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PERSPECTIVE

Pitfalls in forest carbon sink projection

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Abstract Global forests are increasingly crucial for achieving net-zero carbon emissions, with a quarter of the mitigation efforts under the Paris Climate Agreement directed towards forests. In China, forests currently contribute to 13% of the global land's carbon sink, but their stability and persistence remain uncertain. We examined and identified that published studies suffered from oversimplifications of ecosystem succession and tree demographic dynamics, as well as poor constraints on land quality. Consequently, substantial estimations might have been suffered from underrepresented or ignored crucial factors, including tree demographic dynamics, and disturbances and habitat shifts caused by global climate change. We argue that these essential factors should be considered to enhance the reliability and accuracy of assessments of the potential for forest carbon sinks.

Keywords Forest carbon · Carbon sink · Forest age · Land suitability · Forest demographic

A global surge of interest has emerged in initiatives prioritizing carbon-centric afforestation and forest restoration (Strassburg et al 2020), in which forest recovery in China plays a leading role. Forests, which contain the preponderance of land carbon stocks, represent the largest contributor to the recent and future land carbon sink in China (Huang et al 2022a, b; Yu et al 2022a, 2024). These forests are predominantly characterized by fast-growing, young plantations and are also acknowledged as an essential, persistent carbon sink.

As part of the endeavor to realize the ambitious goal of achieving "carbon neutrality" by the year 2060, the Chinese government has announced plans to establish 41.66 million hectares of forest plantations by 2050, with the explicit purpose of augmenting carbon storage (State Forestry Administration of the People's Republic of China 2016). Underpinned by this political impetus, the evaluation and projection of forest carbon stocks and sinks in China are undergoing a resurgence. Typically, the methodologies employed in these assessments fall into three categories: statistical models,

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process-based ecosystem models, and remote-sensing-based machine-learning models (Table 1). Nevertheless, the reported carbon stocks and sinks show significant disparities, indicating considerable uncertainties inherent to these projections (Yu et al 2024). Here, we evaluated published studies and revealed three common pitfalls in the assessments of future carbon dynamics in China's forests.

First, forest species composition changes during succession, which might eventually lead to the development of a different forest type (Fig. 1a). Forest dynamics continuously change, while field measurement captures the species composition only at the time of the survey. Most forests consist of various species that, however, may not be adequately represented at the stand level. For example, if the volume stock of any single species in a forest plot is ≥ 65%, the forest plot is marked as a pure stand (i.e. mono-species forest) in China's national forest inventories (State Forestry Administration of the People's Republic of China 2014). Thus, for instance, a forest plot recorded as *Pinus massoniana* may contain up to 35% of its volume stock contributed from other species, such as *Cunninghamia lanceolata* Hook or/and *Shima superba*. Over the course of some decades, the stand's succession may lead to the emergence of a mixed forest predominantly dominated by *Shima superba*. Nonetheless, many studies assumed that the stand would remain unchanged in carbon stock projections, using age-biomass equations based on *Pinus massoniana*. Even greater uncertainties arise when simplifying forest species by aggregating them into broader categories, such as broadleaf/needle-leaf, evergreen/deciduous, and mixed types. In many cases, the dominant tree species at the time of the survey may not necessarily be the optimal choice for the region, particularly during the early stages of succession when the dominant trees are more likely to be pioneer species rather than climax tree species (Rüger et al 2020). As forest ecosystems progress, pioneer tree species like *Robinia pseudoacacia* and *Betula platyphylla* will gradually be succeeded by other species, leading to shifts in species composition and even forest types (Fig. 1a). Generally, climax communities have a higher carbon saturation compared to pioneer tree species, which may result in an underestimation of carbon capacity when using pioneer species in projections. Moreover, with climate change persistently reshaping climax communities, estimating carbon potential using fixed tree species or forest types can introduce significant biases in long-term projections. Thus, the species composition and its changes should be considered in future simulations of long-term forest carbon dynamics, including climate change impacts on species distribution, species composition within stands, and forest succession trajectory.

Second, the majority of gridded-map-based projections rely on age and biomass relationships derived from field data collected and summarized at the stand level (Table 1). These projections employ a simplified assumption in which the age of future forests is increased incrementally from the baseline

Table 1 Studies of forest carbon stock or/and sink projections in China

Methods		Periods	Carbon sequestration rate (Pg year^{-1})	References
Statistical models	Age-biomass growth model	2001–2050	0.26*	Liu et al (2019)
	Logistic growth model	2011–2050	0.15	Li (2021)
	Age-biomass growth model	2022–2100		Shang et al (2023)
	Forest carbon sequestration model	2010–2060	0.21 ± 0.02	Cai et al (2022)
	Forest carbon sequestration based on the secondary succession theory	2010–2050	0.28–0.42	He et al (2017)
	Age-biomass growth model	2010–2050	0.25*	Huang et al (2012)
	Parameter-sparse empirical models	2010–2060	0.17–0.25	Huang et al (2022a, b)
	Age-dependent statistical model	2020–2060	0.27	Xu et al (2023)
		2060–2100	0.13	
	A semi-empirical model	2000s–2040s	0.17	Yao et al (2018)
	Age-biomass growth model	2010–2050	0.16*	Yu et al (2021)
	Age-biomass growth model	2010–2050	0.13–0.16	Zhang et al (2018)
	IPCC volume-biomass methods	2010–2050	0.10*	Li et al (2018)
Process-based ecosystem models	Integrated terrestrial ecosystem carbon model	2000–2100	0.13*	Ju et al (2007)
	Integrated terrestrial ecosystem carbon model	2001–2100	0.17*	Zhou et al (2013)
Remote-sensing-based machine-learning models	Random forest model	2010–2050	0.83–1.52**	Bastin et al (2019)
	Random forest model	2010–2050	0.32**	Xin et al (2022)

*Calculated based on total carbon storage

**Extrapolated to national total using carbon density and the forest area reported in 2018

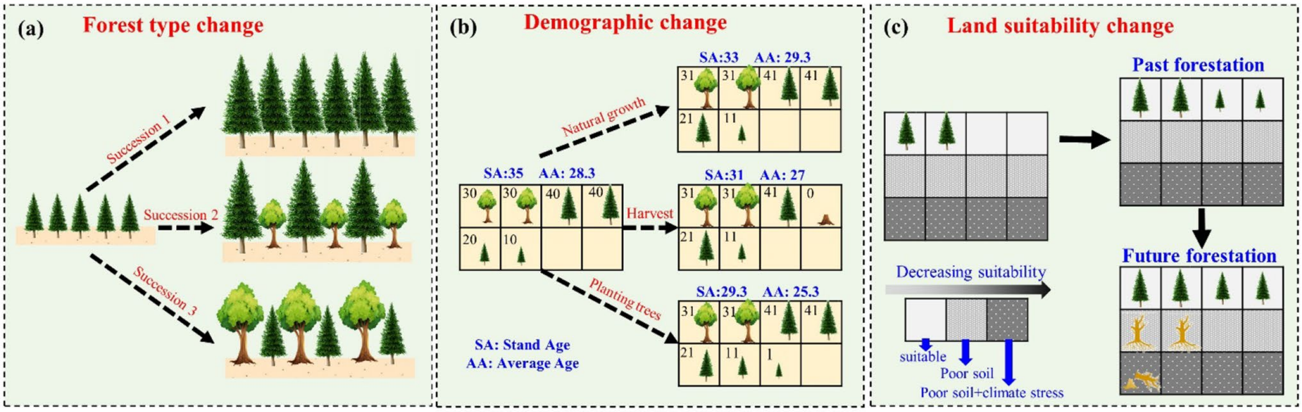

Fig. 1 Conceptual diagram illustrating the three common pitfalls in carbon stock and sink projections. Panel **a**: forest species composition changes during succession, which might eventually develop into a different forest type, e.g., needle-leaf forest to mixed forest. Panel **b**: the dynamics of forest age due to natural growth, harvest, and planting in a stand. The stand age (SA) is the average age of the trees at canopy level, while AA is the average age of all trees in a stand. The changes in the age of trees will not be proportionally propagated to the age of stand. Panel **c**: the future forestation activities might face the challenges of decreasing suitability of lands, including limited accessibility, water resources, nutrients, and rising costs

year to the predicted year using an age-biomass model developed for this purpose (Yao et al 2018; Yu et al 2021). For example, a 20-year-old forest plot (or a grid in a forest map) in 2020 is often assumed to be 60 years old in 2060. This approach is more applicable for short-term estimation or for timber forests routinely harvested with fixed rotation years, whereas it might introduce bias in the long-term projection of non-timber forests (Yu et al 2024), especially for projections relying on gridded maps. This is because the complexities of age accrual in non-timber forests were not fully represented in the approach, where age dynamics are intricately shaped by factors such as mortality, regeneration, and natural growth (see illustrations of age changes in Fig. 1b). This means that when applying an age-biomass model derived from field surveys to project long-term carbon stock in non-timber forests, the stand age of the future forest might not equal to the years between the baseline year and the simulated year. For instance, in the case of fast-growing timber species like eucalypts, which are routinely harvested on fixed rotation cycles of 5–6 years, the change in stand age is predictable and fixed. Conversely, in secondary forests with diverse age and species compositions, the stand age represents the average age of canopy trees. Therefore, the stand age in surveyed stands might not necessarily indicate the cumulative years of stand biomass accumulation. Instead, it reflects the average age of canopy trees that have survived under natural growth and disturbances, in which the annual accrual of stand age will often be divergent from 1 (Fig. 1b). In some instances, the mortality of older trees can even reduce the average age in a gridded forest map. Consequently, even in the absence of disturbances, the assumption that annual age accrual is consistently equal to “1” for forest growth projections might be less suitable for some of the forests. Unfortunately, the assumption has been widely adopted in projections relying on gridded maps. For long-term assessments of carbon dynamics, future studies should either consider tree demographics within stand level or derive annual age accrual information from large samples for large-scale simulations (Dong et al 2023).

Third, the land suitability for future forestation was less considered in carbon dynamics projections. Appropriate planning is required to enhance forest carbon sink and avoid vast ecosystem degradation, in which a critical prerequisite is to locate the suitable land and identify the corresponding appropriate species for forestation. Nonetheless, habitats of tree species will be shaped by climate change, resulting in shifts of land suitability and the choice of tree species. Inappropriate forestation might increase competition for land (Chen et al 2018) and water (Brown 2014), consequently leading to increased food prices and hunger risk (Doelman et al 2020). A study revealed that the potential available lands for forestation mainly distributed along the “Hu-huanyong-line” under projected future climate change scenario (Zhang et al 2022). However, these areas are known to be prone to climatic stresses, which threaten the stability of forest sink (Anderegg William et al 2020; Marcos et al 2023). It is well-acknowledged that climatic extremes, such as heat stress, drought, pests, and diseases, altered ecosystem succession, retarded forest growth, and aggravated tree die-offs (Anderegg et al 2015; Hicke et al 2012; Peng et al 2011; Vicente-Serrano et al 2013). Recent studies have shown that species-specific functional traits, such as big-sized trees, mycorrhizal types, fire adaptability, and leaf longevity, are beneficial for predicting the stability of carbon sequestration (Deng et al 2023; Feng et al 2022; Huang et al 2022a, b; Wang et al 2022, 2023; Luo et al 2023). These mechanisms affecting the persistency and stability of forest carbon sink should be considered for accurate projection of sink potential.

Moreover, climate changes also affect the choice of tree species. These climatic feedbacks on carbon stability and forestation activities were less considered in forest carbon projections. Therefore, we advocate that climate-smart species should be evaluated to identify species-specific land suitability for accurate assessment of forest carbon sink. A recent study has devoted to address this challenge and improved the assessment reliability of future forest carbon sink in China (Xu et al 2023). Regarding the land suitability, a study revealed that forestation showed a tendency to increase on marginal lands, in which carbon sequestration was significantly lower than in non-marginal lands (Yu et al 2023). Additionally, forestation on marginal lands has also increased forestation failures due to water depletion, biodiversity loss, nutrient limitation, and low tree survival rate (Yu et al 2023). Furthermore, previous studies have revealed that planted forests consumed more water than natural forest in water-limited area (Yu et al 2019), while the succession of planted forests also developed toward the depletion of phosphorus in contrary to phosphorus accumulation in natural forests (Yu et al 2022b). Thus, with the large and contiguous lands available for forestation continuously occupied by new trees, crops, and urban expansions in China, future forestation might be increasingly driven to fragmented and marginal lands, which could be suffered from rising forestation costs, and will prone to high failure rate and reduced carbon sequestration potential.

To summarize, all 3 approaches, involving process-based ecosystem models, statistical models, and remote-sensing-based machine-learning models, currently suffer from oversimplifications of ecosystem succession and land suitability in describing forest biomass carbon dynamics. Statistical and remote-sensing-based machine-learning models, which rely directly on the age-biomass relationship in forest biomass carbon estimation, might be more susceptible to tree demographic dynamics in long-term projections. Although promising, it is also challenging to improve tree demographic changes in process-based ecosystem models due to the complex processes involved, such as wood harvest, tree regeneration/mortality, and ecosystem succession. We argue that these essential factors should be addressed in each approach to enhance the reliability and accuracy of long-term assessments of forest carbon sink potential.

Author contributions Y.L.D: wrote the text. Z.Y.: conceived idea and wrote the text. E.A.: co-wrote the text. G.Y.Z.: co-wrote the text. S.L.R.: co-wrote the text.

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