0.43	1.38	1.92

Notes: The yield growth rate required to compensate damages is computed as $r = 1/t[(y_0 - y_t)/\ y_0)\ + 1]$ where t is the time allowed for yield growth (in decades), and $(y_0 - y_t)/\ y_0$ is the share of acreage-weighted average yields loss in the projected climate relative to the baseline climate ($y_t < y_0$). The "Historical Heat Sensitivity" relies directly on the estimated parameters for computing climate change impacts. The "Reduced Heat Sensitivity" reduces by half the marginal effects of temperature exceeding 30 °C, i.e. the curve in Fig. 3 becomes less steep. "Difference" corresponds to the difference in rates between the "Historical Heat Sensitivity" rates and those for the "Reduced Sensitivity" rates

5 Conclusion

In this chapter I illustrate how to assess the yield growth rate requirements to fully compensate yield losses due to climate change based on statistical techniques. The crop statistical model employed allows for nonlinear effects of temperature on yields. In line with results in the literature, the statistical model suggests that exposure to temperature exceeding 30 °C is detrimental to maize yields in the US Midwest. A warming climate would therefore entail an increase in exposure to detrimental conditions and reduce yields. Indeed, I find sample-wide yield impacts around the yield trend of −4.2%, −21.8% and −46.1% for the 1 °C, 3 °C, and 5 °C uniform warming scenarios, respectively. The middle of the road-scenario is plausible by mid-century.

I find that a historical rate in maize yield growth in the US Midwest of 17.4%/decade exceeds the rate (6.56%/decade) needed to compensate a plausible warming of 3 °C within the next 3 decades. However, the net yield trend would be substantially diminished under this scenario due to the countervailing effect of a warming climate. In addition, I explore how the reduction in half of yield sensitivity to extreme temperature reduces the yield growth requirements to offset detrimental warming effects. I find that reducing sensitivity to extreme condition is a more attractive option when warming is imminent and severe. This case study highlights how agricultural policy analysis can assess the magnitude of potential yield losses due to climate change relative to historical yield trends.

The analysis could be extended with a cost-benefit analysis of alternative mean-increasing or variance-reducing technological change. The study also has important limitations including the fact that crop yield models cannot account for CO_2 fertilization or detailed management information that may be explicitly modeled with biophysical approaches. Other limitations include the assumptions about time separability of temperature effects as well as the omission of confounded effects of other inputs with weather conditions.

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Understanding Tradeoffs in the Context of Farm-Scale Impacts: An Application of Decision-Support Tools for Assessing Climate Smart Agriculture

Susan M. Capalbo, Clark Seavert, John M. Antle, Jenna Way, and Laurie Houston

Abstract Climate change and enhanced climate variability will have differing impacts on agricultural producers worldwide. The increasing utilization of precision farming and mobile technologies, together with improvements in data management software, offer expanding opportunities for an integrated data platform that links farm-level management decisions and corresponding behavioral changes to site-specific biophysical data and analytical tools. The goals of this paper are to illustrate how decision support tools can be designed to address the farm-scale economic and environmental tradeoffs associated with changes in climatic conditions and how these farm-scale tools could be linked with regional based analyses to scale up to the information needed for better science-based policy.

We use the *AgBiz Logic*™ platform to evaluate farm-scale climate smart options for the dryland wheat producing area of the U.S. Pacific Northwest. A software tool like *AgBiz Logic* could also be utilized to provide higher quality, more timely data for landscape-scale and regional technology assessment. Decision support tools are at the very heart of the recommendations called for in the recent U.S. Government Accountability Office report 14–755 (U.S. GAO 2014), which speaks to USDA's ongoing efforts to better communicate information to growers in a timely downscaled manner.

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1 Introduction

Climate change and enhanced climate variability will have differing impacts on agricultural sectors worldwide. Whether in the form of increased intra-seasonal variability, severe heat waves, long-term drought or warmer winters, farmers and growers need to be cognizant of the risks and opportunities that future weather patterns may bring to yields and profitability, as well as the possible environmental outcomes associated with changes in management regimes. Despite advances in applied research and analysis over the past half century, making informed management decisions based on integrating climate and environmental science findings at the farm scale remains a challenge. Critical information and data are often missing, and thus the consequences of changes in management practices across many dimensions are not easily identified.

Three key elements are required to improve the capability to make better management, and ultimately, policy decisions: (1) timely and accurate data on climate variability and its impact on yield and cost projections; (2) scientific understanding of the agro-ecological system at the farm scale; and (3) incorporation of those two elements into knowledge products that meet the needs of growers and policy decision makers. The increasing utilization of precision farming and mobile technologies, together with improvements in data management software, offer expanding opportunities for an integrated data platform that links farm-level management decisions and corresponding behavioral changes to site-specific biophysical data and analytical tools. Through the use of data technologies, farm-level information can be integrated with publically available data at the landscape scale for supporting science-based policy and sustainable management of agricultural landscapes.

The primary goal of this paper is to illustrate how decision support tools can be designed to address the farm-scale tradeoffs associated with changes in climatic conditions. We also explore how these farm-scale tools could be linked with regional based analyses to scale up to the information needed for better science-based policy. We illustrate how the three key elements noted above can be addressed within the *AgBiz Logic*™ platform and decision-support framework developed to aid growers in evaluating current and alternative management systems under future climate scenarios. By incorporating both climate change and environmental outcomes, these decision tools can be used to evaluate climate smart options. Our illustrative case study reflects the dry-land wheat producing area of the U.S. Pacific Northwest.

Decision tools and modules such as *AgBiz Logic*, provide essential analytical output for global and national efforts labeled climate-smart agriculture (CSA) which focus on making farms and farmers more resilient to a changing climate. These decision support tools are at the very heart of the recommendations called for in the recent U.S. Government Accountability Office report 14–755 (U.S. GAO 2014), which speaks to USDA's ongoing efforts to better communicate information to growers in a timely downscaled manner.

2 AgBiz Logic as a Decision Support Tool for Addressing CSA

AgBiz Logic is an integrated knowledge platform which collects and allocates grower data to enterprise budgets and saves the budgets. It also saves plans[1] and scenarios which can in turn be used in the economic, financial, climate and environmental modules. A simplified schematic of *AgBiz Logic* is provided in Fig. 1. Climate data from climate models and projections; environmental location-specific data on soil, slopes, rainfall etc.; and site-specific production data and other regional (public) data on prices, costs and transportation information are part of the information-base used and stored by *AgBiz Logic*. Outputs from each of the *AgBiz Logic* modules are inputted into another component of the software tool and/or used to generate metrics and other economic information. The economic and financial calculators are the means for farmers to better understand how climate change may impact their livelihood and their on-farm assets. The components are explained in greater detail in this paper.

AgBiz Logic (available online at http://www.agbizlogic.com/) consists of the following economic and financial calculators:

- *AgBizProfit*™ is a capital investment tool that evaluates an array of short-, medium-, and long-term investments. The module uses the economic concepts of net present value, annual equivalence, and internal rate of return to analyze the potential profitability of a given investment.
- *AgBizLease*™ is designed to help agricultural producers establish equitable short- and long-run crop, livestock and other capital investment leases. The module uses the economic concepts of net present value to analyze an equitable crop share or cash rent lease for a tenant and landowner.
- *AgBizFinance*™ is designed to help agricultural producers make investment decisions based on financial liquidity, solvency, profitability, and efficiency of the farm or ranch business. After an *AgBizFinance* analysis has been created, investments in technology, conservation practices, value-added processes, or changes to cropping systems or livestock enterprises can be added to or deleted from the current farm and ranch operation. Changes to a business' financial ratios and performance measures are also calculated.

Two recent additions to the *AgBiz Logic* decision support platform include the *AgBizClimate*™ and *AgBizEnvironment*™ modules:

- *AgBizClimate* delivers essential information about climate change to farmers and land managers that can be incorporated into projections about future net returns, via changes in expected yields. By using data unique to their specific farming operations, growers can develop management pathways that best fit their operations and increase net returns under alternative climate scenarios.

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[1] Plans consist of a sequence of budgets that describe a particular management and or investment strategy. Plans can be compared to each other and saved as a scenario.

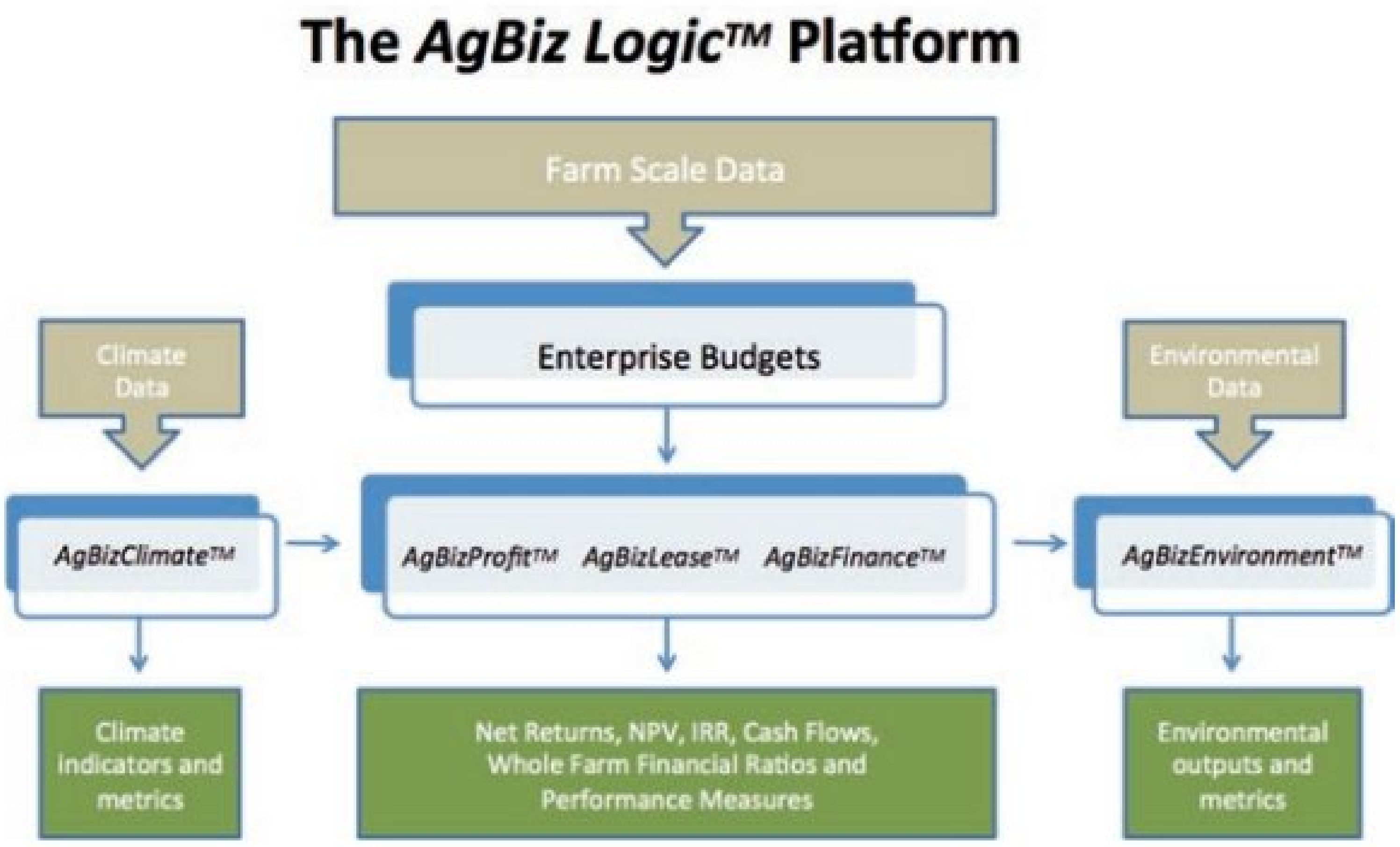

Fig. 1 *AgBiz* logic platform

- *AgBizEnvironment* uses environmental models and other ecological accounting to quantify changes in environmental outcomes such as erosion, soil loss, soil carbon sequestration and GHG emissions resulting in the ability to incorporate on-farm and off-farm environmental outcomes into the decision support software and platform.

The *AgBiz Logic* platform provides both a farmer-level decision support tool and an assessment tool for researchers to realistically determine how climate change and climate change policies may influence and impact regional agricultural sectors. By incorporating regional downscaled climate change information, farm management and financial information, and on-and-off farm environmental impacts of land use changes and management decisions into an interconnected online program, actions of growers and data needs of researchers are linked. The downscaled climate change information influences projected yield and production inputs that change over time. These yield changes are the impetus for producer-generated adjustments in input use, management, and technology adoption that may lessen negative impacts or take advantage of positive opportunities.

3 Addressing the Farm-Scale Tradeoffs Associated with Changes in Climate

AgBiz Logic provides an internally consistent framework for evaluating climate change impacts and investment decisions at the farm scale. Farmers, growers, and land managers can use *AgBizClimate* to explore near-term projections for average weather conditions (e.g., growing degree days, chilling days) relevant to a commodity in their area. With knowledge of these projected changes, users have an opportunity to adjust their investments, yields and production inputs based on how such changes will affect their production and risk. *AgBizClimate* linked to *AgBiz Logic* allows users to step into the world of 20–30 years from present and consider how their current enterprises and operations would continue to serve them in the future, and whether there are any long-range planning decisions they may want to begin considering in order to maintain profitable operations.

What follows is an example of a case study in the mid-Columbia region of Umatilla County, Oregon using modules in the *AgBiz Logic* suite to observe the outcomes of climate change on current and alternative cropping systems (rotation) and on net returns (Seavert et al. 2012). We will first present an example of how *AgBizClimate* can be used to evaluate climate change impacts with changes in yields, tractor, combine and truck costs and production inputs, and we will also demonstrate how the *AgBizProfit* module can be used to evaluate investment decisions associated with changing a crop rotation.

3.1 Initial Setup and Baseline Scenario

The farm operation is a typical 3800-acre dryland wheat farm, in a region that receives between 12 and 18 inches of precipitation annually. In keeping with common practice, the producer uses a winter wheat and fallow crop rotation that includes direct seeding and chemical fallow to conserve soil moisture, increase wheat yields, reduce soil erosion, and reduce fuel usage. Weeds are controlled with glyphosate in the fallow years and other herbicides as needed during the crop years. Pesticides are applied as necessary. Fertilizer requirements are applied at planting using a direct-seed drill. The farm's average yield for winter wheat is 49.5 bushels per acre. One-half of the acres are leased and the farm operator owns the remaining acres. The leased land is based on the landowner receiving one-third of the crop and paying one-third of the weed control, fertilizer, and crop insurance costs (hail, fire and crop revenue coverage) and 100% of the property insurance and taxes. The yield levels are consistent with the yields from the 2007 USDA Agricultural Census for this area.

The data input needs and sequencing of steps are summarized in Appendix A. The producer selects previously generated crop and livestock enterprise budgets from *AgBiz Logic*; if these are not specific to this operation a grower can choose from a set that best reflects their returns and costs (Appendix A, Fig. 5). These previously generated/selected budgets serve as the baseline net returns scenario for comparison once weather variables are introduced. *AgBizClimate* is then used to select the weather station that is closest to the crop or livestock enterprises (Fig. 6). The result is downscaled, site-specific weather forecast information for the producer to use to best assess how climate change will impact the farm or enterprise.

After selecting the weather station in closest proximity to the farmed acres, the producer can select up to three weather variables that he/she believes will most impact wheat yields (Fig. 7). In this example, the number of nights below freezing, accumulated growing degree days and accumulated seasonal precipitation are chosen. Each weather variable has its own specific impacts, as shown in Appendix A, Figs. 8, 9, and 10. The modeled baseline weather condition (black line in Figs. 9 and 10) is an average for each weather variable chosen from 1970 to 1999. The modeled future climate variable is averaged over 2030–2059 for high and low emission scenarios. The solid red and yellow lines show the average, and the shading shows the 5-95th percentile range of resulting from 20 climate models (Figs. 10 and 11).

By the 2030s, the frequency of nights below freezing per year is expected to decrease by 29 nights for the low emissions future and by 34 nights for the high emissions future, as compared with the historical baseline (Fig. 8). From this information, predictions can be made regarding how wheat yields will be impacted from this specific weather variable, using either crop models or grower/expert estimates. In this example yields are increased 20% due to fewer nights below freezing; sensitivity analysis on fluctuations in yields can be incorporated into future analyses.

Figure 9 shows the results for changes in the number of growing degree days. By the 2030s, accumulated growing degree days from April 1 to October 31 are expected to increase by 525° hours for the low emissions future and by 620 degree hours for the high emissions future, as compared with the historical baseline. From this information, wheat yields are estimated to increase 15% due to a higher number of accumulated degree days above 50. Figure 10 shows the results for accumulated precipitation by month. Accumulated water year precipitation is expected to increase by 0.4 inches both for the low emissions and for high emissions future, as compared with the historical baseline. From this information, the producer estimates wheat yields will increase 25% due to an increase in precipitation combined with the time of year of the precipitation.

In Fig. 11, the producer can choose (observe from the available data) how likely his/her wheat yields will be impacted based on Crop Models, Grower Focus Groups, and from their own estimates of yields from Figs. 8, 9, and 10. The producer then enters a final yield estimate for each budget ("Your Changes"). This value will be leveraged to modify each budget used in the analysis. In the example shown, the user agrees with the Crop Models of an increase in wheat yields of 20.3%. However, the user also inserts an additional wheat budget and uses the Grower Focus Group value of 15.0% as a comparison. In *AgBizClimate* users can create new budgets by modifying selected inputs that are directly related to yields (Fig. 12). Examples of changing inputs related to yields include custom harvesting of hay or wheat crops, when paid by the ton.

3.2 Exploring Climate Change Impacts and Investments in Alternative Cropping Systems

Next, we evaluate the impact these changes in yields have on net returns. We also explore the profitability of changing the cropping system. For this region, research suggests that growers may benefit from climate change when they adapt to an annual cropping system of winter wheat and camelina. Camelina is a crop being studied for its potential use as a source of biodiesel fuel for aviation, particularly in regions where dryland cropping systems are predominant.

Using the *AgBizProfit* module we can run a scenario report (using the budgets that were modified using *AgBizClimate)*. Each scenario consists of one to five individual plans that can be compared to each other simultaneously. In this case we compare four plans: (1) the current 2015 winter wheat fallow plan, (2) a winter wheat fallow plan with a 20% increase in wheat yields, (3) a winter wheat fallow plan with a 15% increase in wheat yields, and (4) a change from a winter wheat fallow system to a winter wheat and camelina rotation. On the latter cropping system wheat yields will decline from 50 to 39 bushels per acre (or about 13%) due to reduced soil moisture; however the revenues associated with the decline in wheat yields will be offset by the new revenues from the camelina crop. New crop budgets for these plans will be created for this scenario.

Table 1 reflects the yield changes under each scenario and shows how tractor, combine and machinery hours, truck miles driven, and expected years of life change as a result of the increased volumes of grain, annual acres harvested and the requirement of an additional combine when changing to an annual cropping system with camelina.[2] For the winter wheat and camelina rotation, an average camelina yield of 36 bushels (1800 lbs) per acre is used and the market price is $0.15/lb.; camelina is assumed to be grown in place of fallow. Even though the wheat yields are much less (38.71 bushels per acre, Table 1) and machinery costs higher (crop farming 3800 acres annually as compared to 1900 with the wheat and fallow rotation), the contributions to net returns from camelina compensate for the loss in wheat net returns.

Each of the winter wheat and fallow rotations in 2040 include the additional costs due to increased incidences of weeds, disease and insect infestations attributed to warmer temperatures and higher precipitation. Two additional applications (1 additional herbicide application and the addition of a pesticide application) with material costs are included as well as costs per acre for materials to control insects and diseases. These additional applications increase the tractor and sprayer hours in the wheat and fallow rotations in 2040. However, when camelina is included in an annual cropping system the applications and material costs for four herbicides are removed, which greatly reduces annual tractor and sprayer hours.

The *AgBizClimate* results for per acre returns, total variable cash costs, and net returns of the four cropping systems with crops grown on both owned and leased land are shown in Table 2. The winter wheat and fallow rotation in 2015 has an average net return of $72 per acre on owned land and a $36 per acre on

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[2] Camelina is more difficult to harvest than wheat and combines must slow down to three miles per hour (as opposed to six mph when harvesting wheat), reducing the number of acres harvested in a day and thus requiring the purchase of an additional combine, or custom hiring the additional harvesting.

Table 1 Changes to hours of use and expected life for tractor, combines, machinery and trucks

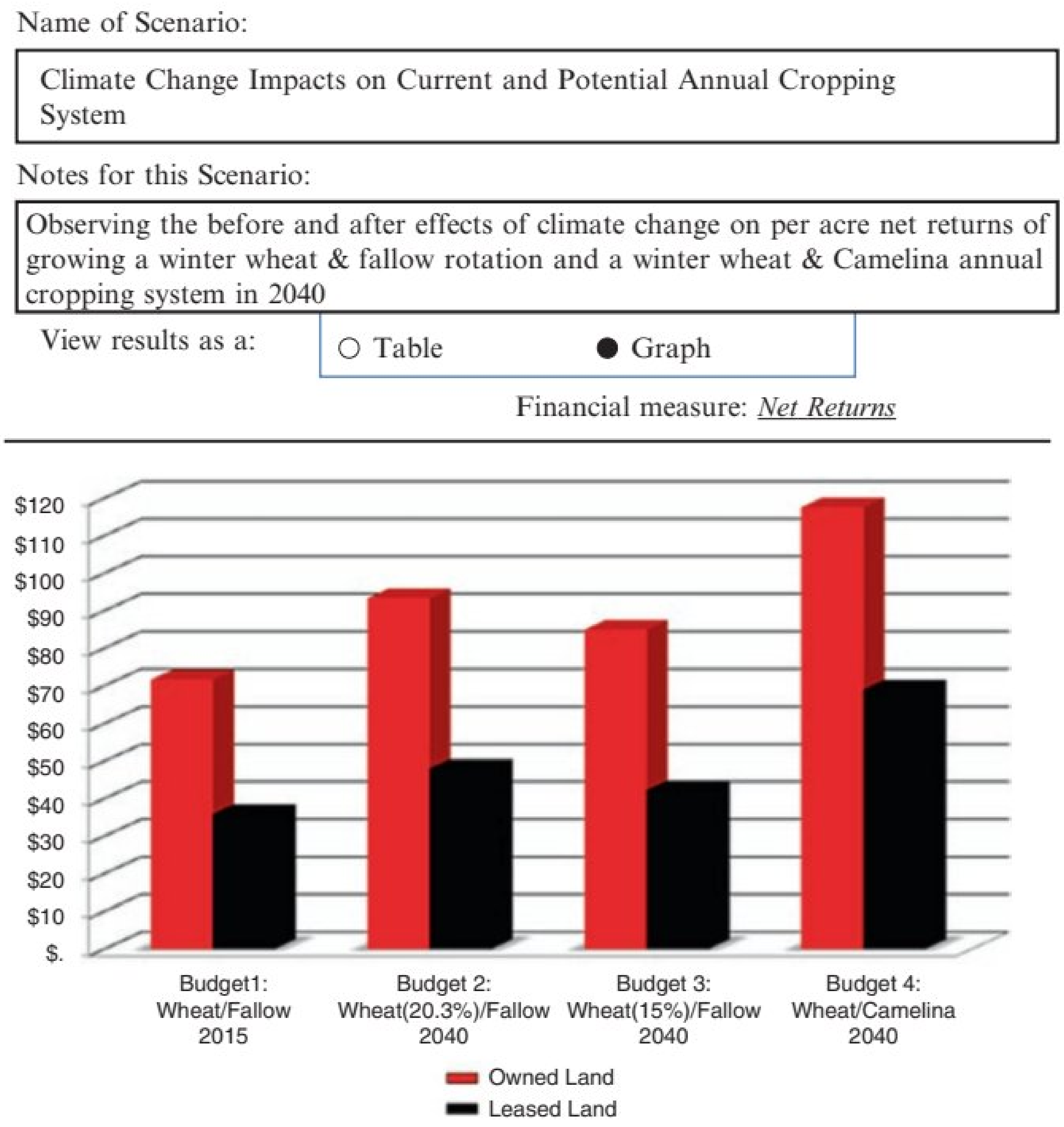
		Base: wheat and fallow rotation, 2015		Wheat (20.3%) and fallow rotation, 2040		Wheat (15%) and fallow rotation, 2040		Wheat and camelina rotation, 2040	
Wheat Yield (bu/ac)		50		60		57		39	
Camelina Yield (bu/ac)								36	
Yield Increase (bu/ac)		–		10		7		25	
		Machinery annual hours and expected life							
Machine	Size	Hours or miles of annual use	Expected Life (Yrs)	Hours or miles of annual use	Expected Life (Yrs)	Hours or miles of annual use	Expected Life (Yrs)	Hours or miles of annual use	Expected Life (Yrs)
Tractor-rubber tracked	485 hp	567	15.0	683	12.5	677	12.6	588	14.5
Combine	30′ Hillside	109	10.0	109	10.0	109	10.0	163	6.7
Additional Combine	30′ Hillside	NA	NA	NA	NA	NA	NA	163	6.7
Rotary mower	26′	167	15.0	167	15.0	167	15.0	NA	NA
Field sprayer	90′	183	15.0	275	10.0	275	10.0	46	59.8
Air seeder	45′	97	15.0	97	15.0	97	15.0	194	7.5
Bank out wagon	850 bu. capacity	120	20.0	144	16.6	138	17.4	181	13.3
Truck & trailer	Semi, used	3000	20.0	3609	16.6	3450	17.4	4528	13.3
Truck	2 1/2 ton, older	2400	20.0	2887	16.6	2760	17.4	3622	13.3

Table 2 Per acre returns, total variable cash costs, and net returns for winter wheat and fallow rotations and winter wheat and camelina annual cropping system for crops grown on owned and leased land

Crops grown on owned land								
	2015		2040		2040		2040	
	Winter wheat	Fallow	Winter wheat (20.3%)	Fallow	Winter wheat (15%)	Fallow	Winter wheat	Camelina
Returns	$322	$0	$387	$0	$370	$0	$252	$270
Total variable cash costs	118	61	130	71	130	71	135	151
Net returns	$204	($61)	$257	($71)	$240	($71)	$116	$119
Average net returns	$72		$93		$85		$118	
Crops grown on leased land								
	2015		2040		2040		2040	
	Winter wheat	Fallow	Winter wheat (20.3%)	Fallow	Winter wheat (15%)	Fallow	Winter wheat	Camelina
Returns	$215	$0	$258	$0	$247	$0	$168	$216
Total variable cash costs	93	49	105	57	106	57	111	135
Net returns	$121	($49)	$153	($57)	$141	($57)	$57	$81
Average net returns	$36		$48		$42		$69	

leased land. The low net returns are largely due to the wheat yield of 49.50 bushels per acre. Now consider the impacts of a changing climate, which in this example result in increased wheat yields. When yields are increased 20.3% in 2040 to 59.55 bushels, the net returns increase to $93 per acre on owned land and $48 per acre on leased land; these net returns must also be adjusted to reflect the increase in herbicides and insecticide application costs. We also provide the results for a smaller change in yields due to climatic changes. As expected net returns decrease slightly when wheat yields are increased only 15% relative to the 2015 crop rotation. The net returns are $85 per acre on owned land and $42 per acre on leased land.

To explore some of the tradeoffs that may be present under climate change we incorporate the profitability of changing the cropping system or adapting manage-



Name of Scenario:

Climate Change Impacts on Current and Potential Annual Cropping System

Notes for this Scenario:

Observing the before and after effects of climate change on per acre net returns of growing a winter wheat & fallow rotation and a winter wheat & Camelina annual cropping system in 2040

View results as a: ○ Table ● Graph

Financial measure: *Net Returns*

Fig. 2 *AgBizClimate* output results

ment to new climatic conditions. For this region, research suggests that growers may benefits from climate change when they adapt to an annual cropping system of winter wheat and camelina. The net returns with a winter wheat and camelina rotation are $117 per acre on owned land and $69 per acre with leased land.[3] Figure 2, shows these results as an *AgBizClimate* output. Sensitivity of net returns to output and input prices are available from the authors but not reported in this paper.

As shown in this illustrative example both cropping systems (winter wheat/fallow versus winter wheat/camelina) and cropping arrangements (owned versus

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[3] Crop leases change in the mid-Columbia region with oilseed crops. The landowner receives 20% of the crop and pays 20% of the fertilizer costs and 100% of the property insurance and taxes. It should also be noted that herbicides are not used in the production of camelina.

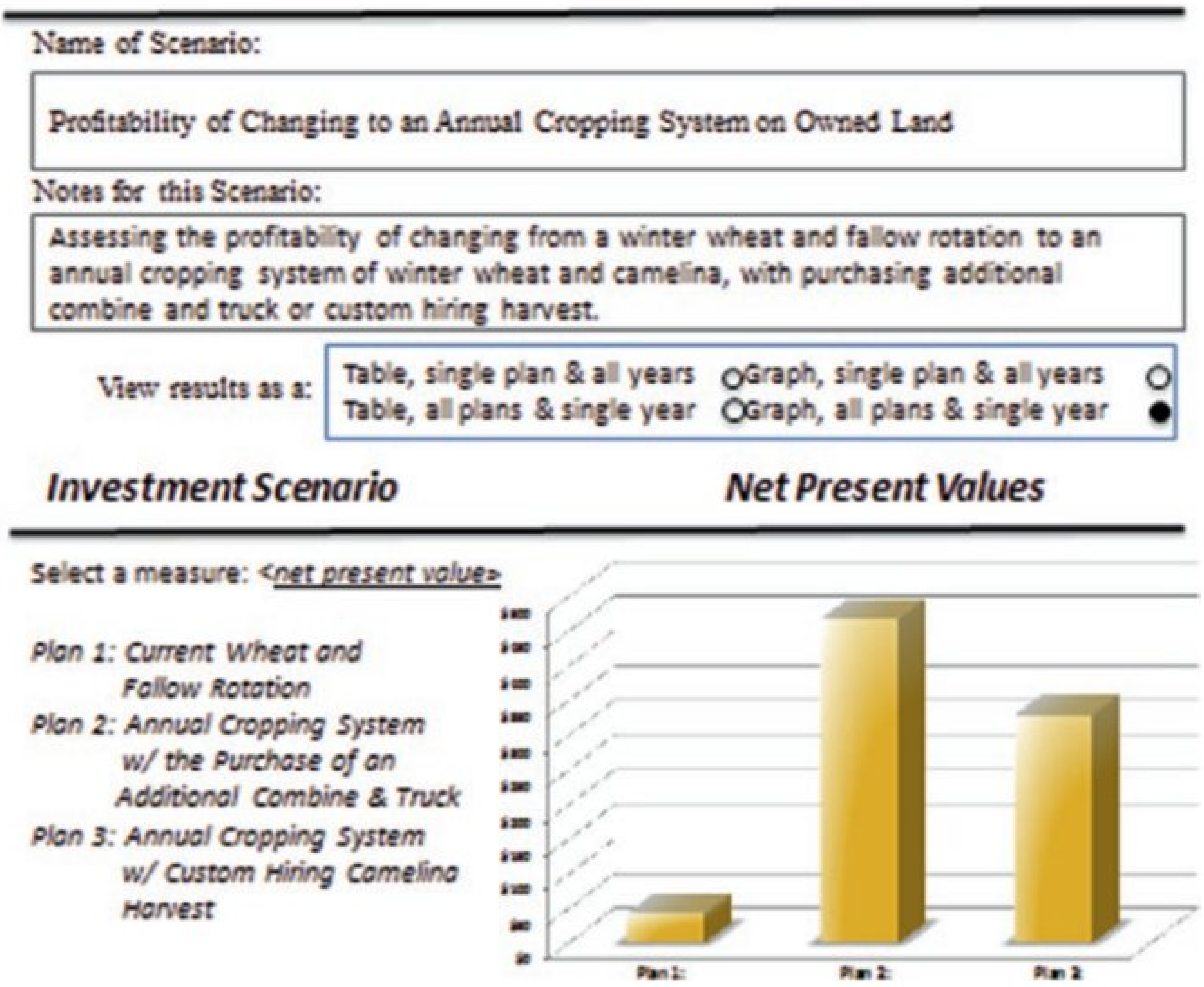
leased) will impact net returns. While many alternative cropping systems can be simulated, we provided only the comparison with the winter wheat/camelina and the original system currently used by a majority of the growers in this region. In both the owned and leased situations, both of which are typical of the arrangements in this area, the net returns per acre are higher with the effects of climate change for winter wheat and camelina annual rotation, regardless of whether the crops are grown on owned or leased land.

3.3 Profitability of Implementing Investment Strategies

Though we have shown that the winter wheat and camelina rotation has higher average net returns, we do not yet know if it is profitable for an individual producer. In order to switch to an annual cropping system that includes camelina, the producer would need to invest in an additional combine and truck. The profitability of this investment will depend on the timing of the cash flows. An alternative would be to custom hire the harvest of the camelina crop, which eliminates the need for the capital outlay of equipment, but also adds a certain amount of risk due to the uncertainty of the custom operator being available at harvest time. Selecting investments that will improve the financial performance of the business involves two fundamental tasks: (1) economic profitability analysis and (2) financial feasibility analysis. Economic profitability will show if an alternative is economically profitable. However, an investment may not be financially feasible: that is, the cash flows may be insufficient to make the required principal and interest payments (Boehlje and Ehmke 2005). In addition agricultural leases may also change with adaptation strategies as additional inputs and costs are incurred by either the landowner or tenant. The more a tenant or landowner contributes to total costs over the length of a lease, the higher the percentage share of the crop return or annual cash rent payment.

Figure 3 is an *AgBizProfit* output showing the results of a capital investment analysis for the adaptation strategies. Based on a discount rate of 4% and a 7 year analysis, the current wheat and fallow rotation has a net present value (NPV) of $57 per acre. The NPV of the annual cropping system with the purchase of an additional combine and truck is $500/acre. Custom harvesting of the camelina crop results in an NPV of $350 per acre. Therefore, the annual cropping system with the additional equipment purchases is the most profitable strategy. However, if a producer does not have the required cash flow to invest in additional equipment, which is needed for this cropping system, then this change in cropping rotations may not be feasible. The *AgBizFinance* module can be used to determine the feasibility of switching to a camelina rotation.

Conducting an *AgBizFinance* analysis requires a detailed balance sheet, description of current loans, capital leases and cash flows for each enterprise in the farm business. This type of analysis is very specific to a particular farm and difficult to demonstrate and discuss without sufficient data. Therefore an *AgBizFinance* analysis and further discussion is not presented in this paper.



Name of Scenario:

Profitability of Changing to an Annual Cropping System on Owned Land

Notes for this Scenario:

Assessing the profitability of changing from a winter wheat and fallow rotation to an annual cropping system of winter wheat and camelina, with purchasing additional combine and truck or custom hiring harvest.

View results as a:
Table, single plan & all years ○Graph, single plan & all years ○
Table, all plans & single year ○Graph, all plans & single year ●

Fig. 3 *AgBizProfit* results for owned land

3.4 Assessing Climate Change Implications for Agricultural Leases

Most of agricultural leases today are based upon what has been done historically or customary for a region. However, as profit margins narrow and climate change impacts yields, production inputs, and crop rotations, there will be a greater focus to base future leases on equitability, where the tenant and landowner are compensated more evenly for their contributions into the lease. Determining the equitability of leases can be explored with a decision support tool such as *AgBizLease,* a module within *AgBiz Logic*. Often times, the net returns on leased land do not equitably compensate the tenant for their financial risk of farming the land. For example, under existing practices, equitable crop leases are established on the percentage of each party's contribution to total costs (Seavert 1999). Using this tool, tenants could review lease terms to determine if current land leases would be equitable in the future. For example, if more insecticides and fungicides are required in future production systems due to a changing climate, those costs could be shared in the same percentages as share of the crop. *AgBizLease* could use the *AgBizClimate* budgets from these analyses to further evaluate the equitability of current lease terms as input costs change, and the resulting sensitivity of net returns.

As shown in Fig. 3, the current crop-share lease is equitable for this winter wheat fallow rotation, however is not profitable for either the tenant or landowner. The accumulated net returns for the tenant and landowner for a ten year lease is −$104 and −$40 per acre. The yields and prices are not sufficient to compensate the tenant for their production inputs and the landowner for their contributions of returns to land, property taxes and both sharing the fertilizer, herbicide and crop insurance costs. However, if this crop-share lease changed to an annual cropping system of winter wheat and camelina with the same sharing of crop and production inputs, both tenant and landowner benefit with $168 and $216 per acre, but not equitably. The *AgBizLease* program calculated an equitable crop-share lease to be 73% of the crop to the tenant and 23% to the landowner. By sharing the crop based on their contributions to this annual cropping system, the tenant would receive $295 per acre and landowner $89 per acre (Fig. 3).

4 Assessing Environmental Impacts

AgBiz Logic modules are based on the premise that growers maximize net returns over time; the static short run net returns are captured as the difference between revenues and cash costs. Depending upon the scenario, revenues can be defined as revenues associated with selling conventional, market-oriented products or can be expanded to include other services that might be valued by the grower, such as soil carbon, green production, environmental footprint, or other sustainability or risk-management attributes.

To capture the environmental aspects of the production decision, including on-site and off-site impacts, the *AgBizEnvironment* module reflects one of several approaches depending upon whether the environmental impact is considered an input or an output to the production process. Environmental/land quality can be considered as an input into the production process (i.e. soil quality) and thus part of the “natural capital” that impacts growers’ net returns. Environmental quality can also be considered as an output of the production process. Way (2015) describes three possible firm-level profit maximization approaches to capture environmental impacts: (1) a conventional approach where environmental quality is reflected in changes in the natural capital variables; (2) the case where changes in environmental characteristics are best reflected using a multiple output production approach; and (3) a constrained profit maximization approach where environmental regulations constrain the choices and production levels of the grower. Each of these approaches requires information on the environmental outcomes from the production processes and/or how these may impact growers’ net returns.

The *AgBizEnvironment* module utilizes existing environmental models or calculators to quantify the environmental outcomes and links this information either directly to net returns (if we can construct a shadow price or cost of the outcomes) or provides direct measures of environmental issues of concern such as changes in GHG emissions, soil erosion, carbon soil sequestration and energy usage. Examples include the Environmental Impact Quotient Value (EIQ) formula developed by Cornell University, Cool Farm Tool which measures GHG (carbon dioxide, nitrous oxide, and methane) emissions, COMET-farm which is a whole farm carbon and GHG accounting systems, and the Universal Soil Loss Equation (USLE) calculator and its many variations. Outputs from these models or calculators can be categorized as either an input to the production process and/or an (desirable or undesirable) output from the production process. GHG emissions and soil carbon credits are often characterized as outputs, although soil carbon can also be an input to the quality of the natural capital; pesticide use, soil erosion, and soil carbon are considered both production inputs and outputs. Table 3 provides an overview of these environmental simulation tools available within *AgBizEnvironment*, their outputs, and their applicability in producer-decision support frameworks.

Using the *AgBizEnvironment* module and associated environmental calculators, we explored the economic and environmental tradeoffs for switching to a conservation management practice for the winter wheat-fallow rotation. From *AgBizProfit* we calculated the change in farm-level net returns in the mid-Columbia region of switching to no-till (which is a more conservation-oriented, water conserving management practice) from conventional tillage. No-till has lower variable costs and labor requirements given the absence of the tillage operations pre- and post-harvest. However herbicide applications increase under no-till management in order to control weeds that would otherwise be managed with tillage, and equipment (air-seeded) costs increased. Based on research trials, wheat yields in this micro region are essentially the same between the two systems, at about 63 bu./acre. This yield exceeds the 49.5 bu./acre used in the previous example which was estimated from the 2007 Ag Census data. We opted to use the higher research trial yields for the *AgBizEnvironment* since it reflects the conditions in this smaller micro-region (Table 3).

For the baseline scenario, since the yields and revenues were taken to be the same between the two systems, variation in net returns is due to costs. Under this baseline scenario, net returns for no-till exceed the net returns for conventional tillage by approximately $29 per acre, or alternatively the yield advantage from conventional tillage would need to be about 6–7 bu./acre greater than no-till to equalize the net returns (Way 2015). So why do we not see a much larger adoption rate for the no-till management? In part, the answer may reside with combination of risk and expertise. At this point in the software development, *AgBizProfit* does not incorporate risk as it relates to management expertise.

Environmental impacts of concern also could include GHG emissions and possible soil erosion. These impacts were calculated using the COMET-Farm model for calculating changes in nitrous oxide and soil carbon equivalents only and the

Table 3 Summary of the environmental tools available with *AgBizEnvironment*

Simulation tool	Environmental factor	Production input or output	Source
Environmental Impact Quotient (EIQ) Value	Pesticides	Both	http://www.nysipm.cornell.edu/publications/eiq/equation.asp
Cool Farm Tool (CFT)	Greenhouse gas emissions/Carbon Sequestration	Output	https://www.coolfarmtool.org
COMET-Farm	Greenhouse gas emissions/Carbon Sequestration	Output	http://cometfarm.nrel.colostate.edu
Universal Soil Loss Equation (USLE)	Soil Erosion	Both	http://www.ars.usda.gov/Research/docs.htm?docid=10626

Universal Soil Loss Equation (USLE) for estimating changes in soil erosion. Our preliminary results indicate a net gain of 0.2 tons soil carbon (CO_2equv/yr./acre) from the no-till relative to conventional tillage. There is no accounting for carbon dioxide emissions in the COMET-Farm results since this model does not adjust for changes in energy use. COMET-Farm reflects climate and soil models and thus accounts only for the nitrous oxide and soil carbon activity. With respect to soil erosion, the potential average soil loss for conventional tillage is 5.19 tons/acre/year, and for no–till practice the average soil loss is approximately 1.04 tons/acre/yr. Thus no-till is environmentally preferred over conventional tillage in these two dimensions.

It is noted that the long term average soil loss (5.19 tons/acre/year) for the conventional tillage on this farm, with slopes of 7–15% and Walla Walla silt loam soil type, exceeds the tolerable soil loss limit for maintaining productivity (5.0 tons/acre/year). This brings into question the ability of the conventional tillage farm to continue to maintain yields equivalent to the no-till system. Under a multi-year net returns model, we would likely see yields fall relative to a multi-year no-till system and thus the gap in net returns would increase over time.

This example illustrates the approach to quantifying the economic-environmental tradeoffs associated with alternative management practices and lays the groundwork for monitoring changes in soil carbon or other environmental outcomes that could be used in environmental or carbon accounting policies. What remains in future research is to link the climate changes and projected yield changes that are generated through *AgBizClimate* to the environmental outcomes that are generated through *AgBizEnvironment* and integrate with the economic and financial modules for a fully integrated decision-support framework for growers.

5 Toward Landscape-Scale Tradeoff Analysis: Linking to the TOA-MD Platform

This section briefly discusses how farm-level data collected with a farm-level software tool such as *AgBiz Logic* could be combined with landscape-scale data to support regional policy analysis using a framework called TOA-MD (Tradeoff Analysis Model for Multi-dimensional Impact Assessment). We briefly describe the TOA-MD model, and discuss its data requirements and how those could be supported by data generated from *AgBiz Logic*. Also see Antle et al. (2016) for further discussion and an example of the use of the TOA-MD model for analysis of climate smart agriculture.

The TOA-MD model[4] was designed to simulate technology adoption and impacts of climate change or changes in other external drivers within a population of heterogeneous farms. The TOA-MD framework is applied to farmers or growers who choose between the production system currently in use, which in this case would be the winter wheat fallow system, and an alternative production system such as annual cropping (winter wheat camelina), with the choice of system based on the distribution of expected economic returns in the regional farm population.

Unlike the *AgBizLogic* platform, TOA-MD is a model of a farm population, not a model of an individual or "representative" farm, and therefore TOA-MD can simulate an adoption rate for a region (i.e., the proportion of farms that would switch to the alternative production system). TOA-MD is based on a statistical description of the population of farms. Accordingly, the fundamental parameters of the model are population statistics – means, variances and correlations of the economic variables in the models and the associated outcome variables of interest. With suitable biophysical and economic data, these statistical parameters can be estimated with observational data for a production system in use, combined with experimental, modeled or expert data for a new system that is not yet in use and thus not observable.

The analysis of technology adoption and its impacts at the regional scale depends critically on how the effects of the new technology interact with bio-physical and economic conditions faced by farm decision makers. A key element in the TOA-MD analysis is reliable estimates of the effect of the new "technology" (i.e., the changes in the farming system that farmers could adopt) on the farming system's productivity and profitability. This information can come from various sources, including from formal crop and livestock simulation models, from experimental or observational data such as the information that can be obtained from a set of growers using *AgBizLogic*, or from expert judgment.

The TOA-MD model can be used for what Antle et al. (2014) describe as "adoption-based tradeoffs". Adoption-based tradeoffs occur when the adoption rate of a technology changes in response to an economic incentive or other factor affecting technology adoption. An important example of an adoption-based tradeoff is the

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[4] See http://tradeoffs.oregonstate.edu.

analysis of GHG mitigation through soil carbon sequestration that occurs when farmers are offered a contract to sequester soil carbon (e.g., see Antle and Stoorvogel 2008). In this type of analysis, the prices faced by the farmers for outputs and inputs are held constant, so the observed changes in behavior are induced by the incentive provided to change management in ways that increase the buildup of the soil carbon. The adoption can also be induced from changes in climate that occurs over a longer time frame.

6 Data Requirements for the TOA-MD Model and How It Links to Farm-Scale Decision Support Tools

The parameters of the TOA-MD model are the means, variances and co-variances (or correlations) of the economic returns to each production system being represented in the analysis, and these statistical parameters of the other outcomes of interest, e.g., environmental outcomes such as the change in soil carbon. These statistics represent the farm population of interest, thus the data to be used are ideally obtained from a statistically representative sample of the population of farms and collected over a long enough period of time (e.g., multiple growing seasons) so that statistical methods can be used to account for seasonal variation and other factors that could affect the observed outcomes. The data can be grouped into the following categories:

(i) prices, outputs and costs of production of each production activity;
(ii) farm characteristics, including farm size, family size, and non-agricultural income; and
(iii) other relevant environmental or social outcomes.

The conventional way to obtain the farm production data is to conduct a survey, such as the surveys done periodically by government agencies (e.g., agricultural census or other statistical surveys such as the Agricultural Resource Management Survey in the United States or the Farm Accountancy Data Network data collected in European Community countries). There are limitations to these kinds of data. One is that these data are often collected periodically, e.g., the U.S. agricultural census is carried out on 5-year intervals, and then only made available to researchers with a substantial delay of a year or more. Another major limitation is that these data often lack sufficient detail, particularly for management decisions such as fertilizer and chemical use, machinery use, and agricultural labor. A third limitation is that these surveys can be extremely expensive both for respondents (e.g., to complete large elaborate questionnaires) and for organizations collecting the data (e.g., to employ enumerators, data entry workers, quality control specialists, etc.).

A tool like *AgBiz Logic* could be utilized to provide higher quality, more timely data at lower cost. As portrayed in Fig. 1, a data system that linked farm management software to a confidential database could provide near real-time data on management decisions, and do so for a statistically representative "panel" of farm decision makers over time. Moreover, the level of detailed management data utilized by *AgBiz Logic* would provide the needed level of detail for implementation of analysis using a tool such as TOA-MD. Also, users of *AgBiz Logic* would have every incentive to enter accurate information because they would be using this information to make their actual management decisions. Finally, a tool like *AgBiz Logic* provides a user-friendly, efficient way for farmers to enter data, thus substantially reducing the cost of data collection.

Several considerations need to be incorporated to facilitate a linkage between *AgBiz Logic* and the TOA-MD framework. First, a statistically representative group of farms would need to be identified who would agree to use *AgBiz Logic* and allow their data to be used in a landscape scale analysis. This would involve a sampling process similar to identifying a sample of farms for a farm-level economic survey. Second, software would need to be designed to transmit and assemble the individual farm data into a database that could subsequently be used to estimate TOA-MD parameters while maintaining confidentiality of individual producers. Note that data would need to be collected over multiple growing seasons in most cases to account for crop rotations and other dynamic aspects of the farming system. Farm household characteristic data could be collected as a part of *AgBiz Logic*, or could be collected using a separate survey instrument. Environmental and social outcome data collection would need to be tailored to the specific type of variable. For example, measurement of soil organic matter could require infield soil sampling and laboratory analysis, possibly combined with modeling, or the use of specialized sensors.

In addition it is important to project from current biophysical and socioeconomic conditions into plausible future conditions. This is currently being done on a global scale using new scenario concepts called "Representative Concentration Pathways" and "Shared Socio-Economic Pathways." To translate these future pathways into ones with more detail needed for agricultural assessments, "Representative Agricultural Pathways" are being developed (Valdivia et al. 2015). The data acquired through tools such as *AgBiz Logic* can be combined with these future projections to implement regional integrated assessments using the new methods developed by the Agricultural Model Inter-comparison and Improvement Project (Antle et al. 2015).

7 Conclusions

The use of a decision support tools such as *AgBiz Logic* can provide farmers better information on the relative impacts of adapting to a change as reflected in changes in future climate conditions, changes in future policies, prices, and costs or changes in terms of lease arrangements. It can also be used by researchers to understand how decisions about new programs, management options, technologies and varieties may impact a producer's net returns and ultimately his/her choices with respect to adoption of alternative management practices or cropping systems. By

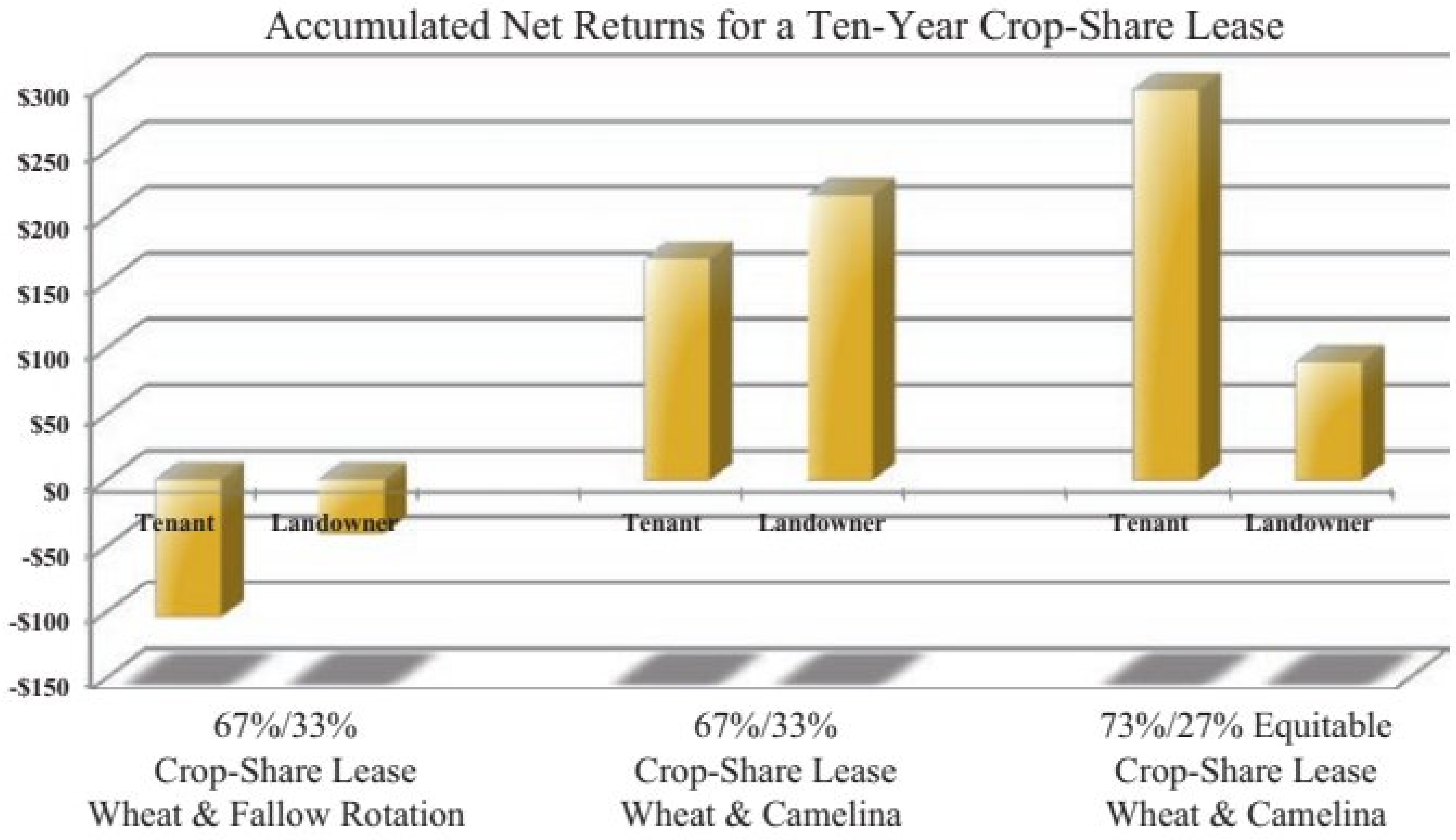


Fig. 4 *AgBizLease*: results when crop-share leases for a wheat and fallow rotation change to an annual cropping system

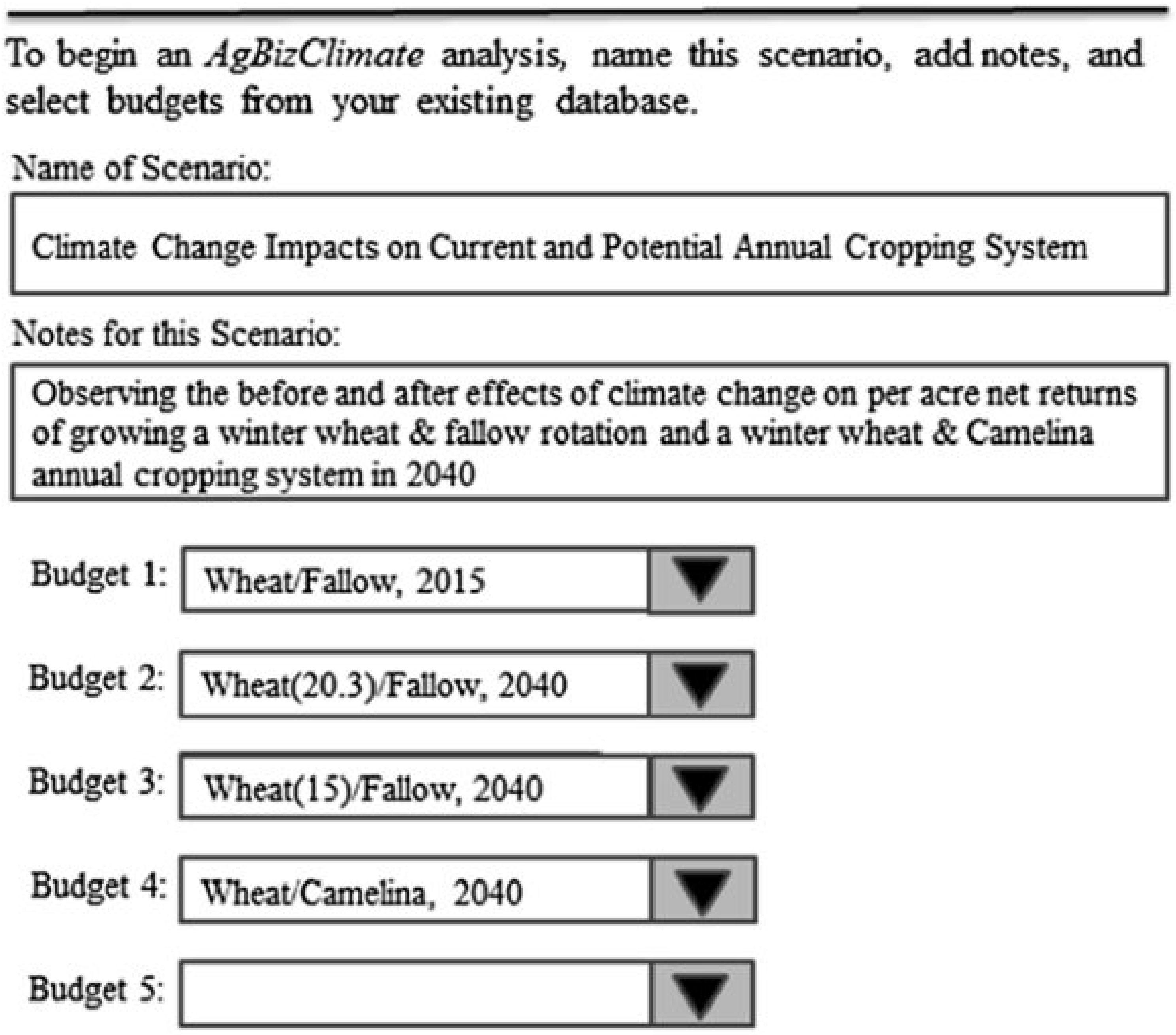
incorporating both climate change and environmental outcomes, these decision tools can be used to evaluate climate smart options at the farm-scale.

The examples in this paper illustrate how an integrative decision support tool that is properly fine-tuned for the specific applications can better inform growers and land owners of how changes in climate will impact their operations and their environmental outcomes. *AgBizClimate* was used to show the impacts of climate change to wheat production. *AgBizProfit* was used to show adaptation strategies to an annual cropping system. *AgBizFinance* can be used to show the feasibility of purchasing additional equipment to farm the annual cropping system. *AgBizLease* showed how changing to an annual cropping system also changes the sharing of the crop, and *AgBizEnvironment* showed the tradeoffs of economic returns to environmental impacts (Fig. 4).

A software tool like *AgBiz Logic* could also be utilized to provide higher quality, more timely data for landscape-scale and regional technology assessment. As portrayed in Fig. 1, a data system that linked farm management software to a confidential database could provide near real-time data on management decisions, and do so for a statistically representative "panel" of farm decision makers over time. Moreover, the level of detailed management data utilized by *AgBiz Logic* would provide the needed level of detail for implementation of analyses using a tool such as TOA-MD. Users of *AgBiz Logic* would have every incentive to enter accurate information because they would be using this information to make changes to future management decisions. Finally, a tool like *AgBiz Logic* provides a user-friendly efficient way for farmers to enter data, thus substantially reducing the cost of data collection.

Acknowledgements This material is based upon work supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award numbers 2011-68002-30191, 2014-51181-22384 and 2012-38420-30208 (Regional Approaches to Climate Change - Pacific Northwest Agriculture; Developing a Sustainable Biofuels System in the PNW: Economic, Policy and Commercialization Analysis; National Needs Graduate and Postgraduate Fellowship Grants Program (NNF) - Graduate Education in the Economics of Mitigating and Adapting to Climate Change:Evaluating Tradeoffs, Resiliency and Uncertainty using an Interdisciplinary Platform), The Northwest Climate Hub, the Agricultural Model Intercomparison and Improvement Project (AgMIP), and Oregon Agricultural Experiment Station.

Appendix A: How *AgBiz Logic* Works and Its Web-Based Presence



To begin an *AgBizClimate* analysis, name this scenario, add notes, and select budgets from your existing database.

Name of Scenario:

Climate Change Impacts on Current and Potential Annual Cropping System

Notes for this Scenario:

Observing the before and after effects of climate change on per acre net returns of growing a winter wheat & fallow rotation and a winter wheat & Camelina annual cropping system in 2040

Budget 1: Wheat/Fallow, 2015

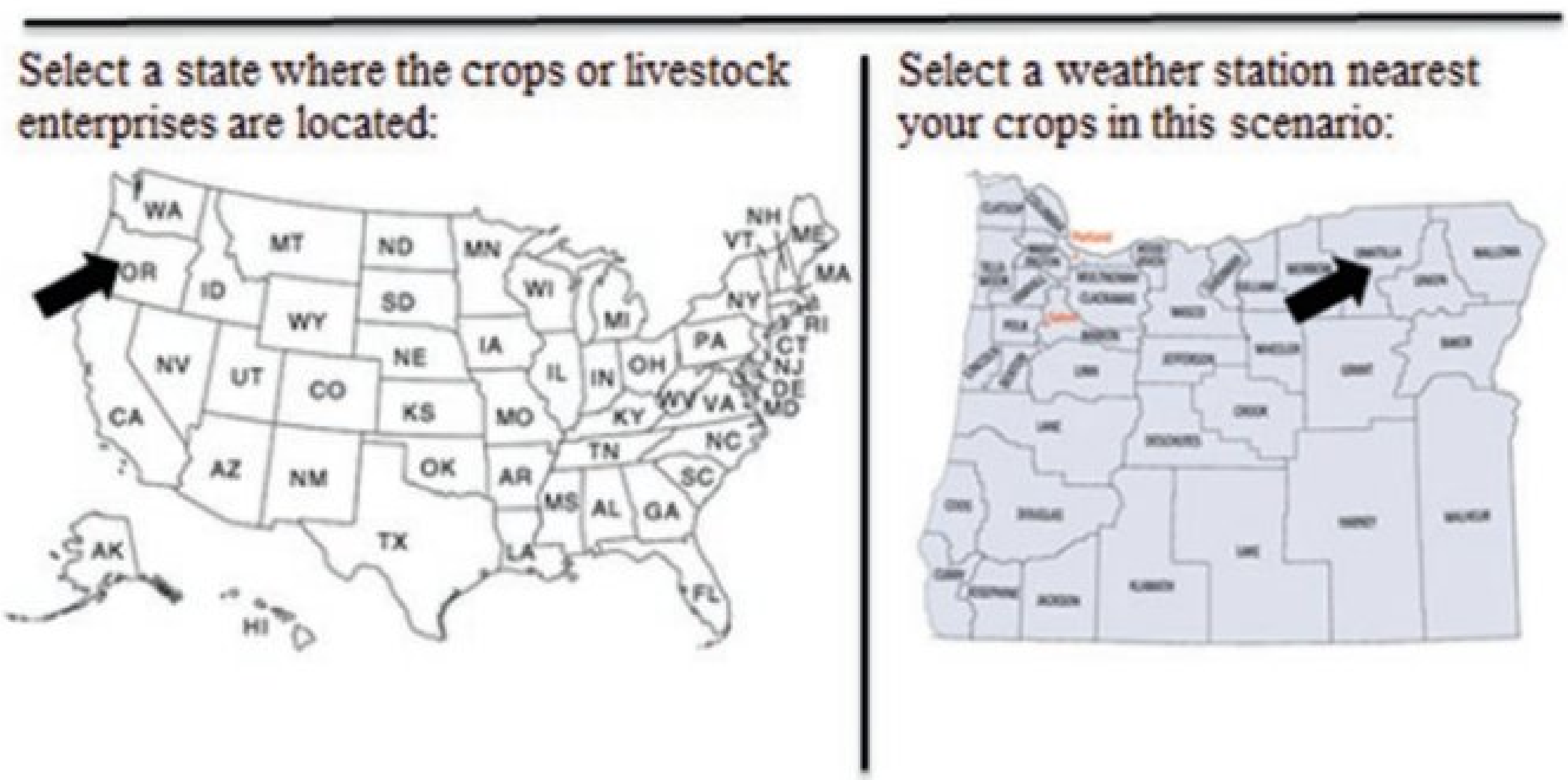
Budget 2: Wheat(20.3)/Fallow, 2040

Budget 3: Wheat(15)/Fallow, 2040

Budget 4: Wheat/Camelina, 2040

Budget 5:

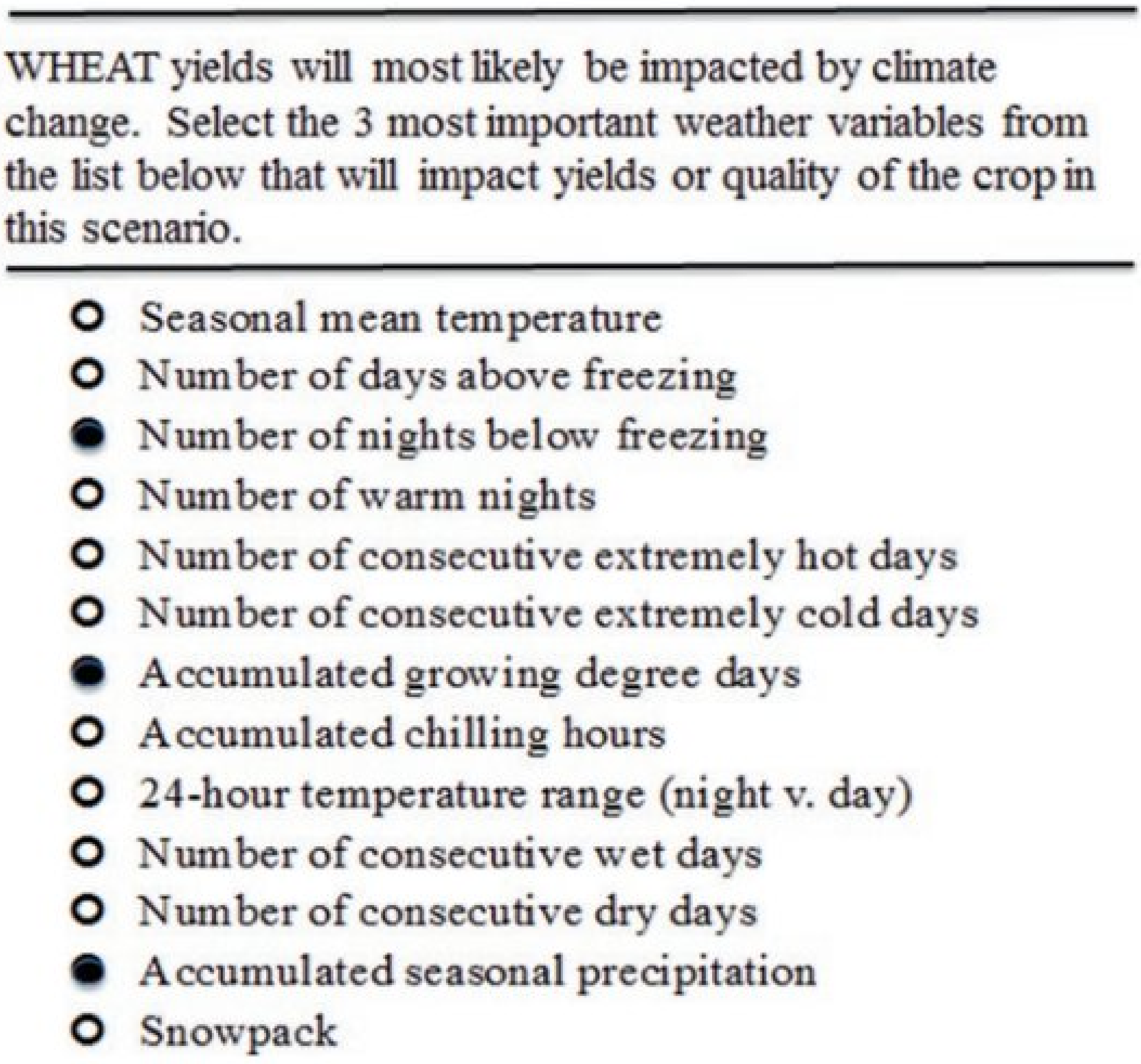
Fig. 5 Naming a scenario, inserting notes for a scenario and selectin *ABL* budgets



Select a state where the crops or livestock enterprises are located:

Select a weather station nearest your crops in this scenario:

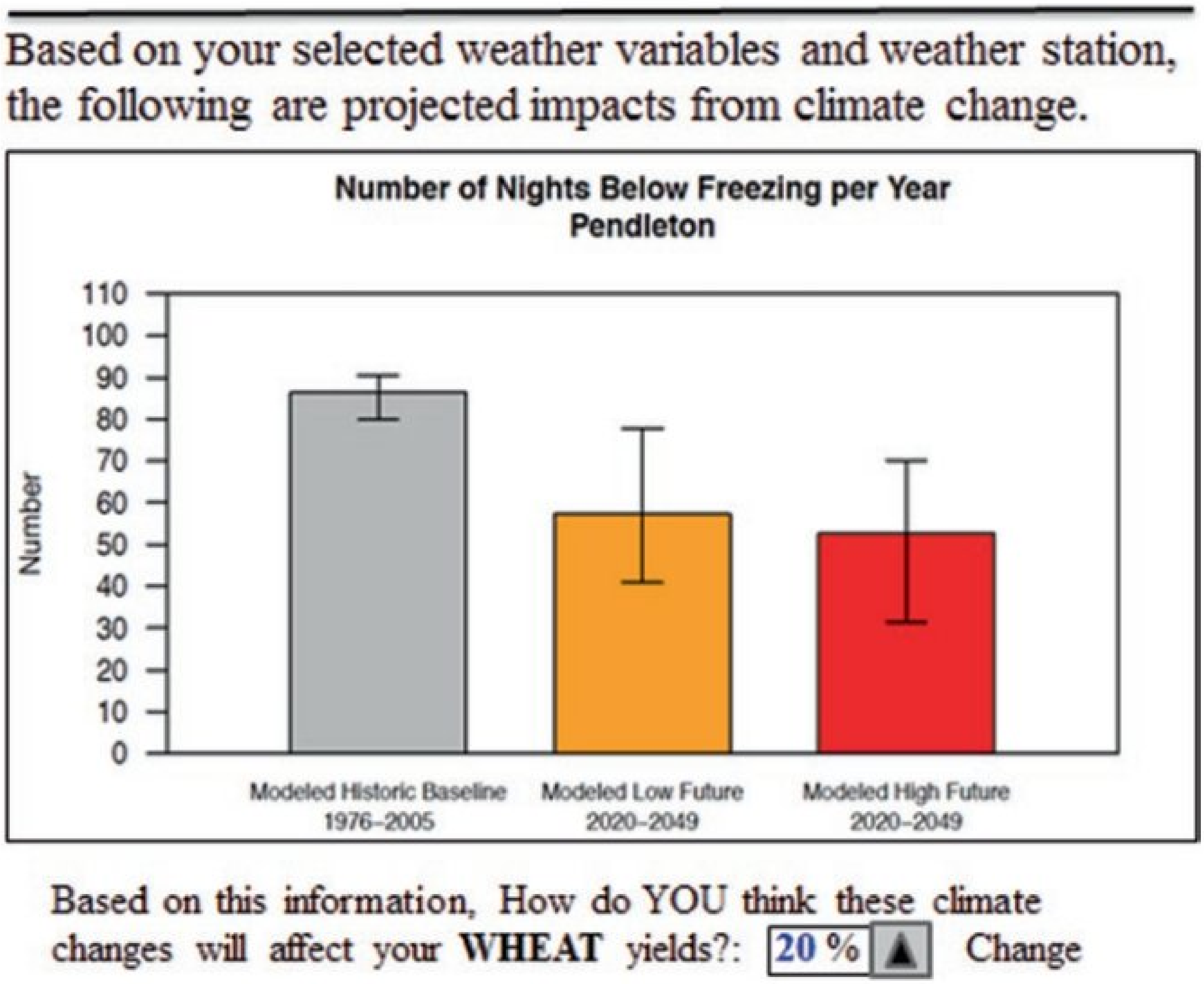
Fig. 6 Selecting Oregon and Umatilla county as the state and county with the closer weather station to crops grown



WHEAT yields will most likely be impacted by climate change. Select the 3 most important weather variables from the list below that will impact yields or quality of the crop in this scenario.

○ Seasonal mean temperature
○ Number of days above freezing
● Number of nights below freezing
○ Number of warm nights
○ Number of consecutive extremely hot days
○ Number of consecutive extremely cold days
● Accumulated growing degree days
○ Accumulated chilling hours
○ 24-hour temperature range (night v. day)
○ Number of consecutive wet days
○ Number of consecutive dry days
● Accumulated seasonal precipitation
○ Snowpack

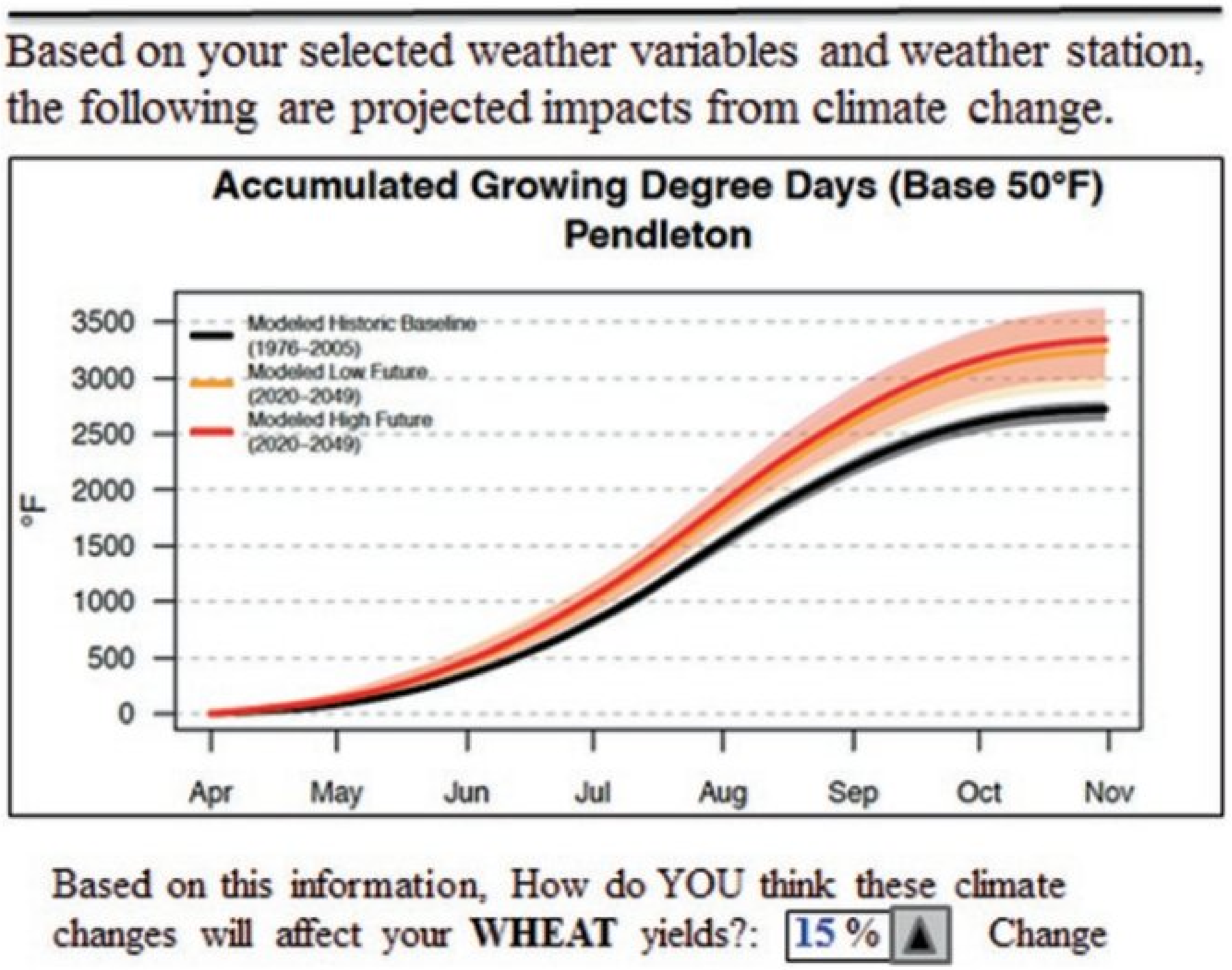
Fig. 7 Weather variables that will likely impact yields or quality of products for crop and livestock enterprises



Based on your selected weather variables and weather station, the following are projected impacts from climate change.

Based on this information, How do YOU think these climate changes will affect your **WHEAT** yields?: 20 % ▲ Change

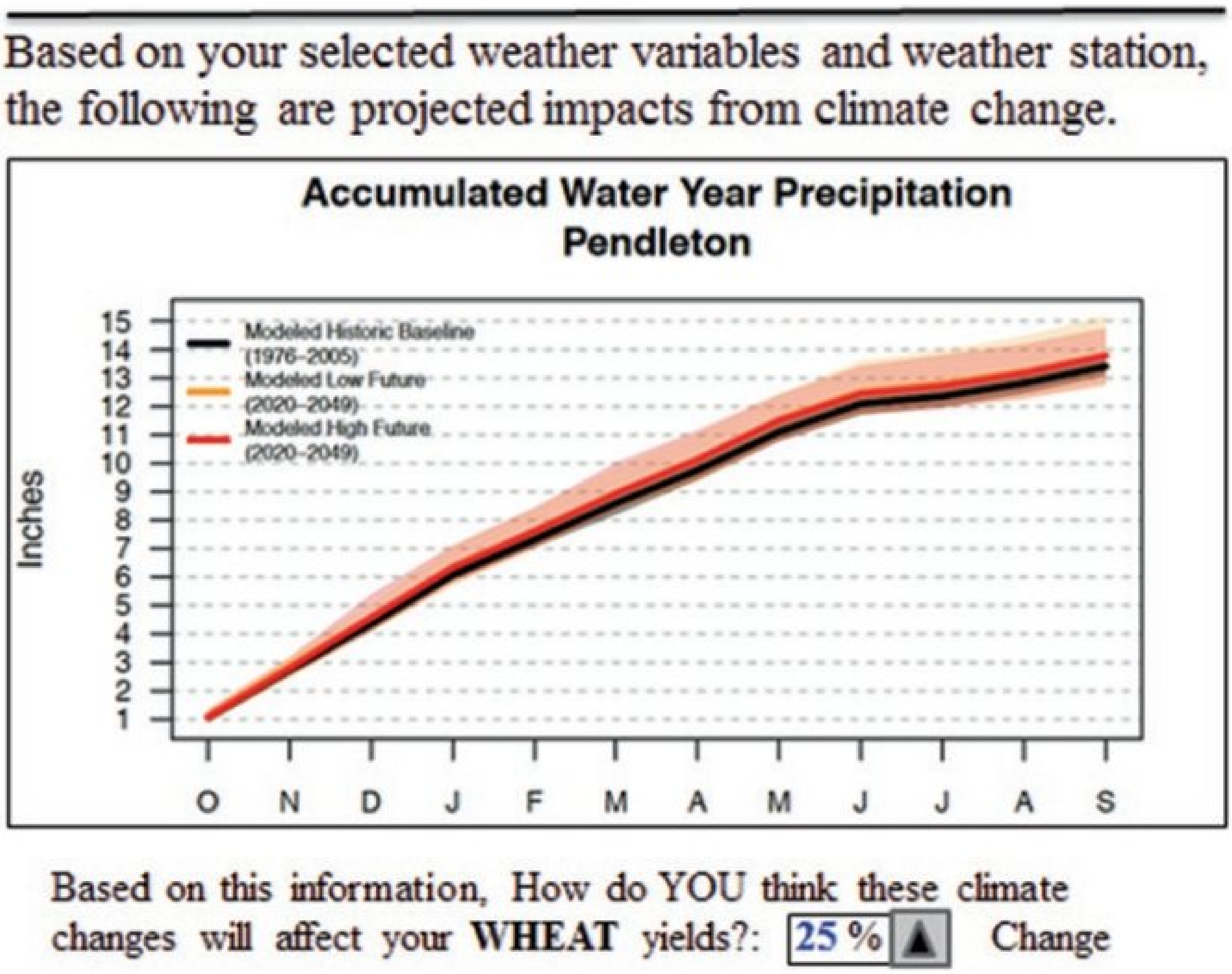
Fig. 8 Weather variables that will likely impact yields or quality of products for crop and livestock enterprises



Based on your selected weather variables and weather station, the following are projected impacts from climate change.

Based on this information, How do YOU think these climate changes will affect your **WHEAT** yields?: 15 % ▲ Change

Fig. 9 Weather variables that will likely impact yields or quality of products for crop livestock enterprises

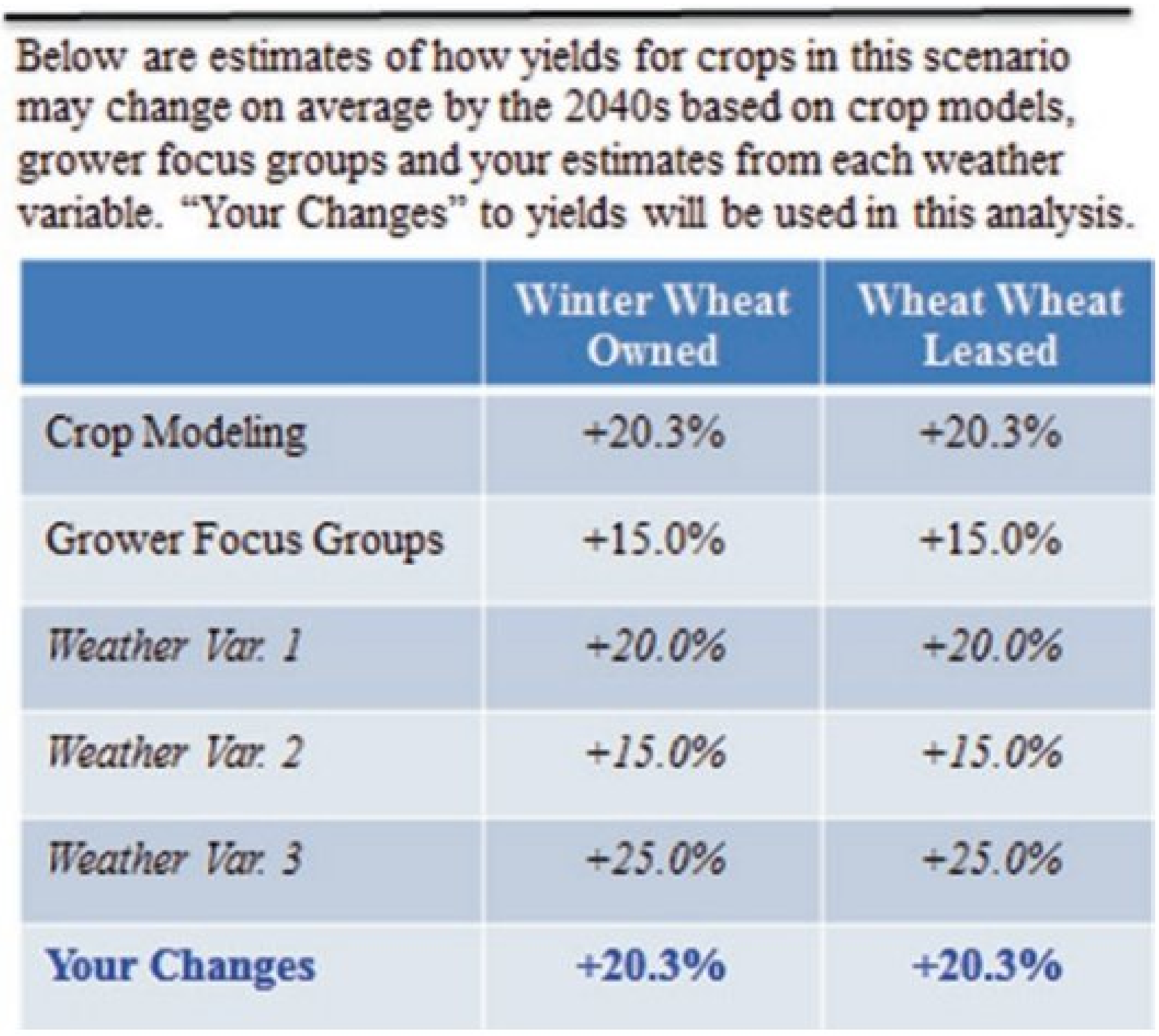


Based on your selected weather variables and weather station, the following are projected impacts from climate change.

Accumulated Water Year Precipitation
Pendleton

Based on this information, How do YOU think these climate changes will affect your **WHEAT** yields?: 25 % ▲ Change

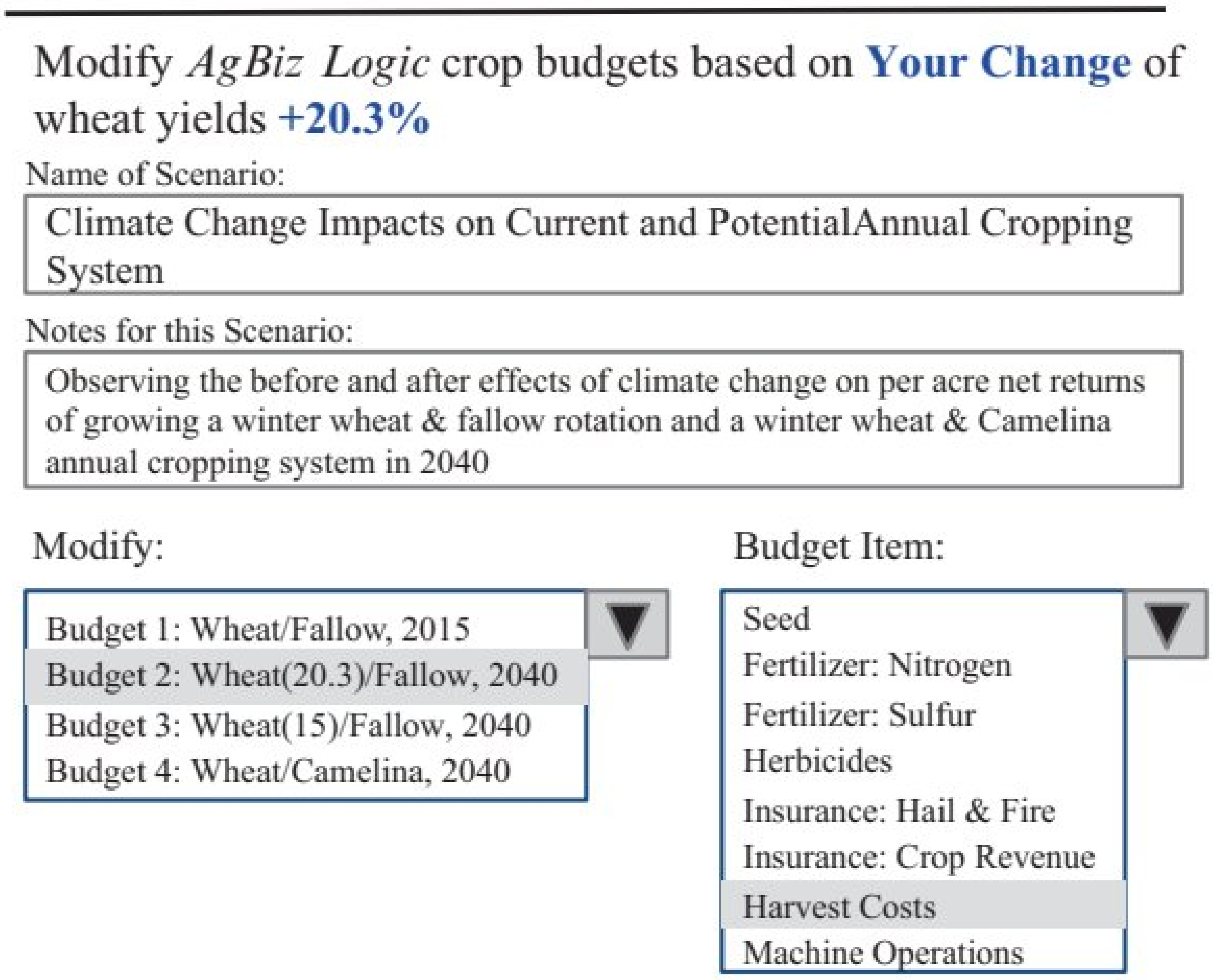
Fig. 10 Weather variables that will likely impact yields or quality of products for crop and livestock enterprises



Below are estimates of how yields for crops in this scenario may change on average by the 2040s based on crop models, grower focus groups and your estimates from each weather variable. "Your Changes" to yields will be used in this analysis.

	Winter Wheat Owned	Wheat Wheat Leased
Crop Modeling	+20.3%	+20.3%
Grower Focus Groups	+15.0%	+15.0%
Weather Var. 1	*+20.0%*	*+20.0%*
Weather Var. 2	*+15.0%*	*+15.0%*
Weather Var. 3	*+25.0%*	*+25.0%*
Your Changes	**+20.3%**	**+20.3%**

Fig. 11 Weather variables that will likely impact yields or quality of products for crop and livestock enterprises



Modify *AgBiz Logic* crop budgets based on **Your Change** of wheat yields **+20.3%**

Name of Scenario:

Climate Change Impacts on Current and PotentialAnnual Cropping System

Notes for this Scenario:

Observing the before and after effects of climate change on per acre net returns of growing a winter wheat & fallow rotation and a winter wheat & Camelina annual cropping system in 2040

Modify:

Budget 1: Wheat/Fallow, 2015
Budget 2: Wheat(20.3)/Fallow, 2040
Budget 3: Wheat(15)/Fallow, 2040
Budget 4: Wheat/Camelina, 2040

Budget Item:

Seed
Fertilizer: Nitrogen
Fertilizer: Sulfur
Herbicides
Insurance: Hail & Fire
Insurance: Crop Revenue
Harvest Costs
Machine Operations

Fig. 12 Modifying 2015 crop budgets for 2040 production

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Part III

Case Studies: Policy Response to Improving Adaptation and Adaptive Capacity

Can Insurance Help Manage Climate Risk and Food Insecurity? Evidence from the Pastoral Regions of East Africa

Michael R. Carter, Sarah A. Janzen, and Quentin Stoeffler

Abstract Can insurance cost-effectively mitigate the increasingly deleterious impacts of climate risk on poverty and food insecurity? The theory reviewed in this chapter suggests an affirmative answer if well-designed insurance contracts can be implemented and priced at a reasonable level despite the uncertainties that attend climate change. Evidence from the IBLI index insurance project in the pastoral regions in East Africa suggest that these practical difficulties can be overcome and that insurance can have the impacts that underlay the positive theoretical evaluation. At the same time, continuing analysis of the IBLI experience suggests that much remains to be done if quality index insurance contracts are to be scaled up and sustained. We conclude that insurance is not an easy, off-the-shelf solution to the problem of climate risk and food insecurity. Creativity in the technical and institutional design of contracts is still required, as are efforts to forge the more effective public-private partnerships needed to price insurance at levels that will allow insurance to fulfill its potential as part of an integrated approach to social protection and food security in an era of climate change.

There is ample evidence that climate shocks create and sustain poverty and food insecurity in rural regions of the developing world. There is also ample evidence that climate change is increasing the frequency and severity of climate shocks.

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Together these pieces of evidence in turn provoke the question: Can insurance cost-effectively mitigate the increasingly deleterious impacts of climate risk on poverty and food insecurity?

Two inter-related claims suggest an affirmative answer to this question:

1. After a shock is realized (*ex post*), insurance payments should help families maintain their economic assets (physical and human) and their long-term economic viability. In simpler terms, insurance should help families avoid a (potentially inter-generational) poverty trap.
2. Because it increases *ex post* security, insurance should also have an *ex ante* effect through increasing the expected level and certainty of returns to investment. This *ex ante* 'risk reduction dividend' should allow more families to escape poverty and food insecurity.

Taken together these two arguments suggest that insurance can be a cost-effective instrument to address food insecurity in the face of climate change. As opposed to a policy that simply treats the casualties of climate shocks with, say, food aid transfers, an integrated policy that includes an insurance element may reduce the total required social protection expenditures by addressing the causes, not just the symptoms, of food insecurity. Such an integrated policy cost effective if it allows more more households to maintain and achieve economic viability so that they can take care of their own needs.

The goal of this paper is to interrogate these claims and reflect on obstacles that may limit the efficacy of insurance as an instrument to manage climate risk. To do this, we proceed in several stages. First, in Sect. 1, we use recent theoretical modeling to explore the relative cost effectiveness of insurance as a device to manage the food insecurity induced by climate change. This modeling exercise assumes that:

- A contract can be designed that offers quality protection to inured individuals (*i.e*., insurance payouts correlate well with household losses) and avoids the problems of moral hazard and adverse selection that can undercut the commercial sustainability of insurance;
- Households understand and trust the insurance and make purchase decisions based on a standard model of economic rationality; and,
- Insurance is commercially priced at the same proportionate levels observed in US crop insurance markets (128% of the actuarially fair price).

Under these assumptions, we find that while the logic outlined above holds and that integrated social protection, which employs an insurance element, can be a part of smart public policy, especially in the face or climate change. We do find that the relative benefits of an integrated social protection begins to weaken as climate change worsens and insurance itself becomes increasingly expensive.

While the theoretical case for insurance-augmented integrated social protection is clear, can it work in practice–that is, can the three conditions assumed by the theoretical analysis be met in practice? To provide insight into this question, we then turn to a specific case study–livestock insurance in the pastoral regions of northern Kenya and southern Ethiopia–to consider the practical barriers that limit the feasibility of insurance as a mechanism to help manage increasing climate risk. Section 2 first shows how satellite-based index insurance has been developed to overcome the most pressing barriers to using insurance for managing risk among low wealth, spatially disperse rural households. Empirical impact evaluations of the Kenya and Ethiopia programs generally support the *ex post* and the *ex ante* insurance impacts outlined above.

While this evidence from the pastoral regions of East Africa is promising, even in this area the expansion and sustainability of the insurance contract remains fundamentally challenged by a number of issues, including contract quality, demand and pricing. After putting forward a framework for thinking about the factors that limit the quality of index insurance, Sect. 3 reviews new evidence on the quality of the East African insurance contracts and considers possible future steps for improving their quality. Section 4 then summarizes our findings concerning whether insurance can in practice play a useful role in managing climate risk and food insecurity.

1 The Logic of Insurance as a Device to Mitigate the Impacts of Climate Change on Food Insecurity

In an earlier paper, Ikegami et al. (forthcoming) identify what might be termed a social protection paradox. They compare two social protection scenarios.

In the first scenario, which mimics the targeting of conventional social protection programs, a fixed government budget is used to bring all poor households up to the poverty line, or as close to the poverty line as the budget permits. This conventional scenario is purely progressive in the sense that larger transfers go to poorer households. In contrast, a second scenario considered by these authors–which they term a triage policy–is not purely progressive. Instead, the fixed government budget is first allocated to the vulnerable non-poor to keep them from falling below a critical asset threshold, thereby stemming their descent into long-term poverty. These transfers to the vulnerable non-poor are contingent transfers that are only made if an unfavorable shock occurs and threatens the vulnerable with economic collapse. After the contingent needs of the vulnerable are met through these transfers, any remaining budget is then allocated progressively to the poor, again moving all poor households as close to the poverty line as possible.

To compare the effectiveness of these two social protection schemes in managing poverty, Ikegami et al. forthcoming employ a dynamic simulation model, similar to the model developed below. In their model, shocks are realized and individuals optimally choose current consumption and the amount of assets to carry forward to generate future income. Based on household asset and consumption levels, an omniscient government then allocates its budget in accordance with its social protection policy regime. Results are derived for both the standard and the triage regimes. Ikegami et al. forthcoming find that while the extent and depth of poverty are lower in the short term under the conventional needs-based approach, those results are reversed in the medium and long terms. In other words, the poor are paradoxically better off in the medium term despite less social assistance being allocated to them and more social assistance targeted to vulnerable but non-poor households.

The reason behind this paradoxical reversal is that when aid is concentrated solely on the neediest and not the vulnerable non-poor, then the number of aid-eligible poor people slowly swells over time, diluting the resources available for each poor individual. In contrast, transfers to the vulnerable both prevent them from falling below the threshold (and becoming poor) and allow them to successfully build up assets and eventually move away from the threshold and the vulnerability that it implies. Over time, under the triage policy an increasingly large share of the social protection resources become allocable to the poor whose ranks have not grown. We might anticipate that this social protection paradox revealed by Ikegami et al. forthcoming will only become larger in the face of climate change.

Building on this work, Janzen et al. (2015) ask whether or not the contingent transfers envisioned in the Ikegami et al. forthcoming triage policy can be implemented via an insurance contract. Implementing these transfers as an insurance contract would have two advantages. First, it may be able to rely on self-selection, obviating the need for the government to monitor needs and issue payments.[1] Second, having an insurance contract available could also offer a benefit to non-vulnerable households, including poorer households. To the extent that these latter households pay a portion of the insurance cost, they would be provisioning a portion of their own social protection.

While this logic may seem compelling, prior theoretical studies have suggested that insurance could actually increase the likelihood of collapse by vulnerable house- holds.[2] However, these other studies ask what happens if vulnerable households are forced to purchase insurance. In contrast to these other theoretical analyses, Janzen et al. (2015) allow individuals to optimally decide and how much insurance to purchase. This difference is subtle but important as Janzen et al. (2015) find that the most vulnerable households optimally purchase only minimal insurance unless it is subsidized. These same households quickly switch to full insurance as soon as they successfully accumulate a small amount of additional productive assets.

Using their model, Janzen et al. (2015) go on to show that the discounted present value of a hybrid policy (which subsidizes insurance and makes cash transfers to close the poverty gap for all poor households) is less than the cost of a conventional transfer program that simply closes the poverty gap for all poor households. After briefly reviewing the Janzen et al. (2015) model, this section then extends their analysis to consider the relative cost effectiveness of an insurance-based hybrid social protection scheme in the face of different climate change scenarios.

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[1] The Ikegami et al. (forthcoming) policy assumes an omniscient government that can observe shocks and issue precisely the transfer required to protect vulnerable households from slipping into a poverty trap.

[2] See Chantarat et al. (2010) and Kovacevic and Pflug (2011).

1.1 Theoretical Model of the Ex Post *and* Ex Ante *Impacts of Insurance on Poverty*

Janzen et al. (2015) analyze the following dynamic model of a house- hold optimally allocating its resources across consumption, accumulation of assets that generate income through a risky production process, and purchase of an insurance contract that protects the household against asset losses:

$$\max_{c_t, 0 \le I_t \le A_t} \quad \mathrm{E}_{\theta,\varepsilon} \sum_{t=0}^{\infty} u\left(c_t\right)$$

$$\text{subject to:} \qquad (1)$$

$$\begin{aligned}
&c_t + pI_t \le A_t + f\left(A_t\right) \\
&f\left(A_t\right) = \max[F^H\left(A_t\right), F^L\left(A_t\right) \\
&A_{t+1} = \left(A_t + f\left(A_t\right) - c_t\right)\left(1 - \theta_{t-1} - \varepsilon_{t+1}\right) + (\delta(\theta_{t+1}) - p)I_t \\
&\delta\left(\theta_{t+1}\right) = \max((\theta_{t+1} - s), 0) \\
&A_t \ge 0
\end{aligned}$$

The first constraint restricts current spending (consumption plus insurance purchases) to cash on hand (current assets plus income). As shown in the second constraint, the model assumes that assets are productive ($f(A_t)$) and that the households have access to both a high and low production technology, $F^H(A_t)$ and $F^L(A_t)$, respectively. Fixed costs associated with the high technology make it the preferred technology only for households above a minimal asset threshold. As has been demonstrated elsewhere, this non-convexity in the production function can lead to multiple equilibria and a poverty trap. Households with assets above a critical threshold level will strive to reach to a higher, non-poor equilibrium level of asset holdings and consumption. Those who begin with assets below that level (or whom shocks push below that level), will settle down at a lower level of asset holding typified by lower consumption and a poor standard of living.

Assets are subject to stochastic shocks (or depreciation). The random variable, $\theta_{t+1} \ge 0$ is a covariant shock and $\varepsilon_{t+1} \ge 0$ is an idiosyncratic shock.[3] Both shocks are exogenous and realized after decision-making in the current period (t), but before decision-making in the next period ($t + 1$) occurs. While these risks affect all households, they play an especially important role for households in the vicinity of the critical asset threshold. Because a shock can send households in this vicinity into a downward spiral to the low level equilibrium, we will refer to these households as the 'vulnerable.'

A unit of insurance can be purchased at a price p and the insurance payout is based on the realized covariant shock according to the linear indemnity schedule:

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[3] The distinction between these two stochastic elements will become important later when we consider feasible insurance mechanisms in the next section.

$$\delta(\theta_t) = \max((\theta_t) - s), 0), \tag{2}$$

where *s* is the contractually determined depreciation rate above which insurance indemnity payments begin. Note that this insurance mechanism is akin to an index insurance mechanism as it only pays based on common or covariant shocks and does not provide protection against idiosyncratic shocks.

The third constraint is the equation of motion for asset dynamics: period *t* cash on hand that is not consumed by the household or destroyed by nature is carried forward as assets in period $t + 1$. Finally, the non-negativity restriction on assets reflects the model's assumption that households cannot borrow. This assumption implies that consumption cannot be greater than current production and assets, but it does not preclude saving for the future.

Figure 1 presents some of the key results from the Janzen et al. (2015) analysis of this dynamic model. The horizontal axis represents time periods ("years") in the dynamic model. The vertical axis measures the headcount poverty rate for a stylized economy under three scenarios: An autarky scenario in which no insurance contracts are made available; A market-based insurance scenario in which insurance costs 120% of its actuarially fair price; and, A targeted insurance subsidy scenario in which the government pays half of the commercial insurance premium for all households that hold assets less than the level required to generate an average income equal to 150% of the poverty line. In all cases, the simulation assumes that households behave optimally based on the price of insurance and the dynamic choice problem displayed above.

As can be seen from Fig. 1, under the autarchy scenario with no insurance, headcount poverty steadily increases over time by about 25%, rising from 40% to 50% of the population. Under the targeted insurance subsidy scheme, there is an initial uptick in consumption poverty from 40% to 50%. This initial rise reflects the decision of vulnerable or near poor households to consume at levels below the poverty line in order to invest and (or) purchase insurance. However, over the longer-term, when insurance is partially subsidized for less well-off households, consumption poverty eventually falls to about 15% of the population, as opposed to the 50% level that occurs when there is no insurance market. This long-term drop in consumption poverty when insurance is available and subsidized reflects the fact that a significant fraction of the vulnerable ultimately escape the poverty trap. In contrast, without insurance, more of these vulnerable households fail and swell the ranks of the income poor. When an asset insurance market simply exists, but contracts are not subsidized, the impacts on poverty dynamics are qualitatively similar to the impacts of subsidized insurance, but quantitatively, the impacts are roughly two-thirds the magnitude of the impacts of subsidized insurance. This smaller impact occurs because the risk reduction dividend effects are smaller when insurance is more costly.[4]

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[4] Janzen et al. (2015) discuss in detail how the price of insurance changes optimal insurance purchase and asset investment decisions.

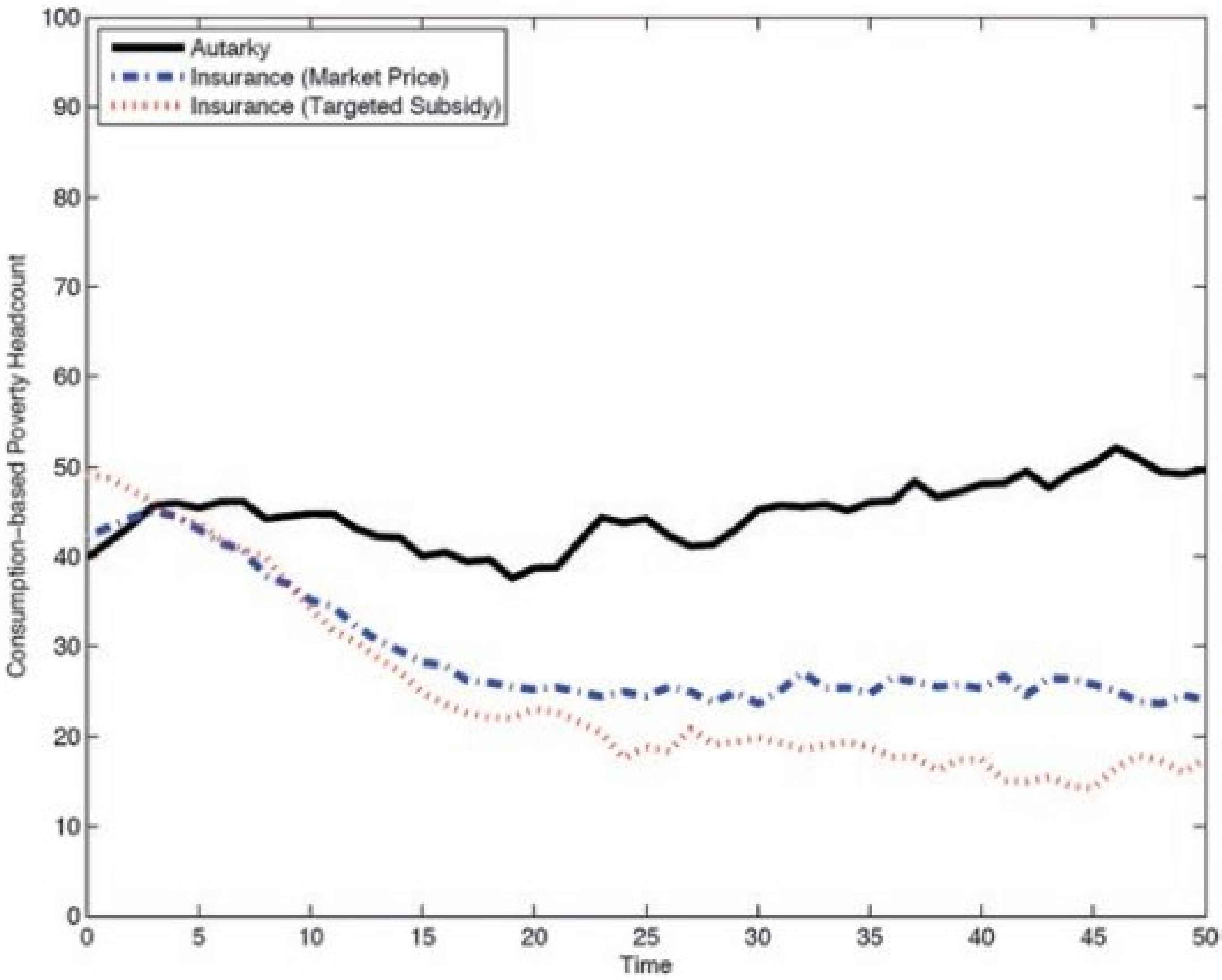

Fig. 1 Consumption poverty headcount (Source: Janzen et al. (2015))

To gauge the cost-effectiveness of insurance subsidies from a public finance perspective, Janzen et al. (2015) sum the cost of all required cash transfer payments and add to that amount the cost of targeted insurance subsidies. Their analysis reveals an intertemporal tradeoff. The cost of transfers cum insurance subsidies is initially quite high, but over time total social protection costs are higher under the scheme that only provides cash transfers. Achieving the lower long-term poverty measures afforded by insurance subsidies costs more money in the short- term, but leads to substantial long term savings. Using a 5% discount rate the net present value of the two public expenditure streams over the 50 year time horizon of the simulation are 16% lower under the targeted subsidy scheme. Note of course that the public expenditures are only a portion of the full cost of social protection under the insurance scheme as individuals are in some sense privately provisioning a portion of the cost of their own "social" protection.

1.2 *Analysis of Climate Change Scenarios*

The analysis reported in Janzen et al. (2015) assumes a baseline risk scenario that is roughly calibrated to the climate conditions of the pastoral regions of East Africa circa the year 2000. In order to explore the effectiveness of the insurance cum social protection scenario explored by Janzen et al. (2015), we took their model and slowly increased the frequency and severity of the covariant shocks. Figure 2a shows the

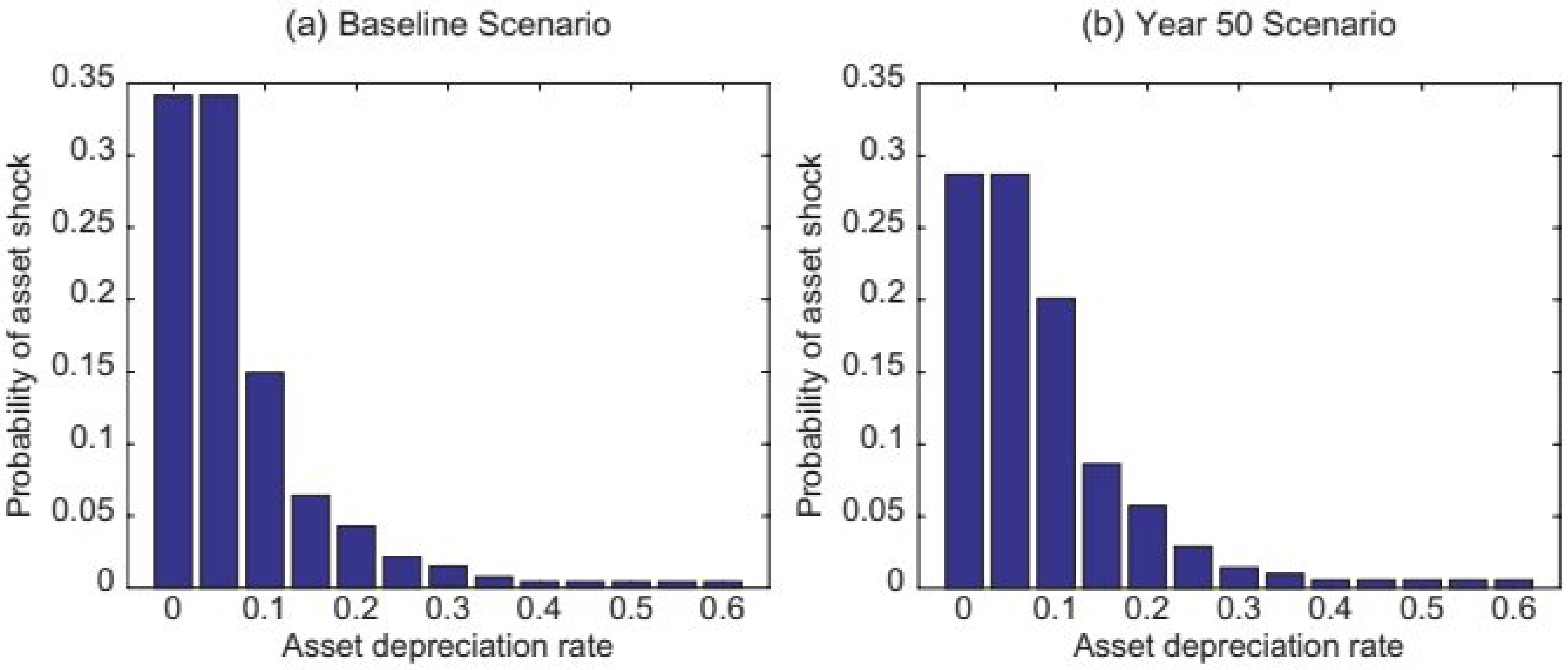

Fig. 2 Climate change scenarios

baseline scenario on which these results are based.[5] Over a 50 year simulation scenario, we then allowed the climate to worsen every decade. Figure 2 shows the distribution of shocks assumed to exist in the final decade of the simulation. The analysis assumes that individuals are fully informed about the less favorable climate and adjust their behavior accordingly. The cost of insurance is also re-priced with every shift in climate, raising its costs, and the cost of the associated targeted insurance subsidies.

Figure 3 explores the costs of using subsidized insurance as part of a social protection package that seeks to eliminate poverty by transferring to every indigent household the amount of money necessary to lift them to a level of consumption achievable at the poverty line. The vertical axis measures the percentage change in government expenditures relative to the the year-zero transfers that would be required to close the poverty gap for all households under the alternative social protection policies. Results are again shown for three policy scenarios (autarkic risk management; unsubsidized insurance; and, subsidized insurance for poor and vulnerable households). For ease of comparison, we also include the social protection cost trajectories for a given policy both with and without climate change.

As can be seen, as climate change kicks in at year 10 of the simulation, the costs of cash transfers needed to close the poverty gap for all poor households begins to skyrocket above the costs absent climate change. Interestingly, even though insurance becomes increasingly expensive, it manages to hold steady the total cost of social protection (insurance and cash transfers) across the first 3 decades of climate change. This result attains in part because during the first decade of the simulation, many households are able to escape vulnerability and accumulate sufficient assets such that they are no longer eligible for insurance subsidies.

However, when the fourth round of climate change kicks in at year 40 of the simulation, the total costs of social protection begin to accelerate. The hybrid social protection continues to be cost-effective public policy, but as risk rises to an ever higher level, even the hybrid policy begins to loose its effectiveness in absolute terms.

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[5] The risk levels at baseline in the simulations that follow are similar, but not directly comparable

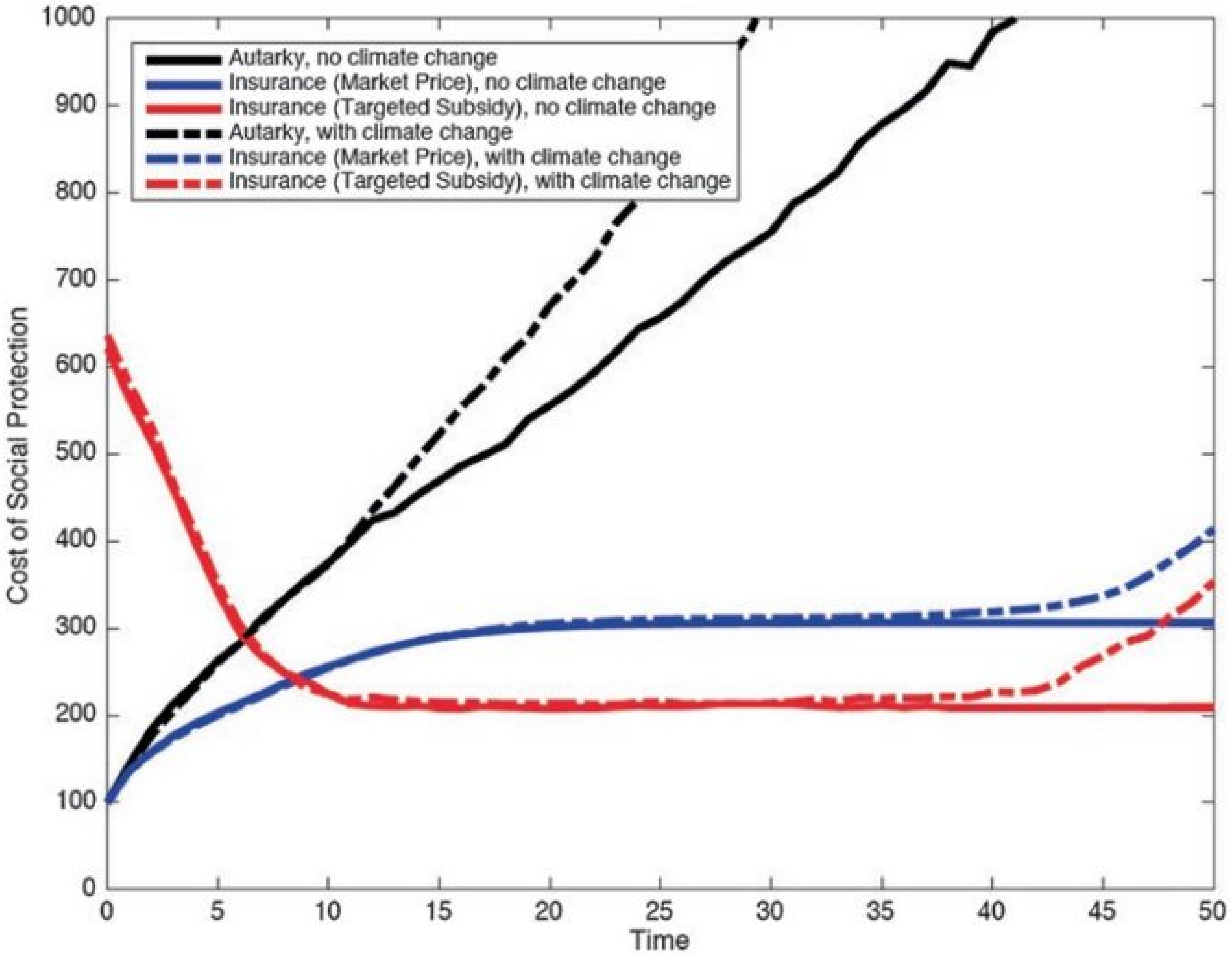

Fig. 3 Cost of social protection

2 Index Insurance as a Solution: Livestock Insurance in the Pastoral Regions of East Africa

Section 1 employed abstract modeling techniques to consider the public finance case for insurance as a mechanism to offset the negative impacts of climate change on poverty and food insecurity. While it is relatively easy to implement an insurance policy in a theoretical model, a key question is whether it is possible to implement an insurance scheme in the real world that offers quality insurance protection, while keeping administrative costs, moral hazard and adverse selection in line.

Conventional agricultural insurance, which requires field visits to verify loss claims by individual households, has a dismal record when applied to small-scale rural house- holds, especially those located in isolated areas. In a study of a conventional insurance program established with heavy subsidies for the small-farm sector in Ecuador, Carter et al. (2014) find that the costs associated with a single loss verification visit may exceed $400. Given that the total annual premium associated with the typical small scale farmer is less than $100, it is easy to see why the business case for individual insurance evaporates. Cutting corners on loss verification is an open invitation to morally hazardous behavior. Moreover, given that it is not cost effective to individually rate the loss probabilities for each and every small-scale farmer, conventional insurance is also subject to problems of adverse selection in which those households most likely to experience a loss are also most likely to buy the insurance. As summarized by Hazell and Valdes (1985) and Hazell (2006), the net result of these problems has been loss ratios well in excess of 100%, implying that the insurance cannot be financially sustained.

Against this backdrop, index insurance appears as a promising, cost-effective solution. Under index insurance, loss verification is not required because payouts are based on an index. For agricultural insurance the index might be yields measured directly or predicted by satellite-based biomass growth indicators for an insurance zone.[6] The index is meant to be highly correlated with, but not identical to, the losses experienced by individual farmers. In principal, index insurance should eliminate problems of high transactions costs, moral hazard and adverse selection. However, its key advantage is also its achilles heel. If the insurance index is only weakly correlated with farmer losses (as Clarke et al. (2012) show in the case of rainfall insurance in India), then index insurance is more similar to a lottery ticket than an insurance contract. Lottery tickets are as likely to pay out when farmers have good crops as when they have bad crops, meaning that lottery ticket 'insurance' is likely to destabilize farmer income by perversely transferring money from bad to good states of the world.

If index insurance is to be part of the solution to helping manage climate risk, then the challenge is clearly to design an insurance index that is sufficiently well correlated with farmer losses such that it offers real *ex post* protection and thereby incentivizes *ex ante* investment such that the risk reduction dividend is gained. The remainder of this section focusses on one of the better researched index insurance projects, the IBLI (index-based livestock insurance) program in the semi-arid pastoral zones of northern Kenya an southern Ethiopia.

2.1 Designing the IBLI Index Insurance Contract

As detailed by Chantarat et al. (2013), the IBLI project began with the notion that satellite measures of vegetative growth, which had been in use for some time as part of famine early warning systems, might provide a reliable measure of forage availability for pastoral households. This measure was then transformed into an

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[6] Because the index is the same for all households in the insurance zone, it does not matter in terms of payout probabilities whether high or loss risk producers select into purchasing the insurance, eliminating the adverse selection problem (assuming that the insurance is priced correctly for each zone). Moreover, as long as the zone is large enough, then moral hazard problems also disappear as no single farmer can influence the index by her actions.

index of predicted livestock mortality losses experienced by pastoral households in drought years.

Figure 4 displays “NDVI” maps for the original IBLI insurance zones in the Marsabit District of Northern Kenya. NDVI (or the Normalized Difference Vegetation Index) measures the intensity of light reflected from the earth’s surface in different spectral bands. NDVI is essentially a ‘greeness’ measure that follows a regular cycle as rains come and forage crops grow. The maps displayed in Fig. 4 are based on a pixel size of 8 km by 8 km–that is, each square of this size receives its own unique NDVI reading on a daily basis as the satellite passes overhead.[7] The plot on the left shows a year with normal conditions, whereas the plot on the right shows a year where drought pressure was severe and livestock losses were high.

While NDVI can clearly distinguish drought from non-drought years, the insurance quality question swings on how well economic losses experienced by pastoralist households can be explained by the NDVI measure. To answer this question, Chantarat et al. (2013) assembled historical data on livestock losses and estimated a non-linear response function that maps NDVI signals into observed livestock mortality losses. Figure 5 gives a sense of the predictive accuracy of this mapping for one of the insurance zones in Marsabit District. Using out-of-sample prediction tests, Chantarat et al. (2013) report that based on the estimated response function and the historical distribution of NDVI, households would have been correctly indemnified 75% of the time when they experienced severe mortality losses (those in excess of 30%). The level of predictive accuracy falls to 60% when losses are 30% or less.

While imperfect, the predictive accuracy of the IBLI mortality was sufficiently high that a pilot project was launched in 2009.[8] While often hampered by implementation problems, the IBLI contract continues to date. Originally rolled out as a randomized controlled trail, the IBLI case study provides an excellent opportunity to learn, not just if index insurance can be implemented, but if it also delivers the expected *ex post* and *ex ante* effects that motivate the use of index insurance as a cost-effective device to help mitigate the costs of climate change. We turn now to consider some of that evidence.

2.2 *Impacts of the IBLI Contract on* Ex Post *Coping and* Ex Ante *Investment*

Severe drought in northern Kenya in 2011 resulted in high rates of livestock mortality in the IBLI pilot zone, with mortality estimates ranging from 25% to 50%. In accordance with the contract, all insured households received indemnity

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[7] The current version of IBLI operates with much smaller grids based on changes in satellites and satellite technology.

[8] More recent work by Barré et al. (2016) proposes specific quality measures and a safe minimum standard for contract quality.

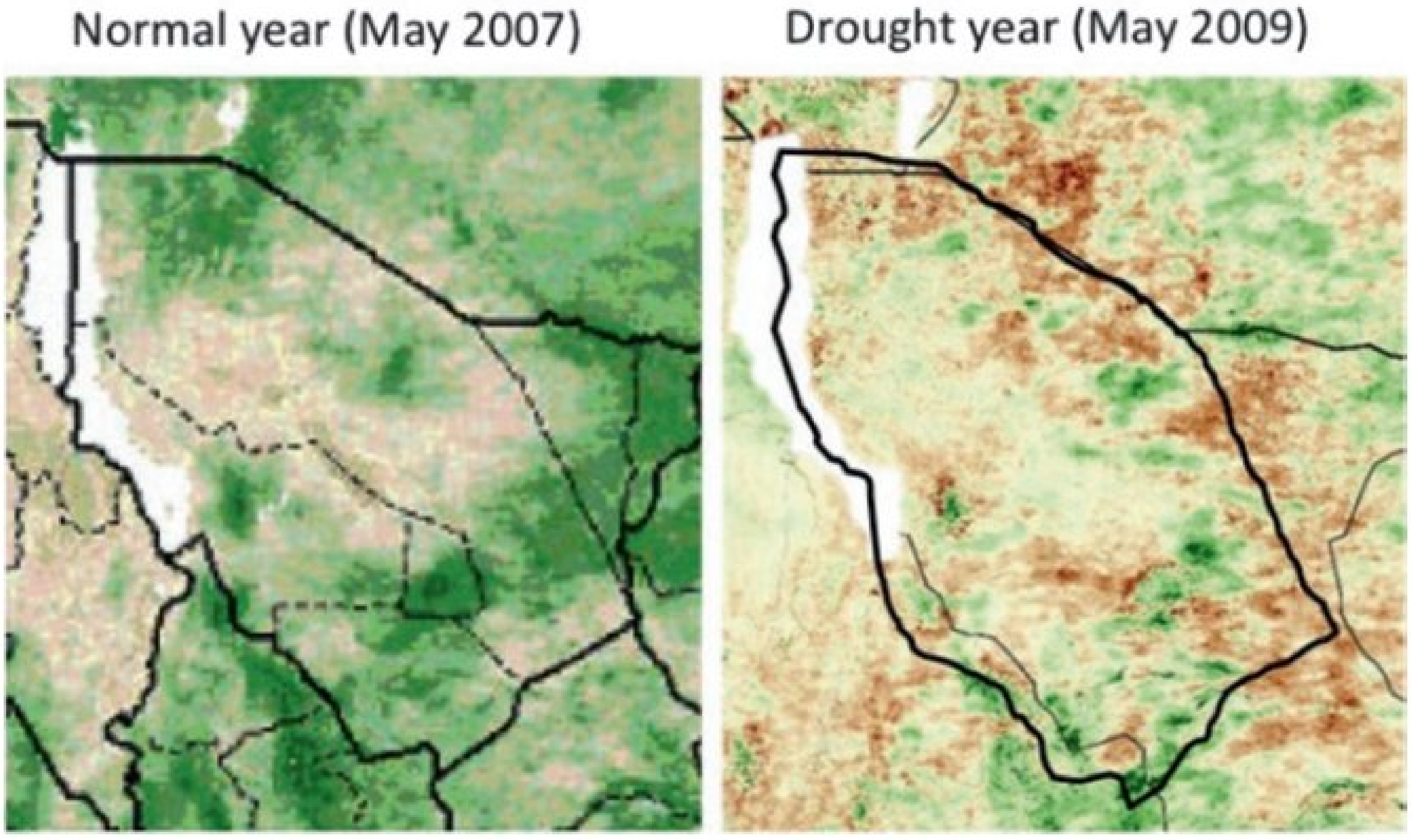

Fig. 4 Satellite-based NDVI measures of forage availability

payments in October 2011. These payments coincided with the round 3 survey of IBLI study households. While the coincidence of the survey and the payments made it impossible to observe the short run impacts of the payments on coping strategies, households were asked what their coping strategies had been the third quarter of 2011 (the period immediately preceding the payouts, but well into the period of drought losses) and what they anticipated their coping strategies would be in the fourth quarter of 2011. Janzen and Carter (2013) use this data to study the impacts of insurance on families' ability to maintain their assets and food security during and after the severe drought. They achieve causal identification of impacts by exploiting randomly distributed inducements for households to actually purchase the insurance.

The first half of Table 1 summarizes the results of the Janzen and Carter (2017) analysis. The table reports the estimated percentage point reduction in the indicated coping strategy caused by insurance. For example, when pooling all households together, insurance causes 25% point reduction in the probability that the household relies on meal reduction to cope with the drought in the immediate post- payout period.

The first column of the table displays the estimated average impacts of insurance. Looking at the post-payout period, we see that on average insured households reduce anticipated reliance on meal reductions by 25% points and anticipated reliance on livestock sales by 36% points. Looking at the quarter 3, immediate pre-payout figures, we see–perhaps surprisingly–that insurance reduced by 20% points households' reliance on meal reduction. This decrease presumably reflects households' anticipation of the impending insurance payments, which allowed them to reduce hoarding of available food and other stocks.

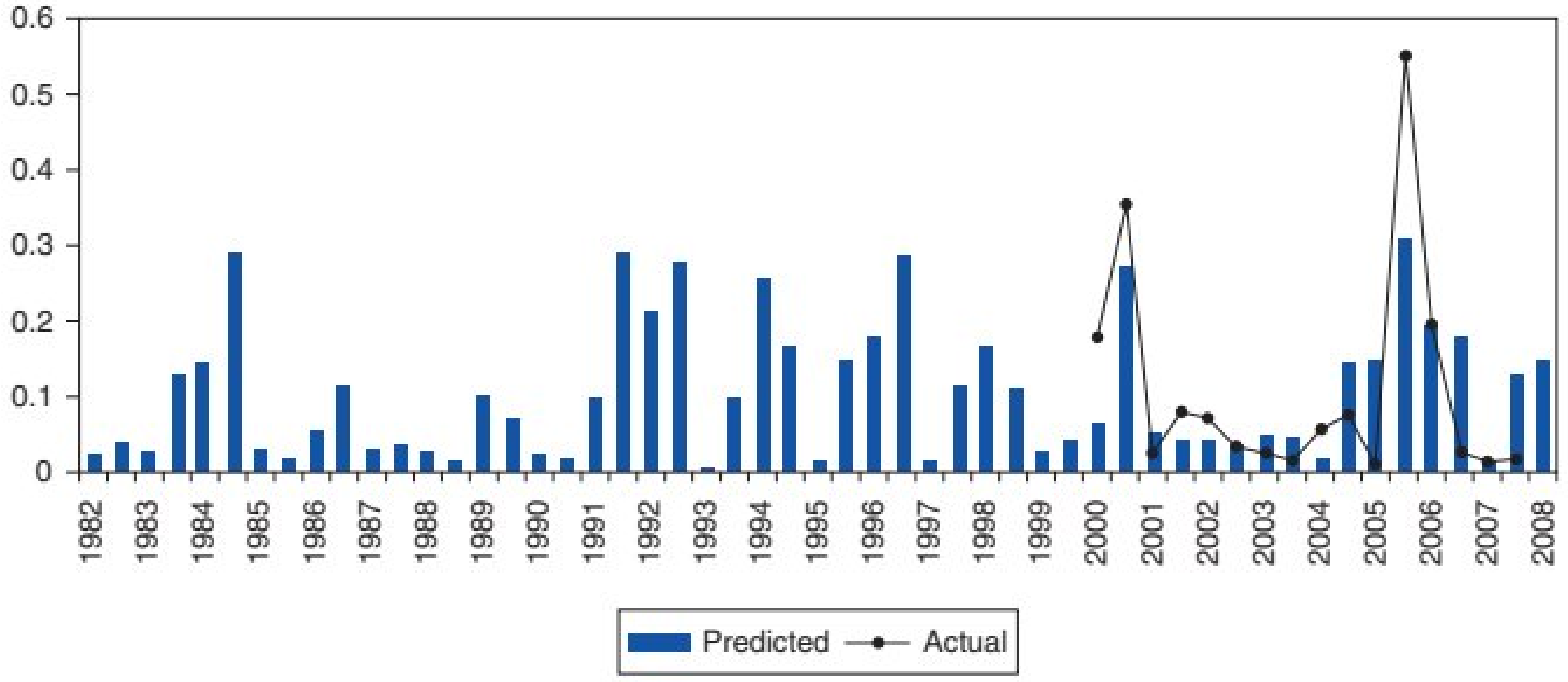

Fig. 5 Predicted versus actual mortality losses

Table 1 Causal Impacts of Insurance.

	All	Poor	Non-poor
Ex Ante Risk Management Strategies			
Reduce Meals	−20% points	−30% points	–
Sell Livestock	–	–	–
Ex Post Risk Coping Strategies			
Reduce Meals	−25% points	−43% points	–
Sell Livestock	−36% points	–	64% points
Overall Welfare			
Income	+3%	+1%	–
MUAC scores	+1 s.d.	–	–
Investment			
Expenditures on Livestock	+72%	–	–

Sources: Janzen and Carter (2017); Jensen et al. (2014a); Jensen et al. (2016)

While these average effects are impressive, looking beyond the averages tells a richer and perhaps more compelling story. As discussed by Janzen and Carter (2017), poverty trap theory (and other theoretical perspectives) suggest that poorer house- holds will confront shocks by holding onto productive assets and destabilizing consumption. While this 'asset-smoothing' behavior reflects an understandable effort to avoid falling into a long-term poverty trap, its impacts on the next generation's human capital are potentially large.[9] At the same time, wealthier households would be expected to respond *ex post* to a shock by selling assets and smoothing consumption.

Motivated by these theoretical propositions, Janzen and Carter (2017) use threshold estimation techniques to test for the presence of a critical asset threshold around

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[9] See the analysis in Carter and Janzen (2015) for an effort to model these consequences as well as references to other empirical literature that documents this asset smoothing behavior.

which coping behavior switches between asset and consumption smoothing. This estimated threshold is used to distinguish between the poor and non-poor in Table 1. the results are striking. The average post-payout results disguise a strongly heterogenous pattern of insurance impacts. The decrease in meal reductions as a coping strategy is driven almost entirely by poorer households below the threshold, whereas the reduced reliance on livestock sales is driven almost entirely by households above the estimated threshold. These estimates tell an interesting story about the impact of insurance on *ex post* coping strategies. It appears to equally help both poor and non-poor (or at least less poor) households avoid costly coping strategies with potentially deleterious long-term consequences. But the mechanism through which insurance achieves this end is distinctive across the two sub-populations.

The second half of Table 1 reports the results of two additional impact evaluations that take advantage of rich panel data collected for the evaluation of IBLI. Both studies (Jensen et al. 2014b, 2016) also use randomly distributed premium discount coupons to instrument for IBLI purchases. Jensen et al. (2014b) show that insured households demonstrate improved child health (as measured by MUAC) and increased income per adult equivalent. An examination of production strategies also finds that house- holds with IBLI coverage reduce herd sizes and invest more heavily in health and veterinary services for their remaining herd, which is associated with increased milk productivity (and milk income) within the herd. Without explicitly estimating a threshold (as in Janzen and Carter (2017)), Jensen et al. (2016) also reveal heterogeneous impacts, at least for income:[10] the impact on income is significant only for the poorest households. These changes signal the kind of ex ante investment impacts discussed in the introduction, complementing the ex post impact findings of of Janzen and Carter (2017).

3 Limitations to Index Insurance as a Solution for Climate Change and Food Insecurity

While the economic case for index insurance as a smart response to managing climate risk and food insecurity is well developed, and while the IBLI project itself has shown that workable contracts can be devised that deliver the anticipated *ex ante* and *ex post* benefits of insurance, it remains far from clear whether index insurance can be scaled and operate as an essential part of the solution to the problem of climate change and food insecurity. Two of the fundamental challenges that may prevent index insurance from reaching its potential are:

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[10] Jensen et al. (2014a) find no statistically significant difference in impacts for income, MUAC, or investment in their original analysis. They do find a larger impact in milk productivity among poor households, which may partially explain the heterogenous income results revealed in the latter study.

1. *Demand*: Similar to other settings, Jensen et al. (2014b) found that poorer households (in this case, smaller herds) are less likely to purchase IBLI coverage, that liquidity plays an important role in the purchase decision, and that demand is price sensitive. In the model presented in Section 1, Janzen et al. (2015) find that the most vulnerable households, despite having the most to gain from insurance, also have a high opportunity cost of insurance that may inhibit demand for an otherwise valuable product.
2. *Pricing*: A variety of factors have tended to push the price of index insurance contracts in developing country agriculture–including the IBLI project–to levels well in excess of 150% of the actuarially fair price.[11] Small project size is clearly a problem (as many insurance companies do not see it worth their while to participate in these markets), as are thin data problems which makes insurers have imprecise estimates of loss probabilities. Carter (2013) suggests that insurance pricing seems to reflect an 'uncertainty loading,' meaning an extra mark-up that charged when data are of mixed quality and loss probabilities uncertain. Solution to these problems may ultimately require a mixed private- public reinsurance model to keep the price of insurance in the range that it is rational to buy it.

While these challenges are clearly important, in the remainder of this section, we focus on a third, equally important challenge–that of providing scalable high quality contracts. While the IBLI contract was designed with much more care and attention to the ability of the index to adequately cover losses (see Section 2 above), even the IBLI contract shows signs of quality slippage as more data and experience become available. This section analyzes these challenges and suggests a way forward to address them and make IBLI an efficient instrument that protects Kenyan herders from the threat represented by climate change.

3.1 The Quality Challenge to Index Insurance

Unlike conventional insurance, index insurance includes a remaining uninsured "basis risk": a farmer or herder may encounter losses when the index does not trigger, or that the index may trigger when she does not have any loss. In the model above, this element was captured with the idiosyncratic risk component. Losses triggered in the model by idiosyncratic shocks were not compensated in the model. It is now widely recognized that basis risk may prevent index insurance to achieve its promise of delivering affordable protection to poor households (Miranda and Farrin 2012; Jensen and Barrett 2015). Clarke (2016) shows that because of basis risk, the most risk averse households may not be interested in purchasing index

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[11] The actuarially fair price of an insurance contract is the price that is just equal to the expected indemnity payments to the farmers. Clearly the price must be marked up in excess of that amount in order to cover administrative costs, cost of capital, etc. However, a price that is, say, 150% of the actuarially fair price means that the farmer (or whoever is paying the insurance premium) is paying $1.50 for every $1.00 of protection for the farmers.

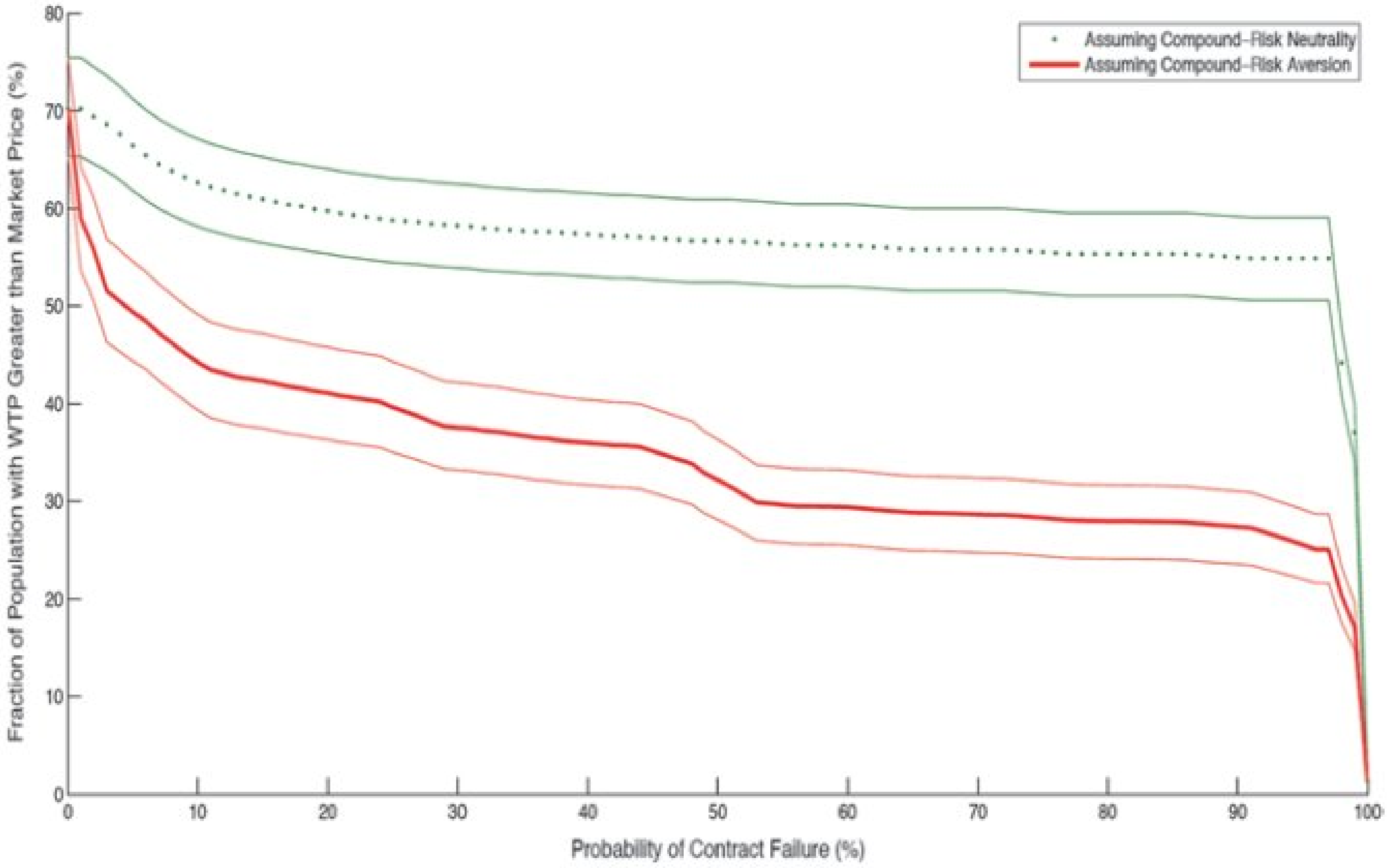

Fig. 6 Impact of basis risk on willingness to pay for index insurance (Source: Elabed and Carter (2015))

insurance products. Indeed, if they have losses, pay a premium, and fail to receive insurance premiums, they end up in a worse situation than without insurance.

Basis risk may be an even bigger problem than work like Clarke (2016) suggests. Elabed and Carter (2015) use a field experiment in Mali to show that behavioral fac- tors related to basis risk further affect insurance demand. Specifically they show that people dislike the uncertainty of insurance payments, which, added to the original uncertainty of shocks, creates a "compound risk aversion" (the aversion to the combination of two uncertain events) among some households. This behavioral reaction generates a drop in insurance demand from 60% approximately for compound-risk neutral individuals, to only 35% of the population when compound-risk aversion is taken into consideration (Fig. 6).

While the necessity to reduce basis risk is now well acknowledged, there exists a debate regarding its exact definition, which harms efforts to increase overall index insurance quality. For example, there is a disagreement on whether basis risk should measure rainfall index correlation with farmers' rainfall shocks (i.e. accuracy of the index as a rainfall predictor) or its accuracy as a predictor of farmers' overall losses overall quality of the protection). Clearly it is the latter that matters from the farmer's perspective and that will influence her insurance purchase decision. A misplaced focus on accuracy of the index as a predictor of, say, rainfall, can lead to inappropriate index insurance products, which trigger payments when rainfalls are low in a given region rather than when farmers have actual losses, as rainfalls in a given region and actual individual losses are, at best, imperfectly correlated. Before analyzing the different sources of low quality of protection, let us step back and examine the objectives of index insurance.

For households, a good insurance means an insurance which improves their well- being by protecting their consumption and assets (see Barré et al. 2016). In addition, the quality of insurance as a development instrument stems from its ability to foster investments and reallocation of resources– and thus generate higher income– by removing risk. In other words, an insurance product needs to be evaluated based on its efficiency in stabilizing highly volatile income streams for poor farmers or herders. As a consequence, an index insurance product should be carefully analyzed to determine if its expected payments are actually correlated with households' losses, or if the insurance rather acts as a weather derivative–or even worse: as a lottery ticket (Jensen et al. 2014b; Barré et al. 2016). In India, Clarke et al. (2012) have shown that insurance payments actually correlates poorly with farmers' low yield events (Fig. 7).

The inadequacy of indemnity payments, observed in India and other settings, raises the issue of index insurance quality. Several sources of errors lead to low levels of index insurance quality. As shown in Fig. 8, for products which aim at covering all types of shocks, these sources of error relate:

- *Design risk* occurs when an insurance index is poorly correlated with *average* losses in the insurance zone covered by the index; and,
- *Idiosyncratic risk* occurs when the individual's losses differ from the average losses in her insurance zone.

In the theoretical model presented in Section 1, the insurance contract exhibited idiosyncratic, but not design risk.

The red line shows the point estimate for an Epanechnikov kernel with a bandwidth of 0.8. The green lines show the 95% confidence intervals for the point esti-

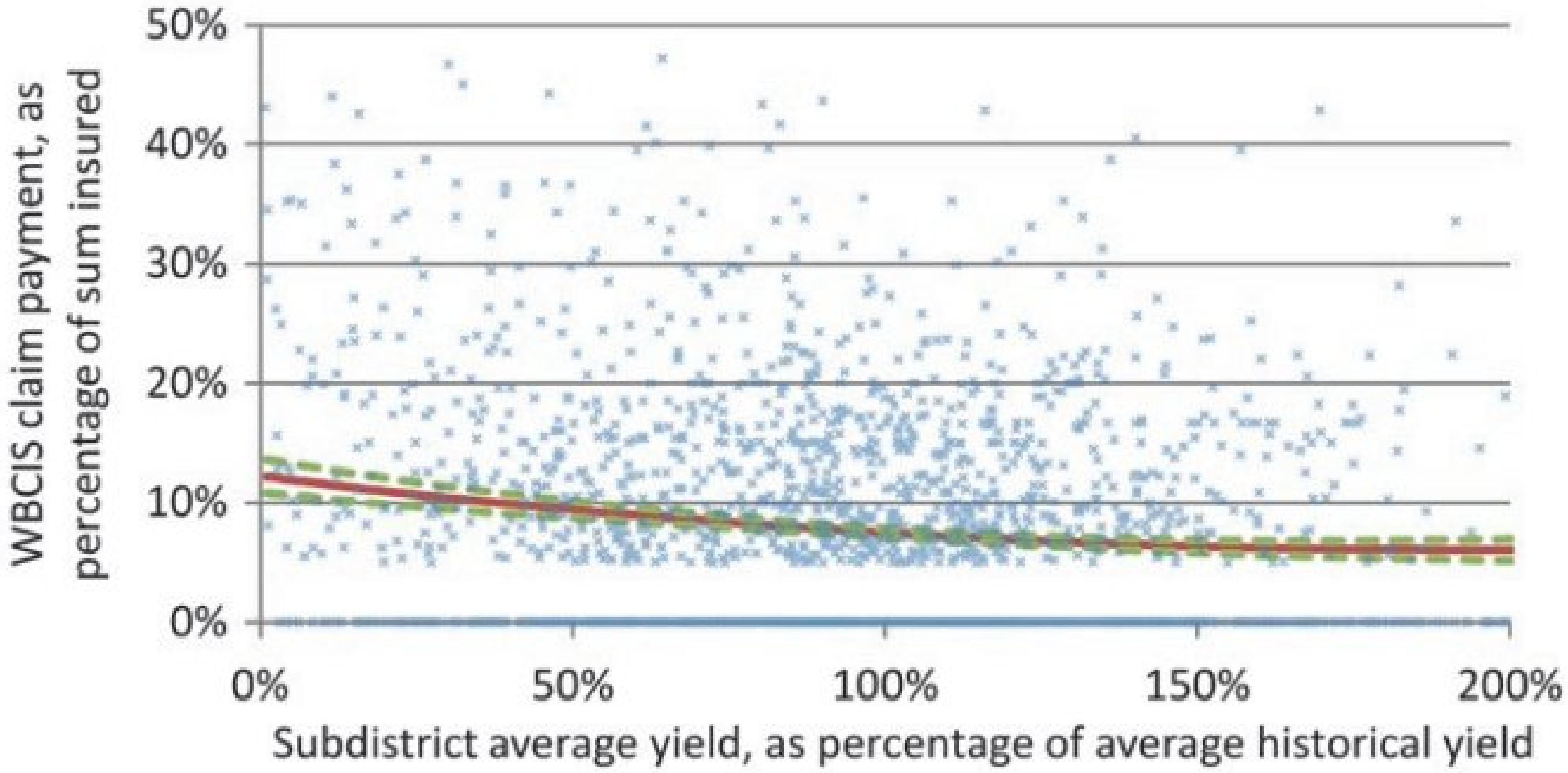

Fig. 7 Relationship between average yields and insurance payments in India (*Source*: Clarke et al. (2012))

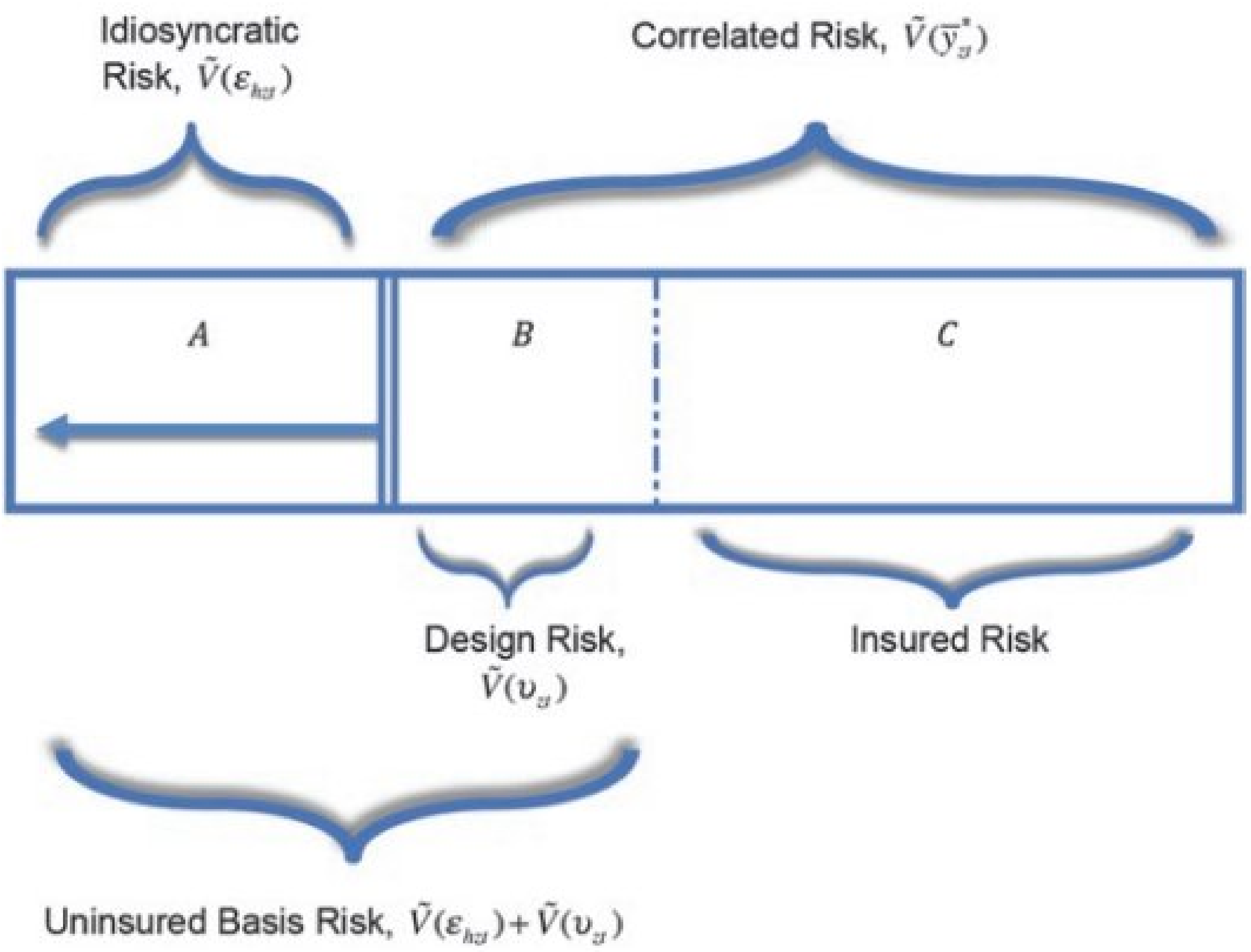

Fig. 8 Insured and uninsured risk under index insurance (Source: Elabed et al. (2013))

mate. The blue dots represent the scatter plot of claim payments for the respective district yield levels.

Design risk emerges from prediction errors embedded in the index. The average loss within a defined geographic zone can be measured by indices based on several methods: crop cutting, satellite information, weather stations, etc. The contract formula then maps the index into payouts (and, implicitly, losses). Both the index and the mapping necessarily include some errors, which can be limited by using good indices and good insurance designs, but will not be eradicated.

However, even if design risk can be eliminated by improving even further the predictive power of the index, there typically remains some uninsured risk at the individual level. Pure idiosyncratic risk may induce households to encounter agricultural losses. For instance, a single farm's crop may suffer damage from idiosyncratic factors such as animal damage. Local communities often have some informal risk management strategies to cope with such type of pure idiosyncratic shocks when other villagers are not affected. Nevertheless, idiosyncratic risk diminishes the overall protection provided to farmers or herders.

The relative magnitude of both design and idiosyncratic risks are both influenced by the nature of the contract and its geographic scale. In terms of Fig. 8, how much risk appears as idiosyncratic and how much appears as correlated depends on the geographic scale of the index. As the geographic zone covered by a single index increases in size, household losses will correlate less well with the insurance index. For example, a weather-based index that covers households within 30 kilometers of the weather station will track outcomes worse than an index that covers households within 1 kilometer of the weather station. Similarly, an area yield index at the level of a state or province will cover individual farmer losses less well than an index where yields are measured at the level of each municipality or village. However in practice, reducing the geographic scale of the index too much leads to issues related to moral hazard, i.e. the fear that households may become able to manipulate the index.

Finally, for products which do not aim to cover all types of shocks (such as insurance products based on a rainfall index), an additional source of low quality arise from uncovered covariate risks (e.g., locusts, tsunamis). This type of error is related to the traditional distinction between single-peril and multiple-peril insurance products, but the difference is not as clear in the case of index insurance: satellite-based products such as IBLI, for instance, are supposed to cover all types of shocks related to lack of forage- including increase in livestock diseases- but cannot detect shocks which are not related to the ground vegetation- such as a new epidemic affecting well-fed livestock. These uncovered covariate risks further decrease the quality of the protection offered to poor households. Of course, households may be still interested in affordable index insurance products which only protects from one type of shock (*e.g*. drought), but the overall protection provided by this type of product has to be carefully analyzed and put in perspective with the price of the product and the probability that a farmer is made worse off with the insurance than without it.[12]

The lack of a strong negative correlation between the insurance indemnities and income shocks due to yield losses will result in a low demand for the insurance product (Clarke 2016; Smith and Watts 2009). Low correlation will not only fail to protect farmers, but eventually seriously damage livelihoods, because poor households pay high premiums to purchase protection, and plan on being protected when making investment decisions. Thus, a detailed analysis of the sources of errors needs to be conducted before implementing an index-based insurance and after its implementation, in order to rule out low quality products and pave the road for future product improvements. While this type of analysis is rarely undertaken in practice, IBLI is one of the most studied index insurance programs, and its quality has been closely scrutinized before and after implementation.

3.2 *IBLI's Quality Effort and Remaining Weaknesses*

IBLI's initial design considered carefully the above quality challenges, employing the available data. Indeed, as summarized in Sect. 2 above, Chantarat et al. (2013) conducted a rigorous ex-ante analysis intended to design the best performing index insurance product in the Kenyan ASALs. However, ex-post analyses have been less optimistic regarding IBLI's index performance in terms of basis risk and contract quality. Jensen et al. (2014a, b) and have investigated IBLI's performance using data collected between 2009 and 2012 (4 years, eight rainy seasons). This dataset was

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[12] Note that if farmer pays for an insurance that only covers a sub-set of rainfall events, and then she suffers an uncovered pest invasion, she is actually worse off then if she had the invasion but not purchased the insurance. Clarke (2016) discusses these issues in detail.

employed for the impact evaluation of the IBLI pilot and includes detailed information on livestock dynamics, which can be used to assess the actual protection offered to herders over the period.

Jensen et al. (2014a) decomposes basis risk in several ways. First, by considering livestock surviving rates, the authors show that outcomes for insured households do not stochastically dominate outcomes for uninsured households. Actually, as expected, the insurance contract reduces the mean survival rate (taking into account insurance payments) but reduces skewness of the survival rate distribution. Simulations based on a constant relative risk aversion (CRRA) utility function shows that most households are actually better-off with the insurance at the commercial premium rate, but the benefits vary across locations and households.

To unpack these results, the authors decompose uncovered risks between design risk (the IBLI index was a poor predictor of average losses) and idiosyncratic risk (the individual suffered a worse loss than her neighbors on average did). At the aggregate level, design risk is relatively low since IBLI reduces covariate risk by about 62.8%. However, when individual idiosyncratic risk is added, IBLI only covers between 23.3% and 37.7% of the total risk. Note that at the individual level, the precision of the index when covariate losses are above the strike point is much higher, between 43.1% and 78.6%, which is closer to the objective, but still unsatisfying in some districts. Moreover, covering covariate shocks is arguably a first priority, as households may have informal insurance mechanisms when they receive adverse idiosyncratic shocks (Mobarak and Rosenzweig 2012).[13] Overall, these results call for caution when assessing insurance ex-ante, given that ex-post quality may be lower than expected based on ex-ante, out-of-sample predictions.[14]

An analysis of the consequence of basis risk on insurance demand was further performed by Jensen et al. (2014a). First, basis risk may deter insurance purchase. Second, while index insurance avoids moral hazard issues and individual-level adverse selection, it leaves some room for spatiotemporal adverse selection: households can buy insurance when they anticipate a bad climatic season in a given location, or not buy insurance if they expect a good climatic season in that location. Indeed, households may have an idea of the future season based on their information at the time of the insurance sale, as forage is affected by previous seasons and by the current season early rains. Thus, pastoralists can buy more insurance when they anticipate a bad climatic event– while on the other hand, price tends not to adjust to changing conditions.

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[13] The complementarity of informal and formal insurance is not straightforward, and depends on the structure of the informal networks and of the index insurance, a point reinforced by Boucher and Delpierre (2014).

[14] The difference between ex-ante and ex-post assessments is striking. Factors explaining this mismatch may include: the use of an out-of-sample prediction which was never used in the design process (thus avoiding overfitting better); the application to a different time period (which was not available at the time of the contract design); the use of more detailed household data; and the computation of mortality rates and basis risk in a different manner.

The analysis shows that price, liquidity and social relationships have a strong impact on index insurance demand. In addition, both basis risk and special adverse selection play a major role. In particular, households in districts with high idiosyncratic risk (which cannot possibly be covered by the index insurance) are much less likely to purchase the IBLI product compared to households living in districts with a higher share of covariate risk. Design risk, on the other hand, plays a much smaller role in diminishing demand by about 1% only, compared to idiosyncratic risk, which explains about 30% of the demand.[15] This conclusion is relatively pessimistic regarding IBLI's potential, as contract design can only address inherent basis risk by lowering the geographic scale of the index. In pastoral regions, where individual households may seasonally migrate across large spaces, there are natural limits to how much a forage index like IBLI can be downscaled.

There are, of course, additional challenges to index insurance quality.[16] However, these issues of basis risk relate directly to the core economic value of the insurance product. If an index insurance does not pay pastoralists when they have losses, it does not matter how precisely it is priced, how efficiently it is implemented, and whether demand is low or high: households are not protected.[17] Index insurance products offer imperfect protection by definition, but efforts have to be made to provide the highest quality of protection as possible. Fortunately, there are several improvements that IBLI has realized in the last year or plans on including, which can improve household protection in several manners.

3.3 *The Way Forward*

Since the introduction of IBLI pilot project in 2009, the program has introduced some improvements and is planning further changes based on recent studies which it conducted. As the project has developed, we learned a lot about the strengths and weaknesses of IBLI. New ex-post data have become available at the household

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[15] Note that design risk is difficult to measure with a short panel and a limited number of observations, as insured catastrophic losses are rare events by definition.

[16] These challenges relate to contract pricing and implementation (Chantarat et al. 2013), and non-price factors such as trust and liquidity (Jensen et al. 2014b), among others. Climate change also intensifies these challenges, as it creates some short-term uncertainties around future payments (Carter 2013) and may lead to very high premiums if climatic conditions deteriorate in the long-run (Collier et al. 2009; Carter and Janzen 2015).

[17] Of course, for households with full information, demand should be a good indication of the value of an insurance products. However, even for households who understand the product sold, the value of an insurance is difficult to assess ex-ante (Clarke and Wren-Lewis 2013). In addition, households do not always understand very well the insurance product, given the complexity of some index insurance schemes, the low levels of literacy in some contexts, and the poor quality of some marketing/information campains. For that reason, implementation of index insurance projects should focus on the quality of the protection offered rather than on the demand for these products only.

level, as well as longer term satellite information. IBLI has also expanded in scale in four districts in Northern Kenya and one district in neighboring Southern Ethiopia. This combination of factors has brought new opportunities and challenges. While IBLI has already operated some modifications since the studies mentioned above, further studies are planned to help continue improving the product design and the protection it provides to herders.

Notably, the program has evolved from an asset replacement mechanism to an asset protection philosophy. From an economic point of view, it is more efficient to intervene early and protect households' productive assets, rather than compensating them after the received a shock and possibly employed other costly coping strategies (Janzen and Carter 2017). In addition, as the project extended to geographic areas where livestock mortality data were lacking (in particular Southern Ethiopia), IBLI had to rely exclusively on NDVI data. Thus, payments would be triggered when NDVI data indicate a deterioration of the climatic conditions.

This move towards early payments have been accompanied by improvements of the product design. Since 2013, in order to limit spatiotemporal adverse selection, IBLI has started to disaggregate more the index, so that households located in different locations receive appropriate (different) insurance contracts. At this disaggregated scale, a larger share of shocks should be considered as covariate risk by the index, and as such reduce the effect of idiosyncratic risk (Jensen et al. 2014b).

Additional analyses have been conducted to further improve index quality. Vrieling et al. (2014) have investigated the possibility to combine remote sensing indices over longer periods in order to increase the predictive power of IBLI's formula. Based on newly constructed remote sensing from 1981 to 2011, the authors show how combining remote sensing indices allow a higher predictive power at a highly disaggregated level–i.e., there is still scope for reducing the magnitude of idiosyncratic risk by downscaling the insurance index. On the other hand, Klisch et al. (2015) have realized technical improvements in the computation of the vegetation index which can be used to detect droughts.[18]

Finally, Vrieling et al. (2016) have conducted some work on the temporality of the payments. The initial IBLI designed considered fixed dates for beginning and end of season in each district location. However, Vrieling et al. (2016) show that it is possible to use a phenomenological model to describe the temporality of forage development, based on historical NDVI data in each location. This change offers the potential to predict more accurately livestock mortality in each district, but also to provide payments one to three months earlier to pastoralists. These early payments could allow pastoralists to protect their herd by buying forage, water or medicine for instance, and prevent other shocks associated with low levels of forage such as animal diseases.

Additional research is required, however, on the relationship between insurance quality and temporality of payments. If early payments do not compromise the cor-

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[18] These improvements regard the smoothing and filtering of satellite data, the modelling of uncertainty, the spatial and temporal aggregation of satellite data, and the timing of satellite data acquisition and processing.

relation between insurance payments and household's losses, then they are clearly valuable. However, there may be some trade-offs between early protection and accurate protection. Future work will analyze these trade-offs, as well as measure how the identified improvements in satellite indices computations translate into higher index insurance quality for herders.

4 Conclusions

We began this paper with the question:

Can insurance cost-effectively mitigate the increasingly deleterious impacts of climate risk on poverty and food insecurity?

The answer, it seems is both yes and no. Theory suggests that if quality insurance coverage can be delivered and the expected *ex post* and *ex ante* impacts take place, then the answer should be yes. Indeed, research on the Index-based Livestock Insurance (IBLI) pilot project in Kenya indicate that these conditions can be met giving further power to the likelihood of a yes answer.

And yet, even within the generally positive environment of the IBLI project, there is ample evidence of the limitations to index insurance. Demand has often been tepid and unstable. Outreach and administration costs have been high. Pricing by a private insurance industry made nervous by climate change has pushed costs up. Finally, the effective quality of the IBLI contact has been scrutinized and found wanting. Efforts to scale the IBLI contract to nearby pastoral regions has proven challenging.

While efforts are underway to respond to these challenges, their breadth and depth make clear that index insurance is not a sliver bullet that can be pulled off the shelf and used to mitigate the food insecurity and other consequences of climate change. Skeptics might suggest that these challenges are insurmountable. Others–and we count ourselves among them–remain undeterred given the evidence that index insurance can be a valuable instrument if these problems can just be solved. Doing so will require continued creativity, piloting and evaluation to see if indeed these not inconsequential challenges can be overcome.

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Can Cash Transfer Programmes Promote Household Resilience? Cross-Country Evidence from Sub-Saharan Africa

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Abstract Several new initiatives of cash transfer programmes have recently emerged in sub-Saharan Africa, and most target poor rural households dependent on subsistence agriculture. This paper synthesizes the key findings of From Protection to Production Project (PtoP) of FAO and discusses the role of cash transfer programmes risk management tool to increase resilience in sub-Saharan Africa. Results show that such programmes have important implications for household resilience. Although the impacts on risk management are less uniform, the cash transfer programmes seem to strengthen community ties (via increased giving and receiving of transfers) and allow households to save and pay off debts, and decrease the need to rely on adverse risk coping mechanisms. One important finding related to climate change, as illustrated by the Zambia case, is that households receiving cash transfers suffered much less from weather shocks, with poorest households as the biggest gains, and food security increased, although differing across countries. The paper concludes that social protection programmes could be more effective as safety nets by explicitly accounting for climate risk in their design and implementation.

JEL Classification I38 • Q01 • Q18

1 Introduction

Almost three quarters of economically active rural populations in sub-Saharan Africa (SSA) are smallholder farmers, making them important players in national agricultural development plans. Thus agricultural development that contributes to

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increasing the productivity, profitability and sustainability of smallholder farming is critical for reducing poverty and improving food security and nutrition. Agriculture in SSA, however, is increasingly exposed to a variety of risks and uncertainties, including market risk, production risks, climate variability, pest and disease outbreaks and windstorms, and institutional risks (Antonaci et al. 2012). The main premise is that by providing a steady and predictable source of income, cash transfer programmes can enhance household and community level resilience by improving human capital, facilitating changes in productive activities by relaxing liquidity constraints, improving natural resource management, and improving the ability to respond to and cope with exogenous shocks (e.g., Handa et al. 2015; Asfaw et al. 2012). The ultimate aim is to strengthen and improve resilience for rural producers to allow them to prevent future fluctuations in consumption and move to the next welfare level (Antonaci et al. 2012).

Government strategies for managing agricultural risks at the household or community level have taken different forms in different countries, but are generally classified into three groups:

1. mitigation/adaptation activities designed to reduce the likelihood of an adverse event or reduce the severity of actual losses. Risk mitigation options are numerous and varied (e.g., irrigation, use of resistant seeds, improved early warning systems, and adoption of better agronomic practices);
2. risk transfer, such as commercial insurance and hedging; and
3. resilience-improving mechanisms to withstand and cope with events ex ante.

Examples of these government strategies include social safety net programmes, buffer funds, savings, strategic reserves, contingent financing, insurance, etc. There are many definitions of resilience in the literature but the common thread in all definitions is the notion that resiliency reflects an ability to successfully manage or withstand a shock or stress (e.g., Alinovi et al. 2010).

Unlike in other parts of the world, most farmers in SSA have no access to government or market-based risk management tools; when they do, government programmes or private sector initiatives to manage price and production instability are often insufficient. Moreover, social protection programmes are seldom institutionalized, and are rarely used as risk management instruments to address food and nutrition insecurity. However, an increasing number of African governments over the last 15 years have launched social protection programmes including cash transfers, workfare and public works programmes and in-kind safety nets.

Cash transfer programmes in African countries have tended to be unconditional (where regular and predictable transfers of money are given directly to beneficiary households without conditions or labour requirements) rather than conditional (more common in Latin America and which require recipients to meet certain conditions, such as using basic health services or sending their children to school). Most of these programmes seek to reduce poverty and vulnerability by improving food consumption, nutritional and health status and school attendance. There is robust evidence from numerous countries (especially within Latin America and increasingly SSA) that cash transfers have leveraged sizeable gains in access to health and education services, as measured by increases in school enrolment (particularly for girls) and use of health services (particularly preventative health, and health monitoring for children and pregnant women) (e.g., Fiszbein and Schady 2009; Davis et al. 2012).

Building on the existing literature, this paper synthesizes the key findings of the From Protection to Production Project (PtoP) of FAO, which studies the impact of cash transfer programmes on household economic decision-making. The cash transfer programmes studied here are government-run cash transfer programmes in SSA. The paper is organized as follows. First we examine cross-country results to test their magnitude and distribution (i.e. heterogeneity) of impact on productivity and economic indicators, and the implications of these impacts on resilience. We will also explore the underlying programme design and implementation features that mediated the impacts. Section 2 provides an overview of the evolution of social cash transfer (SCT) programmes in SSA while Sect. 3 presents the conceptual framework on the linkages between cash transfers and economic impacts and resilience. Section 4 presents the impact evaluation design and data collection methods. Section 5 presents a synthesis of key cross-country findings, while Sec. 6 ends with a short conclusion and policy implications.

2 Overview of selected SCT Programmes in SSA

SCTs launched by African governments over the past 10 years have provided assistance to the elderly and to households that are ultra-poor, labour-constrained, and/or caring for orphans and vulnerable children. Typically, ministries of social development manage the programmes. The main types of social protection instruments used in African countries include cash transfers, workfare and public works programmes, and in-kind safety nets.

Workfare and public works programmes supply temporary employment to recipients able to contribute their labour in return for benefits, at the same time creating public goods in the form of new infrastructure, making improvements to existing infrastructure, or performing and delivering services (Del Ninno et al. 2009). In-kind safety nets (e.g. food aid, supplementary feeding and school feeding schemes, etc.) help recipients to access food, health care, education, and other basic goods and services. Other, more common instruments in parts of Southern Africa include social insurance schemes – primarily social pensions and health insurance.

Some of the African social protection instruments implemented during the last decade include the Kenyan Cash Transfer for Orphans and Vulnerable Children (CT-OVC), the Malawi SCTP, Mozambique's Programa de Subsidios de Alimentos (PSA), Ethiopia's PSNP, the Livelihood Empowerment Against Poverty (LEAP) programme in Ghana, the CGP in Lesotho, South Africa's Child Support Grant and Old Age Pensions, Rwanda's Vision 2020 Umurenge Programme, Burkina Faso's nationwide school feeding scheme under the Burkinabé Response to Improve Girls' Chances to Succeed (BRIGHT) integrated programme, Zambia's CGP and the

Zimbabwe SCT. Several other countries, including Uganda, Tanzania and Liberia, have also pursued safety net programmes (Asfaw et al. 2012). Our study focuses on the programmes described in the remainder of this section.

The Lesotho CGP provides an unconditional cash transfer to poor and vulnerable households. The primary objective of the CGP is to improve the living standards of OVC including nutrition and health status and increased school enrolment (Pellerano et al. 2012). The CGP is targeted at poor households with children, including child-headed households. As of the end of 2013 the programme reached approximately 20,000 households and 50,000 children (Pellerano et al. 2014). The Kenyan CT-OVC is the Government's flagship social protection programme, reaching over 130,000 households and 250,000 OVC across the country as of the end of 2011 (Asfaw et al. 2012). In Ethiopia, the cash transfer programme initiated by Tigray regional state and UNICEF aimed to improve the quality of lives of OVCs, elderly and persons with disabilities as well as to enhance their access to essential social welfare services such as health care and education via access to schools in two selected woredas (districts) (Berhane et al. 2015).

The Malawi SCTP was initiated in 2006 in the pilot district of Mchinji, providing small cash grants to ultra-poor, labour-constrained households. The SCTP objectives included reducing poverty and hunger in vulnerable households and increasing child school enrolment. By March 2015 the SCTP covered 100,000 beneficiary households and had gone to full scale in 10 districts, and the Government of Malawi expects to have enrolled over 175,000 households by the end of 2015. The programme was fully executed by the Government of Malawi through the District Councils by Social Welfare Officers (Handa et al. 2015).

The Ghanaian LEAP programme provides cash and health insurance to extremely poor households to improve short-term poverty and encourage long-term human capital development. LEAP started a trial phase in 2008 and began expanding gradually in 2009 and 2010, currently reaching over 70,000 households with an annual expenditure of approximately USD 20 million (Handa et al. 2014). The programme is fully funded from the Government of Ghana's general revenues, and is the of its National Social Protection Strategy's flagship programme. The LEAP programme operates in all 10 regions of rural Ghana. Within regions, districts are selected for inclusion based on the national poverty map; within districts, local DSW offices choose communities based on their knowledge of relative rates of deprivation (Handa and Park 2012).

In 2010, Zambia's Ministry of Community Development and Social Services (MCDSS) began implementing its own CGP in the three districts (Kalabo, Kaputa, and Shongombo) with the highest rates of mortality, morbidity, stunting, and wasting among children under 5. The CGP includes all households with a child under five years of age. Eligible households receive 55 kwacha a month (equivalent to USD 12) irrespective of household size, an amount considered sufficient to purchase one meal a day for everyone in the household for one month. The goal of the programme is to reduce extreme poverty and the intergenerational transfer of poverty, and as of March 2014 the programme reached 20,000 ultra-poor households (Daidone et al. 2014a).

Our impact evaluations focus on measuring the primary objectives of these programmes, including food security, health, and nutritional and educational status, particularly of children. Most programmes are located in some kind of social ministry, administered by professionals with backgrounds in the social sciences, including economists with specialization in the social sectors. The impact evaluations are most often implemented by research institutions and consulting firms with specializations in these social sectors.

3 Role of Cash Transfer for Building Resilience: Review of Selected Evidence

The potential benefits of cash transfer programmes are built around the premise that the provision of regular and predictable cash transfers to very poor households, in the context of missing or thin markets, has the potential to both generate economic and productive impacts at the household level (e.g., Handa et al. 2015; Asfaw et al. 2012; Covarrubias et al. 2012; Boone et al. 2013). In rural areas most beneficiaries depend on subsistence agriculture and live in places where markets for financial services (such as credit and insurance), labour, goods and inputs are lacking or do not function well. Cash transfers often represent a dominant share of household income, and can be expected to help households in overcoming the obstacles that block their access to credit or cash. This, in turn, can increase productive and other income-generating investments, influence beneficiaries' role in social networks, increase access to markets, improving the ability to deal with exogenous shocks, and strengthen household and community level resilience (Asfaw et al. 2012).

The predominant view from the literature is that social protection, including cash transfer programmes, may protect beneficiaries from shocks, reduce use of negative coping strategies that undermine longer-term livelihood sustainability, and reduce household risk adversity towards more profitable, yet more risky, activities. One group of empirical literature investigates the impact of social protection on recovery from shocks. Evidence shows that a public works programme in India reduced income fluctuations, while a public works programme in Ethiopia protected households from the negative effects of crop damage on child growth. Nonetheless, although a food-for-work programme in Ethiopia increased risk sharing within treated villages, it also reduced households' capabilities to manage idiosyncratic crop shocks – perhaps as a result of food aid crowding out informal insurance, and subsequently leaving beneficiaries inadequately insured to manage idiosyncratic risk (Dercon and Krishnan 2003). Conditional cash transfers (CCTs) in Latin America also facilitated recovery from shocks; some of the positive effects include reduced child labour in Nicaragua, protection of consumption for coffee farmers in Nicaragua and Honduras during global price drops, income diversification in Brazil and the decline in school dropouts in Mexico.

A second group of empirical studies looks at the impact of social protection on adverse coping strategies. The evidence generally shows a reduction in the use of adverse coping strategies that deplete household assets. One study finds that

Ethiopia's PSNP dissuaded 60% of beneficiaries from engaging in distress sales during a drought (Devereux et al. 2005). The Michinji Malawi Social Cash Transfer pilot scheme reduced begging for food or money by 14%, and reduced school dropout rates by 37% (Covarrubias et al. 2012). In Ghana and Kenya, the LEAP and CT-OVC programmes reduced child labour, distress asset sales and indebtedness. The impact on risk coping behaviour is also influenced by gender and programme design. In the Mchinji pilot scheme, children in female-headed households benefitted from the social cash transfer programme via a decline in non-household wage labour and an increase in participation in household chores, whereas children in male-headed households only experienced a decline in school absenteeism. Yet, these gender-specific outcomes are also a reflection of the constraints facing the households, as female-headed households are also single-guardian households that face challenges in balancing domestic work with income-generating activities (Covarrubias et al. 2012). In addition, cash and in-kind transfers may increase social capital and strengthen informal safety nets and risk-sharing arrangements, provided that appropriate mechanisms and an enabling environment are created.

A third group of studies shows that SCT programmes can have impacts on household decision-making over labour supply, the accumulation of productive assets and productive activities, which would subsequently have implications for resilience. Todd et al. (2010) and Gertler et al. (2012) found that the Mexican PROGRESA programme led to increased land use, livestock ownership, crop production, agricultural expenditures and a greater likelihood of operating a microenterprise. From their analysis of a conditional cash transfer (CCT) programme in Paraguay Soares et al. (2010) found that beneficiary households invested between 45–50% more in agricultural production and that the programme also increased the probability that households would acquire livestock by 6%. Martinez (2004) found that the BONOSOL pension programme in Bolivia had positive impacts on animal ownership, expenditures on farm inputs, and crop output, although the specific choice of investment differed according to the gender of the beneficiary. In contrast, Maluccio (2010) found that the Red de Proteccion Social (RPS) programme in Nicaragua had muted impacts on the acquisition of farm implements and no impact on livestock or land ownership. With respect to SSA, Covarrubias et al. (2012) and Boone et al. (2013) found that the Malawi SCT Programme (SCTP) led to increased investment in agricultural assets, including crop implements and livestock and increased satisfaction of household consumption by own production. Gilligan et al. (2009) found that Ethiopian households with access to both the Productive Safety Net Programme (PSNP) as well as complementary packages of agricultural support were more likely to be food secure, to borrow for productive purposes, use improved agricultural technologies, and operate their own nonfarm business activities. In a later study, Berhane et al. (2011) found that the PSNP led to a significant improvement in food security status for those that had participated in the programme for 5 years versus those who only received 1 year of benefits. Moreover, those households that participated in the PNSP as well as the complementary programmes had significantly higher grain production and fertilizer use. However, beneficiaries did not experience faster asset growth (livestock, land or farm implements) as a result of the programmes (Gilligan et al. 2009).

4 Methodology

4.1 Programme Evaluation Design and Data

The core of the quantitative analysis for the Lesotho, Malawi, Zambia and Kenya studies was an experimental design impact evaluation. In Ghana and Ethiopia the evaluation designs were quasi-experimental. Table 1 summaries the key evaluation design features of the cash transfer programmes.

In Lesotho, participation in the programme was randomized at the level of the electoral district (ED). First, all 96 EDs in four community councils were paired based on a range of characteristics, with 40 pairs randomly selected for this survey. Within each selected ED, two villages (or clusters of villages) were selected, and in every cluster a random sample of 20 households were selected. Baseline survey data was collected followed by public meetings with a lottery to assign EDs (both sampled and non-sampled) to either treatment or control groups. Selecting the treatment ED after baseline survey helped to avoid anticipation effects (Pellerano et al. 2012). The baseline household survey was carried out in 2011 prior to distribution of cash transfers; a follow up panel survey took place in 2013. A total of 3102 households were surveyed; 1531 programme eligible households (766 treatment and 765 control) were used for impact evaluation analysis, with remaining 1571 programme ineligible households used for analysis of targeting and spillover effects. The baseline analysis report (Pellerano et al. 2012) shows that randomization was quite successful.

Table 1 Core evaluation designs

Country	Design	Level of randomization or matching	N	Ineligibles sampled?
Ethiopia	Non-experimental (PSM and IPW)	Household level within a village	3351	Yes
Ghana	Propensity Score Matching (IPW)	Household and Region	1504	No
Kenya	Social experiment with PSM and IPW	Location	2234	No
Lesotho	Social experiment	Electoral District	2150	Yes
Malawi	Social experiment	Village Cluster	3200	Yes
Zambia	Social experiment	Community Welfare Assistance Committee	2519	No

All studies are longitudinal with a baseline and at least one post-intervention follow-up. N refers to households sampled at follow-up

Source: Davis and Handa (2015)

In Kenya's CT-OVC, the impact evaluation utilized a randomized cluster longitudinal design, with the baseline quantitative survey fieldwork carried out in mid-2007. Within each district, two locations were chosen randomly to receive intervention and two were selected as controls (Ward et al. 2010). This method of randomization was not as robust as in the case of Lesotho due to the fewer units over which the randomization took place. Approximately 2750 households were surveyed in seven districts (namely, Nairobi, Kwale, Garissa, Homa Baye, Migori, Kisumu and Suba). Two-thirds of households were assigned to the treatment group. These households were re-interviewed (first round) two years later, between May and July 2009, in order to assess the impact of the programme on key welfare indicators (Ward et al. 2010). The re-interview success rate was approximately 83%. The second round follow up study was conducted between May and August 2011 with a more detailed economic activity module (including wage labour, self-employment, crop and livestock activities, etc.) to capture potential investment and productive activity benefits of the programme on families. For the household level analysis, we relied on data collected at the baseline (2007) and the second round follow up in 2011, with a sample of 1811 households. However it is important to point out that for many of the outcome variables of interest to the PtoP project, we have only one data point (i.e. no baseline).

In Zambia the baseline survey was carried out in September–October 2010, with follow ups in 2012 and 2013. Communities were randomly assigned to treatment group (incorporated into the programme in December 2010) or control (to be brought into the programme at the end of 2013). Baseline data collection began prior to group assignment. The study includes 2515 households (1228 treatment and 1287 control). Analysis of the baseline data shows that randomization appears to have worked well; greater detail on the randomization process can be found in Seidenfeld and Handa (2011).

In Malawi, baseline data was collected in 2013 and a follow up survey 17 months later in 2014 (Handa et al. 2014). Treatment and control groups each represent about half of communities sampled. The sample is divided between Salima and Mangochi districts which count, respectively, 2192 and 2160 households. Of these households 1775 and 1756, respectively, meet the eligibility criteria. The longitudinal impact evaluation includes 3531 eligible households and 821 ineligible households at baseline.

In Ethiopia, the impact evaluation design was non-experimental; it follows a longitudinal design, with a baseline household survey conducted in mid-2012, followed by separate monitoring surveys, and finally a 24 month follow-up in 2014. The evaluation sample includes three groups of households: treatment beneficiaries, control households, and ineligible households. The development of ranking lists of eligible households based on meeting targeting criteria was a vital component. Treatment and control households were both selected from the list of eligible households. The sample comprises 3664 households at baseline, of which 1629 were beneficiaries and 1589 were control households. In addition 446 sample households were randomly selected for the study from households who were noneligible to receive support from the programme either because they were less poor and/or because of the presence of able-bodied members. Attrition between baseline (May–August 2012) and endline (2014) was 8.7% or 4.36% per year (Brehane et al. 2012).

The Ghanaian LEAP programme impact evaluation takes advantage of a nationally representative household survey implemented during the first quarter of 2012. It focuses on 7 districts across 3 regions (Brong Ahafo, Central, Volta). The initial treatment sample of 700 households were randomly drawn from the group of 13,500 households that were selected into the programme in the second half of 2009. Households were interviewed prior to indication of selection to lower anticipation effect. The baseline survey instrument was a reduced version of the national household survey instrument, and the national survey sample and the treatment household sample were surveyed at the same time by ISSER. The strategy was to draw the control households from the national survey using PSM techniques. A comparison group of 'matched' households were selected from the ISSER sample and re-interviewed 2 years later, in March–April 2012, along with LEAP beneficiaries to measure changes in outcomes across treatment and comparison groups (Handa and Park 2012).

4.2 Analytical Methods

In PtoP project impact evaluation, we seek to answer the question: "How would cash transfer beneficiaries have fared in the absence of the programme?" The identification of the counterfactual is the organizing principle of an impact evaluation as it is impossible to observe a household both participating in the programme and not. The goal is to compare participants with non-participants who are as similar as possible except for receiving the programme in order to measure the differential impact of the intervention. The "with" data are observed in a household survey that records outcomes for recipients of the intervention. The "without" data, however, are fundamentally unobserved since a household cannot be both a participant and a non-participant of the same programme (see Asfaw et al. 2012 for detail).

However, the outcomes of non-beneficiaries may still differ systematically from what the outcomes of participants would have been without the programme, producing selection bias in the estimated impacts. This bias may derive from differences in observable characteristics (e.g., location, demographic composition, access to infrastructure, wealth, etc.) or unobservable characteristics (e.g., natural ability, willingness to work, etc.). Some observable and unobservable characteristics do not vary with time (such as natural ability) while others may vary (such as skills). Furthermore the existence of unobservables correlated with both the outcome of interest and the programme intervention can result in additional bias (i.e., omitted variables).

The validity of experimental estimators relies on the assumption that the control group units are not affected by the programme; this is also referred to as the Stable Unit Treatment Value Assumption (SUTVA) (Rubin 1980; Djebbari and Hassine 2011). However control households can be affected through market interactions and informal transaction and risk sharing (which is also known as non-market interaction). Depending on the nature of the design and the availability of data, different analytical models can be used to estimate the impact of the programme.

Towards this end, two approaches (i.e. a difference-in-difference (DD) estimator and a single difference approach combined with inverse probability weighting and propensity score matching) were used in most of the evaluations, depending on the nature of the design and availability of data (see Asfaw et al. 2012 for detail). When baseline data are not available, as is the case for some of our outcome variables in some countries, the single difference method was applied. When panel data were available with pre- and post-intervention information, which is the case with most of the countries, a DD approach was used. By taking the difference in outcomes for the treatment group before and after receiving the cash transfer, and subtracting the difference in outcomes for the control group before and after the cash transfer was disbursed, DD is able to control for pre-treatment differences between the two groups, and in particular the time invariant unobservable factors that cannot be accounted for otherwise (Wooldridge 2002).

The key assumption is that differences between treated and control households remain constant throughout the duration of the project. If prior outcomes incorporate transitory shocks that differ for treatment and comparison households, DD estimation interprets such shocks as representing a stable difference, and estimates will contain a transitory component that does not represent the true programme effect. When differences between treatment and control groups exist at baseline, the DD estimator with conditioning variables has the advantage of minimizing the standard errors as long as the effects are unrelated to the treatment and are constant over time (Wooldridge 2002). Control variables are most easily introduced by turning to a regression framework which is convenient for the DD, or by combining DD with propensity score matching or DD with inverse probability weighting (DD-IPW).

All estimators presented above assume the cash transfer impact is constant, irrespective of who receives it. The mean impact of a programme or policy based on this assumption is a concise and convenient way of evaluating impacts. Heckman et al. (1997) justify this approach if researchers and policy makers believe that (a) total output increases total welfare and (b) detrimental effects of the programme or policy on certain parts of the population are not important or are offset by transfers—either through an overarching social welfare function or from family members or social networks.

Overall mean impacts are most helpful when complemented with measurements of distributional impact. Even if the mean programme effect were significant, whether the programme had a significant beneficial or detrimental effect might vary across the distribution of targeted households (Khandker et al. 2010). For example, the impact on poorer households as compared to wealthier households is particularly interesting in the context of programmes that aim to alleviate poverty.

There are a number of ways to present the distributional impacts of a cash transfer programme. For example, one could divide the sample of households and individuals into different demographic groups (e.g., by gender or age cohort), perform separate analysis on each group, and see if estimated impacts are different. Interacting the treatment with different household socioeconomic characteristics is another way to capture differences in programme effects, although adding too many interaction terms in the same regression can lead to issues with multicollinearity (Khandker et al. 2010). Another way to present distributional impacts of cash transfer programmes is by using a quintile regression approach to assess the magnitude of impact for each strata of households. Simply investigating changes in the mean programme effect, even across different socioeconomic or demographic groups, may not be sufficient when the entire shape of the distribution changes significantly.

5 Results and Discussion

In this section, we synthesize key findings from the PtoP impact evaluation reports and discuss the results over three broad groups of outcome variables linked to household resilience: risk management including climate change, investment in livelihood activities and food security. We focus on the quantitative studies and where applicable we supplement the comparative analysis with results from the qualitative evidence that report on similar outcomes. The results discussed are taken from the following references: Asfaw et al. (2014, 2015a, b, 2016), Daidone et al. (2014a, b), AIR (2013), Handa et al. (2014) and Pellerano et al. (2014).

5.1 Can Cash Transfer Promote Ex-Post Risk Management?

By providing a reliable income stream, cash transfer programmes improve risk management by poor rural households. An extra source of income can help households provide for school fees and discourage the need for children to drop-out to work on farms. The transfers flowing in and out of households can also change, and households may engage more in social networks through increased giving and so perhaps be able to rely on these networks in the future. Households can also use that money to pay off debts, purchase on credit, or save the cash. Table 2 presents the cross-country summary of the impact of social cash transfers on risk coping strategies, access to credit, community relations, savings, and debt payments.

Beneficiary households were found to have relied less on risk coping mechanisms thanks to cash transfers. Asfaw et al. (2015b) found households in Malawi to shift away from undesirable ganyu labor as a result of the SCTP. Handa et al. (2015) also found that the SCTP reduced paid work outside the home for children aged 10–17. In the face of negative shocks, use of the cash transfers emerged as the pri-

Table 2 Synthesis of key findings

	Ghana	Kenya	Lesotho	Malawi	Zambia	Ethiopia
Ability to manage risk						
Risk coping mechanisms	+	N/E	+++	++	+	++
Savings	+	N/E	–	N/A	++	N/A
Purchase on credit	+	NS	NS	–	NS	0
Debt payment	++	N/E	–	++	+	N/E
Provide transfer	–	N/E	+	NS	N/E	–
Receive transfer	+	N/E	+	–	N/E	NS
Remittance receipt	+	N/E	–	N/E	N/E	N/E
Agricultural asset						
Agricultural tools	N/E	+	+	++	+++	0
Livestock ownership	N/E	++	+	+++	+++	0
Crop and livestock production and marketing						
Agricultural inputs	0	–	++	++	+++	0
Livestock inputs	N/A	0	0	N/E	NS	–
Land use	N/E	N/E	NS	N/E	++	N/E
Agricultural output	N/E	NS	++	++	++	++
Crop sales	N/E	N/E	0	++	++	0
Livestock by-products	N/E	N/E	+	N/A	N/A	0
Non-farm enterprise (NFE)	NS	0	–	0	+++	0
Household welfare						
Food security	+++	N/A	+++	+++	+++	+++
Consumption	NS	+++	+	+++	+++	++
Dietary diversity	0	+++	NS	N/E	++	+
Home consumption of crop production	N/E	+++	N/E	NS	+	N/E

Note: *N/A* not available, *N/E* not estimated, *NS* no shift, 0 overall mixed shift. + = significant positive impact; and – = significant negative impact. One, two or three '+' or '–' signs refer to the level of the impact

mary coping mechanism for a quarter of the negative shocks among SCTP beneficiary households, and there are declines in ganyu labor and in the use of savings as coping mechanisms. The authors also found a smaller percentage of households engaging in coping mechanisms for negative shocks, particularly for the poorest households (Handa et al. 2015). In Ethiopia, the SCTPP reduced the number of hours per day children were engaged in household activities. In particular, children aged 6–12 in beneficiary households worked fewer hours per day on the family farm and across all other activities compared to those in control households (Asfaw et al. 2015a). However, the impact was more mixed in Lesotho: while boys 13–17 may have seen a reduction in engagement in paid work outside the house, girls have seen an increase due to the CGP (Pellerano et al. 2014). Pellerano et al. (2014) found a reduction in the levels of engagement in occasional and irregular occupations among adults, noting the results to indicate that the cash support effectively worked as a safety net preventing households from depending on low paid and precarious occupations. The authors also found CGP beneficiaries to be less likely to send children to live elsewhere by 6 pp., send children to work by 3 pp., take children out of school by 8 pp., and reduce spending on health by 7 pp. as a response to shocks within 12 months previous to the survey.

The decreased need to engage in negative risk coping mechanisms as a result of cash transfers was also shown through increases in enrolment and other educational outcomes for children. Handa et al. (2015) found that children aged 6–17 increased their net enrolment by 12 pp. as a result of the SCTP in Malawi, with slightly stronger impacts considering primary and secondary school-aged children separately. The authors also found the dropout rate to have dropped for primary school-aged children by 4 pp. and temporary withdrawal (missing more than two consecutive weeks of instruction at any time in the past 12 months) to have decreased by 5 pp. By the endline in Ethiopia, Berhane et al. (2015) found the SCTPP to have raised enrolment by around 6 pp. pp. in Hintalo-Wajirat, with the effect for girls particularly strong (13 pppp). Instead of having to take time out of school to earn extra income, children were more readily participating in school thanks to the SCTPP. In Ghana, the LEAP programme reduced the likelihood of school-aged children (5–17) missing any school by 8 pppp and also reduced the chance of missing an entire week by 5 pppp (Handa et al. 2014). Among younger children smaller households appeared to be more protective, with a larger impact on missing any school in smaller households. However, the significant impact on enrolment is entirely driven by larger households. Handa et al. (2014) also found the impact on secondary enrolment for children aged 13–17 to be similar to estimates for South Africa's Child Support Grant (6 pp) and Kenya's CT-OVC (8 pp). While there were mixed results for engagement in paid work with the Lesotho CGP, the programme increased the proportion of children aged 6–19 enrolled in school by 5 pp., with a larger impact on older boys aged 13–17 (Pellerano et al. 2014). AIR (2013) noted that children living in a CGP beneficiary household in Zambia were 1 pp. more likely to ever enroll in school and 2 pp. more likely to enroll on time, for every year less of education their mother has. The authors attribute this effect to the CGP enabling or motivating mothers who did not enroll children in school at baseline to change their actions and start enrolling their children in school.

Cash transfer programmes were found to strengthen community ties through various channels, while the impact on private transfers was mixed. In Lesotho, the CGP had a significant impact in strengthening the reciprocity arrangements around food sharing in treatment villages. Both the proportion of households receiving and the proportion providing in-kind help in the form of food increased as a consequence of the programme. The impact is strong and significant, 15 and 18 pp. respectively, and the magnitude is larger for households with no labour capacity (Daidone et al. 2014b). Handa et al. (2014) found a positive impact on the value of gifts received and the amount of credit extended to others in Ghana. Meanwhile, in Malawi Asfaw et al. (2015b) found SCTP beneficiary households to be 4% points less likely to receive a transfer. In Ethiopia, Asfaw et al. (2015a) found increases in social capital and subjective belief of individuals' quality of life and control. Treated households were more likely to agree with additional support to poor people, have fewer problems with neighbors, and, similarly, agree that people residing in their community are basically honest and trustworthy. Other opinions of life satisfaction and ability to achieve success marked higher among male-headed beneficiary households compared to male-headed control households. However, there were no impacts observed in either receipt or giving of private transfers in Ethiopia.

Beneficiary households were also found to use proceeds from cash transfer programmes to pay off debts. In Ghana, Handa et al. (2014) observed beneficiary households saving more and being more likely to repay debt; smaller beneficiary households also reduced their likelihood of holding a loan by 9 pp. The authors also found a corresponding significant impact on the amount paid off of 19 pp. of adult equivalent consumption. In Malawi, households overall, and female-headed households and large farm households in particular, reduced debt from previous loans due to the SCTP. Male-headed households and large farm households were also less likely to still owe money for previously contracted loans (Asfaw et al. 2015b). Daidone et al. (2014a) also found larger households to pay down loans as a result of the CGP in Zambia.

5.2 Can Cash Transfer Contribute to Managing Climate Risk?

Climate change poses severe threats to households' wellbeing across the world, particularly in low-income countries where poor households are often exposed to different sources of risk. Adoption of risk management strategies, such as the promotion of social safety nets, are becoming gradually more relevant for improving the households' abilities to manage climate risk. Given the high incidence of climate shocks in Zambia, we also would like to present the findings of Asfaw et al. (2016) who shed light on how households respond to the CGP cash transfer in a context of weather instability. Asfaw et al. (2016) conducted additional analysis by merging the Zambia CGP impact evaluation data with rainfall data obtained from the Africa Rainfall Climatology v.2 (ARC2) (1983–2012).[1] They assessed whether regular and unconditional small cash payments (via the CGP) helped mitigate the negative effects of climate variability, protect and improve smallholders' livelihoods and ensure food security and nutrition.[2] The authors also investigated how the CGP and climate variability affect households on different quintile of the welfare and food security dimensions.

Asfaw et al. (2016) found the CGP to increase total/food and non-food expenditure, which implies the treatment increases households' welfare. As a result of an

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[1] Dekads (i.e. 10 days) at 0.1° covering the period 1983–2012 at ward level.

[2] The outcome variables in the study included total expenditure, food/non-food expenditure, daily caloric intake and dietary diversity index.

increase in food expenditure, both quantity and quality of food consumed responded positively to CGP receipt, implying that households benefitted from the CGP in terms of food security and nutrition. With regards to the effect of climatic variables on welfare and food security, results from Asfaw et al. (2016) show that overall, households in areas that experienced lower than average rainfall had lower levels of daily caloric intake as well as food and non-food expenditures, and this effect was most pronounced for the poorest households in the sample. A possible explanation could be that the decline in rainfall had an initial negative impact on agriculture, livestock production and other water-intensive activities. The decline in volume of production thus affected households' purchasing power, forcing them to improve their coping mechanisms.

This study also finds strong evidence that cash transfer programmes have a mitigating role against the negative effects of climate shocks. Households that participated in the CGP had much lower negative effects of the weather shock, with poorest households gaining the most. This indicates the potential of social protection to support food access for households exposed to climate risk. However, the analysis also indicates that while participation in the CGP is beneficial in mitigating negative effects of climate shocks on food security, it is not sufficient to fully overcome these effects. Thus it is important to ensure that SCTs are well aligned with other forms of livelihood programmes and climate risk management, including disaster risk reduction activities. This result confirms the findings of authors like Eriksen et al. (2005), who found a positive relationship between the ability of people to draw on extra sources of income and the ability to withstand droughts in Tanzania and Kenya, with respect to those who were not.

5.3 Potential of Cash Transfer to Promote Ex-Ante Risk Management

Cash transfers contribute to ex-ante risk management by increasing household adaptive capacity through accumulation of productive assets, increased crop and livestock production and productivity, and linkages with output markets. We look at various dimensions of the productive process in order to ascertain whether households were found to have increased spending in livelihood activities, including crop production, crop input use and asset building. Given that agriculture represents the primary economic activity of the households studied, investment in agricultural assets and increases in crop production prove critical for strengthening livelihoods and ex-ante risk management. Households can also enhance their resilience by diversifying into different income streams, such as non-farm enterprises. Table 2 presents the cross-country summary of the impact of SCTs on investment in livelihood activities.

5.3.1 Impacts on Accumulation of Productive Assets

Beneficiary households overall (and larger sized households in particular) in Zambia owned more axes and hoes, and were more likely to own hammers, shovels, and ploughs as a result of the cash transfer programme (Daidone et al. 2014a). Beneficiary households in Kenya were more likely to own troughs, and male-headed households were also more likely to own machetes and sickles (Asfaw et al. 2014). In Lesotho, Daidone et al. (2014b) found the CGP to increase the use and purchase of scotch-carts. In Malawi, beneficiary households overall, both female and male-headed households, and large farm households owned more agricultural implements (Asfaw et al. 2015b). Handa et al. (2015) also found the SCTP to increase crop production and agricultural assets (sickles in particular). In terms of agricultural asset ownership, beneficiary households in Hintalo-Wajirat were 6 pp. and 7 pp. more likely to own plows and imported sickles, respectively (over baseline shares of 47% and 41%). In contrast, beneficiary households in Abi Adi were less likely to own those agricultural implements. In terms of number owned, there were more negative effects throughout (Asfaw et al. 2015a). However, Berhane et al. (2015) found the SCTPP in Ethiopia to increase a constructed farm productive assets index by 2% in Hintalo-Wajirat.

Cash transfers also led to increased livestock ownership in SSA, particularly of smaller animals. Both small and large beneficiary households in Zambia increased livestock ownership, but the impacts were stronger for large households (Daidone et al. 2014a). Smaller households and female-headed households in Kenya increased their ownership of small livestock (such as sheep and goats) compared to control households. For smaller households, there was about a 15 pp. increase in ownership of small livestock compared to control households, while female-headed households receiving the transfer increased their ownership by 6 pp. (Asfaw et al. 2014). Daidone et al. (2014b) also found the cash transfer in Lesotho to have increased the proportion of households owning pigs by about 8 pp. as well as to have increased the number of pigs owned by 0.1 pp. Whether by number of livestock owned or livestock ownership, SCTP beneficiaries in Malawi faced increases on livestock (also noted by Handa et al. (2015)), such as on chickens, goats and sheep, and pigs (Asfaw et al. 2015b). Meanwhile, in Ethiopia Asfaw et al. (2015a) found the impact on livestock ownership to be more mixed, depending particularly on the area in which the transfer was given. Berhane et al. (2015) found the SCTPP in Ethiopia to increase the likelihood that households own any form of livestock by 7% in Hintalo-Wajirat, with the increase largely driven by the increase in poultry ownership.

5.3.2 Impacts on Crop Production and Productivity

The cash transfer programmes evaluated generally led to increased crop production and productivity. Aggregating all crop output by value, the GCP in Zambia increased the value of all crops harvested by ZMK 146, approximately a 50% increase from baseline, with a larger value increase for smaller households at ZMK 182.

Beneficiary households increased their crop production marketing by 12 pp. and also increased their average value of sales (Daidone et al. 2014a). Production of maize, the main staple commodity, increased in CGP households in Lesotho by around 39 kg more than the control group, and more so for households with more available household labour. Sorghum production increased by around 10 kg, with a larger impact in severely constrained households, likely because sorghum requires less labour as compared to other major crops. Furthermore, results on home gardening were consistently larger for unconstrained and moderately labour-constrained households compared to households with no adult members fit to work (Daidone et al. 2014b). In Malawi, beneficiary households increased groundnut production and productivity, with fewer and mixed impacts on other crops. Medium farm households and male-headed households also increased maize yields. Ultimately, both male-headed households and medium farm households increased the value of crop production as a result of the SCTP. Households were more likely to sell any crop, and the value of crop sold increased for female-headed households, small farm households, and medium farm households (although it decreased for large farm households) (Asfaw et al. 2015b). In Ethiopia, Asfaw et al. (2015a) found households to have decreased their yield of sorghum but to have increased sorghum yields, particularly in Hintalo-Wajirat and among male-headed households. Ultimately, beneficiary households increased the total value of their crop production by 18%. For the Kenya CT-OVC, Asfaw et al. (2014) found little impact of the programme on crop production. However, there was an impact on the proportion of food consumption coming from own production, particularly for smaller-sized households and female-headed households. The average treatment effect for the share of consumption from home produced dairy and eggs was 20 pp. for smaller households and 15 pp. for female-headed households.

Increased crop production and productivity for beneficiary households also came through increases in land and crop input use. The CGP in Zambia increased the amount of operated land by about 34% from baseline, and 18 pp. more households spent money on inputs, from a baseline share of 23%. This increase in money spent on inputs was particularly relevant for smaller households (22 pp), and included spending on seeds, fertilizer and hired labour. The increase of 14 pp. in the proportion of small households purchasing seeds is equivalent to more than a doubling in the share of households. Small beneficiary households spent ZMK 42 more on crop inputs than the corresponding control households, including ZMK 15 on hired labour, amounting to three times the value of the baseline mean for overall spending, and four times for hired labour (Daidone et al. 2014a). The CGP in Lesotho significantly increased the share of beneficiary households using pesticides (8 pp), especially those who are labour-unconstrained and who are also more likely to purchase pesticides as a result of receiving the CGP. Households purchased seeds more often (7 pp), although there was no statistically significant change in the intensity of purchase (Daidone et al. 2014b). In Malawi, household expenditure on organic fertilizer increased by MWK 158 (from a baseline of MWK 245). Increases on organic fertilizer expenditure also were found at the disaggregated levels (aside from medium farm households, which faced no increase) and at expenditure-per-acre

(Asfaw et al. 2015b). An increase in the likelihood of chemical fertilizer use is also found among male-headed households. In the case of the Ethiopia SCTPP, female-headed beneficiary households were 4 pp. more likely to practice a soil and water conservation technique on their land, a noticeable increase on their baseline mean of 14%. Female-headed households were also 3 pp. more likely to hire labour for farm work from a low baseline mean of 5% (Asfaw et al. 2015a).

5.3.3 Impacts on Non-farm Enterprises

On non-farm enterprises cash transfer programmes were found to have mixed results. In Zambia, non-farm work increased by 20 days overall among beneficiaries and non-farm enterprise by 1.6 days (AIR 2013). Cash beneficiary households participated more often in non-farm enterprises in Kenya if they were female-headed, but less so if they were male-headed; otherwise, there was no impact recoded for the overall sample (Asfaw et al. 2014). In Malawi, results on non-farm enterprise labor were mixed, where beneficiary households were less likely to engage in charcoal/firewood enterprises but were more likely to engage in petty trade enterprises (Asfaw et al. 2015b). In Ethiopia (Asfaw et al. 2015a) and in Ghana (Handa et al. 2014) there were no impacts found on the overall level on the likelihood that households participated more or less often in non-farm enterprises. Pellerano et al. (2014) found a reduction in the proportion of households with an enterprise in operation in the 30 days prior to the survey, but noted that the reduction was mainly driven by households engaging less frequently in home brewing, which is generally small scale and a livelihood strategy of last resort.

5.4 Can Cash Transfer Promote Resilience by Enhancing Food Security?

Households consistently more able to consume an adequate amount of food and a more diverse basket are necessarily more resilient and less food insecure than otherwise similar households. Depending on the availability of data across the different countries, we collected the impacts of cash transfer programmes on consumption, dietary diversity and subjective food security indicators. Table 2 presents the cross-country summary of the impact of social cash transfers on food security, consumption and diet diversity.

5.4.1 Impact on Food Security

As expected, the studied cash transfer programmes unambiguously increased the food security of beneficiary households. The CGP in Zambia increased the percentage of households eating two or more meals per day by 8 pp. as well as the number of households that were not severely food insecure by 18 pp., (AIR 2013). The share of households consuming from part of their harvest also increased by 6 pp., which came from increased groundnut and rice consumption of home production (Daidone et al. 2014a). In Lesotho, Pellerano et al. (2014) found the CGP to reduce the number of months that households experienced shortages of food and decrease the proportion of households not having enough food to meet their needs at least for one month in the previous 12 months. Food security also increased in Malawi thanks to the cash transfer programme: households overall, for example, were 11 pp. less likely to worry whether they would have enough food in the past seven days. The SCTP also allowed households to eat more meals per day, with effects observed for households at all levels except for large farm households. Medium farm households also increased the number of months that last year's maize harvest lasted (Asfaw et al. 2015b). In Ethiopia, there was a reduction on the number of months with problems satisfying food needs in the overall sample and among male-headed households. There was no impact on number of months in the last 12 months that the household ran out of home-grown food, but there were increases on both the number of times a day children ate in the household and the number of times adults ate in the household. Compared to control households, beneficiary households were also less likely to suffer a shortage of food to eat during the last rainy season as a result of the SCTPP. With regards to measures of last resort, beneficiary households reduced their likelihood of consuming seed stock during the last week, compared to control households (Asfaw et al. 2015a).

5.4.2 Impact on Consumption Expenditure

Cash transfers also enabled households to better meet their consumption needs. In Zambia, the programme significantly increased food spending, with the largest share going to cereals, followed by meats, including poultry and fish, followed by fats such as cooking oil and then sugars (AIR 2013). The share of households consuming from part of their harvest also increased by 6 pp., which came from increased groundnut and rice consumption of home production (Daidone et al. 2014a). In Lesotho, Pellerano et al. (2014) detected a statistically significant CGP effect on food expenditure and total consumption when controlling for covariates, including differences in prices across locations, but at low levels of significance. In Kenya, although there was no significant impact on consumption expenditure of cereals and legumes, there was an increase for food spending on dairy and eggs. The programme had no effect on spending on most of the food consumption categories for larger households but it had large increases on three of the outcomes (dairy and eggs, meat and fish and fruit) for smaller households. The programme had larger and positive impacts on female-headed households compared to male-headed households, as in the case of the share of consumption from home produced dairy and eggs. Treated households in Kenya also appeared to consume more animal products, as well as other foods, from their own production compared to control households (Asfaw et al. 2014). In Malawi, there were increases at all levels of daily per capita calories consumed, with those increases in calories coming from food purchases; aside from a decrease for male-headed households, there are no impacts on calories coming from own production. Such results suggest that households are likely using the cash to buy food directly, although calories coming from own production may take more time to see impacts. For both extremely-poor and non-extremely poor household, the pattern holds up: increases in calories consumed come from purchases rather than from own production, with decreases in calories consumed coming from gifts and other sources (Asfaw et al. 2015b). Berhane et al. (2015) found the SCTPP in Ethiopia to reduce the food gap, increase the availability of calories, and to reduce seasonal fluctuations in children's food consumption (Berhane et al. 2015). Meanwhile, Handa et al. (2014) found in Ghana that there was no overall change in food consumption between treated and control households.

5.4.3 Impact on Dietary Diversity

There is also some evidence of improved dietary diversity as a result of cash transfer programmes. There was a clear shift away from roots and tubers (primarily cassava) and toward protein (dairy, meats), indicating a possible improvement in dietary diversity among CGP recipients in Zambia (AIR 2013). In smaller households, the impact of the CGP on food expenditures was concentrated on cereals (where 45% of the impact on food is derived) followed by meat (15%), fats (14%), and pulses (13%). Among larger households, the impact of the grant on food expenditures is driven by meats (32%) and then cereals (30%). In the end, food expenditures increase for both groups of households as a result of the cash transfer programme (Daidone et al. 2014a). In Kenya, the results showed no significant impact on consumption expenditure of cereals and legumes. However there was about a 12 pp. increase for food spending on dairy and eggs. The programme had no effect on spending on most of the food consumption categories for households with larger number of members but it had large, positive, and significant effects on three of the outcomes (dairy and eggs, meat and fish and fruit) for smaller sized households. The programme typically had larger and positive impacts on female-headed households compared to male-headed households, such as on consumption of animal products. Treated households also appear to have consumed more animal products, as well as other foods, from their own production compared to control households. Dairy and eggs consumption from own production increased by about 13 pp. for beneficiary households, and the impact on other types of foods was about 4 pp. The average treatment effect for the share of consumption from home produced dairy and eggs was 20 pp. for smaller households and 15 pp. for female-headed households (Asfaw et al. 2014). In Ethiopia, results from Asfaw et al. (2015a) showed an increase in household consumption of oils and fats, sweets, and spices, condiments, and beverages as a result of the SCTPP. This was mixed with reductions in household consumption of fruits and meats. Berhane et al. (2015) found the SCTPP to have improved diet quality, as measured by the Dietary Diversity Index, in both May 2012 and May 2014 by 13% and 12% respectively. In Ghana, although there was no overall change in food consumption between treated and control households, Handa et al. (2014) found a significant decline in starches and meats and an increase in fats and food eaten out. Smaller households also faced a decline in alcohol and tobacco consumption. Among Lesotho CGP beneficiaries, the increased spending on dairy and eggs (as well as meat/fish and fruit for smaller households) did not translate into an impact on dietary diversity (Pellerano et al. 2014).

6 Conclusions and Implications

The analysis of impact evaluation studies show that cash transfer programmes overall have important implications for household resilience. By providing a steady and predictable source of income, cash transfer programmes can build human capital and improve food security and potentially strengthen households' ability to respond to and cope with exogenous shocks, and allow them to diversity and strengthen their livelihoods to prevent future fluctuations in consumption. Many of the programmes studied increased investment in agricultural inputs and assets, including farm implements and livestock. Beneficiaries in the studied country programmes generally increased crop production and value of crop production. Although differing across countries, food security indicators revealed increases in the proportion of households being food secure as a result of cash transfer programmes. This too was met by increases in consumption and dietary diversity. Although the impacts on risk management are less uniform, the cash transfer programmes seem to strengthen community ties (via increased giving and receiving of transfers) allow households to save and pay off debts, and decrease the need to rely on adverse risk coping mechanisms. Finally, the case study of the CGP in Zambia demonstrates the potential for cash transfers to help poor households manage climate risk. Not only was CGP receipt associated with increases in total/food and non-food expenditure, and subsequently the quantity and quality of food consumed, but the CGP was also found to benefit households even when they were facing climate shocks. The CGP's climate mitigating effect is particularly evident for households at the lowest quintiles of the distribution, meaning that the CGP better protects poorer households against climate variability than richer households. Thus cash transfers can improve poor households' resilience for an uncertain future in terms of climate change.

The differences in impacts across countries can be attributed to a variety of factors, including the availability of labour given the demographic profile of beneficiary households, the relative distribution of productive assets, the local economic context, the relevance of messaging and soft conditions on spending and the regularity and predictability of the transfers themselves. In the case of LEAP in Ghana, irregular payments may have prevented households from increasing consumption, as consumption is driven by permanent income. Instead, the lumpy flow of cash seems to have promoted declines in the number of households with outstanding loans and increases in the number of households with savings. In Ethiopia, the SCTPP targeted households that were particularly made up with either the elderly or youth, which may explain why beneficiary households did not face increases in labour supply or on other dimensions of agricultural production. The amount offered through the Ethiopia SCTPP as a percentage of per capita income is also not as high compared to cash transfer programmes that have found widespread impacts.

Cash transfers can be more than just social assistance; not only can they help vulnerable households avoid the worst effects of severe deprivation, they can also contribute to economic and social development. Since cash transfer programmes impact the livelihoods of households, articulation with other sectoral development programmes in a coordinated rural development strategy could lead to synergies and greater overall impact. Complementary measures to maximize the positive spillover effects of the income multiplier generated by the cash transfer programme should be targeted not only at cash transfer beneficiary households, but also at ineligible households that provide many of the goods and services in the local economy. However, the potential productive impact of the cash transfer is sensitive to implementation, and delays and irregularities in payment can reduce its effectiveness in terms of helping households invest and manage risk.

Existing social protection programmes rarely takes into account climate risk in their design and implementation. Being poverty reduction instruments, social safety-net interventions tend to target mainly economic (wealth and income) criteria. Including environmental risks and vulnerabilities as targeting criteria could help improve the effectiveness of safety nets as risk-coping instruments. This could be done by developing maps of poverty and climate change vulnerability hotspots or by ensuring effective linkage between social protection management and information and early warning systems. Public works programmes, including productive safety nets, can be designed in ways that simultaneously contribute to increasing household incomes, engaging communities in climate-smart agriculture and generating ‘green jobs’ in areas such as waste management, reforestation and soil conservation.

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Input Subsidy Programs and Climate Smart Agriculture: Current Realities and Future Potential

Tom S. Jayne, Nicholas J. Sitko, Nicole M. Mason, and David Skole

Abstract The achievement of Climate Smart Agriculture (CSA) goals in Africa will require widespread farmer adoption of practices and technologies that promote resilience and system-wide collective action to promote *ex ante* climate risk management activities and *ex post* coping strategies. Leveraging public sector resources is critical to achieve goals at scale. This study examines the scope for input subsidy programs (ISPs) to contribute to achieving CSA objectives in Africa. Available evidence to date suggests that in most cases ISPs have had either no effect on or have reduced SSA smallholders' use of potentially CSA practices. However, recent innovations in ISPs may promote some climate smart objectives by contributing to system-level *ex-ante* risk management. In particular, restricted voucher systems for improved seed types that utilize private sector distribution supply chains may prove capable of promoting CSA goals. Generally, moving from systems that prescribe a fixed input packet to a flexible system with a range of input choices holds promise, but fixed systems still hold some benefits. Conditional ISPs would require improved monitoring and compliance as well as defining practices with clearly measurable productivity benefits vis-à-vis CSA goals. The potential of ISPs to achieve widespread CSA benefits must address these challenges and be evaluated against benefits of investments in irrigation, physical infrastructure, and public agricultural research and extension, which may generate higher comprehensive social benefits.

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1 Introduction

There is growing global recognition of the urgent need to identify and implement strategies that make food systems more resilient in the face of increasing climate variability. Nowhere is this more evident than in Sub-Saharan Africa.[1] Because the majority of Africans' livelihoods and agrifood systems rely on rainfed farming, Africa is one of the world's regions most vulnerable to climate change. The Intergovernmental Panel on Climate Change concluded that "climate change is expected to have widespread impacts on African society and Africans' interaction with the natural environment" (IPCC 2014, p. 812).

Climate smart agriculture (CSA) has emerged as an approach to enhance the resilience of farm systems to the effects of climate change. CSA is defined by three principle objectives (FAO 2013):

1. sustainably increasing agricultural productivity and incomes;
2. adapting and building resilience to climate change, and;
3. reducing and/or removing greenhouse gases emissions, where possible.

In Africa and other predominantly agrarian regions, there is particular interest in identifying strategies to encourage farmers to adopt practices and technologies that enable more resilient, sustainable and productive farms, while at the same time identifying system-wide collective action to promote a wide range of *ex ante* risk management activities and *ex post* coping strategies. Given the scope and scale of these requirements, leveraging public sector resources is critical.

Input subsidy programs (ISPs) provide a potentially useful means to encourage system-wide coordination and farmer behaviours that raise agricultural productivity and contribute to resilience objectives in Africa, while potentially mitigating the agricultural sector's contribution to GHG emissions. ISPs vary in their distribution modalities and targeting requirements, but generally share the common attributes of providing inorganic fertilizer, and in some countries, improved seeds, to farmers at below-market prices. Many African governments currently devote a large share of their agricultural sector and national budgets to ISPs. The region spends just over US$1.0 billion each year on ISPs (Jayne and Rashid 2013; Jayne et al. forthcoming). A major challenge to enabling ISPs to promote CSA outcomes stems from the major opportunity costs they entail in terms of foregone public spending on other core CSA investments such as irrigation, agricultural R&D, and extension services that could potentially promote CSA practices more effectively per dollar invested than ISPs. However, there is clearly scope for market-smart ISPs to improve smallholder farmers' access to climate smart technologies and overall resilience. This paper assesses the feasibility of leveraging public investments in ISPs to promote adoption of CSA practices and technologies by African farmers.

The paper is organized as follows. Section 2 begins by defining CSA in the context of African smallholder farming systems. Section 3 briefly examines the range

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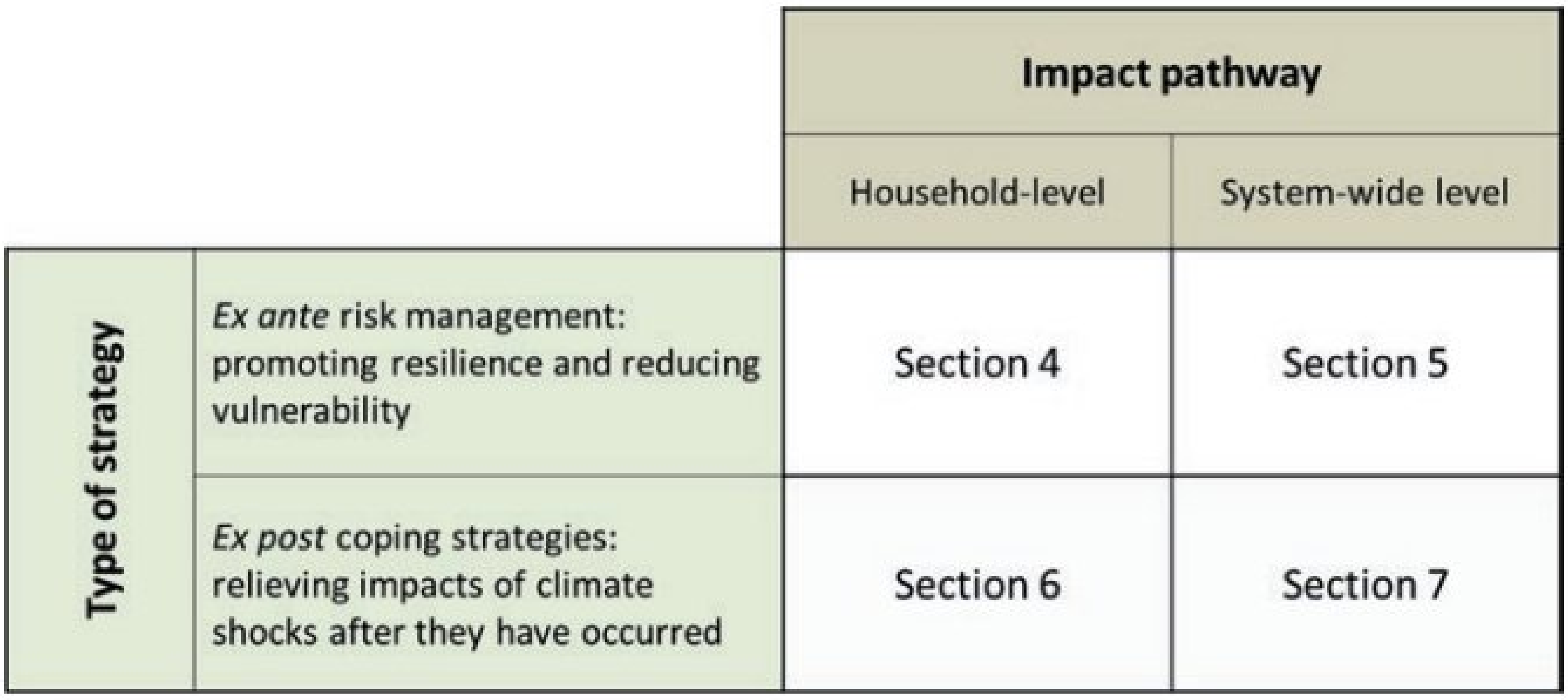
[1] Hereafter "Africa".



		Impact pathway	
		Household-level	System-wide level
Type of strategy	*Ex ante* risk management: promoting resilience and reducing vulnerability	Section 4	Section 5
	Ex post coping strategies: relieving impacts of climate shocks after they have occurred	Section 6	Section 7

Fig. 1 Various dimensions of how input subsidy programs might contribute to climate smart agriculture

of ISP implementation modalities and approaches in Africa. In Sects. 4, 5, 6, and 7, we adopt the 2×2 matrix framework of Lipper and Zilberman (forthcoming) to consider how ISPs may promote resilience of farming systems in the face of climate shocks through *ex ante* risk management strategies, and how ISPs might be designed to mitigate the effects of climate shocks through *ex post* coping strategies. These impact pathways are evaluated across household/farm level and responses at the system-wide/government level (Fig. 1). Section 4 focuses on household-level *ex ante* risk management strategies. Section 5 focuses on system-wide *ex ante* risk management strategies. Section 6 examines the ability of ISPs to support household-level *ex post* responses to climate shocks. Section 7 examines system-wide *ex post* strategies. Section 8 summarizes our findings and discusses potential implications for ISP policies and programs.

2 Defining Climate Smart Agriculture

Although not clearly defined in the academic literature, the term "climate smart agriculture" (CSA) has gained prominence as an emergent agricultural development paradigm (Engel and Muller 2016). The UN Food and Agricultural Organization (FAO), the principle architect of CSA, defines it as an approach that "sustainably increases productivity and resilience (adaptation), reduces/removes GHGs (mitigation), and enhances achievement of national food security and development goals" (FAO 2010, p. ii; FAO 2013). CSA is therefore largely defined by its intended outcomes rather than by a set of specific practices or approaches (Kaczan et al. 2013).

CSA shares many objectives and guiding principles with green economy and sustainable development approaches, including a prioritization of food security and a desire to preserve natural resources. It is also closely linked to the concept of sustainable intensification (SI) (FAO 2013; Campbell et al. 2014). In many cases, SI constitutes a subset of practices that are potentially climate smart under certain current and future climatic conditions. As the FAO Sourcebook on CSA (2013) states, CSA extends these concepts through "a more forward looking dimension, more concern about future potential changes and the need to be prepared for them" (p. 30). Thus, CSA is not a set of new agricultural practices or a new agricultural system. Instead, it is understood as a new approach to guide necessary changes to agricultural systems in order to jointly address challenges of food security and climate change (Lipper et al. 2014; Branca et al. 2011; FAO 2013; Grainger-Jones 2011).

Proponents of CSA emphasize several hallmarks of its approach. First, CSA focuses on risks throughout the food system, with a particular emphasis placed on *ex ante* risks to smallholders resulting from the interaction of changing climate with existing livelihood vulnerabilities (McCarthy et al. 2011; Meinzen-Dick et al. 2013; Grainger-Jones 2011; World Bank 2011). Second, elevating the visibility of emergent risks that smallholders face offers opportunities to focus strategically on practices and technologies that offer multiple benefits in the areas of climate change adaptation, mitigation, and food security. Finally, by linking climate change adaptation and mitigation to smallholder production practices, CSA creates opportunities to link smallholders to previously unavailable sources of support, including climate finance (Meinzen-Dick et al. 2013; Grainger-Jones 2011).

There are a number of SI practices that are often linked to CSA objectives. These include: minimum soil disturbance (zero or minimum tillage); crop rotation and intercropping, particularly with legumes; mulching; crop residue retention; cover cropping; agro-forestry; water management, including irrigation and drainage; integrated soil nutrient management, including efficient use of mineral fertilizer in combination with organic sources; and use of high quality, well-adapted seed varieties. In many cases, these are not new practices, but adoption rates in Africa remain low or sub-optimal (Branca et al. 2011). For the purpose of this paper we will refer to these practices collectively as SI practices, recognizing that they are also closely linked to CSA objectives.

3 ISP Implementation Modalities and CSA in Africa

Following the implementation of structural adjustment programs, spending on ISPs in Africa declined substantially. Yet, in the wake of the global food price spike of 2007/2008 and based on the apparent success of Malawi's subsidy program, Africa has seen a resurgence of ISPs. According to Jayne and Rashid (2013), by 2011 ten African countries spent over $1.05 billion on ISPs, or roughly 28.6% of these countries' total public agricultural expenditures.

The majority of new ISPs in Africa focus on subsidizing improved seed and inorganic fertilizers for staple cereal production by smallholder farmers. A few also provide subsidies for small grains and legumes. Variations in ISP design are most notable in terms of: (i) the extent to which the private sector is utilized to distribute inputs, (ii) the range of inputs available to farmers, and (iii) the socio-economic characteristics of the target beneficiaries.

The distribution system and flexibility of input choices for farmers have important implications for their climate smartness. Most ISPs utilize closed voucher systems, where farmers redeem coupons for a prescribed input packet from government-run or designated outlets, or direct delivery systems, where government or contractors deliver prescribed input packets. These types of systems tend to limit farmers' choice of inputs, are rarely attentive to agro-ecological and livelihood variations across space, crowd out private sector participation, and are frequently characterized by elite capture of inputs (Ricker-Gilbert et al. 2011; Mason and Ricker-Gilbert 2013; Pan and Christiaensen 2012; Mason et al. 2013; Lunduka et al. 2013). Such systems, like those in Zambia and Malawi, tend to undermine the development of private sector market channels, encourage mono-cropping and incentivize the production of crops in regions where they are poorly suited (Mason et al. 2013; Lunduka et al. 2013; Levine 2015). These outcomes are clearly contrary to the goals of CSA.

Recently, however, countries have begun to take tentative steps toward implementing more flexible, open voucher systems for ISPs in order to address some of these shortcomings. In Zambia for example, an electronic voucher system was piloted on a limited scale in 2015/2016, where farmers redeem vouchers with registered private sector dealers for a wide range of inputs. These systems can lower ISPs fiscal cost to government, encourage private investments in input supply systems and extension, and allow farmers to choose appropriate inputs (Sitko et al. 2012). These outcomes are decidedly more climate smart than the dominant model.

However, trade-offs exist between the relative flexibility of an ISP and the promotion of particular technologies or farm practices that may be climate smart. For example, open voucher systems may be less effective for promoting the adoption of seed varieties that are drought, heat, or flood tolerant, as there is no way to ensure that farmers will choose these seed types with a completely open voucher. More closed voucher systems may be more appropriate for encouraging the use of particular technologies. Similarly, closed voucher programs may help private seed firms to forecast demand for seed types, such as legume seeds, which is notoriously difficult to predict from year to year. By providing clarity on the effective demand for particular inputs, closed vouchers systems may prove useful to help overcome input supply constraints that hinder the adoption of certain potential SI and CSA practices, such as legume intercropping and rotations.

4 Can ISPs Promote Household-Level *Ex Ante* Risk Management?

Having reviewed in general terms how ISPs are implemented and potential linkages to SI and CSA practices, we now examine specific strategies that may foster more climate resilient and productive smallholder farm systems. The sorts of SI and CSA management practices we examine include tillage method, intercropping and rotations, the use of manures and residue retention, and agro-forestry, *inter alia*. More broadly, we explore the potential relationship between ISPs and practices that can potentially improve soil characteristics and stabilize yields in the context of climate variability.

4.1 Review of Evidence to Date

The evidence base remains thin but the weight of the available evidence suggests that ***ISPs have had either no effect on or have reduced African smallholders' use of CSA practices***. Empirical evidence across many case studies shows mixed results for many CSA practices considered. In addition, studies show the difficulties posed by delivery mechanisms that provide inputs too late for effective and efficient use by farmers. Finally, the absence of robust agricultural extension services in many African countries makes the diffusion and implementation of CSA practices even more challenging.

More specifically, evidence suggests that ISPs did not affect Ghanaian farmers' investment in soil and water conservation, broadly defined (Vondolia et al. 2012), nor did they affect Malawian or Zambian smallholders' use of manure (Holden and Lunduka 2010, 2012; Levine 2015). And while Malawi's ISP had no statistically significant effect on intercropping (Holden and Lunduka 2010), Zambia's ISP has reduced intercropping in general, but not intercropping involving legumes (Levine 2015). Moreover, Zambia's ISP has negatively affected crop rotation and fallowing (ibid; Mason et al. 2013). The program has contributed to continuous cultivation of mono-cropped maize over time and within seasons, which leave smallholders more vulnerable to climate shocks – the antithesis of CSA. ISPs may increase maize yields in the short run except during extreme weather conditions (see Holden and Lunduka 2010; Mason et al. 2013; Chibwana et al. 2014; Mason et al. 2015; among many others). However, if results similar to Zambia are obtained elsewhere, these yield gains could be coming at the cost of lower soil organic matter and higher soil acidity, both of which will result in lower yields and fertilizer use efficiency in the medium to long run (Marenya and Barrett 2009; Burke 2012).

Empirical evidence on the effects of ISPs on crop diversification is mixed. For example, while Chibwana et al. (2012) and Mason et al. (2013) find that ISPs in Malawi and Zambia, respectively, incentivize households to devote a greater share of their cropped area to maize, other studies from Malawi suggest the opposite (Holden and Lunduka 2010; Karamba 2013) or that ISPs have no statistically significant effect on crop diversification (Karamba 2013). Most likely, the effects of ISPs depend on the range of inputs provided. ISPs that focus less on a specific crop and support a broader range of alternative crops, in particular legumes that add biomass and moisture retention to soil, may generate better outcomes with respect to crop diversification and soil fertility, responsiveness of crops to inorganic fertilizer and other benefits (Snapp et al. 2010).

While ISPs may contribute to sustainable productivity growth by maximizing fertilizer to crop output efficiency, their track record has been disappointing. Jayne et al. (forthcoming) conclude that most African governments to date have focused more on increasing African farmers' use of fertilizer than on providing support for its efficient use.

Another feature of many ISPs that is decidedly *not* climate smart is perennial late delivery of subsidized fertilizer and seeds to beneficiary farmers (Xu et al. 2009; Lunduka et al. 2013; Mason et al. 2013; Namonje-Kapembwa et al. 2015). Late delivery is particularly common when ISP inputs are disseminated through dedicated ISP distribution systems that largely sideline existing input distribution networks. This is how fertilizer for Malawi's ISP and both fertilizer and seed for Zambia's ISP were distributed until 2014/15 and 2015/16, respectively, when each country started piloting agrodealer-based voucher redemption systems (Logistics Unit 2015; ZMAL 2015a; b). Late delivery of ISP inputs results in late planting and/or late fertilizer application, reducing yields and leaving beneficiary households more vulnerable to climate shocks (Xu et al. 2009; Namonje-Kapembwa et al. 2015; Arslan et al. 2015).

Most public agricultural extension systems are seriously under-provisioned to perform their multiple mandates of providing new management advice to farmers, learning from their efforts and difficulties of implementation and liaising with adaptive research systems to generate and disseminate new productive and sustainable practices, including SI practices. Some African public extensions are virtually defunct. Therefore, it should not be surprising that despite heavy spending on ISPs, their impacts on crop yields have been smaller than anticipated (ibid). In Zambia and Malawi, for example, a one-kilogram increase in subsidized fertilizer raises smallholder households' maize output by an average of only 1.88 kg and 1.65 kg, respectively (Mason et al. 2013; Ricker-Gilbert et al. 2011). This low crop yield response to fertilizer is a major reason for the relatively low benefit-cost ratios of the ISPs in Malawi (1.08) and Zambia (0.92) (Jayne et al. 2017).

In response to some of these limitations, many ISPs are currently transforming to more flexible, private-sector, inclusive systems. This creates possibilities for ISPs to be restructured in ways that incentivize farmers to adopt particular SI practices and also bring about system-wide changes that promote resilience. The remainder of this section examines this potential of ISPs, however the discussion is largely conjectural given the limited evidence that ISPs as implemented to date have achieved such benefits.

4.2 Looking Forward: Can ISPs Contribute to Climate Smart Farm Management Practices?

A handful of *ex ante* analyses have explored how ISPs might compare to other programs to promote farmers' use of practices that may be climate smart. For example, Marenya et al. (2012) use 30-year crop simulation models for maize, rice, and sorghum calibrated for several districts in Kenya, Malawi, and Uganda to compare changes in the net present value (NPV) of adopting various soil fertility management (SFM) strategies under two sets of policy regimes: a 50% fertilizer subsidy and carbon credits priced at \$4, \$8, or \$12 per metric ton of carbon sequestered in the soil. The SFM strategies considered include various combinations of inorganic (N) fertilizer, animal manure, and crop residue retention – practices that may be 'climate smart' in some contexts. Their results suggest that carbon credits, especially when priced at \$8 or \$12/mt, produce larger NPV increases than the 50% fertilizer subsidy. While carbon markets are virtually non-existent in Africa, this analysis suggests monetary incentives play an important role in stimulating adoption of climate smart practices. This leaves room for ISPs to deliver monetary incentives to such ends. Yet, this in turn requires that extension systems are capable of delivering appropriate management information and that adoption is effectively monitored, which seems very challenging.

In later work, Marenya et al. (2014) use choice experiments to measure Malawian smallholder farmers' preferences for various hypothetical policy incentives to adopt soil conservation practices, namely minimum tillage with legume intercropping: cash payments, two different types of index-based crop insurance contracts, and fertilizer subsidies.[2] Results suggest that most farmers preferred fertilizer subsidies to cash payments or crop insurance. In addition, farmers generally preferred cash payments to crop insurance, even when the expected payout from the crop insurance was higher than the cash payment. We must be careful, however, in generalizing these results, as they are specific to the choice sets used in the experiments. For example, the expressed preference of fertilizer subsidy over cash payments is likely driven by the fact that cash payment options (ranging from MK 800 to MK 2000) were lower compared to fertilizer subsidy (MK 2000) because of the expected yield gains with fertilizer. Even still, both cases suggest that under the right conditions some combination of conditional subsidy or conditional cash payment can incentivize adoption of farm management practices. Whether or not this leads to a permanent behavioral change, or whether public entities are capable of monitoring adherence to the conditions, remains an open question.

Finally, there is the question about whether raising crop productivity through inorganic fertilizer use might reduce the rate at which forests are converted into farmland and therefore reduce the agricultural sector's contribution to GHG emissions. Recent evidence has begun to question the logic that agricultural productivity growth can arrest rapid farm area expansion and thus conserve the world's forests and grasslands (Hertel 2011; Robertson and Swinton 2005; Byerlee et al. 2014). Instead, a generally positive area response to improved profit incentives is likely to create new pressures for further area expansion and conversion of forest and grasslands to farmland. Policy incentives could play a potential role here. In theory, ISPs could be structured in such a way as to oblige beneficiaries to reduce or maintain the amount of area under cultivation. However, it is not clear whether such

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[2] Farmers also had the option to decline the soil conservation incentives in favor of continuing 'traditional' practices, which in the context of the choice experiments were defined as not using chemical fertilizer or the soil conservation practices.

rules would impose unreasonable demands on food insecure rural households or whether they could be adequately monitored or enforced.

In summary, while ISPs can be theoretically structured in ways that promote farm-level management changes, the oversight, enforcement, and extension costs needed to make this work are high, and may increase the already substantial opportunity costs of large public expenditures on ISPs.

4.3 How Confident Are We That We Know Which Farming Practices Contribute to CSA and SI?

As the development community understandably pushes hard to make progress in helping African farmers, there are major risks of overgeneralization about what kinds of farming practices really contribute to *ex ante* risk management and *ex post* coping strategies. Africa is heterogeneous with respect to its climate conditions, soil types, market access conditions, and factor price ratios. Some parts of Africa are still land abundant; labor and capital may be binding constraints in such areas. Other agricultural areas of Africa are densely populated, facing land pressures and rising land prices. In some of these areas, labor is relatively abundant and hence labor-intensive CSA practices may hold some potential to be scaled-up and incentivized through ISPs. However, in areas with good market access conditions and proximity to urban areas, economic transformation processes are bidding up labor wages and making it difficult for farmers to adopt labor-intensive CSA practices unless they also provide high returns to labor. The heterogeneous conditions of farming systems in Africa warrant great caution against overgeneralization in promoting technologies through ISPs or on their own based on blanket recommendations across wide domains.

As an example, minimizing soil disturbance through no or minimum tillage (MT)[3] strategies are frequently promoted in Africa as a means to mitigate soil erosion, increase soil water retention capacity, and to slow the rate of soil organic carbon (SOC) decomposition, and thus achieve yield growth and stability (Branca et al. 2011; Chivenge et al. 2007). However, yield and soil quality effects of MT practices vary substantially depending on soil type and association of MT with other land management practices, namely crop residue retention and incorporation. Several studies have shown that MT practices lead to an accumulation of SOC in the *surface* layers of soil (0–10 cm), rather than in the *root* zone (Sisti et al. 2004; Chivenge et al. 2007; Carter and Rennie 1982; Hernanz et al. 2002; Doran 1980). Carter and Rennie (1982) find that microbial biomass and potential mineralizable carbon and nitrogen are high in surface soils where MT is practiced. Conversely, these soil properties are higher in lower soil depths when conventional tillage (CT) is applied. The magnitude and location of the SOC pool are important for yield growth and

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[3] In this section we present evidence on both zero and minimum tillage methods, which we will refer to broadly as minimum tillage (MT).

stabilization. As Lal (2006) shows, every 1 mt/ha increase in the SOC pool in the root zone is associated with a 30–300 kg/ha increase in maize yields and a 10–50 kg/ha increase in rice yields. Improving SOC pool in the root zone can simultaneously enhance soil's water retention capacity (Mbagwu 1991; Fernández-Ugalde et al. 2009), increase its cation exchange capacity, and thus nutrient retention (Carter et al. 1992), and improve soil aggregation and susceptibility to erosion (Lal 2006; Paul et al. 2013). Thus, further development of MT technologies may be needed to achieve its potential benefits.

Another potential limitation of MT is that without associated investments in crop residue retention and/or crop rotation, fields tilled using MT frequently experience no yield improvement (Hernanz et al. 2002) or in some cases a dramatic drop in yield relative to CT (Rusinamhodzi et al. 2011; Raimbault and Vyn 1991; Paul et al. 2013). When MT practices are applied in conjunction with crop residue retention, legume rotation, and/or nitrogen fertilizer application, the yield effects of MT tend to be higher than those achieved through CT, but again this is highly dependent on prevailing agro-ecological conditions (Raimbault and Vyn 1991; Govaerts et al. 2005; Dalal et al. 1991; Triplett et al. 1968).

As discussed in Section 3, ISPs in the region are not designed to cope with the high level of regional and farm level heterogeneity in input needs and management requirements. Significant region-specific modifications in the composition of ISP inputsm coupled with region-specific farm management promotion strategies will be required for ISPs to contribute meaningfully to CSA goals, which in turn implies significant modification in the logistical design, implementation and cost of ISPs.

A more obvious way in which ISPs can influence overall productivity is through the injection of greater levels of nitrogen (N) into African soils, where nitrogen is often the limiting nutrient factor (Snapp et al. 2010). Rusinamhodzi et al. (2011) in their summary of evidence on conservation agriculture shows that in 73% of the field studies, high levels of nitrogen fertilizer were required to achieve improved yields under these practices. However, recent advances in soil science and agronomy research show that massive nitrogen (N) injections may not be economically feasible for farmers or be social welfare raising without farmer adoption of complementary soil management practices that allow N to be efficiently utilized by plants (Snyder et al. 2009). Thus, the challenge for large-scale programs, such as ISPs, is promoting carbon management practices together with nitrogen to achieve high nitrogen efficiency (Tittonell and Giller 2013). Paul et al. (2013) demonstrate that without sufficient biomass production (often stimulated by inorganic fertilizer application) SI practices of MT and residue retention do not have an effect on yield stability or SOC. Thus, an ongoing challenge is maintaining a large enough N pool in soils containing little organic carbon, which increases N leaching and gaseous loss pathways, adversely affecting CSA goals (Drinkwater and Snapp 2007). Unfortunately, large-scale efforts to promote SI practices that build up soil organic carbon are largely absent from government programs, are largely untested over the wide range of soil types and agro-ecologies found in the region, and are sometimes discounted by some as not being viable from the standpoint of low-resource farmers.

These several examples underscore the lack of consensus within the crop science community about what viable CSA and SI packages appropriate for heterogeneous smallholder agricultural systems should look like. In addition, there is a great deal of uncertainty over how climate will change in the region over the coming decades (Powlson et al. 2016). For these reasons, we conclude that African governments and the development community need an improved empirical evidence base that establishes the practices that actually promote CSA and SI objectives under the wide range of diverse and uncertain farming conditions found in the region. A precondition for making progress on this front is much greater public expenditure on agricultural R&D and adaptive research across the various economic/biophysical micro-climates. While necessary, increased public funding to agricultural R&D is not sufficient. But without a better evidence base on how practices perform under various conditions, the risk is that ISPs may be misguided in choosing which practices to promote.

5 Can ISPs Promote System-Wide Ex Ante Risk Management?

This section examines the potential of ISPs to encourage system-wide changes in agricultural value chains that promote resilience to risks associated with climate variability. Due to their scale, ISPs may have capacity to influence the broader systems within which farmers operate and thereby influence farmer behavior both directly as well as indirectly through system-wide changes. We identify three potential areas where these system-wide effects are most evident.

5.1 Potential Opportunities

First, as mentioned earlier, by expanding and stabilizing the demand for specified input types and quantities, ISPs can potentially help to overcome some of the persistent risks to commercial legume seed multiplication in the region. Ensuring adequate supplies of these seeds on the market is critical to achieving crop diversification, organic nitrogen fixation, and rotations. However, this potential benefit is mitigated by the trend, among donors and governments, to move toward more open voucher systems. Thus, in many ways there are important trade-offs to consider when promoting particular ISP distribution modalities. While open vouchers are desirable from a farmer choice perspective, restricted-choice vouchers for particular inputs, such as legume seeds, may be necessary to support system-wide improvements in legume seed supply chains. Restricted-choice vouchers may be justified in some instances where there are major beneficial externalities associated with promoting certain inputs and where the social benefits of doing so may greatly outweigh the short-term financial benefits from the perspective of individual farmers. The two approaches may be combined; for example, farmers could be provided an open voucher in addition to a restricted-choice voucher for legume seed. Similar system-wide benefits may accrue by using ISPs to create farmer demand for specific drought-tolerant seed varieties or soil amendments such as lime or inoculants, which are currently not widely used by farmers.

A second way in which ISPs may promote system-wide CSA resilience is through promoting "market-smart" private investments, which could increase private investments in input supply chains and extension services. By encouraging private sector input supply chain development, market-friendly ISPs can foster improved input access conditions for farmers, thus over time making them less dependent on public input supply systems. Private input systems are potentially less prone than public systems to delivery challenges associated with logistical and financial constraints (Jayne and Rashid 2013). There is clear potential for ISPs to promote system-wide investments that are both climate-smart and market-smart and synergistic in their promotion of community resilience to climate variability.

Finally, the move toward digital platforms for delivering ISPs, such as electronic vouchers ('e-vouchers'), create opportunities to use ISPs as delivery mechanisms for other sorts of products, such as weather indexed insurance. This requires that ISP farmer registries collect a wide range of information on beneficiaries, including geographic location and bank information. With this sort of information, ISPs can defray the screening costs of identifying farmers and managing insurance pay-outs when necessary.

5.2 Potential Challenges

Unfortunately, some aspects of ISPs may work against climate change mitigation even as they promote resilience objectives. ISPs increase the quantities of fertilizer manufactured and used in the agricultural production process (holding all other factors constant) and therefore ISP proposals that include increased fertilizer use must account for the additional GHG emissions. Inorganic fertilizer use contributes to GHG emissions both through the soil chemical and biological processes and through the production of synthetic fertilizer. According to a recent estimate, 56% of global non-carbon dioxide GHG emissions occur from agricultural production, and roughly 12% of agricultural GHG emissions occur from fertilizer use (IPCC 2014). The additional contribution to GHG emissions caused by the manufacturing of synthetic fertilizer is also significant (see Appendix 1). Thus, the net impact of ISPs on GHG emissions will depend on the effectiveness with which ISPs can be used to promote adoption of CSA practices that raise soil organic carbon, sequester carbon and depress the rate of forest conversion to farmland and offset the adverse effects of increased fertilizer use on GHG emissions. The empirical evidence on these issues is weak and more detailed research is needed. Appendix 1 provides some empirical estimates of the increased GHG emissions caused from additional use of synthetic fertilizers.

Moreover, there is the issue of opportunity costs. Nationwide ISPs tend to be expensive, and they can bid away scarce public funds that could otherwise be used to buffer communities from the effects of climate variability (e.g., irrigation, agricultural research and extension systems, weather insurance, etc.) or to support *ex post* coping responses (e.g., disaster relief programs). In Africa, where irrigation only accounts for 4% of arable land (You et al. 2012) and where there is huge unmet potential for irrigation expansion, ISPs would seemingly compete against public investment in water control and other *ex ante* risk management strategies. Future research is again needed to determine whether smart ISPs may be structured in ways that leverage private sector investments in CSA inputs and services and produce benefits that outweight those generated from other proven types of public investments in agriculture.

6 Can ISPs Promote Household-Level *Ex Post* Coping Mechanisms?

There may be limited potential for ISPs' ability to improve the *ex post* capacity of farm households to cope with shocks. Expenditures on ISPs occur before growing season weather outcomes are known. The greatest productivity boost from ISPs occurs in favorable weather years, and vulnerability to climate shocks is quite low during these periods. Vulnerability is of course greatest in extreme weather years. Unfortunately, fertilizer application typically contributes little to crop production growth during such years, and does nothing to stabilize crop yields in the face of extreme weather conditions. This inverse temporal correlation between years of great vulnerability to climate shocks and the payoffs from fertilizer application suggest that ISPs may have limited potential as *ex post* coping mechanisms at least for the period of time until the next harvest, generally 6–9 months later.

However, ISPs are frequently scaled-up in the year following a severe weather event as part of drought-recovery strategies. In such cases, ISPs act as tools to support smallholder households to acquire improved inputs and reengage in production following a severe contraction in farm income, and to potentially re-stock depleted resources that were expended during the crisis to smooth consumption. ISPs can also theoretically be used to help farmers replant crops that failed to survive due to late or false onset rains. Yet, in both cases this would require considerable budgetary flexibility and rapid implementation capacity on the part of governments. In addition, because of the annual crop production cycle characterizing most of the region, it may take time at least 6–9 months after a harvest failure before ISPs could contribute benefits to recipients in the form expanded crop output in the next season.

7 Can ISPs Promote System-Wide *Ex Post* Coping Potential?

In their current form, ISPs tend to be costly and therefore compete directly for scarce public sector resources with other CSA risk coping and response strategies, such as disaster risk management plans, rapid repair of damaged infrastructure, emergency feeding, etc. However, ISPs that increase access to weather insurance may help farmers avoid some forms of asset and resource depletion common after a weather shock. In addition, well-targeted ISPs may enable farmers to recover more quickly following extreme weather events. In these ways, ISPs do offer some potential avenues for timely response mechanisms following adverse weather shocks.

8 Summary and Implications for ISPs

In almost all countries where they have been implemented, ISPs have clearly promoted national grain production, at least in the years they were implemented. ISPs have a more checkered track record in terms of their impact on farm-level productivity, commercial input market development, and farm management behaviors that promote SI. Longstanding efforts to encourage policy makers to use "market smart" criteria have been disappointing, which has impeded the benefit-cost ratios of ISPs (Jayne and Rashid 2013; Jayne et al. 2017). It may be unrealistic at least in the near future to expect that political economy issues that have impeded efforts to make ISPs more effective can be easily overcome. But given that ISPs are likely to continue, and often account for a large share of public expenditures to agriculture, it may be worth the effort to encourage ISP reforms in ways that contribute to SI practices and CSA objectives.

This study has considered potential avenues of ISP impact on CSA objectives in terms of a time dimension – *ex ante* risk management strategies vs. *ex post* coping strategies – and at different levels of intervention – household-level behavioral change vs. system-wide changes. Using this conceptual lens we find that ISPs hold some potential to influence farmer behavior with respect to *ex ante* risk management strategies, such as the adoption of sustainable land management techniques, private investment in small-scale irrigation, use of drought-, heat-, and saline-resistant crop varieties, use of hardier livestock breeds, and diversifying land and labor activities. Achieving these ends through ISPs is highly dependent on the existence of coordinated investments in both public extension services and research and development, along with monitoring systems. However, the cost of each component will require much greater public budgets devoted to agriculture to achieve the complementary approach needed.

Where ISPs may provide even greater opportunities to promote CSA objectives is through supporting *ex ante* risk management strategies at the system-wide level. Well-designed ISPs may improve seed system performance for legumes and other improved varieties, as well as serving to link farmers to insurance systems. However, trade-offs exist between market development objectives of new ISPs and some of the system-wide constraints to CSA, such as legume seed supply constraints. For ISPs to improve legume seed supplies or access to particular climate improved seed varieties they may need to promote these through restricted-choice vouchers, in addition to or instead of the flexible vouchers being widely promoted in the region. Managing these trade-offs is important for achieving greater system wide benefits through ISPs.

ISP's ability to improve household-level *ex post* coping mechanisms will likely be through support of post-disaster asset accumulation and reengagement with productive agriculture. Yet these outcomes, again, depend on effective public sector performance, particularly in terms of targeting the most affected households and regions.

In summary, ISPs may serve several catalytic functions at a system-level, which can support CSA objectives. However, ISPs can achieve little without the sorts of coordinated public and private investments in areas such as site specific adaptive research and extension, which are necessary to turn potential CSA practices into profitable and adoptable farm management strategies. Indeed, it is currently not possible to point to many, if any, new practices appropriate for smallholder African systems that are tried, tested, and can be confidently promoted as practices that promote CSA, are profitable, and feasible for farmers to adopt. Promoting certain technologies prematurely will lead to high levels of dis-adoption, disillusionment, and difficulties in getting farmers to participate in future programs.

Based on this analysis we propose the following as potential focal areas for improving the climate "smartness" of ISPs in Africa:

- *Support greater concentration of ISPs on legume and climate improved cereal crops:* Many ISPs currently focus primarily on staple cereal crops and inorganic fertilizers. For ISPs to have a more system-wide effect on cropping systems and management practices, seed system constraints for other crops must be addressed. ISPs can serve a catalytic role in this respect.
- *Develop detailed farm registries for ISP beneficiaries:* Detailed registries, that include geo-spatial information, are necessary to delivery support services such as weather insurance to farmers and to track adherence to targeting criteria.
- *Explore the potential for using ISPs to overcome CSA farm management adoption constraints*, bearing in mind that:

  There is limited consensus on what practices are most effective for heterogeneous smallholder systems, and;
  Extension advice and monitoring capacity remains very thin in most of Africa.

- *Support systems to improve timing of input distribution through ISPs:* ISPs chronically deliver fertilizer late (Xu et al. 2009; Namonje et al. 2015; Snapp et al. 2014). Late delivery reduces yields and crop response to fertilizer. This unfavorably affects the ratio of crop output to GHG emissions.
- *Improve targeting capacity of ISPs:* ISPs must more effectively target farmers who can use fertilizer profitably but are not already using it (or using it well below levels considered to be profit-maximizing). This will reduce crowding out of commercial demand and contribute to increased fertilizer use. In addition, effective targeting following a disaster can help support ISPs to support ex post household recovery efforts.
- *Use extension systems and information and communications technologies (ICTs) to show farmers how the use of fertilizer from ISPs and/or commercially obtained*

fertilizer can become more profitable when complementary SI/CSA practices are adopted.

- *Promote more secure land tenure/property rights (e.g., through registration or land certification):* land tenure security is important for encouraging the adoption of SI/CSA practices that improve productivity, sustainable land management, and increased use of commercially purchased fertilizer (Lawry et al. 2014; Sitko et al. 2014). Efforts to promote secure land tenure rights are a complement, not necessarily a substitute, for ISPs in promoting CSA, but the cost-effectiveness of both may be different and justify different levels of budget support.

8.1 Unresolved Issues for Future Research

Key knowledge gaps include understanding why farmers are not adopting CSA practices or are subsequently dis-adopting them (which could then point to potential interventions to overcome these constraints); determining which practices are profitable for whom and under what conditions; understanding the interactions between CSA practices and ISP inputs (e.g., do selected CSA practices increase fertilizer use efficiency?); identifying cost-effective, enforceable, and scalable ways to implement a potential CSA precondition requirement for ISPs; and comparing the cost-effectiveness of such a requirement to that of other approaches to promote CSA. Given the very mixed results of ISPs, the rampant elite capture and diversion of inputs intended for the programs, and the high price tag and opportunity cost of ISPs in general and in relation to other programs and investments to develop and stimulate uptake of CSA technologies (see Jayne and Rashid 2013; Lunduka et al. 2013; Mason et al. 2013; among many others), linking CSA promotion to ISPs may be a risky proposition.

8.2 Concluding Remarks

There are three overarching challenges to be addressed for ISPs to effectively contribute to CSA objectives. First is the limited understanding of workable approaches for internalizing the externalities associated with GHG-emitting land management decisions of millions of resource-poor farmers in developing countries. This is a problem for social scientists to resolve by developing ways for carbon markets to be linked to smallholders in Africa and that can provide farmers monetary incentives for the adoption of particular GHG mitigating practices, may be a viable strategy for achieving widespread farm management change, but much remains to be worked out before viable programs could be implemented in most of sub-Saharan Africa.

The second challenge is the currently limited on-shelf technologies and management know-how to improve smallholder yield stability and growth in the face of increasing climate variability. Most on-shelf technologies and practices being promoted as being "climate smart" appear to help at the margin, but cannot be relied upon to meaningfully stabilize harvests in the face of major droughts or floods or to arrest the degree of distress migration often associated with it. More effective water and soil fertility management techniques appropriate for the situation of low-resource farmers are needed, and this will requires significantly increased investment in localized, adaptive research for the wide range of smallholder farming systems in sub-Saharan Africa. This is a challenge both for the scientific research community and for policy makers to make the necessary long-term funding commitments to adaptive agricultural research and development programs.

The third challenge is the near absence of effective bi-directional learning and extension systems to help farmers profitably adopt and adapt proven farm management practices. This again presents challenges for policy makers to make the necessary long-term funding commitments and to social scientists to design extension systems that effectively link scientists and farmers disaggregated by particular agro-ecologies and degrees of resource constraints.

Addressing these three challenges is a tall order. For this reason, we believe that much greater progress is needed in each of these three areas before it could be practical or effective to try to use ISPs as a vehicle to make agriculture more climate-smart. This conclusion is not meant to stifle progress where progress can be made, but is rather to point out the scope of the challenges before us. It will take time for the proposals made here to generate meaningful impacts. This is why there is no time to waste in getting started.

Appendix 1: Estimating the Contribution of Increased Fertilizer Use to Greenhouse Gas Emissions

African countries contribute to climate change through emissions of greenhouse gases from agriculture, forestry and land use (AFoLU). As much as one third of all emissions globally are from AFoLU, but in many African countries these emission sources constitute the major components of their national GHG inventories, rather than the industrial or energy sectors. For instance, in Malawi 80% of national GHG emissions are from forestry and agriculture, although the absolute contribution to global greenhouse gas emissions is tiny. As a result of the Paris Agreements of the United Nations Framework Convention on Climate Change (UNFCCC) African countries are developing means and measures to mitigate these emissions through actions in the AFoLU sectors, including reducing emissions from deforestation and forest degradation, conservation of carbon stocks in forests and agricultural soils, improved management of agricultural waste and other interventions. In spite of actions to reduce emissions, agriculture and forestry will surely be impacted by climate change. As such, many African countries are taking a broad view and are also implementing adaptation strategies.

National climate action strategies are being developed by all African Countries through the process of the Nationally Determined Contributions, or NDC, which is the main reporting instrument that is the focal point for each country's international commitments. Climate Smart Agriculture (CSA) is being viewed as one model for adaptation. This model focuses on developing interventions in traditional practices that can increase resilience of agricultural systems to adverse effects of climate change and which can be promulgated at the national level and applied locally at farm scale. One compelling intervention under the CSA model is the national subsidy programs for inorganic fertilizers. Increasing the availability and application of chemical fertilizers is seen as a means to increase crop productivity and provide enhanced fertility to nutrient-poor soils, and buffer adverse effects of drought and other climate impacts.

However, at the same time that these measures provide apparent benefits from an adaptation point of view, the use of inorganic fertilizers also increases GHG emissions in agricultural soils, particularly for non-carbon GHGs such as nitrous oxide (N_20). Using estimation methods defined by the Intergovernmental Panel on Climate Change (IPCC 2006), the FAO (FAO 2014) has published estimates of national emissions from agricultural inputs for many African countries. GHG emissions from the application of synthetic fertilizers has increased 25% between 2000 and 2014, from 16,000 GgCO2e to 20,000 GgCO2e, representing about 3% of the total emissions from all agricultural practices, including land clearing. However there is considerable variation across Africa, with a trend toward higher proportional emissions from fertilizers in poorer countries. For instance, in Nigeria where other inputs and energy contributed more to agriculture than in most countries, only about 1.2% of the total emissions from agriculture are attributed to fertilizer applications on soils in 2012, while in Malawi as much as 18% of total agricultural emissions are attributed to fertilizer applications in 2012. In Zambia the proportion is 4%, while in Kenya it is 2% for 2012.

For the most part these are relatively low emissions compared to other components of the agriculture production system; however subsidy programs are expected to raise fertilizer use, particularly for poorer countries such as Malawi. These emissions of GHG, especially non-carbon GHG such as N_20, represent the negative impacts of measures involving increased use of fertilizer to improve resilience of agricultural soils and plant productivity. Thus, interventions that may have positive influence on adaptation may have outcomes that negatively offset gains in mitigation efforts. For instance, annual emission rates of GHG from fertilizer use in agriculture in Malawi is approximately equivalent to protecting 500 hectares of Miombo woodland from deforestation. The exact magnitude of the offset depends on a complex array of factors that are not being studied, including the type of fertilizer used, fertilizer application rates and timing, influence of episodic events that may be changing with climate changes such as severe rain events, soil conditions and land management.

Most studies, and the IPCC (2006), estimate N emission factors for N_20 to be between 1% and 3% of the nitrogen nutrient in fertilizers. Thus, we can estimate the approximate GHG emissions associated with the application of fertilizer under subsidy programs. We assume an application of 300,000 metric tons of fertilizer, of which half is in the form of urea with 50% N and half in the form of inorganic NPK with 30% N. This would equate to roughly 45,000 metric tons of N from NPK fertilizer and 75,000 metric tons of N from urea. Using IPCC emission factors for N_20 emissions this would result in 1200–3600 metric tons of N_20 per ton of N, which when converted to units of nitrous oxide (multiplied by 44/28) and then to carbon dioxide equivalents using a greenhouse warming potential (GWP) of 300 would be 565,714–1,697,143 metric tons of CO_2 equivalent (CO_2e) greenhouse gas emission. Using IPCC emission factors for urea, we estimate an additional 30,000 metric tons of CO2e. Thus, the total emissions from the application of 300,000 tons of fertilizer of the type we used to make our estimate would be 595,714–1,727,143 metric tons CO_2e per year.

The contributions of inorganic fertilizer to adaption and agricultural resilience would come at a cost to efforts to mitigate emissions from deforestation and degradation; the additional emissions from fertilizer applications would be a significant new emission source and would counter efforts to mitigate emissions in the AFoLU sector.

These estimates are for field applications of inorganic fertilizers. The demand for fertilizer would stimulate production of fertilizers and this production system also produces GHGs, mostly from the large use of energy which are typically from fossil fuels. Although most carbon GHG accounting methods do not attribute production emissions to the end-use emissions, and keep these accounts separate, for the sake of illustration we estimate the additional contribution of producing and transporting 300,000 t of inorganic fertilizer. Several studies suggest an emission factor for fertilizer production to be 2.5–5.67 metric tons of CO_2e per metric ton of fertilizer produced (Kool et al. 2012). Thus, a basic estimate of the magnitude of the emissions associated with the 300,000 additional tons of fertilizer production would be 750,000–1,701,000 metric tons of CO_2e.

Combining both agricultural field emissions with emissions associated with production, we estimate that 300,000 tons of additional fertilizer manufacture and use would result in GHG emissions of between 1,345,714 and 3,428,143 metric tons of CO_2 equivalent. Approximately 55% of these emissions are attributed to the industrial production of fertilizers (which we believe are conservative estimates). These estimates would represent an increase in fertilizer emission of approximately 10%, and would represent an emission that counter offsets approximately 120,000 to 300,000 hectares of reforestation in mitigation projects.

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