Nexus
Research article

Sustainability nexus in China's forestation initiatives

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IN BRIEF

China has announced a series of forestation initiatives to achieve the 30.7% forest cover target. However, our study reveals that these initiatives will trigger large-scale land competition and use conversion, causing serious food security risk. These side effects should prompt a more rigorous examination of future forestation commitments within the framework of the Sustainable Development Goals.

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BROADER CONTEXT

Forestation, encompassing afforestation and reforestation, is a crucial nature-based solution to combat climate change, boost biodiversity, and restore degraded lands, which sequester carbon dioxide and create habitats for wildlife. China's government has launched a series of forestation initiatives to increase forest coverage for both carbon neutrality and ecological resilience goals. However, forestation initiatives will induce unexpectable land competition and land use change, potentially exacerbating land pressure for other critical uses. Historically, a part of China's forestation was achieved through returning farmland to forests, but this paradigm is unsustainable as food security issues are becoming increasingly prominent. How forestation initiatives will reshape China's land system and cause chain reactions are still unexplored but important for its future sustainable development. To explore whether China's forestation initiatives play a positive role overall, this study analyzed its implications on the land-energy-water-emission-biodiversity nexus under the Shared Socioeconomic Pathway. By reviewing ecological actions within a holistic systems context, the results indicate that China's forestation initiatives are not an easy fix, implying threat for food security (SDG2) and social equity (SDG10). Furthermore, this study evaluated and underscored the effectiveness of agricultural synergistic measures, including dietary shift, yield intensification, and cropland protection, on mitigating potential land squeeze and sustainability trade-offs induced by forestation initiatives. An integrated policy approach is essential for addressing these trade-offs implied in forestation. In the long-term, the "Sustainability Nexus" framework developed in this study offers a valuable and transferable tool for periodically reassessing any land-based mitigation strategies under tightening resource constraints. As comparable high-risk "land-squeeze zones" are emerging across Europe, Southeast Asia, South America, and Africa, our insights are timely for refining global forestation pledges.

ABSTRACT

The broader impacts of forestation on sustainability under growing land resource pressure remain poorly understood. In this study, we develop a "*Sustainability Nexus*" framework that leverages an integrated assessment model, an ecosystem service model, and a biodiversity model to evaluate how forestation policies may intensify land competition and reshape ecosystem services, food security, energy transitions, emission mitigation cost, and water consumption. Taking China as a case study, we find that the 30.7% forest cover goal can deliver a gross carbon sink of 18.1 Pg C this century, yet land conversion offsets nearly two-thirds of this gain, leaving a net land use, land use-change, and forestry sector carbon sink of only 5.6 Pg C. While forestation reverses national habitat loss, decreases renewable energy demand by 1.5%, lowers the shadow carbon price by 3.2%, and reduces irrigation water consumption by 2.4% and fertilizer inputs by 5.9%, it simultaneously raises food and bioenergy prices, placing an additional 34.4 million people at risk of hunger. These findings underscore the need to explicitly account for sustainability nexus in forestation planning. Synergistic agricultural measures will be critical for maximizing co-benefits and mitigating unintended trade-offs in future land-based mitigation strategies.

INTRODUCTION

Forestation, which encompasses both afforestation and reforestation (A/R), is an important way to promote land-based carbon dioxide removal and enhance ecological services.[1] This is evident from global initiatives such as the Bonn Challenge, REDD+, and nationally determined contributions (NDCs). In the absence of human disturbances, natural forest regeneration across the world is estimated to amount to a net carbon sink of 44.1–287 GtC and therefore is considered a major step in achieving carbon neutrality, along with other natural climate solutions.[1–4] Forests also offer the broader benefits of natural spaces (e.g., biodiversity, biophysical and sociocultural benefits) and help to circumvent the "value crisis" from a decision-making framework overly centered on carbon markets.[5,6]

Despite the substantial carbon sequestration capacity and biodiversity co-benefits of forests, large-scale forestation has raised concerns about imposing potential trade-offs among the Sustainable Development Goals (SDGs). Emerging research suggests that extensive forestation efforts may intensify competition for limited land resources,[7–9] thereby constraining land availability for other critical purposes such as agricultural production and bioenergy crop cultivation.[10,11] In response to these precautionary critiques, researchers have recently refined forestation potential maps that exclude areas frequently overlapping with existing human activities. These efforts aim to avoid and minimize conflicts over individual rights, insecure land tenure, and nature-dependent livelihoods.[1,4,12–15]

However, current forestation assessments remain largely static, focusing primarily on present-day land-use conflicts while neglecting the dynamic nature of future land demand and structural change.[15–17] For instance, climate mitigation policies and socioeconomic development will profoundly reshape key land-use drivers such as food dietary patterns, agricultural management, habitat conversion, and bioenergy targets, thereby transforming the landscape of future land competition.[18] Yet, forestation initiatives are often examined in isolation from these factors. This highlights the urgent need to situate future forestation planning within a dynamical and systematical land-use background that can evaluate its implications for long-term land-use conflicts.[19]

More importantly, the impacts of forestation could extend far beyond land competition through interconnected feedback loops within other subsystems.[20–22] In 2020, Melo et al. introduced a concept framework that adding forests to the water-energy-food nexus, emphasizing the spillover effects of forestation and their implications for achieving water, energy, and food security.[23] While subsequent studies have sought to quantify the broader impacts of forestation initiatives or potentials, most remain confined to single dimensions such as forestation-water,[24] forestation-food,[25,26] or forestation-carbon prices,[18] resulting an incomplete conclusion about the role of forestation in advancing multiple SDGs under evolving climatic and socioeconomic conditions (Figure S1).

To address these gaps, we developed a novel "Sustainability Nexus" framework that incorporates land dynamics modeling, extends the analytical scope beyond carbon sequestration to encompass the land-energy-water-ecosystem nexus, and establishes a set of indicators to indicate the implications of forestation, including potential co-benefits and side effects. At the core of the framework, Global Change Assessment Model (GCAM)[27] is employed to simulate how forestation initiatives influence future land market equilibrium under socioeconomic development scenarios and how the land system interacts with the climate-energy-water systems. The land use change results generated by GCAM are then downscaled using the Demeter model[28] to further assess changes in ecosystem services through the InVEST ecosystem service model and the GLOBIO biodiversity model.[29] In addition, the food consumption outputs from GCAM are utilized to estimate the population at risk of hunger based on our modified Food and Agriculture Organization (FAO) methodology. Methods Step 1 and Note S1 provide more detailed information on modeling procedures. Overall, the framework provides a systematic tool comprising 12 quantitative indicators across ecosystem services, food security, energy transition, emission mitigation, and water consumption (Figure 1). This enables forestation planners to regularly reassess and guide forestation progress, avioding significant trade-offs among these sustainability goals.[20,31]

In this study, using China's forestation initiatives as an example (excluding Taiwan, Hong kong, and Macau), we demonstrated the Sustainability Nexus analysis process. China, the global leader in large-scale forest restoration, has launched a series of new forestation initiatives to continue the remarkable achievements of its "Grain for Green Program,"[32,33] with a goal of achieving 30.7% forest coverage rate by 2050.[34] However, this pattern, through returning farmland to partial forests, warrants careful examination of its sustainability, as China simultaneously faces severe food security challenges[35,36] and an ambitious expansion of bioenergy.[37,38] Through a comprehensive analysis of China's forestation initiatives, this study aims to provide insights for future global forestation initiatives, particularly for countries seeking to commit to terrestrial carbon removal in their NDCs, helping them better consider the inherent trade-offs and narrow the gap between ambition and implementation.

To explore the implications of China's forestation initiatives, four categories of scenarios are designed within the Sustainability Nexus framework (Table 1). The SSP2-RCP4.5 scenario[39] serves as the reference (REF) scenario, depicting a scenario without extra forestation policy. The *NetZero* scenario represents a market-driven forestation scenario, reflecting how China's 2060 carbon neutrality goal stimulates the adoption of negative emission technologies, with forestation serving as the primary mitigation option in the land system.[40] For the forestation initiatives scenario, we employ the high-resolution forestation dataset from our previous work[34] to explore how a series of governmental forestry goals in 2025-2050 (Afforest) will shape China's land system and SDG goals. This forestation potential dataset provides detailed information about "where," "when," and "what" to afforest to achieve phased forest coverage goals and eventually a total of 257.79 Mha by 2062. Based on that, the *Afforest* scenario provides a reference for a set of synergistic scenarios (Syn-Afforest) that combine forestation with agricultural measures, including dietary shift (DietShift), yield intensification (YieldUp), and sustainable cropland protection (SusCrop), to evaluate whether integrated strategies can alleviate trade-offs induced by large-scale forestation. Further details of scenario design are provided in Methods Step 2 and Note S2.

RESULTS

Intensified land competition

The results indicate that large-scale forestation will inevitably reshape China's land system, triggering substantial land competition and conversion. In the REF scenario, land use change is mainly driven by rising living standards, with approximately 30 Mha of natural pasture and grassland converted into gazed pasture to satisfy growing demand for meat and dairy products (Figures 2A and S7). In contrast, the NetZero and Afforest scenarios reflect a shift from consumption-driven to mitigation-driven land pressure.[16,18] Between 2020 and 2100, 45.4 Mha of natural pasture is converted to biomass plantations and managed forest to increase bioenergy potential and carbon sinks in the NetZero scenario (Figures 2A and S8). When priority is given to expanding unmanaged (natural) forests to achieve the dual goals of carbon sinks and biodiversity, land competition is further intensified (Figure 2A, Afforest scenario). Such forestation targets without biophysical and economic constraints[34] will significantly reduce land resources dedicated to bioenergy crop cultivation and commercial forestry. Compared with the NetZero scenario, an additional 29.4 Mha of gazed pasture, 11.7 Mha of biomass plantations, 9.4 Mha of cropland, and 24.6 Mha of managed forest would be converted to unmanaged forest by 2100.

To capture spatial dynamics of this reallocation, the GCAM national outputs are downscaled with the Demeter model, which is anchored to the LUH2 2015 basemap.[28] The downscaled results indicate spatially heterogeneous responses in different scenarios (Figures 2B–2D and S9). The NetZero target leads to marginal cropland expansion (0.3 ± 0.4 Mha), while the Afforest target leads to marginal cropland contraction (-0.4 ± 1 Mha). In net, cropland area expands in northwestern provinces (e.g., Xinjiang, Inner Mongolia, Gansu, Ningxia) but contracts in other provinces (e.g., Heilongjiang, Jilin, Yunnan) relative to the REF scenario (Figure 1D; Table S1). However, such northwestward shift of cropland may raise concerns over resource efficiency, as historical cropland expansions into water-scarce northern regions have been associated with a 1.5% rise in irrigation withdrawals and agricultural GHG emissions.[43]

Co-benefits for climate change mitigation and biodiversity

Although the potential northwestward shift of cropland may raise concerns about efficiency, the conversion of agricultural land to forest will bring significant co-benefits for mitigating emissions and restoring biodiversity. Historically, the conversion of natural lands to cropland and pasture has been one of the main drivers of biodiversity loss in China,[44] and this trend is projected to persist in the REF scenario as pastureland increases continuously (Figure 2A). Here, the Mean Species Abundance (MSA) index declines by 0.03 in 2050, reflecting continued encroachment of anthropogenic land uses. Although a slight recovery begins after 2050 as some natural land types are passively restored, the overall ecological trajectory remains negative this century relative to the 2010-year level. Habitat quality (HQ), in contrast, remains relatively unchanged in the near term, since future land conversions predominantly occur within already-degraded landscapes (e.g., cropland, biomass plantations, and pasture), where HQ does not differ significantly across these already-degraded landscapes (Figure 3B).

Market-driven forestation under the NetZero scenario will only yield minor biodiversity gains. The MSA index returns to the 2010 baseline level till around 2080, and the HQ index declines further, falling below REF levels, due to increased cropland expansion and landscape fragmentation (Figure S5). Critically, biodiversity hotspots, such as the

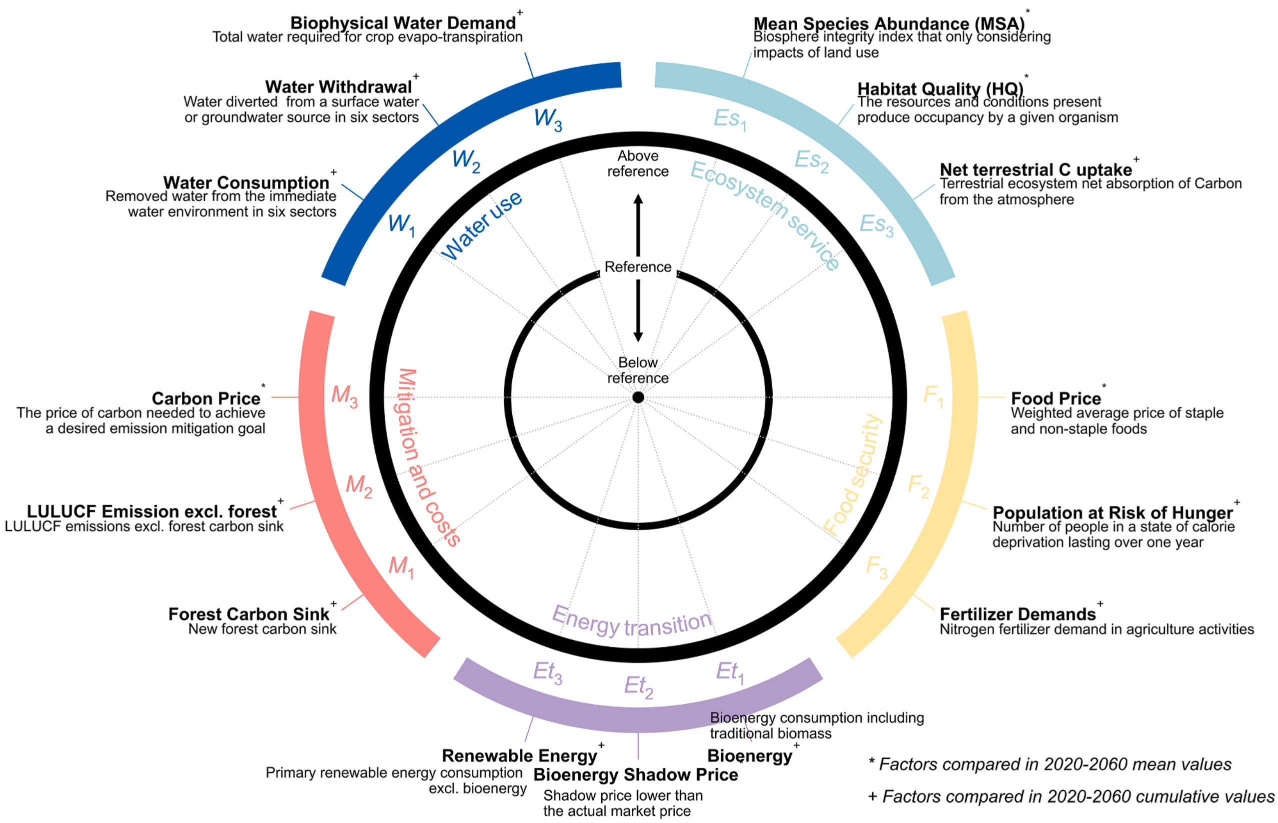

Figure 1. The Sustainability Nexus indicators to analyze forestation's impacts on Sustainable Development Goals
The five implication dimensions are shown in different colors: ecosystem services (light blue), food security (orange), energy transitions (purple), mitigation and costs (red), and water use (dark blue). The plotting code is modified from the fingerprint research of energy IAMs.[30]

mountains of Southwest China, the Indo-Burma region, and the Himalaya region, exhibit varying degrees of habitat quality loss. These results underscore the ecological limitations of carbon-centered, market-driven mitigation strategies, which may improve emissions outcomes while failing to halt biodiversity degradation.

In comparison, the Afforest scenario, centered on natural forest expansion, delivers substantial biodiversity gains. Restoration efforts under China's forestation initiatives are projected to reverse previous biodiversity losses and promote sustained ecosystem recovery (Figures 3A and 3B). Significant habitat-quality improvements are achieved in all provinces (e.g., Hubei, Jiangxi, Guangxi), offsetting losses incurred in the NetZero scenario (Figure 3E). Only in Xinjiang, Gansu, Ningxia, and Henan, HQ gains remain minimal and do not surpass REF baselines in 2060 (Figure 3C, purple quadrant). Net gains in HQ across much of the country underscore the potential of forest-based climate solutions to generate widespread biodiversity co-benefits when ecological restoration is integrated into national decarbonization pathways (Figure 3E and 3F).

Implied trade-offs across sustainability nexus

When expanding our perspective to the whole system to elucidate the trade-offs of forestation on SDGs, we compare the Sustainability Nexus of the NetZero and Afforest scenarios over two key periods: 2020–2060 (Figure 4A) and 2060–2100 (Figure 4B).

In terms of climate benefits, the two scenarios exhibit a marked disparity. From 2020 to 2100, the size of total carbon sinks in the Afforest scenario (18.1 Pg C) is amplified by 7 times compared with the NetZero scenario (2.4 Pg C). In the Afforest scenario, newly established forests are expected to provide a carbon sink potential of 0.36 Pg C yr^{-1} by 2060 and 0.10 Pg C yr^{-1} by 2100 (Figure 4C). These estimates are slightly lower than original estimates of 0.40 and 0.20 Pg C yr^{-1} over the same intervals.[34] The main reason is that GCAM omits "passive carbon uptake" process, that is, the response of forests to biogeochemical factors such as increased atmospheric CO_2 concentration, temperature change, and precipitation change (Note S1).[45–47]

However, a key finding is that land competition will limit the net climate benefits of the whole land use change and forestry (LULUCF) sector. In the *Afforest* scenario, newly established forests primarily expand into grasslands and pastures, causing ecosystem disturbances that reduce the effectiveness of carbon uptake. These land conversions disrupt existing aboveground biomass and soil carbon pools, offsetting nearly two-thirds of gross carbon sequestration gains from forest growth (Figures S10 and S11). As a result, net carbon removal from the LULUCF sector amounts to just 5.6 Pg C by 2100 (Figure 4C). This finding underscores the critical need to account for the interactions between different land cover and land use types when estimating carbon removal potential (SDG13) of forestation initiatives. It also calls for greater definitional clarity in national and international climate pledges, particularly regarding the distinction between forest-specific removals and net sequestration across the broader LULUCF sector. Current reporting practices often aggregate these contributions ambiguously, risking significant overestimation of mitigation outcomes and undermining the transparency and credibility of long-term climate targets.[48]

Forestation also influences energy system dynamics. The implementation of forestation under Afforest scenario will reduce future demand for bioenergy (−7%) and renewable energy (−1.5%). However, due to the limited biomass cultivation caused by land competition, the marginal cost of bioenergy raise, which in turn increases its "shadow price" by 1%–2%. Nevertheless, forest carbon sinks are still a more economical option in the short and medium term. Although bioenergy with

Table 1. Descriptions of the main scenarios in this study

Scenario	Narratives
REF	The reference scenario, based on the socioeconomic characteristics of SSP2-RCP45.[39]
NetZero	The NetZero scenario, in which it is assumed that China will achieve sector-wide carbon neutrality goals by 2060[40] and gradually include land carbon emissions in the carbon budget from 2020 to 2100.
Afforest	The forestation scenario is similar to the NetZero scenario but incorporates a high-resolution forestation constraint, with a linear projection of forest expansion to 257.7 million hectares (Mha) by 2060.[34]
DietShift	The dietary shift scenario, which builds upon the forestation scenario; partial replacement of animal protein with plant protein[41] is assumed.
YieldUp	The yield intensification scenario, which builds upon the forestation scenario; the yields of major irrigated crops, including irrigated corn, wheat, and rice, are assumed to reach 75%, 75% and 90% of the attainable levels by 2050.[36]
SusCrop	The sustainable cropland scenario, in which a moderate forestation pathway with basic cropland protection is assumed.[42]

carbon capture and storage has theoretically long-term emission reduction potential, its technical and deployment costs are still relatively high.[18] Compared with the NetZero scenario, the *Afforest* scenario can reduce carbon price by 6.8% over 2020–2060 and 3.2% over the entire century.

The most pronounced trade-off emerges within the food system. On the one hand, total agricultural inputs, such as fertilizer (−5.9%) and irrigating water (−2.4%), decline over time due to reduced cropland. On the other hand, efforts to stabilize cropland tenure and achieve negative emission goals in a competitive market drive higher crop prices.[49,50] Both staple and non-staple commodity prices rise by 2.3%, mirroring the increase in bioenergy shadow prices (Figures 4A and 4B). Such price changes will disproportionately affect lower-income groups. Previous studies have shown that low-income households are more vulnerable to food price fluctuations due to their limited food purchasing power.[51] To more accurately assess the impact of rising food prices on nutritional status, we improved the FAO's method for estimating the number of undernourished people by explicitly incorporating price shocks into the coefficient of variation (CV) of Chinese household food consumption (see Note S1). Although the current agricultural product volume meets the average minimum nutritional intake requirements in China,[52] the relationship between food price and the inequality of household food consumption will lead to an additional 34.4 million people at risk of hunger relative to the NetZero scenario (Figure 5G).

Effectiveness of agricultural synergistic strategies

As with decarbonization, the decades leading to mid-century are also pivotal for enhancing the adaptive capacity of China's land system. In addition to forestation, agricultural strategies such as healthy dietary shifts, yield intensification, and cropland protection have gained increasing attention for their potential to reduce greenhouse gas emissions while safeguarding food security.[16,34–36] Here, we integrated these synergistic measures with forestation to assess whether a multidimensional policy portfolio can alleviate trade-offs across ecosystem services, food security, energy transitions, emission mitigation costs, and water consumption.

We find that targeted agricultural interventions can substantially mitigate sustainability trade-offs induced by forestation. Among the interventions, our results reveal that dietary shifts yield the most extensive co-benefits. Transitioning toward plant-based diets reduces carbon price, lowers water consumption, and significantly alleviates food insecurity (Figures 5A and 5B). Between 2020 and 2100, the DietShift scenario advances SDG2 and SDG10, decreasing the cumulative population at risk of hunger by 519.5 million relative to the only Afforest scenario. Lower demand for meat and feed crops also helps preserve natural pastures (Figures S10 and S11), contributing SDG13 with an additional 3.7 Pg C of net terrestrial carbon uptake (Figure 5G) and reducing the carbon price by 75.5 USD_{2020} t^{-1} CO_2 (Table S3).

Yield intensification (YieldUp) of staple crops delivers more modest gains and begins to reverse after 2060, with water and fertilizer use increasing by 6%. In contrast, enhanced cropland protection (SusCrop) sustains domestic food production, lowers food prices, improves affordability for low-income households, and reduces the cumulative population at risk of hunger by 191.8 million (Figure 5G; Table S3). However, these gains come at the cost of carbon sinks, which decrease from 18.1 Gt C to 10.1 Gt C (Figure S12), accompanied by increased water consumption (+660.2 km^3), a higher carbon shadow price (+18.9 USD_{2020} t^{-1} CO_2), and rising renewable energy demand (+252.9 EJ).

Notably, the critical challenge for China's food system is the rapid surge in non-staple consumptions, particularly soybean, dairy, and beef consumption, accompanied by growing import dependency.[53] While strengthening wheat, rice, and maize production and stringent cropland protection could bolster staple food self-sufficiency,[36] these measures may fail to satisfy the escalating demand for non-staple foods. Consequently, even with increased domestic staple crop yields and safeguarded cropland, import reliance and land-use pressures will persist. This persistent mismatch underscores the unique role of dietary transformation: shifting consumption toward plant-based proteins offers the largest system-wide relief from land scarcity, emissions burdens, and nutritional inequality.[35,54]

DISCUSSION

In this study, we quantified how China's forestation initiatives influence future land system dynamics and assessed the implications of these land-use changes for the land-emissions-energy-water-biodiversity nexus. Our analysis suggests that the large-scale forestation efforts may generate unexpected trade-offs among different SDGs. Against the backdrop of growing land scarcity, achieving a forest cover target of 257 million hectares by 2060 would increase forestry carbon uptake by 18.1 Pg C; however, by 2100, land contraction reduce the net LULUCF carbon sink to 5.6 Pg C. If such optimistic carbon uptake estimates, which ignore land contraction driven by future socioeconomic development, are interpreted as negative emissions credits,[34,46,47,55] they risk inflating emission budgets for the "hard-to-abate" sectors, creating a misleading pathway toward carbon neutrality.

From an economy-wide decarbonization perspective, China's forestation initiatives can lower the overall cost of emissions reduction. Owing to the relatively low costs of forest-based mitigation,[18] the shadow carbon price is projected to decline by approximately 3.2% over this century. However, unless land-based negative emissions are incorporated into the emissions trading system (ETS), realizing these cost advantages effectively shifts part of the financial burden to

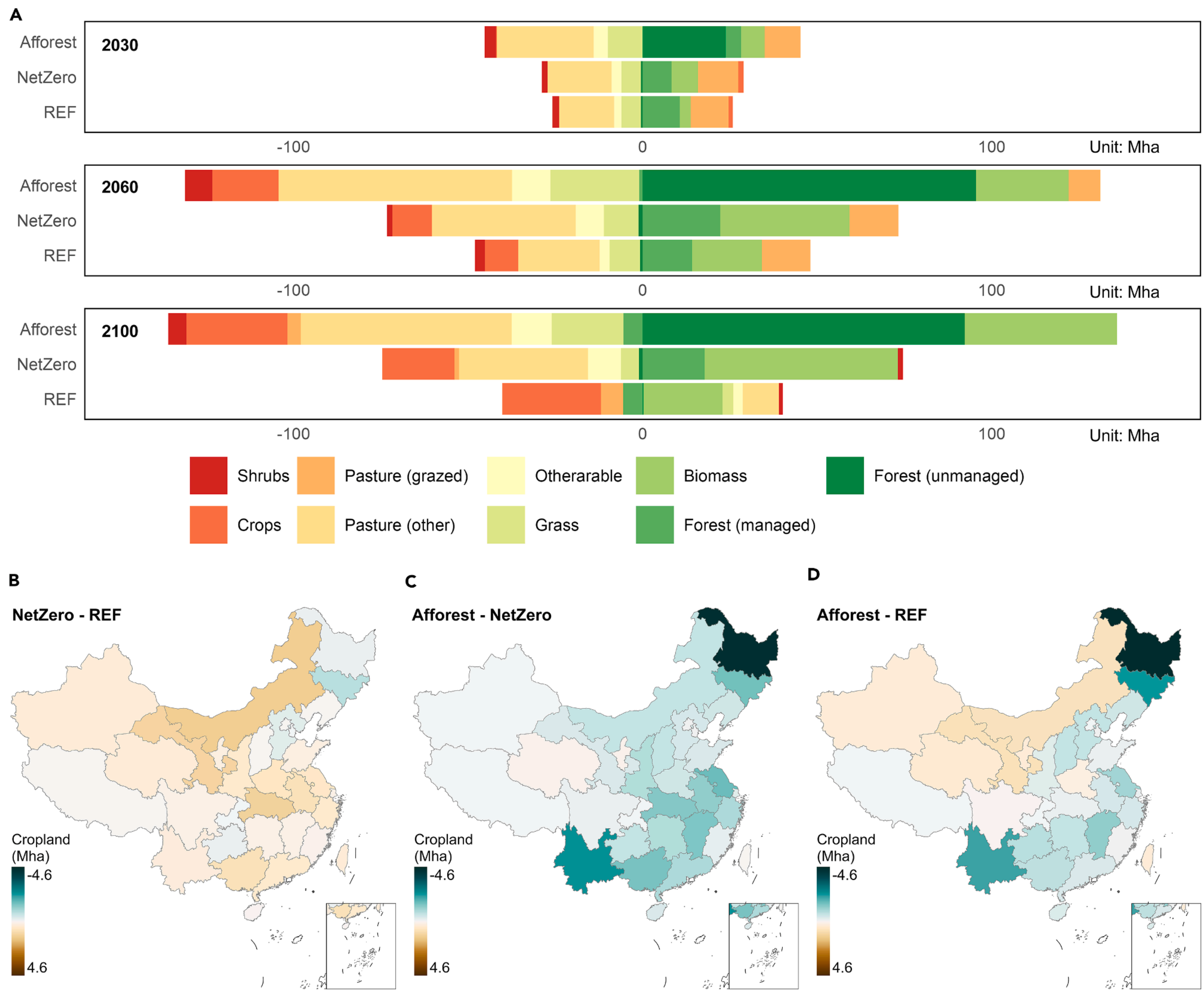

Figure 2. Land-use changes in the REF, NetZero, and Afforest scenarios
(A) Progressive land cover changes (Mha) relative to the 2020 baseline in 2030, 2060, and 2100.
(B–D) Provincial distribution of marginal cropland area changes in China under the REF, NetZero, and Afforest scenarios in 2060.

individuals engaged in forestry production and to government subsidy programs. This occurs because forestation is typically not a cost-effective option for low-income smallholder farmers, and their potential income losses or the fiscal costs of subsidies are not captured in GCAM's shadow carbon price.[56] The Chinese government is currently advancing the expansion of a comprehensive ETS that accounts for land-based negative carbon, aiming both to enhance forest farmers' incomes and to ensure that major emitters bear their share of responsibility. Building on this progress, we recommend the rapid establishment of a robust measurement, reporting, and verification system for forest soil and biomass carbon credits, along with the creation of a transparent registration platform and equitable benefit-sharing mechanisms, leveraging market-based instruments to further incentivize forestation.[57]

Although enhanced carbon sequestration, reduced carbon prices, and notable improvements in species integrity and HQ underscore the potential of forestation to advance SDG 13 (Climate Action) and SDG 15 (Life on Land), these environmental co-benefits come with important trade-offs. Model results indicate that large-scale forestation could raise food prices by about 2.3%, exacerbate income-related disparities, as reflected by a widening CV in vulnerability (Figure S2), and place an estimated 34.4 million people at risk of malnutrition. Especially in major import consumption provinces such as Beijing, Shanghai, Tianjin, and Guangdong,[54] food price increases are likely to disproportionately erode the food purchasing power of low-income households. Besides, the northwestward shift of cropland reallocates agricultural employment opportunities, potentially placing small farmers in traditional breadbasket provinces such as Heilongjiang, Jilin, Shandong, and Henan at a disadvantage. Such outcomes reveal that, without adequate compensatory or redistributive measures, the pursuit of climate and biodiversity goals through land-based mitigation may inadvertently undermine progress toward SDG 2 (Zero Hunger) and SDG 10 (Reduced Inequality), highlighting the need for integrated policy design that balances environmental ambition with social equity.

Our analysis of agricultural synergistic measures, dietary shifts, yield intensification, and cropland protection reveals that shifting to a plant-based diet is projected to preserve existing natural ecosystems, increase carbon sink, reduce the carbon price, and fully offset the hunger risk associated from forestation (Figure 5). However, the dietary shift scenario in this study serves as a theoretical benchmark to assess the upper bound of potential synergies between dietary change and forestation in alleviating land pressure.[54] Achieving sustainable food-system transformation requires consideration of equity, nutrition culture, and local environmental contexts.[58,59] For example, in Tibet and Qinghai, the cold and arid climate is unsuitable

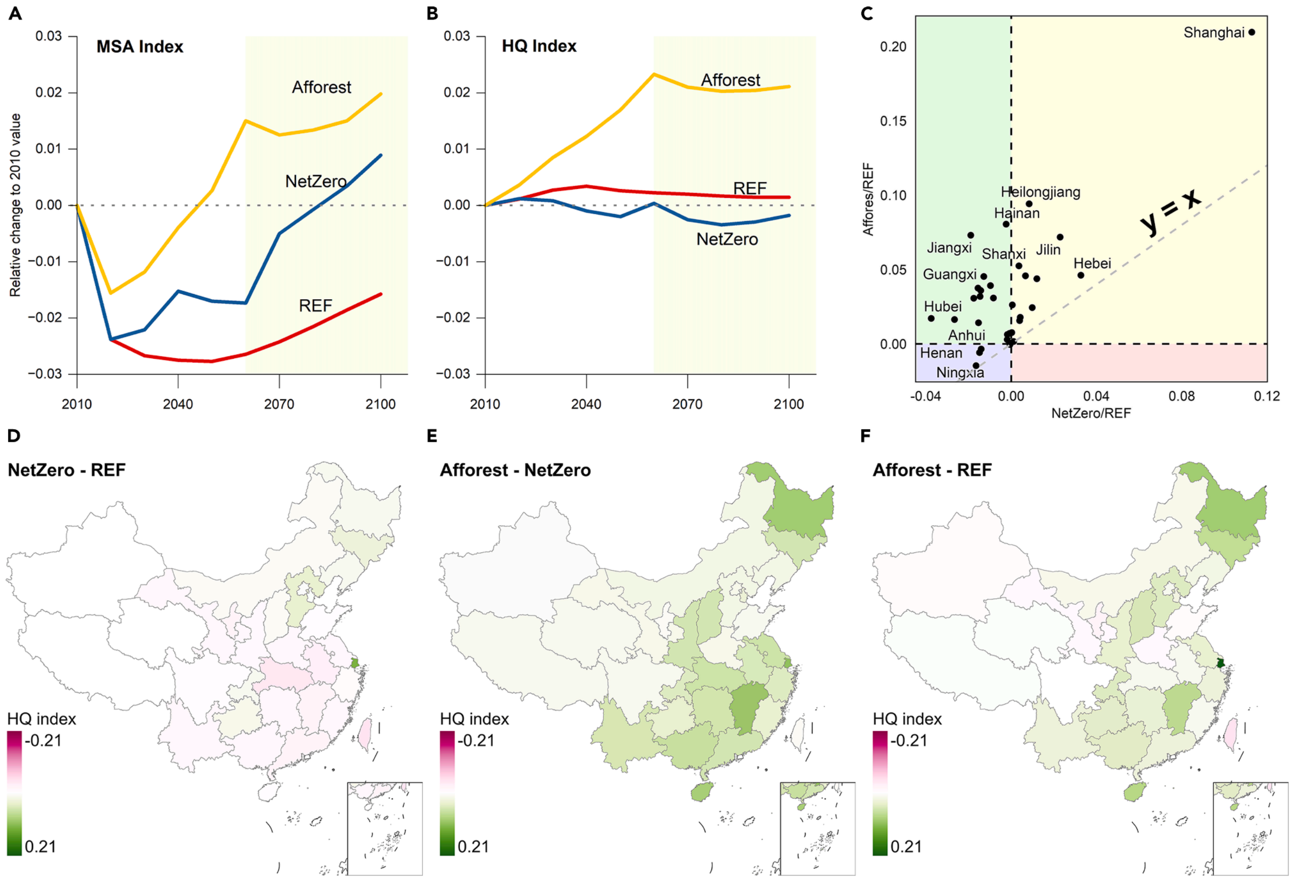

Figure 3. Biodiversity trends measured by mean species abundance (MSA) and habitat quality (HQ) in the REF, NetZero and Afforest scenarios
(A) MSA index and (B) HQ index trends, shown as changes relative to their 2010 baseline levels.
(C) Marginal HQ changes of the NetZero and Afforest policies relative to the REF scenario in 2060.
(D–F) Provincial distribution of marginal mean HQ changes under the REF, NetZero, and Afforest scenarios in 2060.

for vegetable cultivation, and the local population is accustomed to a nomadic lifestyle. As a result, transiting from a traditional diet rich in meat to a plant-based diet will be very hard to realized.[60] Rooted social norms and cultural traditions constrain the adoption of novel dietary patterns, leading to a preference for more socially acceptable yet less transformative dietary shifts. As a result, nearly 80% of the cropland footprint is retained, limiting the potential to substantially alleviate land competition.[54,61]

Moreover, policy innovations are needed to ensure inclusive outcomes. Developing shade-tolerant cash crops and agroforestry systems, which have already been piloted in intercropping poplar, such as wheat systems in Henan, can diversify rural income while conserving carbon stocks.[62,63] These sustainable management practices beneath or around forest canopies combine resource efficiency, ecological protection, and economic development, offering pathways to diversify food supply systems and enhance synergies among ecosystem conservation, food security, and rural livelihoods. In parallel, nutrition-indexed subsidies (e.g., vouchers to purchase, cash-back rebates) can serve as a buffer against volatile food prices for vulnerable households.[64] Furthermore, reducing the frequency of eating out and takeout consumption has also been shown to substantially decrease food waste and balance food prices.[65] Incorporating such social equity mechanisms into forestation and broader land-based mitigation frameworks is critical for ensuring that climate and biodiversity goals are achieved without exacerbating rural vulnerability.

Forestation has been prominently featured in many national climate pledges, with targets ranging from the planting of 5 million trees in Sierra Leone, 2 million in Jordan, and 10 billion in Pakistan, to India's initiative of an additional 3 billion tonnes of carbon sinks from forests by 2030. However, many of these countries may face acute land scarcity due to competing demands for food production and forest expansion.[7] At the same time, high-income countries continue to externalize their domestic land pressures through large-scale imports of biomass-based commodities.[66] As the conflict between internal and external demands intensifies, there is an urgent need to clarify the risks of future land shortages and the trade-offs they may trigger regarding bilateral trade, food security, biodiversity, and overall emissions reduction potential.[67] The Sustainability Nexus framework developed in this study offers a transferable approach to evaluating the multidimensional consequences of land-based policies beyond forestation. By capturing the interactions between carbon, biodiversity, food, and trade systems, it provides a critical foundation for *ex ante* policy appraisal in countries facing complex land-use challenges.

Although the Sustainability Nexus framework developed in this study could be extended to track most land-based solutions or restrictions, a few limitations should be considered when interpreting the results. First, GCAM does not incorporate bilateral feedback between land-use and climate systems in the IAM analysis process when projecting nature-based carbon removal benefits. However, whether these ambiguities should be included in future carbon removal estimates remains unclear, as increased forest fire activity could offset these gains, potentially undermining the Paris Agreement.[68–70] Second, the land use change emission module in GCAM is simplified from the four major carbon flux processes, including clearing, abandonment, harvesting, and others, into only land expansion and land contraction processes

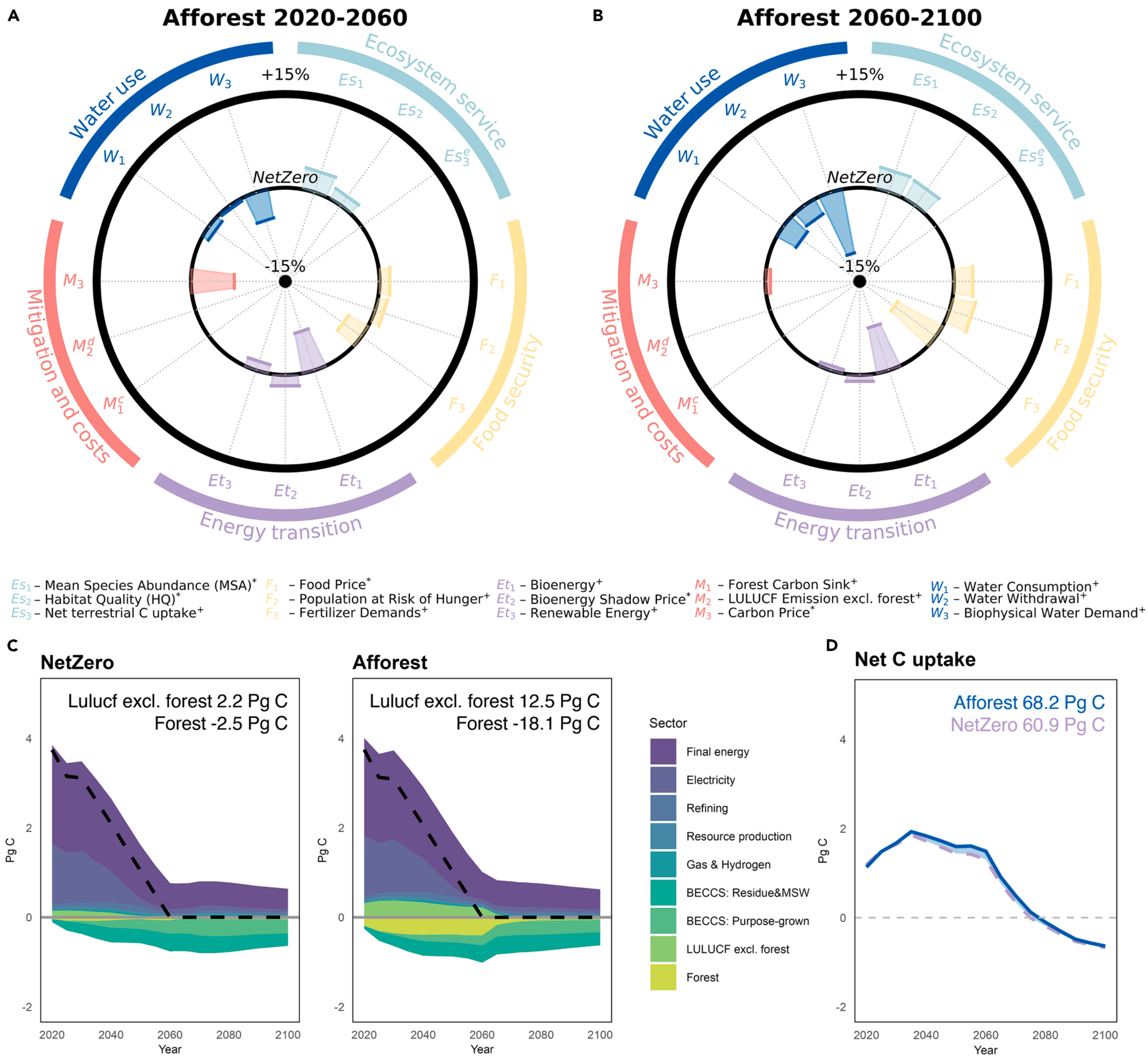

Figure 4. Comparative *Sustainability Nexus* across the land-energy-ecosystem nexus in the NetZero and Afforest scenarios
Relative changes during (A) 2020–2060 and (B) 2060–2100. The five diagnostic dimensions illustrate the marginal impacts of forestation on ecosystem services (light blue), food security (yellow), energy transitions (purple), mitigation and costs (red), and water usage (dark blue). Indicators marked with * denote mean-value comparisons, whereas those marked with + denote cumulative-value comparisons (see Figure 1 for definitions). The forestation-specific carbon sink (M1), LULUCF emissions excluding forests (M2), and net carbon uptake (ES3) span both positive and negative values and are therefore omitted from the figure (A and B). (C) presents the trends of sectoral emissions, and (D) shows the trends of net C uptake in the *NetZero* and *Afforest* scenarios, illustrating the detailed dynamics of M1, M2, and ES3 between 2020 and 2100. The bioenergy and carbon prices in the GCAM are shadow prices used to balance the virtual supply and demand; these shadow prices are typically much lower than the actual market price.

(Note S1). Hence, the carbon removal potential of forests may be underestimated since the residues of soil organic materials, such as surface litter and dead wood, are not included in the model.[71] Meanwhile, the limited spatial resolution of GCAM land market analysis and postprocessing downscaling should be improved to capture fine-scale land management practices and the corresponding influential factors (Table S6). Third, discrepancies in land use module outcomes are inevitable, as IAMs vary in structure, goals, parameterization, and level of detail.[30] Therefore, multiple model comparisons are necessary to obtain more robust conclusions. Finally, previous studies have shown that historical forestation does not universally benefit all species. Certain pollinators, such as bees, may be negatively affected by changes in floral resources.[72] Future research could integrate our framework with earth system models and species distribution models to evaluate the implications of forestation for individual species and functional groups.

Conclusion

Building on empirical evidence that past forestation efforts have historically led to the conversion of cropland and pasture, it becomes essential to evaluate future forestation initiatives within the context of the broader land system. Applying the Sustainability Nexus framework developed in this study, we find that China's forestation commitments are unlikely to achieve the anticipated level of carbon sequestration and may exacerbate food security challenges, particularly for low-income households, due to the resulting squeeze on crop production. The trade-offs between SDG13 (Climate Action) and SDG15 (Life on Land) on one hand, and

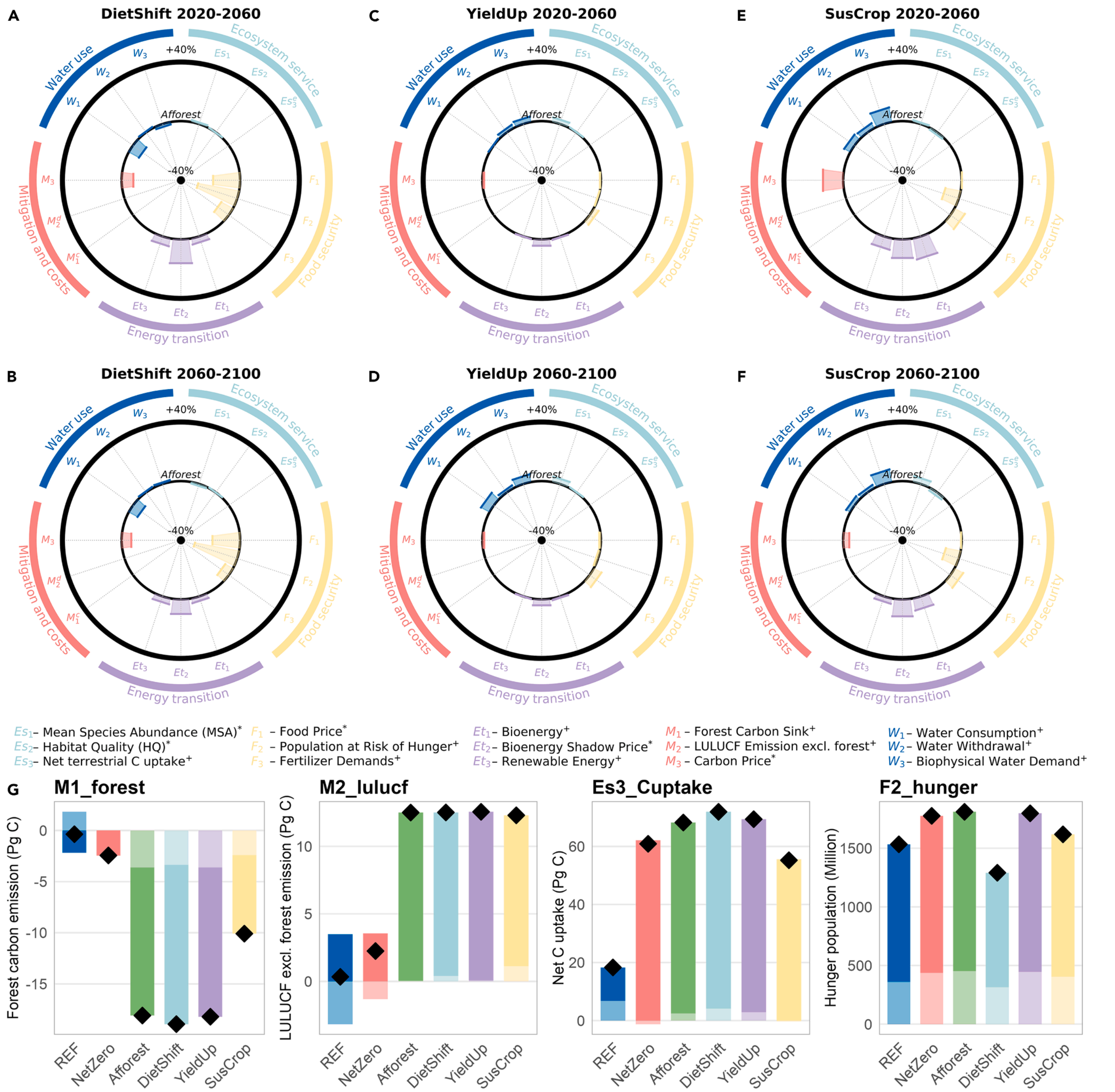

Figure 5. Sustainability Nexus in different potential land-management scenarios relative to the Afforest scenario

The panels show relative changes in the 12 indicators for (A and B) the DietShift scenario, (C and D) the YieldUp scenario, and (E and F) the SusCrop scenario from 2020 to 2060 and 2060 to 2100. Indicators that shift by >40% and invert sign, namely, forest carbon sink (M1), non-forest LULUCF emissions (M2), net terrestrial carbon uptake (ES3), and population at risk of hunger (F2), are omitted from these panels.

(G) Cumulative trajectories of M1, M2, ES3, and F2 from 2020 to 2100.

SDG2 (Zero Hunger) and SDG 10 (Reduced Inequality) on the other, highlight the need for a more cautious and systemic assessment of the negative "leakage effects" associated with large-scale land-use change under land-based climate solutions. Without additional compensatory measures, these unintended impacts are likely to disproportionately affect vulnerable groups. Our findings further underscore the importance of integrating forestation with complementary agricultural strategies, such as yield intensification, dietary shifts, and agroforestry development. Such integrated approaches are especially crucial for countries like China, where population size, economic development priorities, and ambitious climate and biodiversity goals intersect.

METHODS

Step one: The modeling process of Sustainability Nexus framework

To evaluate the multidimensional impacts of forestation under land constraints, we develop a Sustainability Nexus framework (Figure 6) that integrates economy-energy-land-water-climate interactions (via GCAM), ecosystem services (via InVEST), and biodiversity assessments (via GLOBIO). The models are driven by Shared Socioeconomic Pathway (SSP2) assumptions (e.g., GDP, population, technological innovation progress), climate mitigation targets (e.g., forestation,

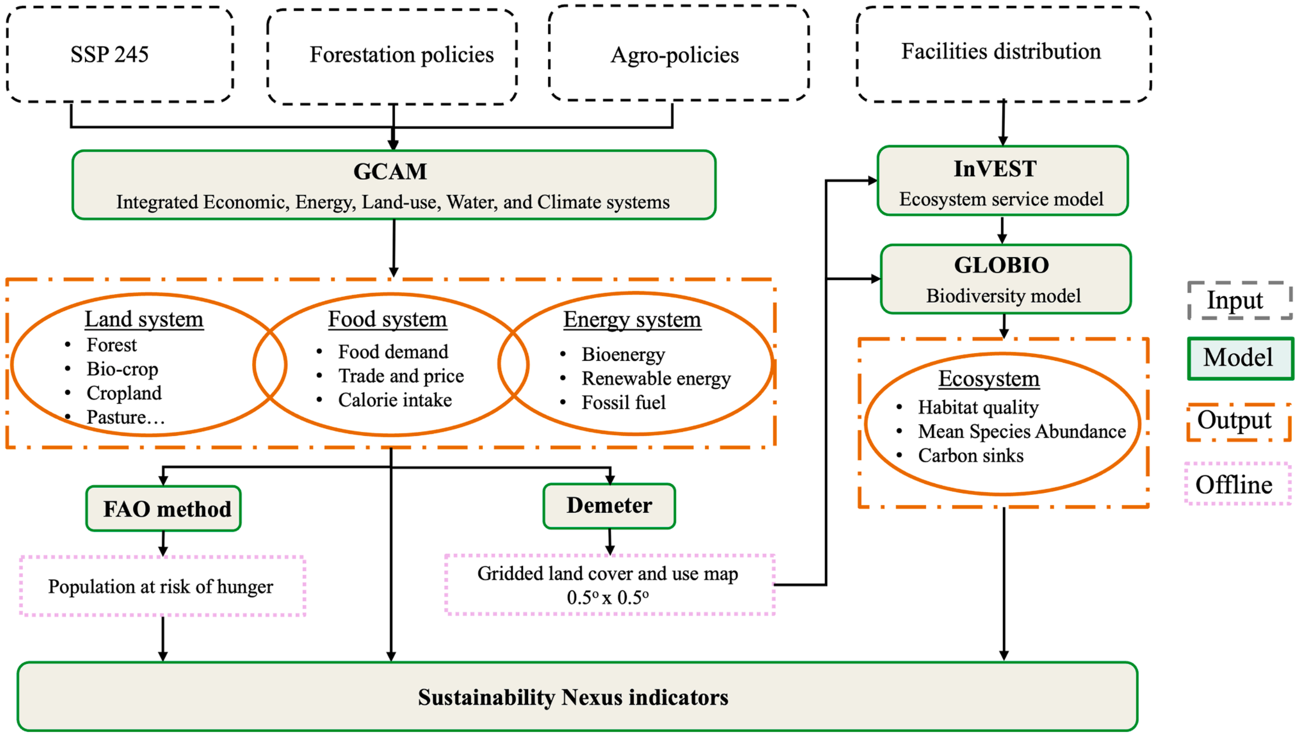

Figure 6. The modeling framework of Sustainability Nexus

carbon neutrality), agricultural policies (e.g., cropland protection, dietary shift, yield intensification), and current infrastructure distributions (e.g., transport facilities, industrial facilities, conservancy facilities). GCAM simulates system-level interactions across land, food, energy, and emission domains, generating outputs such as land allocation, food demand and prices, energy supply structure, and carbon emission sources. Food security risks (i.e., population at risk of hunger) are then calculated using a modified FAO methodology based on food price shocks and caloric intake. Land use outputs are spatially downscaled using Demeter to produce gridded land cover maps, which are input into InVEST and GLOBIO to quantify HQ and MSA.

GCAM model

GCAM integrates representations of the economy, energy, agriculture, land use, and climate system. The model has been developed to describe how socioeconomic development and mitigation policies affect interactions among sectors and to assess the potential ramifications of climate mitigation actions.[18,56] In this study, we employ an updated GCAM version, GCAM 7.1, which classifies forests into hardwood and softwood types (Table S4), to assess how forestation policies and combined measures influence the land market and how these impacts spread to other systems.

GCAM produces a comprehensive set of outputs to quantify the cross-sectoral impacts of afforestation. Land-use outputs include changes in land allocation among cropland, pasture, forest, and other categories, as well as carbon emissions and sequestration from land-use change and forestry. Agricultural outputs cover production, consumption, trade, price indices, and per capita calorie availability. These outputs underpin subsequent assessments of food security, ecosystem services, and biodiversity within the integrated Sustainability Nexus framework. Energy outputs comprise primary energy supply by source, final energy demand by sector, and associated CO_2 emissions. The water module provides estimates of water use and withdrawals for forestry and agriculture, along with biophysical water demand. Economic outputs include regional GDP, carbon prices, and abatement costs.

Demeter model

Demeter, an open-source spatial disaggregation model,[28,73] was employed to downscale projections of future land allocation output by GCAM to further analyze ecological effects with the InVEST ecosystem service model and GLOBIO biodiversity model (Table S5). In Demeter, a historical land cover map with a 0.5° resolution (LUH2) is used as a reference, and the anticipated LULC class changes projected by GCAM are then intelligently allocated to the corresponding grid cells based on biophysical suitability[73,74] (Table S6).

FAO method: Estimates of the population at risk of hunger

Malnutrition is defined as a state of sustained caloric deprivation lasting over one year. In line with previous studies, we employed the nutritional gap analysis methodology developed by the FAO to assess the risk of hunger.[75,76] The core idea is to calculate the gap between nutritional volume intake in the quantitative population and the minimum demand, which is scientifically set.[77] GCAM provides projections of the future per capita mean caloric intake, whereas the minimum dietary energy requirement is obtained from the "Dietary Reference Intakes for China (2023)," which indicates the caloric intake requirements for moderate-intensity exercise levels.[78]

Furthermore, we improved the FAO method by considering the disproportionate impacts for low-income households owing to their limited purchasing power.[51] The empirical relationship between the price of foods and the CV of China's national distribution of household food consumption was determined based on the historical food price and CV data from the Urban Household Survey by the National Bureau of Statistics of China from 2002 to 2009, covering about 10,000 household statistics (Figure S2). Moreover, the mean minimum dietary energy requirement in each year was adjusted by multiplying the food waste rate by 11.3%.[79]

GLOBIO model

The GLOBIO model relies on a set of quantitative relationships that assess the impacts of anthropogenic pressures on biodiversity.[29,80,81]

These impacts are quantified using the MSA metric, a standardized indicator of local biodiversity intactness.[81] MSA values are derived by calculating the ratio of the abundance of each species at a given pressure level to its abundance under undisturbed reference conditions under the same conditions, with values truncated at 1. In our study, only land use pressure was considered as an anthropogenic pressure, and its data were derived from land use predictions from GCAM. A detailed technical overview and the application method of the GLOBIO model were described in previous studies.[80,82]

InVEST model

The InVEST model was used to evaluate changes in HQ, reflecting the capacity of ecosystems to provide resources necessary to sustain biodiversity at a macroecological scale. In contrast to the MSA indicator, HQ represents the suitability of habitats for species survival, reproduction, and long-term persistence rather than the number of species.[83,84] High-quality habitats are relatively intact, maintaining ecological structure and function within the range of historical variability. HQ is influenced by the proximity and intensity of human-centered land uses, including residential areas, transportation infrastructure, industrial facilities, water conservancy projects, and agricultural land (Tables S8 and S9). In this study, HQ was estimated using the Habitat Quality submodule of the InVEST model, driven by Demeter-downscaled land-use data and China-specific terrain inputs. Linear or exponential Euclidean distance-decay functions were applied to characterize how the impacts of different disturbance types diminish with increasing distance.

All sectoral results are synthesized into 12 sustainability indicators to represent dynamics in emissions reduction, energy transition, water use, food security, and biodiversity. Through capturing interlinkages across land, food, energy, and ecosystem domains, the framework enables a holistic evaluation of forestation strategies and quantifies trade-offs across SDG 2 (Zero Hunger), SDG 10 (Reduced Inequalities), SDG 13 (Climate Action), and SDG 15 (Life on Land). Additional model descriptions and uncertainty analysis are provided in Notes S1 and S3.

Step two: Scenario design

REF scenario

In this scenario, the SSP2-RCP4.5 pathway, which uses SSP2 projections for GDP, population, and technology, given a "middle-of-the-road" outlook with no major deviations from historical trends, is adopted.

NetZero scenario

In this scenario, a "slow start, steep end" decarbonization pathway for China[40],peaking CO_2 by 2030 and reaching carbon neutrality by 2060,while the rest of the world experiences a linear decline from 2025, is adopted.

Afforest scenario

The Afforest scenario aligns well with China's governmental goals, such as 30.7% forestry land cover goal by 2050. The potential forestation dataset is based on our previous work,[34] in which three different methods were integrated, including random forest, the process-based dynamic global vegetation model ORCHIDEE, and the WRI forestation potential map, to predict the spatial distribution of potential forest areas across China. By overlapping this prediction with existing land-use data, we generated a comprehensive map of forestation opportunities. Regarding the temporal dimension of forestation, four governmental forestry milestones were aligned with the potential forestation map, corresponding to forest cover targets of 24.1% by 2025, 26.0% by 2035, 30.7% by 2050, and a total afforested area of 257.79 Mha by 2062. For forest type suitability, the MaxEnt v3.4.3 model was employed to determine the optimal forest species composition for each 1-km grid cell.

In this study, the high-resolution forestation map was spatially aggregated to the basin level (Figure S3) for incorporation into the GCAM model as the Afforest scenario. The 15 identified forest types were classified into two categories, hardwood and softwood, to distinguish their respective carbon sequestration rates and land rent costs (Table S4). All newly established forests were represented as unmanaged forests (also referred to as natural forests) within GCAM to prevent their inclusion in timber production and to ensure their role as long-term carbon sinks. Unlike the *NetZero* scenario, in which the forest area evolves endogenously under a carbon neutrality constraint, the forestation scenario involves an exogenous, linear expansion to 257.7 Mha from 2020 to 2060.[34]

DietShift scenario

Following the EAT–Lancet healthy diet recommendation,[85] a shift toward plant-based diets is implemented by adjusting the preference elasticities in GCAM model (animal protein: −0.45; plant protein: +0.45)[41] as a potential combined measure to examine land pressure alleviation under large-scale forestation.

YieldUp scenario

Climate change will negatively affect maize production by 6%–24% and increase wheat yields by 9%–18% and rice yields by 2%–3%.[86] In this study, we propose a *YieldUp* scenario in which the yields of major irrigated crops, includingirrigated corn, wheat, and rice, in the GCAM will reach 75%, 75%, and 90% of the attainable levels by 2050, respectively, through improved management practices under the impacts of climate change.[36]

SusCrop scenario

China's forestation target is limited in this scenario by adopting the 2013–2017 China Forest Resource Inventory baseline (approximately 30 Mha less than GCAM-based 2015 roadmap), and 103.1 Mha of basic cropland is permanently protected to ensure food security.[42] Additional scenario descriptions are provided in Note S2.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Zhifu Mi (z.mi@ucl.ac.uk).

Data and code availability

The potential forestation distribution data used in this study is available at Zenodo: https://zenodo.org/records/8297679. The SSP2 population structure data are available at the IIASA SSP database[87]: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=30. The China 1:1 million public version of the topographic database (2021)[88] is available at National Catalogue Service for Geographic Information Database: https://www.webmap.cn/commres.do?method=result100W. The Household Survey datasets by the National Bureau of Statistics of China are available from the author S.D. on reasonable request. The GCAM simulation results, Demeter downscale results, and InVEST threats data in this study are available at Figshare: https://figshare.com/s/fe9fcdea14e7a8b3c40c.

GCAM is an open-source IAM and can be accessed at https://github.com/JGCRI/gcam-core. Demeter land cover downscale model is available at https://github.com/JGCRI/demeter. The InVEST ecosystem service model is available at https://naturalcapitalproject.stanford.edu/software/invest. The full GLOBIO model is available at https://github.com/GLOBIO4/GlobioModelPublic/wiki, and the simplified version used in this study can be retrieved from https://pure.iiasa.ac.at/id/eprint/17565/. The Python and R codes for main data processing and graphic drawing are available at https://github.com/debibooo/China_forestation. ArcGIS and PowerPoint software were also used to generate the figures.

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AUTHOR CONTRIBUTIONS

Conceptualization: S.D., Z.M., and S.L. Methodology: S.D., Y.O, and Z.M. Investigation: S.D. and Y.Z. Resources: Z.M., S.L., Y.O., and H.X. Data curation: S.D. and H.X. Formal analysis: S.D. and Z.M. Visualization: S.D. Supervision: Z.M. and S.W. Writing – original draft: S.D. Writing – review & editing: all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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