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REVIEW ARTICLE

Climate-smart forestry: an AI-enabled sustainable forest management solution for climate change adaptation and mitigation

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Abstract Climate change is the most severe ecological challenge faced by the world today. Forests, the dominant component of terrestrial ecosystems, play a critical role in mitigating climate change due to their powerful carbon sequestration capabilities. Meanwhile, climate change has also become a major factor affecting the sustainable management of forest ecosystems. Climate-Smart Forestry (CSF) is an emerging concept in sustainable forest management. By utilizing advanced technologies, such as information technology and artificial intelligence, CSF aims to develop innovative and proactive forest management methods and decision-making systems to address the challenges of climate change. CSF aims to enhance forest ecosystem resilience (i.e., maintain a condition where, even when the state of the ecosystem changes, the ecosystem functions do not deteriorate) through climate change adaptation, improve the mitigation capabilities of forest ecosystems to climate change, maintain high, stable, and sustainable forest productivity and ecosystem services, and ultimately achieve harmonious development between humans and nature. This concept paper: (1) discusses the emergence and development of CSF, which integrates Ecological Forestry, Carbon Forestry, and Smart Forestry, and proposes the concept of CSF; (2) analyzes the goals of CSF in improving forest ecosystem stability, enhancing forest ecosystem carbon sequestration capacity, and advocating the application and development of new technologies in CSF, including artificial intelligence, robotics, Light Detection and Ranging, and forest digital twin; (3) presents the latest practices of CSF based on prior research on forest structure and function using new generation information technologies at Qingyuan Forest, China. From these practices and reflections, we suggested the development direction of CSF, including the key research topics and technological advancement.

Keywords Forest management · Climate change · Carbon sink · Carbon forestry · Smart forestry

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Introduction

Forests provide a range of vital ecosystem services, including serving as a carbon sink to mitigate climate change. However, contemporary, human-caused global warming and its derived extreme climate events and other disturbances have presented unprecedented challenges to global forests, threatening their stability and resilience. To address these challenges, we need an innovative solution to sustainable forest management (i.e., Climate-Smart Forestry, CSF) to ensure climate change

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adaptation while optimizing climate change mitigation for the critical period through 2100 when the magnitude of global warming must be controlled below 1.5 °C (IPCC 2018).

CSF first appeared in peer-reviewed literature in 2017, which was defined as "a more specific (climate-oriented) form of the Sustainable Forest Management paradigm" (Nabuurs et al. 2017). Previous research on the CSF concept has primarily addressed mitigation actions, with a focus on greenhouse gas emission reduction and carbon sequestration (e.g., Nabuurs et al. 2018; Verkerk et al. 2020). Realizing the imminent threats from climate change, many studies have also concentrated on evaluating forest adaptation capacity, identifying critical environmental stressors, and developing optimal strategies to enhance forest ecosystem resilience (e.g., Lisella et al. 2022; Sterck et al. 2021). Over the past few years, CSF has evolved to promote both adaptation and mitigation in forest management practices (e.g., Cooper and MacFarlane 2023; Luo et al. 2023; Shephard et al. 2022; Tognetti et al. 2022; Wang 2024; Zhu et al. 2024).

Coinciding with the emergence of CSF, artificial intelligence (AI) has progressed significantly and is capable of solving real-world data problems in virtually all areas of application domains (Holzinger et al. 2023). As a result, forestry is also undergoing a digital transformation towards a "smart" forestry (Ehrlich-Sommer et al. 2024). This new development has recently been integrated into CSF (Wang 2024; Zhu et al. 2024). By leveraging the latest information technologies and AI, CSF seeks to develop innovative and proactive forest management methods and decision-making systems to tackle climate change challenges and thus holds great promise in addressing some unique challenges in forestry, such as the long lifecycle of forests, difficulties in field-controlled experiments, high trial-and-error costs, and the interdisciplinary nature of climate change (Zhu et al. 2024).

In this concept paper, we first discussed the evolution of forestry and the emergence of CSF, based on which we proposed a new definition for CSF. We then analyzed the goals of CSF in improving forest ecosystem stability, enhancing forest ecosystem carbon sequestration capacity, and advocating the application and development of new technologies in CSF, including artificial intelligence, robotics, Light Detection and Ranging (LiDAR), and forest digital twin. Using Qingyuan Forest as an example, we described the application of CSF in forest ecosystem studies. Finally, we suggested the development direction of CSF, including the key research topics and technological advancement.

Concept of climate-smart forestry

Forestry's primary goal has always been meeting societal demands for forest resources, yet society's perception of and need for forests continuously evolves. Forestry development has undergone three major paradigm shifts: traditional forestry before the 1970s, ecological forestry from the 1980s to 2020, and the emergence of CSF in the post-2020 era (Zhu et al. 2024). Traditional forestry was rooted in pragmatism and focused mainly on timber production, management, and utilization. Following the unsustainable exploitation and utilization of forests, ecological forestry emerged. Influenced by the modern environmental movement and the rapid advancement of ecology since the 1970s, this approach highlighted the ecological roles forests play as part of the Earth's life-support systems. Concepts such as close-to-nature silviculture, continuous cover forestry, and ecosystem management were introduced to ensure the health and integrity of forest ecosystems and sustainably supply societal needs for products and services. CSF has recently emerged to address the challenges of climate change driven by human-caused greenhouse gas emissions. Initially conceptualized in the European Union (Bowditch et al. 2020; Weatherall et al. 2021), CSF has rapidly progressed in the United States and elsewhere in recent years (Cooper and MacFarlane 2023; Luo et al. 2023; Shephard et al. 2022; Wang 2024; Zhu et al. 2024).

Building on the solid foundation of ecological forestry, CSF blends the latest developments in carbon forestry and smart forestry and emphasizes the application of new technologies (e.g., informatization and AI) in forestry. Carbon forestry started by emphasizing carbon trading and by focusing on cultivating fast-growing monocultures or managing existing forests to maximize carbon storage (Mitchell et al. 2012). It then developed into an evolved form of sustainable forest management (or climate forestry), which seeks to enhance forest resilience to climate change by adjusting and improving biochemical processes (such as photosynthesis, respiration, and decomposition) and biophysical processes (like water absorption and transpiration) to increase CO_2 absorption, decrease greenhouse gas emissions, and promote sustainable forest resource use, balancing environmental, social, and economic benefits. Thus, carbon forestry becomes a crucial part of nature-based climate solutions (NbCS), similar to the initial concept of CSF (Bowditch et al. 2020; Nabuurs et al. 2018). Smart forestry applies advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, and information technology in forestry. By enabling real-time data collection and feedback, it creates a forest digital twin model—a virtual representation of real forest ecosystems—that simulates forest development, identifies disaster warning signals, optimizes decision precision, and enhances management efficiency for sustainable forest management (Cao et al. 2022; Zhao et al. 2005). Smart forestry is an evolution of digital forestry, with AI and forest digital twin platforms at its core (Buonocore et al. 2022; Luo et al. 2023).

Based on recent advances in forestry research and practices, we define Climate-Smart Forestry as an emerging concept in sustainable forest management, which develops innovative forest management and decision-making systems through the latest technologies like information technology and AI to address climate change challenges, aiming to enhance the resilience of forest ecosystems, improve their capacity to mitigate climate change while maintaining forest productivity and other ecosystem services, and ultimately achieve harmonious development between humans and nature (Fig. 1).

Goals of climate-smart forestry (CSF)

Overview of CSF

Climate-Smart Forestry has three keywords: climate, smart, and forestry (Fig. 1). The "forestry" part has never changed, which still is to provide goods and services to society and the well-being of the environment. However, our management objectives and priorities are changing, and we are now preoccupied with climate change mitigation and adaptation. Consequently, "climate" is prominently featured in CSF. With the inherent complexity of forest ecosystems and the uncertainty and novelty of climate change, advanced technologies must be applied to develop proactive management strategies and practices for CSF. Therefore, CSF has to be "smart" as well. Thus, the goals of CSF are to help forests adapt to climate change so that forests remain resilient and continue to provide ecosystem goods and services, especially neutralizing carbon emissions.

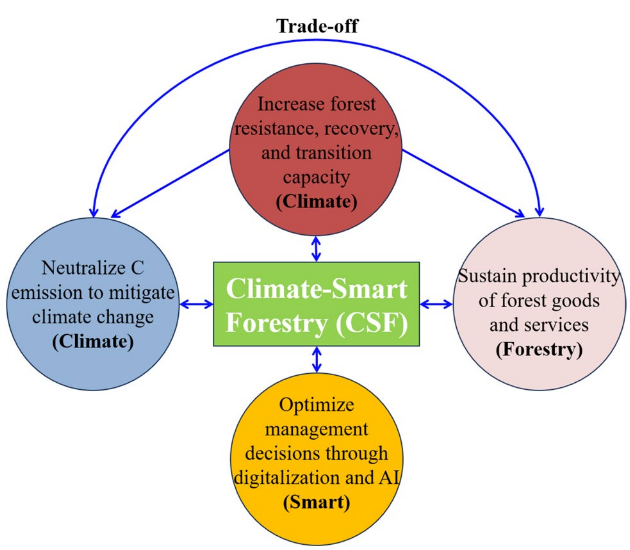

Fig. 1 Conceptual diagram of Climate-Smart Forestry (CSF), modified from Wang (2024)

Adapting forest ecosystems to climate change to improve resilience

Climate change has already begun or is in the process of weakening the resistance and recovery capabilities of forests against disturbances (Forzieri et al. 2022). Therefore, CSF must develop a series of proactive management strategies and practices to adapt forest ecosystems to climate change and ensure their resilience. These strategies include (1) maintaining the status quo, (2) restoring former stable states, and (3) guiding forests toward an ideal state suitable for future climates. The choice of specific strategies and measures depends on factors such as forest type, species, structure, site conditions, management goals, and anticipated climate change scenarios.

When climate and disturbance factors remain within their historical range of variability, CSF focuses on maintaining the current state of forests or restoring them to their original stable states. However, in the face of drastic climate changes and systemic alterations in disturbances, management strategies must focus on transitioning existing forests smoothly into an ideal future state to ensure the sustainability of ecosystem services (Fig. 2). Under novel climatic conditions and disturbances, forest ecosystems often struggle to maintain their current status (Millar and Stephens 2015). Thus, it is crucial to utilize historical multi-source data and real-time survey data to develop forest digital twin models, simulate and forecast future climate and disturbance scenarios, identify suitable species compositions (local or introduced), and develop specific management plans to facilitate an ecosystem transition. This ecosystem should have a structure and function similar to the existing forest, ensuring stable ecosystem service functions while achieving a smooth transition (Fig. 2). For instance, the chestnut blight in the early twentieth century led to the functional extinction of the American chestnut in its natural range. However, forests dominated by the American chestnut transitioned naturally and smoothly to oak-dominated forests, maintaining similar forest structures and ensuring the stability of ecosystem service functions.

Enhancing carbon sequestration in forest ecosystems to mitigate climate change

Terrestrial ecosystems absorb about 30% of carbon emissions, with over 80% of this absorption occurring in forests (Keenan and Williams 2018). Thus, forests are crucial to nature-based climate solutions. Among these solutions, forest-based approaches account for ~70% of the overall mitigation potential (Griscom et al. 2017). To realize this potential, CSF must enhance the carbon storage capacity of forests. Generally, three strategies can be employed to enhance carbon sequestration in forests (Verkerk et al. 2020): (1)

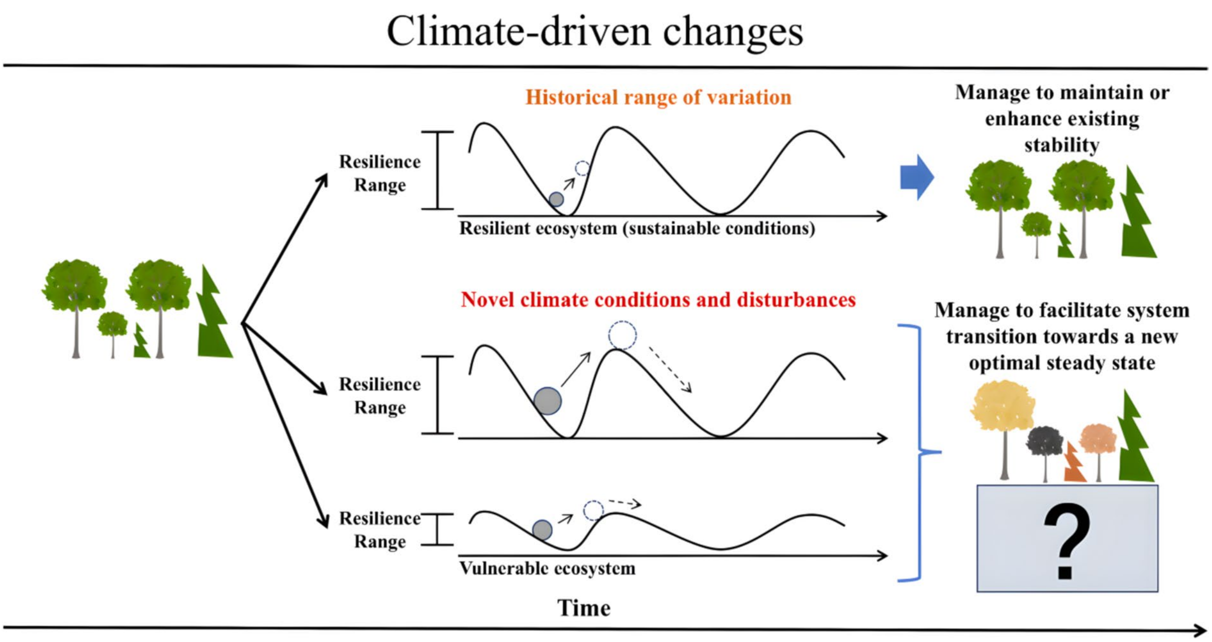

Fig. 2 Hypothetical responses of current forests to climate change-driven disturbances. The stability of current forests leads to the maintenance of current forest conditions when climate change is within the historical range of variation, but the forest will transform to a new alternate stable status (transition) in response to new climate conditions or disturbance stage. Modified from Wang (2024)

Increase forest area: Expand afforestation area and avoid deforestation; (2) Enhance internal carbon storage: Promote forest restoration, improve forest quality, and reduce carbon emissions from disturbances, such as wildfires; (3) Develop climate-smart forest products for external carbon storage: Increase timber production, promote efficient utilization of wood products, and substitute non-wood products.

Due to historical overharvesting and other anthropogenic disturbances, many forests are recovering, displaying significant carbon sequestration potential (CSP). Theoretically, the carbon sequestration potential of any specific forest can be determined by the difference between its carbon carrying capacity (CCC) and current carbon stock. The CCC refers to the maximum carbon storage a forest ecosystem can achieve in dynamic equilibrium under specific environmental conditions and natural disturbance regimes (Gupta and Rao 1994). Research exists on the CCC of forests in different regions and countries (Chen et al. 2022b; Liu et al. 2014), but further studies are needed to clarify the CCC for various forest types, especially concerning the carbon saturation threshold of forest soils (Keith et al. 2010).

In most countries, only a small portion of forests are actively managed. It is crucial to prioritize forests with the greatest carbon sequestration potential to quickly realize their CSP with tailored carbon sequestration strategies. For example, large-scale carbon sinks have mainly resulted from forest recovery following historical destruction in the United States. It is estimated that between 1700 and 1935, U.S. forests released approximately 42,000 Tg C due to logging and land-use changes (e.g., agriculture, pasture, and development). Still, they absorbed around 15,000 Tg C during recovery from 1935 to 2010 (Birdsey et al. 2006). As forests approach their CCC, it remains unclear whether current carbon sequestration rates can remain stable and for how long. Recent studies indicate that the future carbon sequestration potential of existing forests is limited (Roebroek et al. 2023). Under climate change, forests may face more frequent or extreme disturbances, threatening to reverse carbon storage. For instance, in 2023, extreme wildfires in Canada released over 1.5 billion tons of CO_2 into the atmosphere, exceeding Canada's total CO_2 emissions from wildfires over the past 22 years (1.374 billion t) (Chinese Academy of Sciences 2023).

The carbon storage of any forest ecosystem will ultimately reach saturation, equivalent to its CCC, if not disturbed prematurely. At this point, natural disturbances can lead to carbon losses, and forests gradually recover post-disturbance, maintaining a dynamic balance in carbon sequestration. However, through judicious harvesting and timber utilization, we can manage forests as a constant carbon sink by maintaining their carbon stock well below CCC, which opens new opportunities for actively managed forests such as plantations. To maximize this potential, we can take the following measures (Köhl and Martes 2023): (1) Develop CSF technologies: Employ silviculture methods that minimize carbon emissions to increase the yield of timber and other products; (2) Enhance development and utilization of wood and biomass products: Achieve long-term carbon storage;

(3) Substitute wood for high-emission materials: Use wood to replace steel, concrete, and plastics, maintaining carbon storage capacity in wood while reducing greenhouse gas emissions from the production of substituted materials. Lippke et al. (2011) discussed achieving external carbon sequestration by increasing timber production, promoting timber product use, and substituting non-wood products. They compared a 45-year-old rotation-aged plantation (carbon stock = 189 t ha^{-1}) with a mature stand at CCC (carbon stock = 420 t ha^{-1}). Over the next 135 years (three rotation periods), the annually fixed carbon per unit area was found to be 4.2 to 9.7 t ha^{-1} a^{-1} higher in sustainably managed plantations (Fig. 3).

Developing and applying cutting-edge technologies to make better decisions under climate change uncertainty

To effectively address climate change and advance CSF, the application of emerging technologies is crucial (Zhu et al. 2024). Artificial intelligence (AI) plays an important role in the complex process of forestry decision-making. Compared to traditional modeling approaches, AI can effectively overcome challenges such as data limitations, incomplete knowledge, and uncertainties surrounding future climate changes, thus enhancing the accuracy of predictions regarding the future state of forests and optimizing management decisions. Furthermore, CSF can also implement evidence-based practice (EBP), which is widely used in the medical field, by integrating the best research evidence, local management experiences, and human values and needs into real-world decision-making.

High-quality data is foundational for making informed forest management decisions. Therefore, CSF must develop and utilize cutting-edge technologies to enhance data collection methods. For example, utilizing AI and robotics, we can develop Forest Intelligent Data Acquisition System (FIDAS) to enable real-time data acquisition using LiDAR technology. Drones equipped with various specialized cameras and sensors can collect data both above and below the forest canopy, providing real-time, precise, and efficient information that significantly compensates for the limitations of ground survey data (e.g., forest inventory data) and the resolution constraints of satellite data. The application and development of FIDAS will fundamentally transform forest data collection methods and promote advancements in forest science and management.

To make more accurate predictions under uncertain climate conditions, CSF will actively explore the application of Forest Digital Twins. A Forest Digital Twin consists of a set of virtual models that can simulate the structure, composition, and dynamics of a forest in real-time, built at various

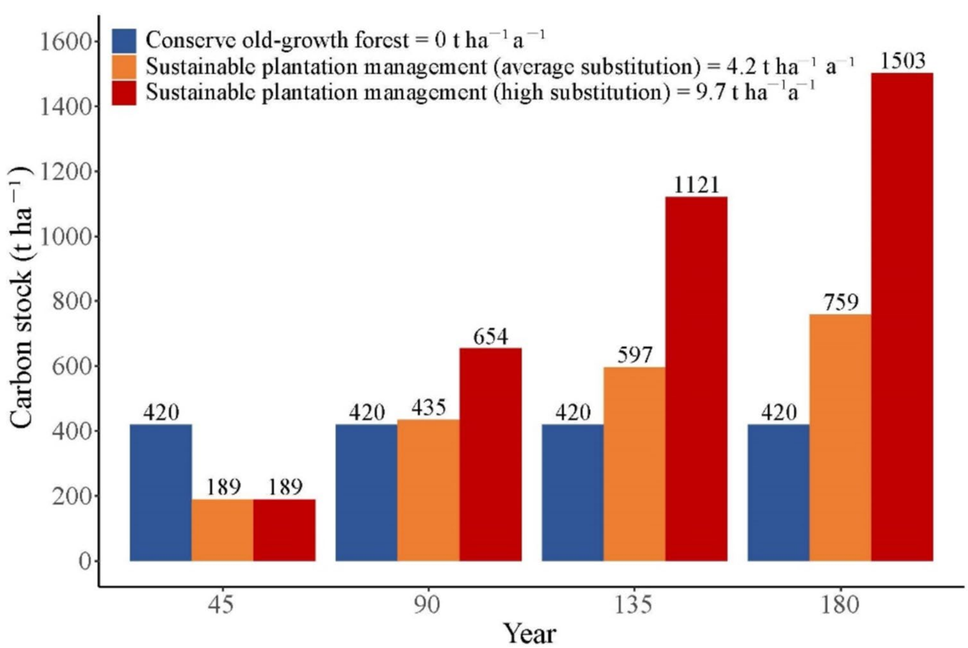

Fig. 3 The impact of management and wood-use alternatives on total carbon mitigation. Assuming the old-growth forest has a carbon carrying capacity (CCC) of 420 t ha^{-1} and the sustainably managed plantation has a carbon stock of 189 t ha^{-1} at the rotation age of 45. The three scenarios are 1) conserving the old-growth forest, 2) sustainably managing the plantation with average substitution, and 3) sustainably managing the plantation with high substitution. At 180 years after three harvests, *in-situ* C stock is 420, 189, and 189 t ha^{-1}, *ex-situ* C stock is 0, 570, and 1314 t ha^{-1}, and C sequestration rate is 0, 4.2, and 9.7 t ha^{-1} a^{-1}. This figure was produced with the data provided by Lippke et al. (2011). Modified from Wang (2024)

spatial scales (from stand scale to global scale). By utilizing different climate scenarios and time resolutions, the Forest Digital Twin provides more accurate predictions of future forest states. When combined with three-dimensional virtual reality, this platform can assist researchers and managers in visually forecasting future forest changes and identifying critical factors essential for formulating CSF policies, strategies, and practices.

Case study of CSF: forest structure and function using next-generation information technology

Case area

Qingyuan Forest CERN, a National Observation and Research Station, has established a comprehensive observation platform within a typical independent watershed spanning 536 ha. This platform includes multiple 50-m-tall observation towers (Qingyuan Ker Towers), permanent sample plots, and a network of hydrological stations. It primarily utilizes a flux tower system for carbon and water flux observations, along with multi-platform LiDAR as the main method for monitoring forest structure (Zhu et al. 2021) (Fig. 4). Based on this framework, advanced information technologies such as the IoT, AI, and big data have been integrated into the study of forest ecosystem structure and function. A three-dimensional, holographic forest ecosystem observation research methodology system centered around the Qingyuan Ker Towers, has been designed to achieve multi-scale, multi-factor, and full-process data acquisition, storage, computation, analysis, simulation, visualization, and scientific application in forest structure and function, thereby fostering knowledge innovation in forestry and ecology and

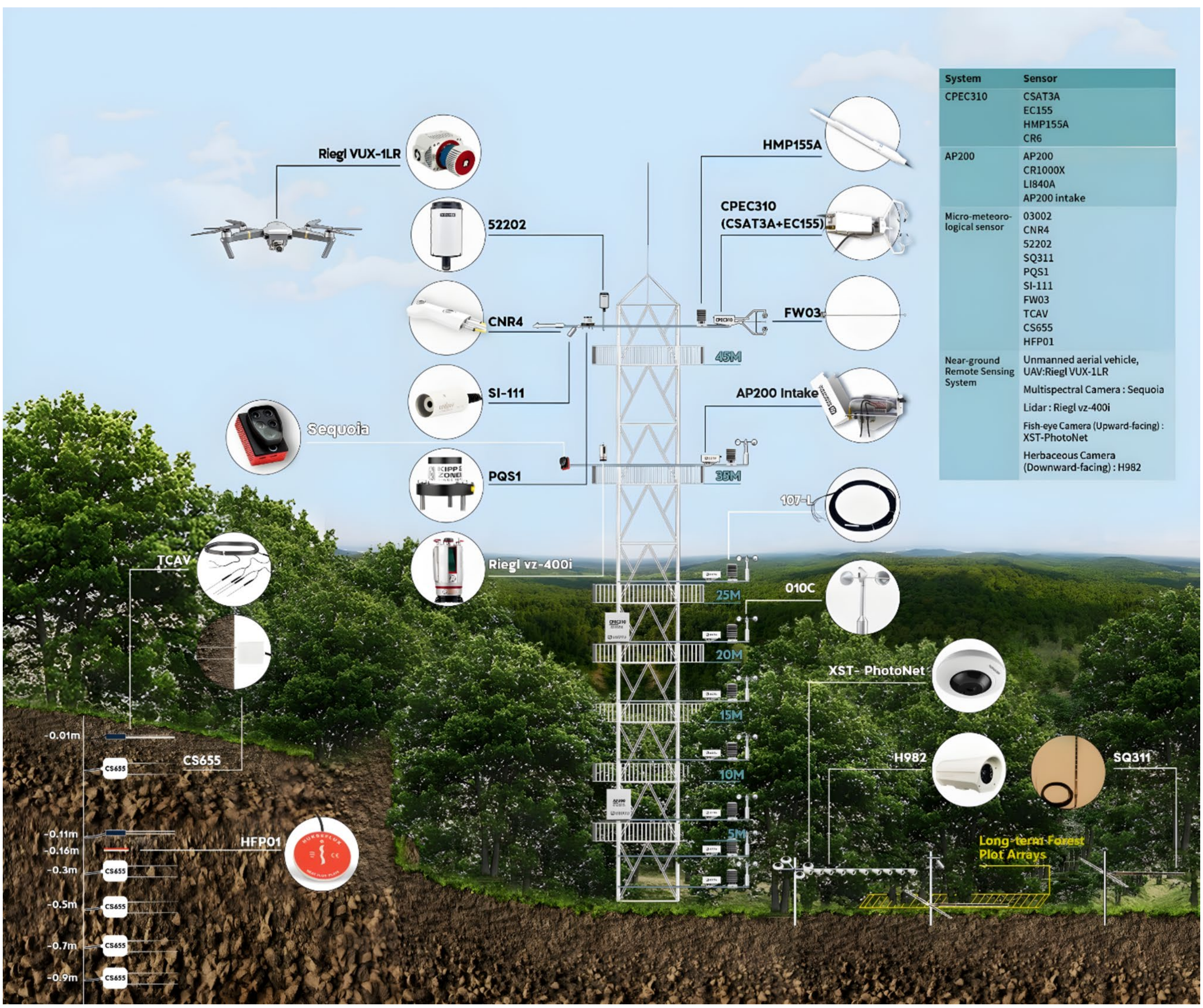

Fig. 4 Configuration of the Qingyuan Forest CERN

providing pathways for exploring paradigm shifts in research and management (Gao et al. 2023; Zhu et al. 2023).

Data collection

The development and application of a Forest Intelligent Data Acquisition System is crucial for realizing CSF. The Qingyuan Forest CERN has established a three-dimensional structure collection informatization system centered on LiDAR, using near-surface remote sensing (ground-, tower-, and drone-based) as the main platforms. This system enables dynamic monitoring across multiple scales and factors, including forest phenology, canopy structure (such as leaf area index), and greenness (Li et al. 2023). The point cloud data and high-resolution visible/multispectral images have been collected (Chen et al. 2022a) and fine structural information on canopy has been obtained (Lu et al. 2020; Yu et al. 2020), facilitating the automated collection of key structural elements to support analyses of the relationships between forest structure and function and their responses to climate change (Gao et al. 2023).

IoT-based data transmission

Real-time and efficient data transmission is a vital component of the Forest Intelligent Data Acquisition System. The Qingyuan Forest CERN has achieved network coverage for observation plot arrays and constructed an IoT platform supporting comprehensive data access, intelligent gateways, and cloud-edge collaboration. This platform allows for the connection of numerous sensors (Fig. 4), facilitating the uploading of collected data while providing remote control instructions from the server to the sensors. Ultimately, this system aggregates heterogeneous and abundant data from the Qingyuan Ker Towers, field plot arrays, and carbon flux facilities. By developing general hardware modules with multi-source and heterogeneous all-factor interfaces, stable and reliable access to carbon flux data in variable conditions in the field can be achieved (Gao et al. 2023).

Data analysis, management, and applications

Analysis and application of forest three-dimensional structure and other information

CSF requires the application of AI algorithms to analyze vast amounts of data, enabling real-time and accurate predictions of climate change impacts, thereby developing and implementing effective forest management measures.

The Qingyuan Forest CERN has integrated three-dimensional structural information of forests for data storage and analysis, creating a one-stop intelligent forest management platform. This platform will develop into a "holographic perception + AI + decision support" system for monitoring and displaying three-dimensional forest structure and carbon sink. Important functionalities include (Gao et al. 2023): (1) Displaying three-dimensional scenes of virtual terrain, incorporating digital elevation model data acquisition, terrain texture selection, and local terrain texture modification; (2) Realizing three-dimensional environmental expressions, incorporating memory optimization, large terrain chunk loading, and multi-threading strategies to enhance system responsiveness; (3) Enabling queries of individual tree information within the watershed; (4) Embedding growth prediction models into ecological environment virtual simulations for dynamic modeling of tree growth; (5) Supporting the import and export of vector and raster data for forest vegetation condition analysis; (6) Reconstructing three-dimensional stand using ground-based LiDAR and tree growth models, employing Digital Twin technology to preliminarily simulate various thinning schemes for larch plantations, thereby facilitating intelligent management decisions in forestry.

Analysis and management of forest ecosystem carbon–water flux data

With the support of IoT and data centers, intelligent management has been achieved for major plots and equipment. The system integrates monitoring data from the atmosphere, hydrology, biology, and soil for storage, analysis, management, and sharing (Gao et al. 2023). The main carbon flux instruments can perform intelligent control measurements and automatic calibration operations, completing data correction calculations, quality assessments, and estimation of characteristic quantities (Fig. 4). Through thematic maps and user-defined options, calculations of forest carbon flux are conducted, displaying key variables in real time, such as forest carbon flux and automatically diagnosing the operational status of main carbon flux instruments at the Qingyuan Ker Tower platform (Gao et al. 2020). The “hydrological automatic observation station network” and IoT, structured in a three-level arrangement, transmitting and displaying hydrological monitoring indicators in real time. By combining forest structure and carbon flux observations, scientific questions related to carbon–water cycling, hydrological processes, and regulation mechanisms in forest ecosystems are being researched (Gao et al. 2023).

Conclusions and prospects

With anthropogenic climate change as the “defining issue of our time” (United Nations 2020), the emergence of CSF is inevitable, and it will undergo further development and gain wide acceptance and applications. CSF aims to enhance the resilience of forest ecosystems under a changing and uncertain climate, ensuring that ecosystem functions do not deteriorate despite possible changes in ecosystem states. This resilience can be accomplished by resistance, recovery, and positive transformation. CSF aims to improve the capacity of forest ecosystems to mitigate climate change, a critical part of achieving the "carbon neutrality" goal. The carbon sequestration potential of forest ecosystems is immense, making them a central component of nature-based climate solutions. Understanding the interaction mechanisms between forest ecosystems and climate change is crucial for achieving efficient, stable, and sustainable forest ecosystem functions, ultimately realizing the harmonious relationship between humans and nature. Given the urgency of enhancing the carbon storage capacity of forests and the complexity of ensuring the resilience of forest ecosystems through climate change adaptation, CSF must deliver forest management methods and decision-making systems using the latest technologies, such as AI and digital transformation, to address the challenges posed by climate change.

In the future, CSF should focus on the following research areas: (1) Understanding mechanisms of resilience and carbon storage: Clarify the mechanisms for forming and maintaining the resilience and carbon sink capabilities of forest ecosystems and develop multi-faceted management methods to enhance forest resilience and carbon storage in response to climate change and natural disturbances. (2) Exploring new paths for emission reduction and carbon sequestration: Investigate methods to reduce carbon emissions caused by natural disturbances, develop "carbon-based" industries, and achieve *ex-situ* carbon storage through timber production, utilization, and material substitution. (3) Conducting comprehensive assessments of forest climate change mitigation effects: Evaluate the comprehensive effects of forests on mitigating climate change to balance the singular emphasis on carbon sink functionality.

Additionally, CSF should prioritize the development of the following key technologies: (1) Smart sensing technologies: Develop low-cost, multifunctional micro-sensors and associated platforms suitable for diverse environments to enhance the ability to acquire massive amounts of multi-source data (high precision, high frequency, and wide coverage), thereby transforming the paradigms of forestry data acquisition. (2) Data analysis methodologies: Create a methodological framework based on AI and digital twins for data processing, scenario analysis, and predictive simulation, aimed at reducing uncertainties in modeling simulations caused by the high heterogeneity of existing forestry data sets, numerous interfering factors, and uneven distributions, thus revolutionizing traditional forestry research paradigms. (3) Intelligent decision support systems: Develop a forest management system that promotes "harmonious coexistence between humans and nature" in the context of climate change, incorporating AI decision-making modules into this system and establishing a visual decision-making platform to transform the forestry management paradigm.

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