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Disorderly urban adaptation to climate change: qualitative modeling of finance, land use, and the built environment

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This article develops the concept of "disorderly" urban adaptation to describe processes of change that unfold through exogenous shocks, abrupt policy shifts, and sharp adjustments in asset valuations and risk ratings. We present an approach to studying disorderly urban adaptation through qualitative modeling of interactions among three sub-systems: the built environment, land use, and finance. This approach sheds light on key features of disorderly adaptation, such as temporal and spatial mismatches, balancing and reinforcing feedbacks, and lags that "desynchronize" processes of sub-system change. We illustrate this approach through a discussion of research on the interaction between fire risk, insurance, land use, and the built environment in California, where mega-fires in 2017–2020 triggered a process of disorderly adaptive change. We suggest that this approach can aid in understanding and planning for emerging trajectories of urban change in many contexts and in relation to various hazards.

Urban adaptation to climate change is often described and studied as a process that unfolds through well-ordered steps: (1) anticipating future climate change impacts; (2) assessing urban vulnerability; (3) evaluating measures to address these vulnerabilities; (4) implementation[1–4]. "Urban adaptation" is what happens when plans are implemented. In line with this description, many scholarly assessments of urban adaptation focus on "tracking and analyzing outputs" of urban adaptation plans, based on the premise that such plans "currently represent the majority of adaptation activities on the ground"[4]. Plan evaluation is used to study whether "adaptation [is] taking place, where, by whom, and in what ways"[5]. The conclusion reached by such assessments based on plan evaluation is that "progress toward adaptation has been…patchy, with entire regions not yet planning for adaptation, many cities planning but not implementing, or implementing piecemeal projects"[6].

But in many cases—perhaps, indeed, in most cases—both climate impacts and processes of adaptive change are unfolding well ahead of carefully planned and well-coordinated actions. This is most evident following large-scale disasters, to which individuals and collective actors respond reactively and in real time. Scholarship that examines such processes of change often treats them as a negative consequence of a lack of planning and coordination among relevant stakeholders[7]. An example is the literature on "unmanaged" retreat from risk-prone areas that is driven either by actual disasters or by "push" factors[8,9], such as increasing costs (via rising insurance premiums or mitigation requirements) or climate gentrification[10]. Such scholarship operates with a "deficit model"[11] that defines adaptive change in terms of what it lacks: anticipation, planning, and coordinated action[12]. Such deficit models imply a normative judgment: "unmanaged, unstrategic, ad hoc retreat misses opportunities to contribute to societal goals"[8] and exacerbates inequalities[13].

This article develops the concept of "disorderly" urban adaptation as an alternative to these approaches. The purpose of this concept is to characterize *processes* of adaptation, not to evaluate *outcomes*[14]. Specifically, disorderly urban adaptation refers to change processes that unfold through exogenous shocks, abrupt policy shifts, and adjustments in financial asset valuations and risk ratings. In contrast to the "plan evaluation" literature, the concept of disorderly adaptation highlights the current centrality of adaptive change processes that result from disjointed and at least partly uncoordinated actions. In contrast to discussions of "unmanaged" or "unplanned" urban adaptation, disorderly adaptation nonetheless involves planning and attempts at coordination at different scales and in different sectors. Analysis of disorderly adaptation thus emphasizes how adaptive change processes are structured by decision-making arrangements and institutions that comprise socio-ecological systems. In this sense, while "orderly" urban adaptation corresponds to descriptions of planned adaptation, disorderly urban adaptation does not correspond to unplanned adaptation or to related concepts in the broader literature on adaptation, such as "spontaneous"[15] or "autonomous"[16] adaptation.

Table 1 summarizes key distinctions between orderly and disorderly urban adaptation. These distinctions are heuristic and are not meant to imply that adaptation patterns should be sorted into orderly and disorderly

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Table 1 | Characteristics of orderly versus disorderly adaptive change processes

	Orderly urban adaptation	Disorderly urban adaptation
Information and risk perception	Anticipation of long-term climate impacts by planners and public officials (via modeling, scenario building); consensus views about future risks	Short-term environmental and economic signals rather than anticipation of climate change per se; divergent risk perception among actors at different scales and sectors
Coordination	Cross-sectoral and cross-scale planning; explicit coordination around climate issues	Disconnects among scales and systems; adaptation to climate risk in tension with diverse sub-system imperatives
Distribution of burden	Compensatory measures to address harms of adaptive change (e.g., displacement, disamenities)	Limited compensatory measures in disjointed and at least partly unplanned change processes
Stakeholder engagement	Engagement with parties affected by adaptive change	Limited and fragmented engagement with affected parties (e.g., in localities)
Nature and timing of adaptive change	Change processes gradual and deliberative, often in advance of disruptive events	Change processes abrupt and punctuated; periods of risk accumulation followed by rapid sub-system change

types. Orderly adaptation represents a kind of ideal that could only exist in a closed system with monocentric rather than polycentric decision-making arrangements. Meanwhile, in practice we observe a wide range of variants of adaptation that combine orderly and disorderly elements.

A central challenge for urban researchers is to develop approaches for studying processes of disorderly adaptation. This article proposes one such approach, which treats disorderly urban adaptation as a complex socio-ecological system problem and employs qualitative modeling to characterize adaptive change dynamics in urban areas. To illustrate this approach, we describe the results of research on urban adaptative change following the mega-fires that swept through the US state of California in 2017–2020. The fires have shaped pathways of disorderly adaptive change in communities that were directly impacted. For example, the Town of Paradise, California, which experienced widespread destruction in the 2018 Camp Fire, has recovered to only a fraction of its former population, though efforts continue to attract both former and new residents[17,18]. Meanwhile, the City of Santa Rosa, which lost thousands of homes in the 2017 Tubbs Fire, rapidly rebuilt, but has undergone substantial changes in the built environment of structures and landscapes: larger, fire-proofed homes and investments in fuel reduction are part of an adaptive pathway of "hardening"[17,19–21]. The fires are also shaping disorderly adaptive change in areas not directly impacted, as the effects of these events ramify through social and economic systems. Such indirect effects are most dramatically observed in the roiling insurance crisis that was precipitated by the fires: sharp rate increases and reduced availability have placed a mounting financial burden on homeowners, reduced the financial resilience of households and communicates, and threatened mortgage and housing markets across the state[22–24]. These changes are already impacting patterns of land use, as, for example, the unavailability and cost of insurance makes it difficult to rebuild after fires or to finance new development, particularly for projects that include affordable housing[25,26]. Meanwhile, changes to the built environment—including the hardening of structures and the mitigation of landscapes (e.g., through fuel reduction and the maintenance "defensible space")—are unfolding in an uneven pattern across the state.

The concept of disorderly urban adaptation is borrowed from discussions of orderly and disorderly decarbonization. Explicit comparison with discussions of orderly and disorderly decarbonization is useful because these discussions highlight processes and dynamics of change that we also observe in disorderly adaptation. "Orderly" decarbonization is understood to involve planned and coordinated steps that shape a smooth pathway to a low-carbon future. Orderly decarbonization pathways are characterized by consistent policy direction, coordination among stakeholders, and government expenditures to mitigate transition costs and risks[27]. Disorderly decarbonization pathways, by contrast, involve "late, sudden and/or unanticipated shifts in policy, the economy and financial system"[27]. Where orderly decarbonization results from coordinated planning, disorderly decarbonization results from "disconnects between governments, businesses, and households with respect to policy commitments, financial incentives, regulations, and immediate needs"[28]. These disconnects arise from the structure of decision-making arrangements, including the "interdependencies and distributed nature of economic and financial systems" and the "historic shielding of climate change externalities from citizens and businesses," which creates path dependencies and leads some actors to "avoid or defer action"[28]. Importantly, disorderly pathways are still *decarbonization* pathways. They sit between "orderly" pathways and pathways in which "we continue to increase emissions, doing very little, if anything, to avert physical risks"[29]. And disorderly pathways still involve planning, management, and strategic action. Indeed, much discussion of disorderly decarbonization is driven by organizations that advise governments and businesses on how to navigate such pathways (e.g., Nelson et al.[29]). The characterization of disorderly decarbonization is a tool for planning.

Like disorderly decarbonization, disorderly urban adaptation is often crisis-driven, at least partially reactive, and episodic: periods of risk accumulation are followed by periods of rapid change. Disorderly adaptation may be directly driven by climate change impacts. It may also unfold as the effects of such events ramify through policy responses or social systems. Financial mechanisms such as insurance and property, mortgage, and bond markets are particularly important in this process, to the extent that actual or anticipated climate change effects precipitate shifts in asset valuation and risk rating (and corresponding responses by regulators, property owners, and policymakers). As with disorderly decarbonization, legacies of moral hazard play a central role in disorderly adaptation, which is shaped by the historical shielding of key stakeholders from externalities, such as homeowners and local governments in high-risk areas that do not bear the full costs of disaster response, relief, and reconstruction. It is also shaped by the character of decision-making about adaptive change, which is distributed among property owners, real estate developers, municipal governments, and state agencies, acting on specific problems and interests, based on diverse preferences and perceptions of risk. While disorderly adaptation is disjointed, however, it is not unplanned or unmanaged. It involves all kinds of planning and management by individuals, community groups, governments, and private firms. Nor is disorderly adaptation unstructured. Indeed, the point of characterizing disorderly adaptation is to understand *how* it is structured and to identify opportunities for shaping adaptive change.

Table 2 describes key features of disorderly adaptation processes and compares them with disorderly decarbonization, summarizing the dimensions outlined above: change dynamics, the role of financial mechanisms, the structure of decision-making arrangements, and the legacies of moral hazard in shaping the political economy of change processes.

Our approach to qualitative modeling of disorderly change maps interactions among three sub-systems: land use, the built environment, and finance. We characterize land use, the built environment, and finance as systems to draw attention to the complex of institutions and decision-making arrangements that define change dynamics within and among them. These sub-systems both influence and are influenced by the level of environmental risk. As such, they are central to processes of disorderly adaptive change. Importantly, the states of these systems are also important outcomes of adaptation.

Table 2 | Processes and dynamics of disorderly change

	Disorderly decarbonization	Disorderly urban adaptation
Change dynamics: risk accumulation followed by abrupt shifts in policy, asset valuation, and risk assessment	Slow action on decarbonization due to sunk costs, backsliding on commitments, and "hedging"[94] against high and low carbon energy futures interrupted by climate shocks that lead to rapid policy shifts, revaluation of economic assets	Risk accumulation via urban development in hazard-prone areas interrupted by actual and anticipated climate impacts that lead directly to change in land use and the built environment or ramify through shifts in social and economic systems
Role of financial mechanisms: change in asset valuations and risk assessments due to explicit or implicit incorporation of climate risk	Tensions between large sunk capital costs in fossil fuel infrastructure versus prospect of rapid devaluations; uncertainties due to changing policy stances (e.g., shifting commitments to decarbonization)	Sunk costs in existing patterns of settlement versus sharp repricing of assets (e.g., property markets) or risk (e.g., insurance cost and availability); "overshoot" (e.g., insurer or lender withdrawal) in response to large events
Decision-making arrangements: dispersed across scales and sectors; spatial and temporal mismatches	Energy producers, consumers, governments; mismatches in costs and benefits of emissions and climate change impacts (e.g., costs borne by future generations, low historical contributors to emissions)	Property owners, developers, government entities; mismatches between decisions about land use/built environment and costs of environmental risk (e.g., disaster response and recovery)
Legacies of moral hazard: shielding from climate externalities generates path dependencies and shapes political economy of change	Fossil fuel producers shielded from externalities via explicit and implicit subsidies; lock-in to "fossil modernity"[95] in industry, transportation, land use	Residents and local governments in high-risk areas shielded from costs through disaster relief, subsidized insurance, firefighting costs; lock-in to existing patterns of settlement

Table 3 | Charecteristics of the land use, built environment, and finance sub-systems

	Land use	Built environment	Finance
System state	Distribution of people, structures, and activities	Materials and design of structures and landscapes	Allocation and pricing of capital, assets, risk transfer mechanisms
Decision-making arrangements	Local and regional government land use controls interact with decisions of private developers, homeowners, renters; individual property owners make locational decisions in response to "loading" of climate risk costs in particular places	Developer, property owner choices about design and materials of structures shaped by state and local building codes, regulation of landscapes (e.g., defensible space codes), financial mechanisms (e.g., insurance building standards)	Financial firms interact with regulatory bodies; public disaster finance (response, relief, recovery, risk transfer) and private finance (insurance, mortgage markets) influence decisions of private property owners & local governments
Adaptation outcomes	Change in number of people and structures in high-risk areas; change in composition of population or patterns of land use (e.g., from residential to parkland or vacant lots)	Change in design and materials of structures (e.g., home hardening, flood proofing) and landscape characteristics (e.g., fuel reduction, coastal protection)	Change in financial resilience due to availability and cost of finance (e.g., mortgages, municipal bonds), risk transfer (e.g., hazard insurance), and disaster finance

Table 3 defines key outcomes for each sub-system and describes decision-making arrangements and adaptation outcomes. The land use sub-system includes government land use regulations, as well as decisions by private developers and property owners that determine the number of people, structures, and activities that are exposed to environmental risk. The built environment subsystem includes government building codes, regulations, and enforcement actions, as well as decisions of property owners, that determine the vulnerability of structures and landscapes that are exposed to environmental hazards. The finance sub-system includes private actors and public actors (policymakers and regulators) that determine the cost and availability of both capital (e.g., through mortgages or construction loans) and risk transfer instruments (e.g., insurance) in high-risk areas.

Our approach to studying disorderly adaptation as a socio-ecological systems problem draws on three concepts from the broader literature on systems dynamics and socioecological systems to describe change dynamics both within and among the built environment, land use, and finance sub-systems. First, urban climate adaptation emerges from the interplay of *balancing and reinforcing feedbacks* among sub-systems. Second, these feedbacks are mediated by *temporal and scalar mismatches* that occur when the consequences of decisions manifest months or years after they are made, or when the effects of these decisions extend beyond the jurisdictional boundaries defined by extant decision-making arrangements[30–32]. Third, temporal and spatial mismatches lead to *lags* in feedback that produce what we refer to as "desynchronization" among subsystems. Desynchronization can take the form of both slow response to environmental risk (leading to risk accumulation) and of subsequent "overshoot" as sub-systems rapidly adjust to shocks[32]. We will suggest that these dynamics—and in particular the concepts of mismatches, lags, and desynchronization—are crucial to patterns of disorderly urban adaptative change.

Results

To study disorderly adaptive change following the California wildfires, we conducted research on interactions among three sub-systems that interact with wildfire risk. Along with land use and the built environment, we focus on insurance as a component of the financial system that our research suggested has been the key mechanism and driver of adaptive change in the California case. These sub-systems are part of what we refer to as the High Fire Risk Area (HFRA) system. We refer to the HFRA rather than any administratively designated category of fire risk (such as CalFire's Fire Hazard Severity Zones or the "Wildland Urban Interface") because different actors understand risk in different ways (e.g., insurer mapping of risk may not line up with mapping by public agencies). The HFRA is thus an area in which high fire risk is a factor in adaptation, whether or not it lies in an officially designated risk zone.

On the basis of interviews, document review, stakeholder meetings, and public forums (see description in methods section), we built a conceptual model of the HFRA system by developing two diagrams. The first is a causal loop diagram (Fig. 1) that represents high-level relationships among the subsystems. The second is a detailed conceptual diagram (Fig. 2) that describes interactions within and among the insurance, built environment, and land-use sub-systems. These diagrams are qualitative descriptions of relationships observed in our research. The arrows in the diagrams represent relationships that have been verified by multiple sources of information. These models do not, however, imply a claim about the strength of relationships. Rather, these models capture interactions that change in strength over time. Indeed, given temporal mismatches, there can be long periods in which a particular relationship is so weak that it has little to no impact on the system's dynamics.

The causal loop diagram presented in Fig. 1 indicates four major factors influencing the state of the HFRA system: fire risk; the availability and

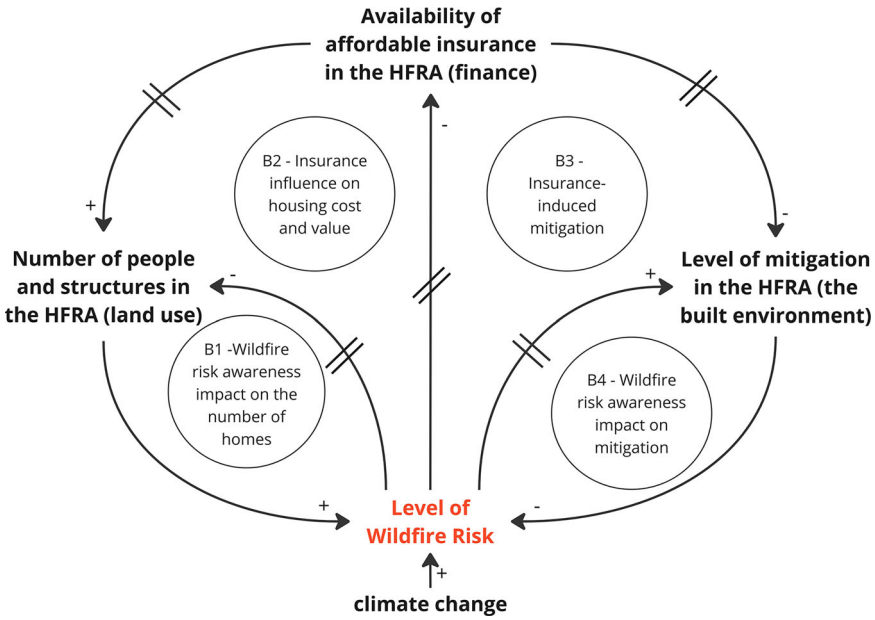


Fig. 1 | Causal loop diagram of the HFRA system. The figure describes four factors influencing the state of the HFRA system: fire risk; the availability and affordability of insurance coverage; the level of mitigation in the built environment including both structures (via home hardening) and landscapes (via fuel reduction and other treatments); and the number of people and structures in the HFRA. It describes four "balancing" feedbacks (B1-B4) among these factors as well as time lags, indicated by // notation.

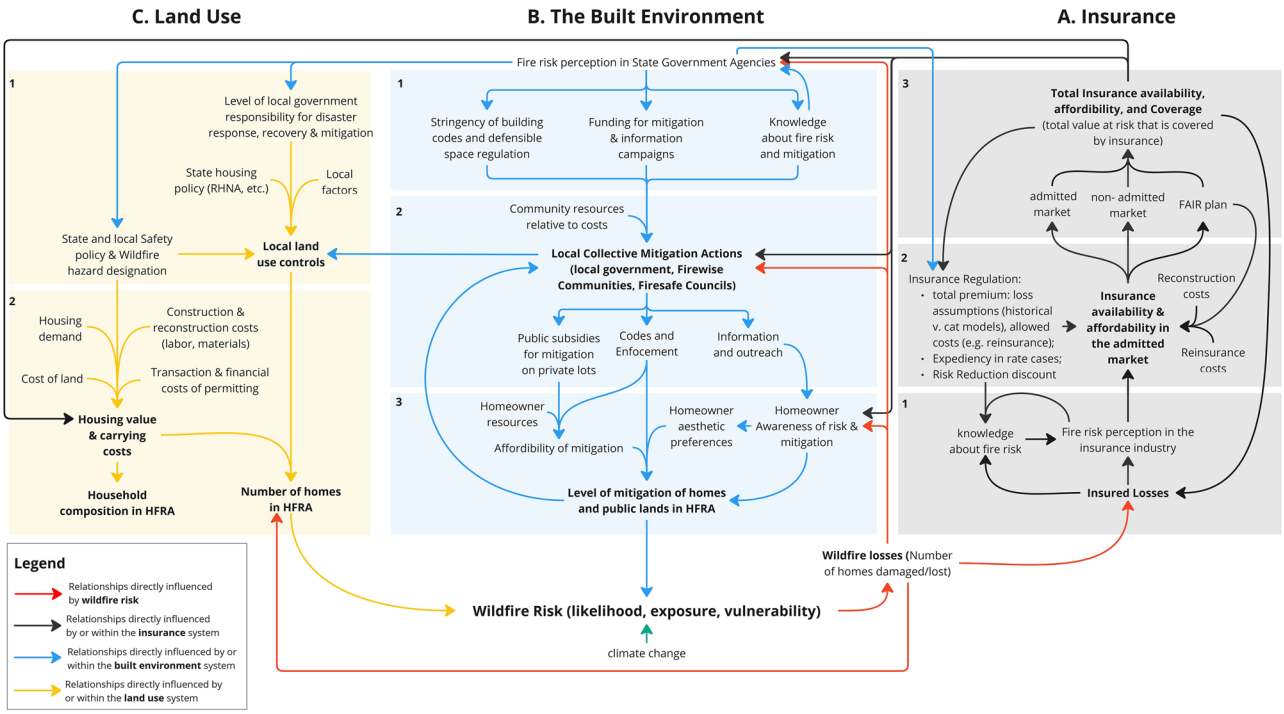


Fig. 2 | Detailed conceptual model of the HFRA system. The figure describes decision-making arrangements and interactions within and among HFRA sub-systems: insurance (**A**), the built environment (**B**) and land use (**C**). Arrows represent relationships that may change in strength over time.

affordability of insurance coverage; the level of mitigation in the built environment including both structures (via home hardening) and landscapes (via fuel reduction and other treatments); and the number of people and structures in the HFRA. These factors are also significant outcomes of urban adaptation and critical indicators of individual and community-level vulnerability and resilience.

The causal loop diagram describes four "balancing" feedbacks (B1-B4) through which an increase in wildfire risk would trigger processes that reduce fire risk. It also includes time lags, indicated by // notation. These time lags were found to play a critical role in HFRA system dynamics. For example, in the absence of lags, wildfire risk reduces the number of structures and people in the HFRA (B1) and increases investment in mitigation measures such as fuel reduction and home hardening (B4). But these feedbacks experience long time lags due to factors such as fire suppression and post-disaster relief policies that allow homeowners and local governments to offload the cost of fire risk and thereby support continued development in the HFRA. Feedbacks related to insurance (B2 and B3) are also characterized by time lags. In the absence of lags, the cost of insurance rises in response to increasing fire risk. Higher insurance premiums then influence the carrying costs of residence in the HFRA (B2), leading to shifts in developer decisions and locational choice by homeowners that result in fewer structures and people in the HFRA. Increased insurance cost or decreased insurance availability in the HFRA also incentivizes individual and collective investment in mitigation (B3) to the extent that premium

pricing reflects property-level and community-level risk. But due to factors such as imperfect information flows, divergent preferences and risk perceptions, regulatory constraints, and the absence of shared standards, time lags are observed at multiple points in these causal loops. Insurance pricing and availability change more slowly than fire risk, and increased insurance rates may not produce rapid shifts in mitigation or land use.

The pervasive time lags in this system—and corresponding mismatches in rates of sub-system change—explain the persistence of different states of the system and the character of regime shifts when they occur. Time lags explain why this system experienced long periods of "risk accumulation" without balancing feedbacks prior to the 2017–2018 fires. Time lags also explain why, after the fires, rapid changes in some sub-systems were not immediately met by corresponding adjustments in others. Such "desynchronization" may lead to periods of disorderly adaptive change, characterized by disruptions in parts of the HFRA system and uncoordinated or only partially coordinated responses by homeowners, local and state governments, regulators, insurance companies, and other actors. An episode of such disorderly adaptive change is observed in California since the 2017–2018 fires, as rapid shifts in the pricing and availability of insurance in response to increased perception of fire risk were not met by rapid adjustment of the built environment and land use.

The remainder of this section describes these two states of the HFRA system in California: the pre-2017–2018 "risk accumulation" regime and the post-2017–2018 "disorderly adaptation" regime. These descriptions draw on the detailed diagram of the HFRA system presented in Fig. 2. This diagram explicitly characterizes the social institutions and decision-making arrangements that comprise the insurance, mitigation, and land use subsystem. As noted above, the strength of the relationships indicated by the arrows in the diagram has changed over time. The purpose of the diagram, therefore, is to guide research into these changes in order to understand how shifts in one sub-system ramify through other parts of the HFRA system.

Risk accumulation

Section A of Fig. 2 describes the insurance sub-system. Prior to the 2017–2018 fires, fire risk perception in the California insurance industry was low, despite significant accumulation of wildfire risk. This dynamic is described in A.1, which indicates that fire risk perception in the insurance industry is shaped by the level of insurer knowledge about fire risk and loss experience[33,34]. Prior to the 2017–2018 fires, insurers discounted the likelihood of fire risk in the absence of significant recent fire loss experience[33,34]. Insurer risk perception was further limited by the state of, and cost of access to, detailed scientific information about wildfire risk[33,35,36]. California property insurance providers—which were partly constrained by regulators (see below)—did not rate wildfire risk as a catastrophe peril[33–35].

A.2 describes the pricing and availability of insurance in the "admitted" market, which historically accounts for the vast majority of policies in California. Admitted market policies are sold by private insurers but are regulated by the California Department of Insurance (CDI), which controls various aspects of market entry, price, and coverage. With the creation of the current regulatory regime in 1988, California transitioned from being one of the least regulated to one of the most regulated state insurance markets[37,38]. Under this system (which is currently undergoing reform—see below), state regulators approve insurance rates based on a 20 year "lookback" at prior loss experience[25]. Notwithstanding major fires such as the Cedar (2003) and Witch (2007) fires, on the eve of the 2017–2018 fires such a lookback would have revealed relatively low levels of loss, particularly when compared with the losses that were to come[34]. Due to regulation and low insurer risk perception, premiums in California in 2017 were "dramatically lower than premiums in other disaster-prone states" despite high property valuations, high construction costs, and rapidly accumulating fire risk[39]. In this context, admitted market insurance was affordable and widely available, and broad insurance coverage was maintained.

Part B of Fig. 2 describes actions to mitigate fire risk through changes to the built environment of structures and landscapes. The drivers of both collective and individual action on mitigation include fire risk perception (driven by fire loss and mediated by fiscal impacts of fire loss on government) and, under certain conditions, insurance. B.1. describes collective mitigation actions by the California State government. Despite a primary focus on fire suppression[31], the state government in California put in place elements of a "proactive" fire mitigation strategy prior to the 2017–2018 fires. It established guidelines for defensible space that defined zones of reduced fuel around buildings in the HFRA, mandated inspection and enforcement of defensible space requirements, introduced the concept of home hardening through the use fire resistant construction materials, and incorporated elements of home hardening into the building code in 2008[40]. However, the impact of these measures on total mitigation was limited. Rates of inspection and property owner compliance with defensible space requirements varied across localities. Rates of enforcement (e.g., via fines) were generally low[40,41]. Surveys of local governments indicate various barriers to property-owner compliance with defensible space requirements, including the cost of such measures in both financial resources and time, aesthetic preferences (e.g., for plants next to buildings), and lack of enforcement[40,41].

Since insurance availability and cost were not significant problems prior to the 2017–2018 fires, insurance was not a driver of mitigation action. The state took limited preliminary steps to link insurance to mitigation. For example, in 2014, the CDI approved insurer filings that lowered premia for groups of homeowners that organized Firewise Communities, a designation that requires development of a fire hazard reduction plan and performance of a certain number of volunteer hours of mitigation work, among other actions. But in the context of overall low insurance rates and wide insurance availability, this step provided limited incentive for homeowners to invest in mitigation, evidenced by the fact that on the eve of the 2017 fires only around 150 communities containing 75,000 households had received a Firewise designation[42].

Section C of Fig. 2 describes land use change, which is influenced by risk perception in state and local governments, insurance availability and pricing, fire losses, and broader housing market conditions. The pre-2017–2018 period witnessed rapid housing development in the HFRA in California. Land use restrictions in urban cores drove residents to seek lower-cost housing in the suburban and ex-urban periphery[43]. Fire suppression and disaster relief policies—whose costs are primarily covered by federal and state governments—increased short-term safety and cross-subsidized residence in the HFRA[44]. Local governments in the HFRA, which generally control land use, were thus incentivized to increase property tax revenue by encouraging local development while bearing few costs associated with such development[31,44–46].

Inexpensive and widely available insurance has been cited as one mechanism that "shield[ed] homeowners [in the HFRA] from paying the full price of protecting their risky investment from nearby natural hazards"[47] prior to the 2017–2018 fires. While the impact of low-cost insurance coverage of disasters on high-risk areas has not been established by rigorous studies[48,49], insurance availability is a prerequisite to development in the HFRA, insurance premiums are an important component of HFRA carrying costs, and development was not substantially impeded in the pre-2017–2018 period by insurance cost or availability. Moreover, high levels of insurance coverage made reconstruction more likely in the aftermath of fires, thus maintaining the existing number of structures of the HFRA in the face of increasing structure loss.

Disorderly adaptation

This risk accumulation regime was disrupted by the 2017–2020 fires. Perhaps the most important driver of this disruption was a dramatic shift in insurer risk perception that ramified through the HFRA system. Time lags are key to understanding the consequences of these events. The private insurance industry's response to the fires has been rapid, with significant shifts in pricing, availability, and total coverage. The response to this disruption by state insurance regulators has lagged private sector adjustment. Changes in the built environment and land use, meanwhile, have been slower still. The result has been a period of disorderly adaptive change, as

homeowners, community organizations, local and state governments, regulators, and the insurance sector adjust to significant disruptions in uncoordinated or at best partially coordinated ways.

The 2017–2018 fires delivered a financial shock to the California property insurance industry. Industry observers claim that the 2017 fires alone "wiped out 26 years of underwriting gains," and that the industry experienced a $10 billion underwriting loss in the 2017 and 2018 fires[34]. The fires thus served as a wake-up call that "[reset insurer] expectations on loss potential from wildfires"[50]. In response, actors in the insurance industry developed and deployed tools such as catastrophe models, risk scoring methodologies, and standards for fire mitigation to improve their understanding of fire risk[33,35,51,52]. These tools further heightened insurer risk perception throughout the HFRA.

A.2 in Fig. 2 indicates that, given increased perception of fire risk, insurers will seek to adjust both rates and underwriting (decisions about whether to offer policies to certain properties or areas)[33–35]. These adjustments are mediated by regulation. For example, if regulations limit rate increases, insurers may reduce the availability of insurance in HFRA or pull out of a market altogether[34,35,53]. In the case of California in the post-2017–2018 period, insurers indeed faced intense pressures to increase premiums and reduce exposure to wildfire risk. Among these pressures were insurers' own changing risk perception, the soaring costs of reinsurance[54], downgrades from specialized firms (such as AM Best) that evaluate insurer financial health[55], and growing costs of reconstruction[33]. In response, insurers increased the price of insurance in the California HFRA. One study found a 43.7% cumulative premium increase for admitted market policies in California between 2018 and 2023. Large further increases have been approved by regulators in 2024–2025. These jumps in total premiums suggest dramatically higher proportional increases in the HFRA[56], in some cases by factors of five or six, amounting to a significant proportion of the annual earnings of low-income residents[23]. Premium increases have been limited, however, by regulation. Rate cases can take many months to process, and through late 2024 regulators excluded both modeled estimates of current risk and rapidly rising reinsurance costs from consideration in rate-making[33,34,54].

Given such limitations in their ability to respond to increased perceived risk through premium increases, California insurers sought to reduce their exposure to wildfire-prone areas. Initially, this response took the form of policy non-renewals, leading to limited availability of admitted market policies in the HFRA[33]. But as legislative efforts to reform the regulatory system in the early 2020s failed to advance, by 2023–2024 major insurers were taking more drastic actions to reduce their exposure to California fire risk, culminating in announcements by some of the largest property insurers in the state that they would not write new policies[53]. Regulators have responded to the collapse in the admitted market with initiatives to stabilize the market, such as the Sustainable Insurance Strategy, which will allow insurers to increase premiums in exchange for expanded coverage in the HFRA[33,34]. The ultimate impact of these policies is uncertain (see discussion below).

A.3 indicates two recourses for homeowners faced with increased cost or unavailability of insurance on the admitted market. Homeowners may choose to leave their homes uninsured (if they do not carry a mortgage) or underinsured[33]. Alternatively, homeowners may seek coverage either through an "insurer of last resort" or through the "non-admitted" market of insurance that is not regulated by state insurance commissions. Both alternatives offer more expensive insurance with lower levels of coverage than is available on the admitted market[24,33]. Coverage through California's insurer of last resort—the FAIR plan—has swelled as the admitted market eroded. Between 2018 and 2024, total exposure of the FAIR plan rose from $50 billion to $392 billion, and policies in force increased from about 150,000 to over 400,000[57,58]. Regulators and many private industry specialists do not view the increased use of the FAIR plan as sustainable—a concern that has been sharpened by the 2025 Los Angeles wildfires, which generated massive losses in the FAIR pool[33,34]. Moreover, increased exposure in the FAIR plan feeds back to the admitted market, since admitted market insurers are required to participate in the FAIR plan pool and must assume at least some of the losses in this pool[33,34].

To summarize, the 2017–2018 and subsequent fires disrupted insurance markets, resulting in sharp premium increases and declines in availability and coverage. This disruption is widely regarded as constituting a crisis for the State of California[34,58,59]. Insurance affordability and coverage influences individual and community recovery from disasters[49], and is itself an important factor in individual and community resilience. As such, insurance coverage is an important adaptation outcome, and is increasingly identified as a goal in local government adaptation plans[48]. Similarly, insurance affordability and coverage shape the distributional impact of climate adaptation. High insurance rates mean that more low-income households will be uninsured, burdened by increased insurance costs, or forced to move from the HFRA due to mounting carrying costs of residence[24,33].

The combination of massive losses from wildfires and the ensuing insurance crisis has increased perception of wildfire risk for state and local governments, community organizations, and individuals. Heightened risk perception has, in turn, led to increasing focus on mitigation of wildfire risk through changes to the built environment such as home hardening, fuel reduction, and the maintenance of defensible space around structures.

B.1 in Fig. 2 describes action on mitigation in the built environment by the state government, including the legislature, the executive, and regulatory bodies. The state government has dramatically increased its spending on "proactive policies" that mitigate fire risk through fuel reduction and maintenance of defensible space[60]. Between 2016 and 2024 the budget of CalFire, the state's wildfire response and risk reduction agency, nearly doubled (from $2.2 to $4 billion), and spending on mitigation, which had previously been a minor component of the CalFire budget, soared to $2.6 billion[61,62]. The state government also acted to disseminate knowledge about fire risk by increasing the frequency of revisions to its fire risk maps, conducting research and issuing technical advisories, and requiring local governments and homeowners to disclose information about fire risk reduction measures[60,63–65].

The link between mitigation and insurance has been a particular concern for state policymakers. For example, the California Department of Insurance's "Safer from Wildfires" initiative requires insurers to provide discounts for specific mitigation actions. Interviews conducted in 2023 and 2024 suggest, however, that the connection between insurance and mitigation investments has been weakened by the lack of feedback from mitigation actions to lower premiums or greater availability. The Safer from Wildfires framework is deemed ineffective (see below), and the insurance industry has opposed reforms that would require the incorporation of mitigation into modeling that is used for underwriting decisions[33]. State lawmakers and experts increasingly express frustration that billions of expenditures on wildfire mitigation have not substantially improved insurance availability or lowered premiums[66].

B.2 describes actions to mitigate fire risk that are taken by local collective actors, including government entities (e.g., city and county governments, fire protection districts) and community organizations (such as Firewise Communities and Firesafe Councils). Various factors increased local collective action on mitigation since the 2017–2018 fires. Among these are increased fire risk perception due to experience with fire and information campaigns, state support for collective and individual mitigation (e.g., through grant programs), state mandates (e.g., defensible space requirements), and the insurance crisis, which was cited in many interviews as a "wake up call" that has been the most important motivator of local collective action. Increased mitigation actions by local collective actors include: fuel reduction on public lands such as parks and open space; heightened enforcement of defensible space requirements through inspections and fines for non-compliant properties; public subsidy for mitigation on private property (e.g., screening vents), which is funded either through local tax assessments or through state and federal grants; and the dissemination of information about fire risk.

Community organizations such as Firewise Communities and Firesafe Councils play a significant role in local collective action on mitigation. These entities receive technical, financial, and organizational support from state and local government but are organized "from below" by residents and depend on highly motivated community members[33]. They disseminate information about fire risk and mitigation (e.g., through door-to-door organizing), administer some grant programs, and organize community mitigation projects[33]. Firewise and Firesafe organizations also serve as a channel through which individual preferences feed back into collective decisions, whether by influencing the choices of local governments or by shifting broader community attitudes about mitigation[33]. The dramatic growth in the number of these organizations is itself an indicator of increasing local collective action on mitigation. In 2024, the 800th Firewise community was designated in California, up from only 137 in 2017[33,67,68]. Interviews suggest that this growth of Firewise communities has been driven primarily by the insurance crisis, since participating homeowners receive a discount (albeit often small) for Firewise designation, and since the insurance crisis has dramatically increased fire risk awareness.

At the same time, our interviews suggest that local collective action on mitigation is highly constrained and falls far short of fire safety standards held by local governments and engaged citizens. For example, while building codes have been made more stringent for new construction, no local jurisdictions that we studied require costly home hardening retrofits. Similarly, local authorities have been slow to adopt requirements such as large tree removal on private property or "zone zero" requirements (five feet of space around structures with no flammable materials) that imply significant costs for homeowners and substantially alter the aesthetic character of individual lots and neighborhoods[33]. These difficulties stem from homeowner resistance to mitigation and denial about fire risk (see below). Stakeholders in community organizations and local government view such resistance as the most challenging problem for further action on mitigation[33].

Significant variation was observed in local collective actors' ability to overcome these constraints. For example, some local governments inspect lots annually, impose fines on homeowners for non-compliance, and report high compliance (over 90%)[33]. Other local governments inspect lots only sporadically and do not have significant mechanisms of enforcement, due to limited funding, lack of staff, and lack of homeowner support for such programs[33]. Well-resourced communities with active community organizations and/or high fire risk perception (due to recent fire experience, among other factors) have worked to secure state and federal grants or have instituted local assessments to pay for mitigation. In other jurisdictions such funding has not been mobilized, and local actors anticipate significant resistance to passing spending measures. The differential ability of localities to mobilize organizational and financial resources to increase fire safety is a potentially significant driver of distributional outcomes amid processes of disorderly adaptive change (see "Discussion").

B.3 describes mitigation action by homeowners on private lots, which includes defensible space measures—such as the clearance of brush and dead leaves—and home hardening measures, such as installing class A roofs, covering vents, and replacing old windows. Interviews suggest that homeowner motivation to mitigate has increased since the 2017–2018 wildfires, driven by higher perception of risk, stricter enforcement of defensible space requirements, information and outreach campaigns, and, in particular, by the insurance crisis. They also suggest that an important role is played by community mobilization and by demonstration or neighbor effects: living in a community in which other property owners have implemented mitigation action spurs homeowner action.

At the same time, significant barriers to homeowner action on mitigation persist. For many homeowners, the perception of fire risk is low, due to outright denial ("this can't happen to me"), competing priorities, or lack of information (in cases where community organization is weak, or local government is not active). Homeowners also face significant resource constraints in implementing home hardening measures—which can require large one-time investments running to tens of thousands of dollars[69]—and in maintaining defensible space, particularly given the limited availability of subsidies to help cover these costs. Many homeowners resist mitigation measures due to opposition to government intrusion on private choices or to attachment to the aesthetic qualities of their property. Finally, given the limitations of inspection regimes discussed above, homeowners in many local jurisdictions are not required to comply with existing state or local codes.

As we have noted, interviews consistently suggested that dropped insurance coverage and steep premium increases are the single most important factor in increasing fire risk perception and in motivating action on mitigation by both homeowners and local collective actors. However, the impact of insurance is limited by the absence of clear feedback from mitigation to insurance availability and cost. Homeowners receive limited information about the reason for premium increases or dropped policies, and little to no information about actions that they could take to reestablish coverage[33,70]. Firewise community designations have limited value in incentivizing mitigation due to the small size of discounts (often less than 5%). Meanwhile, discounts required by the state's Safer from Wildfires policy were reported to be far too small to impact mitigation choices[33].

Turning to C in Figure 2 (land use), many factors that contributed to the accumulation of fire risk through land use patterns—specifically through development in the HFRA—are still in place after the 2017–2020 fires[31]. Pressure for development continues to be driven by the high cost of housing in metropolitan cores, by the shielding of governments and individuals in the HFRA from costs associated with fire risks, and by the incentives of local governments in the HFRA to increase their property tax base. In recent years, these dynamics have been inflected by state government efforts to increase housing production by superseding local land use controls. For example, the state government has limited the ability of local governments to restrict the construction of accessory dwelling units and required local governments to meet targets for developable land through their general plans[71–73].

In the medium term, the state push for increased housing production could relieve pressure on development in the HFRA by increasing availability of housing in the metropolitan core. But state mandates on housing production also apply to communities in the HFRA, and in such areas state housing policy is colliding with new initiatives to encourage fire safety. Since the 2017–2020 fires, state agencies have provided technical support to localities in incorporating fire safety into land use planning[64] and added wildfire risk, among other climate hazards, as a factor to be considered in defining housing production requirements for local governments[74]. The state has also updated its fire hazard maps[33,75] and acted to require more frequent updates to safety elements of General Plans to reflect current hazard data (California Government Code 65302). To date, however, state authorities have resisted efforts by local jurisdictions to use safety concerns as a rationale for avoiding housing production requirements. The State's Department of Housing and Community Development has argued that it lacks information to assess either the level of risk or the value of mitigation measures (such as improved evacuation routes) in reducing risk. Moreover, to date it has prioritized housing production goals over fire safety[33,76]. Meanwhile, sanctions for local governments' failure to meet housing goals—such as the so-called "builders' remedy"—have in some cases led to housing construction in the HFRA[77]. Thus, in the short term, state housing policy is limiting the ability of local governments to restrict new development in high-risk areas, even in cases where local governments are motivated to do so. For all these reasons, government land use controls have responded slowly to wildfire risk, while pressures for construction in the HFRA persist, particularly given the state's emphasis on housing production and ongoing housing shortages in the metropolitan core.

By contrast, housing value and carrying costs—particularly the price and availability of insurance—have exerted a faster and larger impact on land use patterns. For homeowners, insurance rate hikes have significantly increased the carrying costs of housing in the HFRA, increasing levels of housing burden for low-income households and driving some homeowners to move out of the HFRA[33]. For developers, difficulty in obtaining construction insurance, alongside worries that homeowners may struggle to buy

homes where it is difficult or expensive to purchase insurance, is deterring new development in the HFRA[33,78]. Further, there is evidence that market values for houses in high-fire-risk areas are being discounted[79,80], signaling a change in housing demand in the HFRA.

Distinct issues relating to land use change arise in areas that are rebuilding following large wildfires. Due to widespread underinsurance prior to the fires, escalating construction costs, requirements for expensive upgrades (e.g., for septic systems), and high post-fire insurance costs, many existing residents are unable to rebuild in these areas and are forced to either leave their lots vacant or sell them[33,81]. These factors have resulted in slow rebuilding in some localities, such as the Town of Paradise, which was devastated by the 2018 Camp Fire, and areas of Santa Cruz County that were impacted by the 2020 CZU Lightning Complex Fires[33]. It is not clear whether such areas will recover to their pre-fire population, raising the possibility that the fires have led to permanent change in land use patterns. Many pre-fire owners do not have sufficient resources to rebuild (given factors such as underinsurance). Lots that are sold to contractors are rebuilt and sold to new residents, resulting in displacement of prior residents who were financially devastated by the fires[33]. In some areas, third-party construction has proceeded rapidly (in Santa Rosa, for example). In others (such as Paradise) third-party rebuilding has been slowed by high prices for construction and insurance, and by limited demand for relatively remote properties in high-risk areas[33].

Discussion

This article has introduced the concept of disorderly urban adaptation and proposed a method for qualitative modeling of urban systems that can aid in characterizing disorderly change processes. In this section, we address the significance of this approach for practitioners and scholars, the normative implications of disorderly adaptation, and the limitations of our research.

The concept of disorderly adaptation and the methodology we have proposed for characterizing disorderly change are significant for urban planners and practitioners in two important ways: First, by using tools of systems analysis to model disorderly change in the local context, planners can better understand how important but under-analyzed dimensions of urban adaptation are unfolding. Second, these tools can aid planners in understanding the direct and indirect implications of policy choices.

As Maskell et al. have recently argued,[82] although it is often assumed that carefully planned processes of change have "greater scale and transformative potential," planned adaptation is "failing to drive transformations at the necessary speed and scale" to address climate impacts. Moreover, we suggest that much of the adaptation that is actually taking place has characteristics of disorderly change that we have described here. For this reason, alongside planning for orderly adaptation—which is generally assumed in urban adaptation plans—local governments should also plan for disorderly change. The approach to studying disorderly adaptation we have described in this article provides a starting point for such planning. Qualitative models make it possible to identify key mechanisms and drivers of disorderly change—many of which fall outside the usual purview of urban planning generally and of adaptation planning in particular. For example, in the preceding analysis of the California HFRA, financial mechanisms such as insurance markets and regulation are important drivers of disorderly adaptation. Planners concerned with managing disorderly change in this context will have to address issues such as the interface between insurance risk rating, insurance regulation and land use patterns, and the development of fire safety standards by public and private entities that translate between mitigation actions and insurance pricing and availability. Precisely such mechanisms are currently the most active areas of reform in California and seem likely to play a central role in processes of urban adaptation moving forward. Yet such planning is taking place outside the purview of urban planning, in areas such as insurance and fire safety regulation.

Our qualitative model also provides insight into how such changes will impact processes of urban adaptation. In early 2025, the CDI rolled out a "Sustainable Insurance Strategy" that grants insurance carriers the ability to raise rates in exchange for maintaining a market share in the HFRA that is at least 85% of their statewide market share. Meanwhile, the Insurance Institute for Business and Home Safety (IBHS) has recently developed a Wildfire Prepared Home standard that establishes stringent property-level standards for mitigation that insurers are beginning to accept as a meaningful indicator of risk reduction. Local governments, recognizing that insurance pricing and availability are existential matters for urban futures, are beginning to adopt these insurance-based standards as local code[33]. The growing acceptance of common standards for risk reduction in the built environment by insurers, regulators, property owners, and local governments would strengthen feedbacks between mitigation and insurance. As such, they may serve to "resynchronize" sub-systems in the broader HFRA system that have experienced highly disparate rates and patterns of change during the period of disorderly adaptation.

The concept of disorderly adaptation also contributes to scholarly discussions of adaptation[14,15,82]. Over the last few decades, scholars have drawn distinctions among different forms of adaptation: anticipatory versus reactive, public versus private, and planned versus "spontaneous." More recent discussions recognize that many adaptation processes are not neatly classified in these terms and have called for "more nuanced examinations of the interplay between" different forms of adaptation.[82] The systems approach to qualitative modeling we have presented in this article offers a tool for such analysis, providing a framework for understanding processes in which different types of adaptation are intertwined and co-constitutive[83]. Consider, for example, a key adaptation action that relates to our case material: the "hardening" of privately owned homes and the maintenance of "defensible space" on privately owned property. Such actions must, at the end of the day, be taken by individual property owners. But this putatively "autonomous" action is influenced by the actions of insurers, regulators, real estate agents, and local and state governments that share information, shift preferences, and shape incentives. In this sense, individual decisions are structured by other decision-making units at various scales and in various sectors that are "planning" for different reasons and with different aims. The value in using systems tools (such as causal loop diagrams and qualitative modeling) to characterize change processes lies in their ability to map interactions between actors in complex systems and to thus better understand factors influencing adaptive change and the impacts of policy interventions.

The distinction between orderly and disorderly adaptive change is descriptive and is not, in the first instance, normative. It identifies features of change processes but does not imply an evaluation of such processes. That said, the disorderly character of adaptation may have significant normative implications. Disorderly adaptation is driven by actions that are at least partly uncoordinated—for example, by the independent actions of local governments or community organizations. In disorderly change processes, higher resource individuals and communities will be able to place themselves on more resilient and potentially lower-cost trajectories of adaptation. Examples beyond the California HFRA include local government financing of coastal protection to reduce insurance premiums (a recent example is a seawall built in Foster City, California[84]) and "elite infrastructural secession" from electricity grids to increase resilience to blackouts and climate extremes (observed in many localities, from South Africa[85] to the United States[86]). Disorderly processes of change are also less likely to provide compensation for those that are affected by climate impacts. In California, such considerations come into play in relation to individuals who are displaced by either the direct impacts of wildfires or by the loading of climate change costs onto housing in the HFRA (via insurance premiums or costly home hardening or landscape fuel reduction requirements). Such individuals do not receive compensatory support in the form of buyouts or other assistance, and, indeed, are largely invisible, as little information exists about their movements or the size of these effects. In this way, disorderly adaptation processes can lead to greater inequalities between high and low resource communities.

Our model also provides insight into normative questions that arise from attempts to manage disorderly change processes. For example, if the aforementioned Sustainable Insurance Strategy works as intended,

insurance availability will expand due to large further increases in prices, imposing painful adjustments and additional housing burden on many households and communities in the HFRA. One predictable consequence of the strategy, if it succeeds in compelling admitted market insurers to write more policies in the HFRA, will be competition for the "good" risks in fire-prone areas of the state. This competition may give renewed impetus to standards like the Wildfire Prepared Homes standard. It will also favor communities that can marshal the organizational and financial resources needed to make significant one-time and ongoing investments in fire risk reduction to meet such standards. One plausible future scenario is that these reforms could reinforce divergent adaptation pathways. Well-resourced communities and individuals will be able to enter a virtuous circle of investments in mitigation and lower and more available insurance, which will in turn bolster property values and augment community resources. Low-resource communities, meanwhile, will be stuck in a vicious circle: With meager resources to invest in mitigation they will be unattractive to admitted market insurers, and will experience low availability and high premiums that will further undermine their ability to invest in mitigation. Qualitative models like the one presented in this paper can aid planners in understanding such unintended consequences of attempts to manage disorderly change.

One potential limitation of the approach we have described relates to its generalizability. The California case and similar US cases in which the authors have direct research experience served as a basis for developing our general understanding of disorderly adaptation. An important question for further research is the extent to which it applies to other geographies and hazards. A recent review[82] suggests that "mixed" forms of adaptation (public *and* private action, planned *and* spontaneous, active *and* reactive) are pervasive. At the most general level, the systems analysis tools we have proposed for qualitative modeling are likely to be relevant for studying such adaptation processes. The specific emphasis in our models on land use, the built environment, and finance may be relevant to a more restricted though still broad range of cases and invites future comparative research. For example, we observe disorderly change processes like those described in California in many areas of the US that are facing increasing wildfire loss, insurance market disruption, and varying levels of adjustment in land use and the built environment[31,44,87]. Our model can be employed to investigate how patterns of adaptive change are influenced by factors such as differences in state insurance regulation (which affect the responsiveness of premiums to changing risk perception and other insurance market dynamics[38]) or in state and local land use and building codes and levels of enforcement[88,89]. The model might also be employed in international comparisons between countries with US-style insurance regulation and countries with solidaristic disaster insurance systems—in which, for example, hazard insurance premiums take the form of a flat assessment across all policyholders[90]. Similarly, the model seems readily applied to other hazards in contexts in which adaptation dynamics are closely tied to changes in financial systems. For example, the interplay between insurance, the built environment, and land use has been shaping urban change on the Florida coast for a number of decades[10,91]. In Florida, similar dynamics have also been traced in relation to other financial mechanisms, including bond ratings[92] and property markets[93]. That said, the penetration of financial mechanisms such as insurance and mortgage markets is far from universal. Indeed, the US is somewhat of an outlier in the importance of insurance in adaptive change processes. Further research might consider whether there are contexts in which this approach is not helpful or requires significant modification—for example, by modeling other complex systems, such as electricity, that interact with land use, the built environment, and individual and collective resilience outcomes.

Another limitation concerns the qualitative nature of the relationships we have described. Qualitative analysis was selected at this stage as a tool for identifying significant relationships in complex socio-ecological systems. It was also selected due to the paucity of quantitative data on many of the interactions that we studied.[49] While the relationships described in the diagrams were confirmed by multiple sources of information, qualitative analysis cannot capture the strength of these relationships, either in comparison to each other or as they change over time. However, we hope that qualitative modeling can provide the basis for seeking out data appropriate for establishing quantitative understanding of the relationships we have identified.

Methods

Our research on the California HFRA involved three components that were conducted iteratively. (1) *Study system characterization* involved identifying key actors and institutions of sub-systems in the California HFRA; (2) *Data collection* comprised qualitative research (e.g., policy reviews, interviews) to characterize key actors, systems and sub-system interactions; (3) *Qualitative modeling* employed both causal loop diagrams to characterize high-level relationships and detailed conceptual models of interactions among sub-systems.

Study system characterization

Study system characterization involved preliminary research to identify key drivers of adaptation outcomes (in land use, the built environment, and financial resiliency) and key actors and institutions involved in shaping these drivers. Thus, for example, our preliminary research identified state defensible space codes, local government inspection and enforcement, and interactions among community organizations (such as Firewise Communities and Firesafe Councils) and property owners as key drivers for mitigation of landscapes through fuel reduction.

Data collection

Once we identified key actors and institutions in HFRA sub-systems we collected data about relationships within and among sub-systems, and about their change over time. This research included: (1) review of academic papers, evaluation reports of outcomes for previous fires in California, planning documents, and news articles; (2) participation in public forums organized by California state and local government agencies relating to insurance and wildfire risk; (3) participation in stakeholder workshops with community-based organizations, local fire departments, and staff from local governments organized by the Smart and Connected Communities research team in Alameda and Marin counties, California; (4) formal interviews with officials in California state and local governments, including regulators, city planners, and fire departments ($n = 8$), individuals who work in the insurance industry, including insurance companies, insurance research organizations, and agents ($n = 7$), and participants in community organizations, including Firesafe Councils and Fire communities ($n = 6$).

Qualitative modeling

Based on the data collected in this research, we built a conceptual model of the HFRA by developing the two diagrams presented in the results section above. Our approach to developing these diagrams was iterative. Based on preliminary research, we drew simple diagrams of the HFRA system. These diagrams then guided further research that added complexity and nuance. In this sense, the diagrams served as both research instruments and visualization tools.

Data availability

The datasets generated and/or analysed during the current study are not publicly available due to privacy concerns, confidentiality agreements, and the conditions of our human subjects protocol.

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Competing interests

The authors declare no competing interests.

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