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Future land-use competition constrains natural climate solutions

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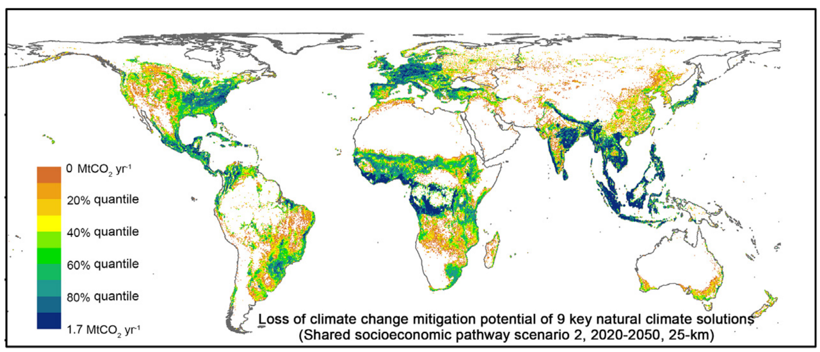
HIGHLIGHTS

- The impact of future land-use change on NCS was analyzed.
- About 0.3–2.8 $GtCO_2\ yr^{-1}$ or 4–39 % of original NCS potential would be lost.
- Cropland expansion was the key driver of NCS potential loss.
- The loss was most severe in the tropics.
- A sustainable development pathway was key to reduce the impact.

GRAPHICAL ABSTRACT



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ABSTRACT

Natural climate solutions (NCS) are an essential complement to climate mitigation and have been increasingly incorporated into international mitigation strategies. Yet, with the ongoing population growth, allocating natural areas for NCS may compete with other socioeconomic priorities, especially urban development and food security. Here, we projected the impacts of land-use competition incurred by cropland and urban expansion on the climate mitigation potential of NCS. We mapped the areas available for implementing 9 key NCS strategies and estimated their climate change mitigation potential. Then, we overlaid these areas with future cropland and urban expansion maps projected under three Shared Socioeconomic Pathway (SSP) scenarios (2020-2100) and calculated the resulting mitigation potential loss of each selected NCS strategy. Our results estimate a substantial reduction, 0.3–2.8 $GtCO_2\ yr^{-1}$ or 4–39 %, in NCS mitigation potential, of which cropland expansion for fulfilling future food demand is the primary cause. This impact is particularly severe in the tropics where NCS hold the most abundant mitigation potential. Our findings highlight immediate actions prioritized to tropical areas are important to best realize NCS and are key to developing realistic and sustainable climate policies.

1. Introduction

Achieving the Paris Climate goal of limiting global warming to below 2 °C requires a concerted effort to decarbonize our economies and reduce greenhouse gases in the atmosphere (Roe et al., 2019; Seddon et al., 2020). Natural climate solutions (NCS) are a suite of nature stewardship strategies (also called pathways)—protection, restoration, and management of various ecosystems, which contribute to a sizeable potential for climate change mitigation (Bossio et al., 2020; Fan et al., 2017). The collective of 20 NCS strategies can provide over 30 % of the mitigation needed by 2030, among which forest restoration offers the largest mitigation potential by 3.1 $GtCO_2\ yr^{-1}$ (Griscom et al., 2017). NCS are thus increasingly being incorporated into climate change mitigation strategies and targets (Smith et al., 2020). For example, NCS has been regarded as a key strategy for countries to fulfil their Nationally Determined Contribution (NDC) committed under Paris Agreement. NCS also opens up opportunities in private and

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public sectors for carbon credit investment on NCS-based carbon projects (Koh et al., 2021).

Implementing NCS by protecting and restoring ecosystems relies on setting aside large-scale natural areas for climate mitigation purposes. These natural areas for NCS will compete with the land needed to support socioeconomic development (e.g., population growth and GDP increment) (Nagendra et al., 2018; Qiu et al., 2019; Seto and Ramankutty, 2016). Particularly for developing countries, there is an increasing demand for expanding croplands to safeguard food production and urban areas to sustain their socioeconomic developments (Popp et al., 2017; Zheng et al., 2021). In the past decades, fulfilling such land-use demand has caused extensive losses of natural ecosystems at both regional and global scales (Ellis et al., 2021; X. Liu et al., 2021a; Turner et al., 2007; Yue et al., 2013). With the human population projected to further increase to 9.7 billion by 2050, the land-use competition is likely to continue or even intensify (Bren d'Amour et al., 2017).

Impact from land-use competitions, especially those between climate change mitigation and securing food provision (e.g., cropland), has been identified as one of the key issues in climate change mitigation studies (IPCC, 2019; Meyfroidt et al., 2022). However, in previous estimation of NCS mitigation potential, impact of land-use competition (e.g., incurred by cropland expansion) has not been taken into consideration as they overlooked the inevitable cropland expansion in the next few decades (Fargione et al., 2018; Griscom et al., 2017). Understanding how NCS potential is limited by future land-use competition is important as it provides us with a more realistic and equitable estimate. It also allows us to evaluate the tradeoff on a more spatially explicit scale, allowing specific countries/regions to make more informed decisions that reduce tradeoffs and potentially enhance synergies. For example, knowledge of hotspot areas where NCS mitigation potential is most vulnerable in the future would be helpful to guide prioritized and proactive efforts to ensure the integrity of NCS and its long-term contribution to NDC. Ensuring the best potential of NCS is also relevant to international initiatives (e.g., SDG 13 - combating climate change), and countries' policies of reducing carbon emission, such as China's CO_2 Peaking and Carbon Neutrality policy (Z. Liu et al., 2021b). Nevertheless, owing to the uncertainties and interconnectedness of factors that determine the demand and spatial pattern of future land-use (e.g., population, crop yield and diets), the impact of future cropland and urban expansion on NCS remains largely unknown.

Here, our study incorporates geospatial approaches and scenario analysis to evaluate how future land-use competition (2020–2100) between cropland/urban expansion and natural areas potential usable for NCS will constrain NCS mitigation potential. We aim at (i) facilitating a better understanding of the attainable NCS mitigation potential under the threat of future land-use competition and (ii) providing decision-makers and international climate initiatives with spatially explicitly information that can be used for guiding prioritized efforts to best realize the NCS mitigation potential.

2. Materials and methods

2.1. Overview

In this study, we modelled and mapped the extent to which future land-use competition between socioeconomic development and climate mitigation would constrain the mitigation potential of NCS for the period 2020–2100 (Fig. 1). Note that the land-use competition here refers to contests in the land that can be used for multiple purposes rather than the competition in land tenure and claims owning to market behaviors (Meyfroidt et al., 2022). Specifically, we first projected the future land-use changes caused by the two main socioeconomic demands—urban expansion (provision of human settlement) (Seto et al., 2012) and cropland expansion (provision of food; pasture was not considered) (Sections 2.3 & 2.4) (Foley et al., 2011). To account for various future development conditions, we mapped the land use changes under Shared Socioeconomic Pathways (SSPs) scenario framework. Second, we estimated the expected (without land-use competition) cost-effective mitigation potential of nine topmost NCS strategies (also known as NCS pathways), representing protection, restoration and improved management across various natural areas (e.g., forest, grass and wetland). We then mapped the losses of the natural areas that have potential for NCS provision and consequently the loss of NCS mitigation potential due to future land-use changes under each SSP scenario (Section 2.5). We also reported the uncertainties in our analysis following IPCC guideline (Section 2.6).

2.2. Narratives of SSP scenarios

SSP scenarios provide projections with a set of plausible futures by accounting for various possible development trajectories across sectors, such as socioeconomic development (e.g., population and diet habit), technology improvement (e.g., agriculture yields and energy source), environment conditions (e.g., regulation level and willingness of environmental

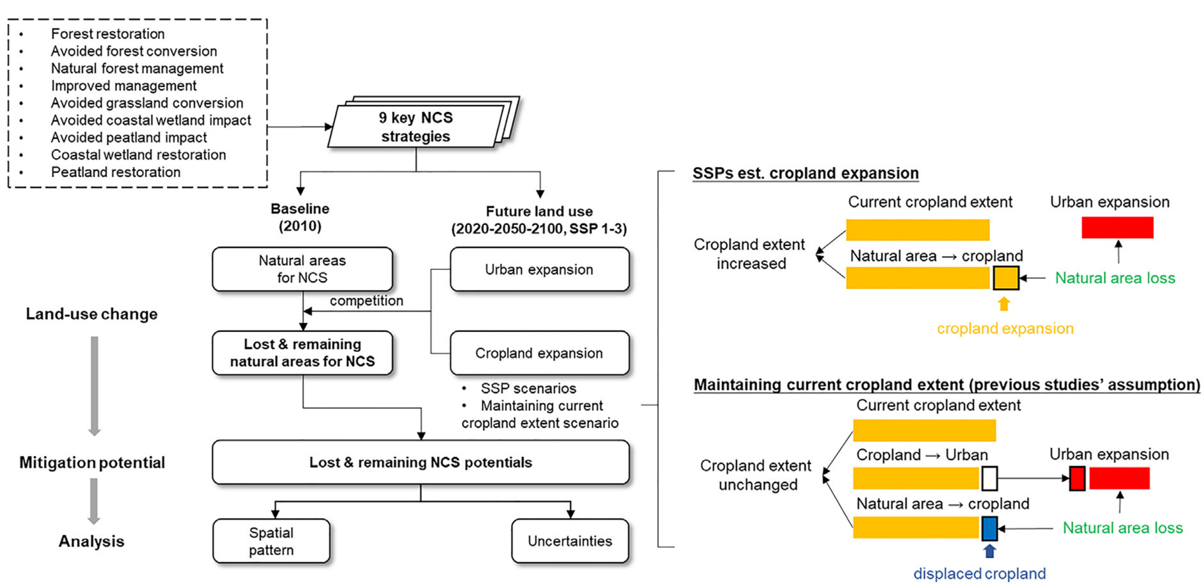

Fig. 1. Conceptual flowchart of our method (left panel) and illustrative diagram of cropland expansion under SSP scenarios and maintaining current cropland extent scenario (right panel).

protection), and international relationship (e.g., trade and cooperation) (Grassi et al., 2021; Riahi et al., 2017). SSP scenarios framework has been widely incorporated into scientific reports (IPCC AR6), earth system models (6th climate model intercomparison project, CMIP6), as well as other researches involving projecting future land-use, climate change and socioeconomic development (O'Neill et al., 2017). Three distinct SSP scenarios were selected, reflecting an increasing but varying degree of future land-use competition (Popp et al., 2017):

- SSP 1 (Sustainability - low challenges to mitigation and adaptation) assumes a future with low growth in population and food consumption, diet change, strong environmental regulation, and high improvements in agricultural yield.
- SSP 2 (Middle of the road - moderate challenges to mitigation and adaptation) assumes the world does not shift markedly from historic trend, but rather in a path between SSP 1 and SSP 3.
- SSP 3 (Regional rivalry - high challenges to mitigation and adaptation) is built upon marked population growth, intensive resource consumption, a slowdown in technology and agricultural yield improvement, and insufficiently controlled environment degradation.

Table 1 summarizes key assumptions and narratives of SSP 1–3 scenarios relevant to this study. It should be noted that there are huge number of detailed assumptions and complex parameterizations involved in the entire SSP scenario framework. Full details can be found in SSP database (https://tntcat.iiasa.ac.at/SspDb/).

2.3. Future land-use changes under SSP scenarios

We mapped and projected the future extent of urban expansion and cropland expansion under SSP 1-3 scenarios. The future land-use changes were divided into two periods, 2020-2050 and 2050-2100, because (1) both 2050 and 2100 are policy-relevant as they have been widely used as a target year for climate goals (IPCC, 2018; Tollefson, 2020); (2) it helps to better illustrate the differences of the near-term and long-term impact of land-use change on NCS mitigation potential across SSP scenarios; and (3) under some SSP scenarios (e.g., SSP 1), the global population will reach its peak in around 2050. The associated changes in the demand of urban areas and cropland will result in different land-use change patterns for the second half of the century and will thus have different impacts on NCS mitigation potential (Fig. S3).

We obtained the baseline and projected land-use maps from Li et al. (2017). This land-use dataset is in 1-km resolution and contains six land-use classes, including water, forest, grassland, cropland, urban and barren, following MODIS IGBP classification scheme. This dataset is generated by using a Future Land-Use Simulation model (FLUS) to spatially allocating the future land-use demand from IMAGE model (Liu et al., 2017; Stehfest et al., 2014). We used its 2010 land-use layer as our baseline land-use map. All the land-use maps used in this study were calibrated to this baseline map (Supplementary information). This dataset also provides 1-km land-use projections under Special Report Emissions Scenarios (SRES). While the SRES is an earlier IPCC scenario, "symmetric" SSPs (where both the challenges to mitigation and to adaptation are either high or low, i.e., SSP 1-3) greatly resemble scenarios of SRES families (O'Neill et al., 2017; Riahi et al., 2017). We followed systematic analogies between two scenario families and mapped SRES-based land-use projections to SSP families (van Vuuren and Carter, 2014), i.e., SRES B1 to SSP 1, SRES B2 to SSP 2, and SRES A2 to SSP 3. SSP 4 (low mitigation challenge + high adaptation challenge) and SSP 5 (high mitigation challenge + low adaptation challenge) are asymmetric SSP scenarios, so there is no corresponding analogy in SRES scenario. Thus, SSP 4 and SSP 5 are not included in our analysis. Our future analysis shows that the cropland area projected by Li et al. (2017) (SRES scenarios) is on average 7–19 % lower than the areas projected by the corresponding SSP scenarios, suggesting the estimated impact of cropland expansion on NCS mitigation potential would be conservative (Table S1).

We used the latest 1-km urban projection product from Chen et al. (2020) to obtain urban expansion maps from 2010 to 2100. This urban projection product is generated by: (1) building a panel regression model using historical urban land areas and variables including population, urbanization rate and GDP; (2) applying this model to project future urban land areas (demand) with variables projected by SSP scenarios; and (3) spatially allocating urban expansion pixels with a land-use allocation model (FLUS). SSP 1 scenario shows a compact and dense spatial pattern of future urbanization, while SSP 3 shows an opposite trend—a sprawled and low-density spatial pattern.

The urban expansion projection data was calibrated with the baseline land-use map to ensure temporal consistency (Gao and O'Neill, 2020; Seto et al., 2012). At last, we extracted the 1-km projected urban extent and cropland extent from 2020 to 2100 under SSP 1–3 scenarios and overlaid them with the baseline land-use map in 2010 to map natural area losses in the future. It should be noted that the natural areas here refer to forest, wetland and grassland potentially usable for NCS rather than natural areas completely free from historical disturbance (Drever et al., 2021; Ellis et al., 2021). The projected natural area loss across SSP scenarios and time periods are presented in Fig. S5.

It should be further noted that the reason for using land-use projection data from Li et al. (2017) is because it is the only land-use projection map product at 1-km resolution, while other datasets are in coarse resolution (mostly >10 km) (Fujimori et al., 2018; Hurtt et al., 2020; van Vliet et al., 2017). Using high-resolution land-use projection allows us to uncover land-use changes in small patches and thus helps to provide spatially-explicit information that will beneficial to decision-makers. It has also been reported that using a 10-km data would miss out at least 60 % of small-scale land-use change that could be identified in 1-km resolution data (Li et al., 2017). Another consideration is that previous estimation of NCS potential is based on a non-mitigation condition (i.e., baseline

Table 1
Parameters and assumptions related to our study of SSP 1–3 scenarios.

	SSP1	SSP2	SSP3
Urbanization	Well managed and high-level urbanization	Continuation of historical pattern and medium-level urbanizations	Poorly managed and low-level urbanization
Population growth	Low	Medium	High
Land-use change regulation	Strong regulation to avoid environmental tradeoffs	Medium regulation; slow decline in the rate of deforestation	Limited regulation; continued deforestation
Land productivity growth	High improvements in agricultural productivity; rapid diffusion of best practices	Medium pace of technological change	Low technology development
Food consumption	Low growth in food consumption, low-meat diets	Material-intensive consumption, medium meat consumption	Resource-intensive consumption
Energy tech change	Directed away from fossil fuels, towards efficiency and renewables	Some investment in renewables but continued reliance on fossil fuels	Slow tech change, directed towards domestic energy sources
Globalization	Connected markets	Semi-open globalized	De-globalizing
International trade	Moderate	Moderate	Strongly constrained
International cooperation	Effective	Relatively weak	Weak, uneven

scenarios without applying additional mitigation efforts (Fargione et al., 2018; Griscom et al., 2017). Thus, to make consistent analysis on the impact of land-use competition on NCS potential, the land-use projection data should also be under non-mitigation scenarios. Li et al. (2017) is one of the only few land-use projection datasets under non-mitigation scenario.

To further validate the land-use projection data we used, we carried out a series of benchmark tests, including validating with current land-use/ google earth images and comparing with other land-use projection products (Supplementary information). Based on tests, we conclude that the projections of cropland and urban expansion used in the study are relatively conservative and in acceptable accuracy.

2.4. Future land-use changes under maintaining current cropland extent scenario

In addition to mapping future land-use changes (i.e., urban expansion and cropland expansion) under SSP scenarios, we also mapped another future land-use change scenario – maintaining current cropland extent scenario. This scenario assumed the total amount of cropland areas maintained the same as baseline level of 2010 from 2010 to 2100 (Fig. 1). This additional scenario was originated from the key assumption embedded in previous NCS mitigation potential estimations: “current extent of cropland land can effectively feed projected future populations as future global food demand can be met via an ideal yield increases” (Fargione et al., 2018; Griscom et al., 2017). When calculating and projecting NCS mitigation potential, previous studies do not take the land-use competition between future cropland expansion and natural areas needed for implementing NCS into consideration.

We compared the resulting impacts of future land-use changes on NCS mitigation potential between the scenarios with cropland expansion (projected by SSP scenarios) and scenario maintaining current cropland extent (assumed by previous studies). This comparison could help to demonstrate whether previous studies overestimate the NCS mitigation potential by not considering the impact of future cropland expansion.

Specifically, under maintaining current cropland extent scenario, the only land-use competitions to NCS comes from urban expansion and displaced cropland (Fig. 1). The displaced cropland refers to the new cropland area to compensate for the cropland loss resulted from urban expansion (van Vliet, 2019; Zuo et al., 2018). To keep the current cropland extent unchanged, the amount of displaced cropland should be equaled to the cropland converted to urban areas.

We used an importance sampling-based Monte Carlo approach to map the spatial extent of displaced cropland (Fig. S4) (Haight and Travis, 1997). The importance weight matrix was constructed by two sub-weight matrices—the distance to the existing cropland and the density of the surrounding cropland area.

- Distance to existing cropland (W_1):

We used the *Euclidean Distance* in ArcMap software to calculate the Euclidean distance to the closest existing cropland (cropland in 2020 for 2020–2050; cropland in 2050 for 2050–2100).

- The density of surrounding cropland area (W_2)

We calculated the fraction of cropland pixels (cropland in 2050 for 2020–2050; cropland in 2100 for 2050–2100) within each 25 km × 25 km grid.

- Weight matrix (W)

The weight matrix for importance sampling was then determined by $W = W_1 \times W_2$. W was then normalized the weight to a scale of 0–1.

SSP scenarios give different narratives on international trade (Popp et al., 2017), i.e., a moderate international trade under SSP 1 and SSP 2 but a constrained trade for SSP 3 (Table 1). Thus, for SSP 3 scenario we divided the world into 5 economic regions (Riahi et al., 2017) and deliberately constrained the displaced cropland within the corresponding regions (van Vliet, 2019) (Fig. S8). Taking together the extent of future urban expansion and displaced cropland, we mapped future land-use changes and resulting natural area losses under maintaining current cropland extent scenario.

2.5. Estimating the lost cost-effective NCS mitigation potential

We estimated and mapped the expected (without land-use competition) and the lost (with land-use competition) NCS mitigation potential under each SSP scenario. Nine key NCS strategies were selected, including avoided forest conversion, restoration, natural forest management and plantation forest management, avoided grassland conversion, avoided coastal wetland impact, avoided peatland conversion, coastal wetland, and peatland restoration (Griscom et al., 2017; Griscom et al., 2020). Such selection was due to two considerations: (i) these strategies provide the topmost abundant NCS mitigation potential among NCS strategies; (ii) these strategies can be directly or indirectly mapped by geospatial data, making it possible for us to spatially project how they would be affected by future land-use changes.

We drew from the framework of Griscom et al. (2017) to estimate the maximum mitigation potential on a yearly basis. The maximum mitigation potential (M_{max}) of each NCS strategy was estimated by multiplying potential extent of NCS provision (A_x) and flux intensity (F_x), i.e.,

$$M_{max} = A_x \times F_x \tag{1}$$

It should be noted that as A_x was estimated by the baseline year 2010, while future A_x gain is not included. We updated and provided a better estimation of A_x with newly available spatial datasets and calibrated the updated A_x to the baseline land-use map in 2010, offering a relatively more reliable estimation of expected NCS potential. Double counting among strategies was avoided, e.g., forest restoration and peat forest restoration.

We used the widely-adopted mitigation cost of \$100 $MgCO_2^{-1}\ yr^{-1}$ as the cost-effective level to meet the 2 °C warming target (Fargione et al., 2018). We used the ratio (% of $M_{max,}$ $ratio_{cost\text{-}effective}$) of each NCS strategy from Griscom et al. (2017) to calculate how much NCS mitigation potential can be obtained at the cost-effective level ($M_{cost\text{-}effective} = M_{max} \times ratio_{cost\text{-}effective}$).

For the land-use changes under each SSP scenario and each NCS strategy, we calculated mitigation potential loss at cost-effective level by

$$M_{loss} = L_x \times F_x \times ratio_{cost\ -\ effective} \tag{2}$$

where L_x is the lost areas that have NCS provision potential (A_x). We directly applied the $ratio_{cost\text{-}effective}$ to calculate mitigation potential loss at cost-effective level because L_x is a geographical sub-set of Ax and has the same geographic span as A_x. L_x was mapped by either approach: (i) If A_x can be mapped directly from geospatial data (e.g., forest restoration), L_x is obtained from overlaying the A_x with the projected areas of urban expansion and cropland expansion; (ii) If A_x can only be indirectly estimated from geospatial data (e.g., avoided forest conversion), we prorate the loss of the corresponding nature areas (e.g., forest) and deduct the resulting area from A_x. Detailed descriptions for the calculation of each NCS strategy are presented in Supplementary information.

2.6. Uncertainty estimation and aggregation

We acknowledge that the uncertainties in land-use projection data and other input datasets would affect our analysis. We followed the IPCC Good Practice Guidance and Uncertainty Management to estimate the uncertainties of the loss of NCS mitigation potential at a 95 % confidence interval. According to Eq. (2), the uncertainties of our analysis could be broken down into two parts: (i) the lost areas that have NCS provision potential (i.e., uncertainty in L_x). For the uncertainty of cropland expansion, we obtained the maximum and minimum cropland projection generated by multiple paralleled models of the corresponding SSP and SRES scenario and utilized a Monte Carlo approach to estimate the standard deviation. Since the uncertainty in urban expansion projection is not provided in the data set, we set the uncertainty to 25 %. The uncertainty of cropland displacement was estimated by repeating 100 runs of the displaced cropland simulation. (ii) The carbon flux intensity (i.e., uncertainty in F_x). The uncertainties in F_x of each NCS strategy were obtained from Griscom et al. (2017). Under this scheme, we estimated the uncertainties of both sources of each land-use change driver across NCS strategies and SSP scenarios. At last, we aggregated the uncertainties into the total uncertainties of each NCS strategy and SSP scenario (Eggleston et al., 2006). The resulting uncertainties are presented Supplementary dataset 2.

3. Results and analysis

3.1. NCS mitigation potential loss in 2020–2100

We find that a total of 101–186 Mha of natural areas will be converted to either urban areas (12–15 Mha) or cropland (87–174 Mha) between 2020 and 2050 (Fig. S5; Supplementary dataset 1). Such drastic land-use competition would translate to a considerable loss (1.0–2.1 $GtCO_2\ yr^{-1}$ or 14–27 %) of the expected cost-effective climate mitigation potential across nine NCS strategies (7.6 ± 1.1 $GtCO_2\ yr^{-1}$, ±95 % CI) (blue bars in Fig. 2; Supplementary dataset 2). The smallest mitigation potential loss, 1.0 ± 0.1 $GtCO_2\ yr^{-1}$, is found under the sustainable development scenario (SSP 1) (Fig. 2a). Despite being the least loss among all scenarios, the amount still equates to the commitment—reducing 1.0–1.2 $GtCO_2$ emission in 2025—declared within the United States' Nationally Determined Contribution (NDC) (Fargione et al., 2018). The unsustainable scenario, SSP 3—regional rivalry pathway, leads to the largest mitigation potential loss (2.1 ± 0.3 $GtCO_2\ yr^{-1}$), more than doubling the loss under SSP 1 scenario.

In our projection beyond 2050, the mitigation potential loss decreases to 0.3–0.4 $GtCO_2\ yr^{-1}$, or 4–6 %, under SSP 1-2 scenarios (Fig. 2b). By comparison, SSP 3 scenario is expected to undergo an elevated NCS loss (2.8 ± 0.4 $GtCO_2\ yr^{-1}$ or 39 %), exceeding pre-2050 levels. This likely stems from the predicted declines in human population after 2050 in SSP 1-2 scenarios, and the resulting drop in socioeconomic demands (i.e., lands for human settlements and crops) (Chen et al., 2020; Vollset et al., 2020). Comparing three SSP scenarios, the discrepancy in their mitigation potential losses over the century emphasizes the importance of sustainable development to NCS. Otherwise, under an unsustainable future (e.g., SSP 3), the mitigation potential of NCS will be subject to intense and continuous land-use competition up until the end of the century.

Between the two land-use change drivers, we find that cropland expansion is the dominant contributor (>90 %) to mitigation potential loss (Fig. 2). Fulfilling the demand for continued agricultural production would cause cropland expansion across 101–186 Mha of natural areas by 2050. This translates to a massive reduction of 1.0–2.0 $GtCO_2\ yr^{-1}$, or 13–26 % of the expected mitigation potential. By comparison, although global urban areas are estimated to expand to 158–165 % of the 2010 baseline level, the resulting 87–174 Mha loss in natural areas limits the NCS mitigation potential by only 0.07–0.08 $GtCO_2\ yr^{-1}$. This matches recent studies on future cropland demand (Popp et al., 2017; Rosenzweig et al., 2014), and the projections generated by the paralleled models of the same SSP scenario (Fig. S6).

We further estimated the mitigation potential loss when future cropland maintaining current extent (i.e., no cropland expansion), which is the key assumption of previous estimates of NCS's mitigation potential provision (red bars in Fig. 1; Supplementary datasets 1–2) (Fargione et al., 2018; Griscom et al., 2017). Under this scenario, a minimum reduction in NCS (0.1–0.2 $GtCO_2\ yr^{-1}$) is expected, <2 % of the expected mitigation potential. This points to a discrepancy in mitigation potential loss between previously assumed no cropland expansion and salient cropland expansion projected by SSP scenarios (Fig. 1). SSP scenarios already incorporate potential yield growth, technology advancement and implementation of environment protection policy into the cropland demand prediction. However, even the SSP scenario (SSP1) with the most optimistic yield growth predicts a mitigation potential loss 6.2 times greater than that from maintaining current cropland extent scenario. It indicates that previous studies may have overestimated the NCS mitigation potential as accounting for such unavoidable cropland expansions would inevitably compete with NCS.

Our finding also implies that to reduce future cropland demand and alleviate the land-use competition driven by cropland expansion, it is of great necessity to increase the current crop yield (production/ha) and close the yield gap between current yield and potential yield (maximum yield that can be reached) (FAO, 2015; Mueller et al., 2012). For example, it was found that closing the yield gap greatly offsets the natural habitat losses due to cropland expansion, e.g., from 13 % (business-as-usual) to 1 % in sub-Saharan Africa where habitat losses are found the most evident (Williams et al., 2020). Thus, we highlight that strategies for closing the yield gap are pivotal in balancing climate mitigation needs and future cropland demand, such as sustainable agriculture intensification (Zuo et al., 2018), improving agriculture management practice (e.g., irrigation) (Mueller et al., 2012), and optimizing

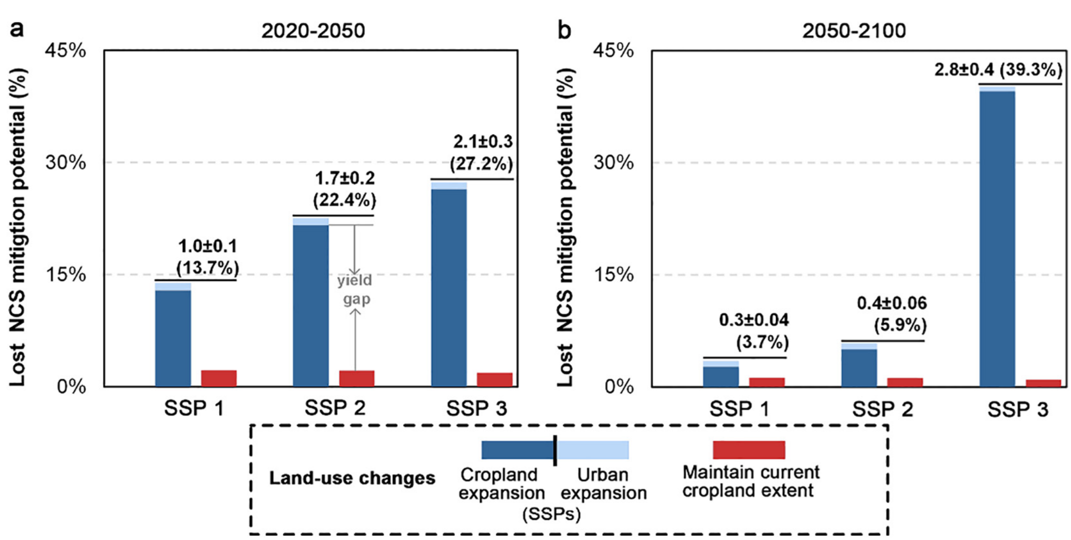

Fig. 2. Mitigation potential loss under each SSP scenario. NCS mitigation potential loss due to urban expansion and cropland expansion (blue bars) during the period 2020–2050 (a) and 2050–2100 (b). The NCS mitigation potential loss under maintaining cropland extent scenario is also estimated as a comparison with the loss under SSP scenarios (red bars). Total ($GtCO_2\ yr^{-1}$, ±95 % CI) losses of NCS mitigation potential compared and the relative (%) loss in comparison with the expected NCS mitigation potential (without considering land-use competition) are provided.

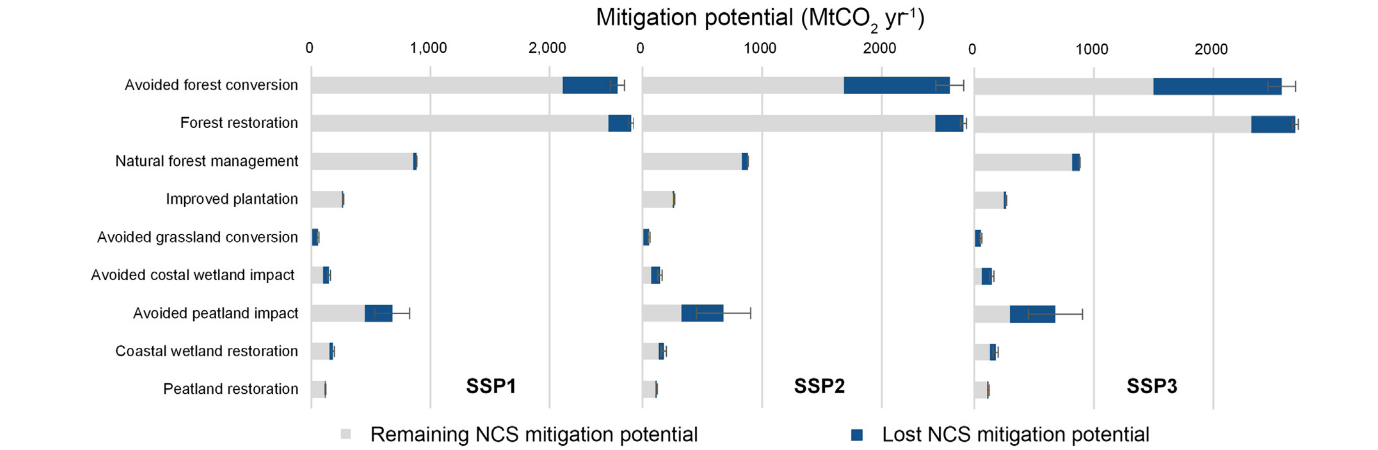

Fig. 3. Lost mitigation potential ($MtCO_2$ yr^{-1}) of each selected NCS strategy during 2020–2050. The error bar represents the 95 % CI.

cultivars (Pellegrini and Fernandez, 2018). It is also worth noticing that increasing cropland yield might have certain side effects. For example, emerging evidence has shown that increase in crop yield and production would incur a rebound effect (i.e., excessive food consumption), which consequently might in turn stimulate cropland expansion and cause NCS mitigation potential loss (Meyfroidt et al., 2022). Besides, increasing crop

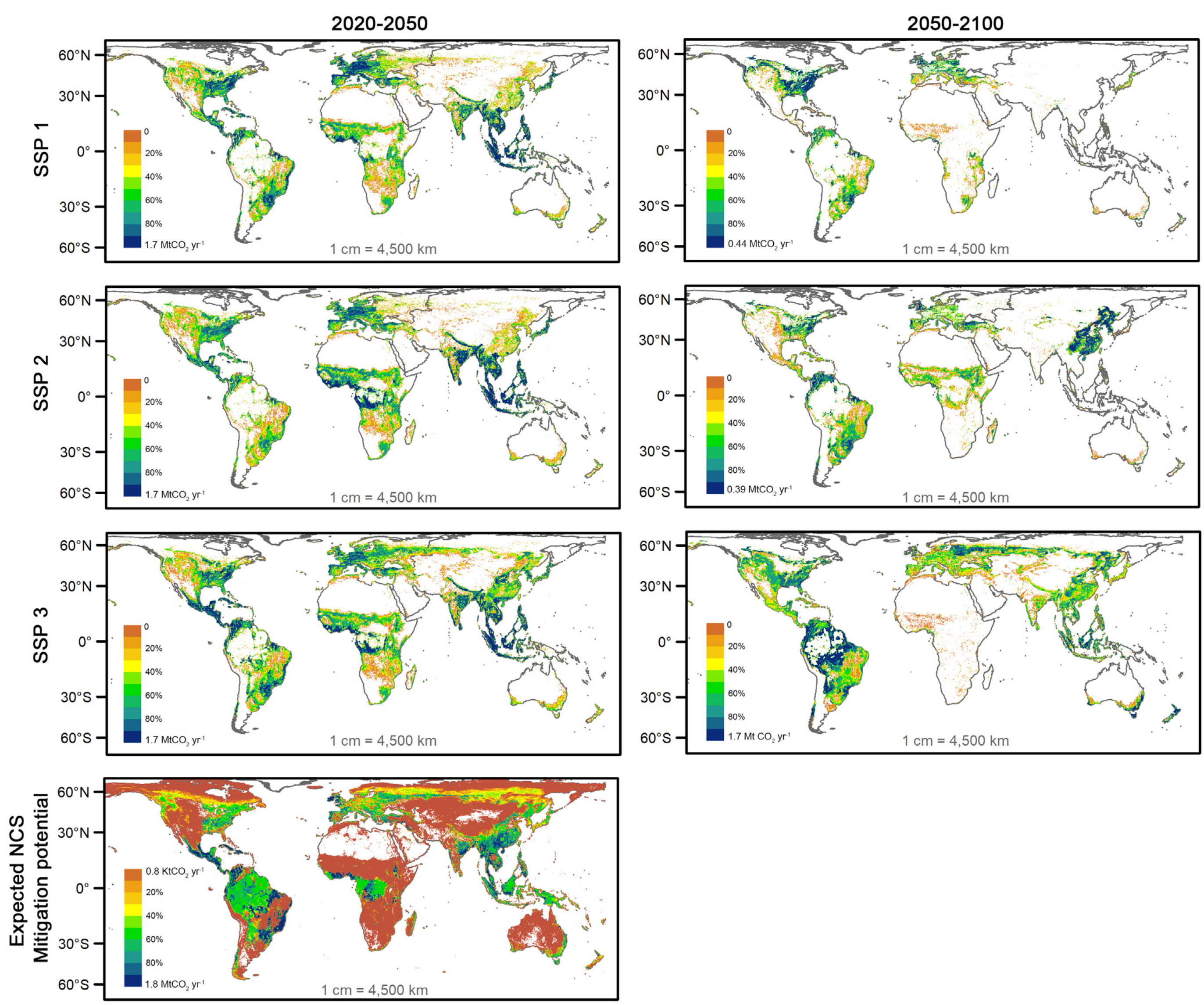

Fig. 4. The expected and lost NCS mitigation potential loss at a 25-km resolution. The percentages present percentage quantiles of NCS mitigation potential loss.

yield would incur tradeoffs between increasing GHG emission due to larger amount of inputs (e.g., fertilization) and reducing GHG emission by lowered agricultural land expansion demand.

Forest-based NCS are mostly threatened among all selected NCS strategies, contributing to 65–73 % of the total mitigation potential loss between 2020 and 2050 (Fig. 3; see the loss of 2050-2100 in Fig. S7). Among forest-based NCS, the mitigation potential loss from avoided forest conversion strategy stands out, totalling 0.4–1.0 $GtCO_2$ yr^{-1}, which is over twice as much of the loss as the second-largest strategy —avoided peatland impact (no double counting among strategies). Other forest-based strategies, including forest restoration, natural forest management and improved planation, together account for 0.2–0.4 $GtCO_2$ yr^{-1} of the loss. The substantial reduction in forest-based NCS is likely because the forest is pervasive in the terrestrial ecosystem and possesses a relatively higher potential for avoiding emission and/or sequestering carbon than other land-use types (Cook-Patton et al., 2020). Furthermore, we note that albeit with a similarly high mitigation potential, avoided forest conversion strategy is much more affected than the forest restoration strategy (0.19–0.37 $GtCO_2$ yr^{-1}). Given a relatively low opportunity cost, protecting existing forest from land-use change should be given prioritized attention (Gibson et al., 2011).

3.2. Spatial pattern of NCS mitigation potential loss

To further identify the hotspot of NCS mitigation potential loss and enable strategic NCS implementation, we mapped the spatial pattern of mitigation potential loss of the collective 9 NCS strategies and compared it with the expected NCS mitigation potential. For a better demonstration, we merged the expected and lost NCS mitigation potential to 25-km grids (Fig. 4). During 2020–2050, we observed a similar and spatially clustered pattern of the NCS loss across SSP scenarios, while a minor different pattern in Central America, mid-Africa and East European region. However, during post-2050 period, the spatial pattern of NCS loss varied prominent between SSP 1&2 and SSP3.

We took a closer insight into the spatial pattern of NCS loss with SSP 2 scenario (2020–2050) as it is most similar to the business-as-usual condition (Williams et al., 2020). Our results reveal that the tropics and subtropics, particularly the regions between 10°S to 30°N, are the hotspot of mitigation potential reduction, such as South and Southeast Asia, Central and West Africa, and Central America (Fig. 5a). Tropical and subtropical areas altogether explain up to 88 % of the total mitigation potential loss (Fig. 5e), whilst most of the regions therein have a noticeably higher loss than the average level (12 $MtCO_2$ yr^{-1}), e.g., Indonesia (408 $MtCO_2$ yr^{-1}), the Democratic Republic of the Congo (173 $MtCO_2$ yr^{-1}), and India (158 $MtCO_2$ yr^{-1}). By 2050, 47 % of countries, including 69 of 128 tropical countries (54 %) and 22 of 34 subtropical countries (65 %), are expected to lose at least 25 % of their original mitigation potential (Fig. 5c-d). Among these, 39 (30 %) and 12 (35 %) countries in the tropics and subtropics, respectively, have an alarmingly high loss ratio (≥75 %). These areas with a high risk of impermanence also correspond to regions with high NCS mitigation potential (Fig. 5e). This suggests that regions holding the most NCS mitigation potential, like tropics and subtropics, are at the same time—most vulnerable, facing intense constraints from the land-use sector.

4. Discussion and conclusions

Despite holding a promising potential for complementing emission reduction, NCS are constrained by the land-use competition between socio-economic interests and climate mitigation needs. By analysing the impact of future land-use competition that has been largely overlooked in previous estimations of NCS mitigation potential, our study highlights three key findings: (i) a substantial amount of NCS mitigation potential (0.3–2.8 $GtCO_2$ yr^{-1} or 4–39 %) is forecast to be lost due to future land-use competition regardless of which SSP is followed. Losing such a sizeable climate mitigation potential from NCS will postpone the year of reaching net-zero emissions and significantly lower the probability of limiting the warming to 2 °C (Rogelj et al., 2018). Approaches ensuring no delay in making efforts to

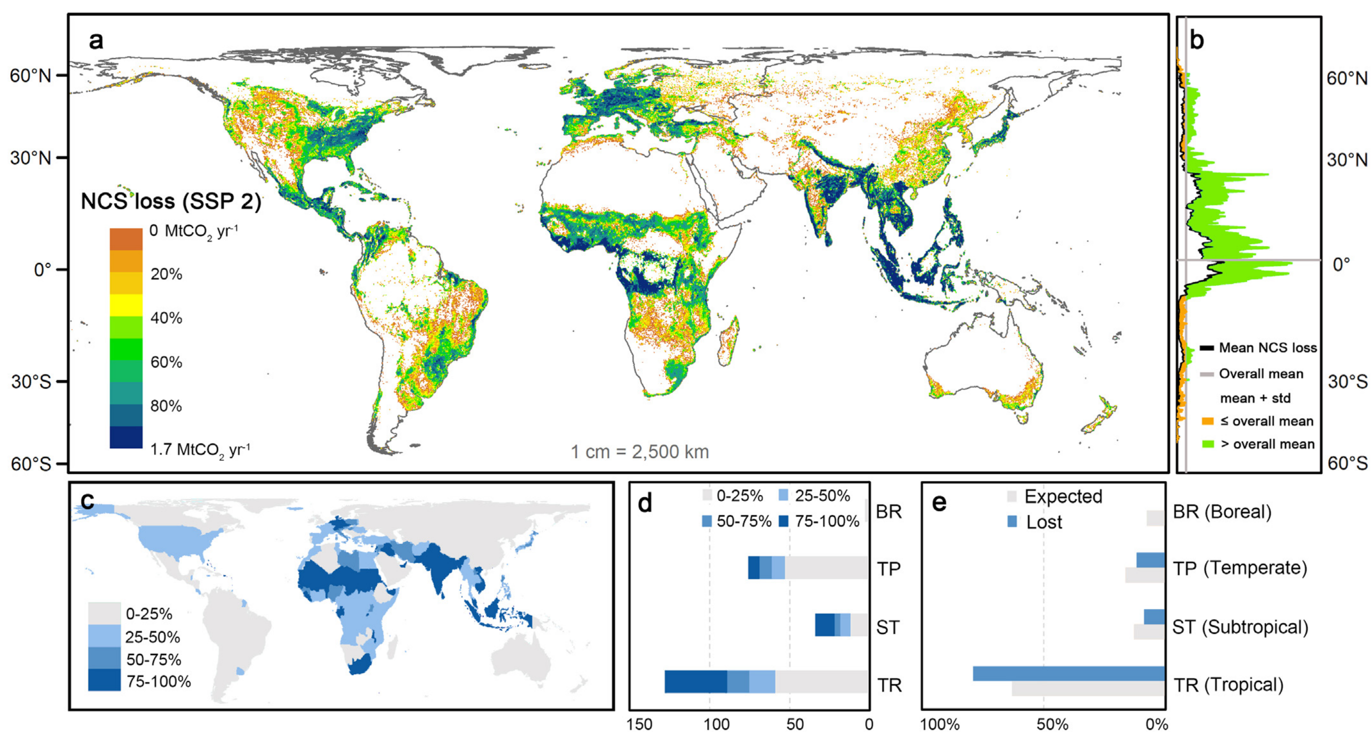

Fig. 5. Mitigation potential loss at a 25-km resolution (SSP 2; 2020-2050) (a). Mean NCS mitigation potential loss aggregated to latitudinal transect (black line) and the corresponding standard deviation below (orange shaded area) and above (green shaded area) the overall mean value (b). Spatial distribution of countries losing 0–25 %, 25–50 %, 50–75 %, and 75–100 % of their original NCS mitigation potential (c) and its numbers across climate zones (d). Percentage of the loss and expected mitigation potential of each climate zone (e).

protect natural areas for NCS should be taken, such as taking immediate actions (Qin et al., 2020), increasing government incentives and subsidies for high-cost NCS strategies (Roe et al., 2019), and encouraging stakeholders' involvement in the voluntary carbon market (Bossio et al., 2020); (ii) developing towards a more sustainable future is significant to NCS. Under a sustainable world (SSP 1), NCS is least affected (0.3–1.0 $GtCO_2\ yr^{-1}$ or 4–14 %) and only requires protective efforts for the next few decades; if the world develops towards an unsustainable future (SSP 3), NCS will face a more radical constraint (2.1–2.8 $GtCO_2\ yr^{-1}$ or 27–39 %) and require long-term endeavours to protect natural ecosystems against land-use changes, notwithstanding related barriers in other sectors; and (iii) 47 % of all countries globally would lose ≥25 % of its NCS mitigation potential, whilst the loss is most prevalent and severe in the tropics (54 % of countries' loss ≥25 % and 30 % of countries' loss ≥75 %). Proactive actions across sectors should be prioritized in these regions to minimize the underlying limitations whilst maximizing NCS's potential.

Unfortunately, highly vulnerable areas are meanwhile subjected to other constraints to implementing NCS rather than land-use competition alone. These constraints can include weak governance and political will, high dependency on fossil fuels, contests in land tenure and claims, and higher political risk to protect NCS's potential (Griscom et al., 2019; Meyfroidt et al., 2022; Nagendra et al., 2018). Furthermore, many countries within these areas have a poor financial capacity to implement NCS, as well as to steward and incentivize climate mitigation actions by themselves (Griscom et al., 2020). There is still a limited portion of climate finance (<5 %) going towards battling climate impact, even though increasing attention being paid (Seddon et al., 2020). Besides, albeit with a few pledges (e.g., SDG Target 13.a & COP26) promising to the developing countries, many of which are also in the tropics, global efforts to follow through with the financial assistance have been lacking. Thus, we advocate that there should be more international agreement and assistance, as well as tangible actions, particularly targeted at tropical areas to help ensure the integrity of NCS mitigation potential.

We note that our estimation on NCS loss is conservative because we only considered two drivers of land-use change, but did not account for other potentially influencing factors, e.g., wildfire and human-induced fire (Berenguer et al., 2021; Radeloff et al., 2018), pasture expansion, drought (Xie et al., 2015). For example, impact of future expansion of pasture and cropland for Bioenergy with Carbon Capture and Storage (BECCS) were not included in our analysis because there is no corresponding spatially-explicit projection maps available under SSP scenario framework (de Oliveira Silva et al., 2016; De Sy et al., 2015). Nevertheless, compared with the demand of 2010, future pasture demand in 2050 is projected to increase by 6 % (204 Mha) and 7 % (231 Mha) under SSP 2 and SSP 3 scenarios, respectively, but to decrease dramatically by 24 % (770 Mha) under SSP 1 scenario (Fig. S9). It indicates that the projected pasture expansion under SSP 2–3 scenarios (medium−/intensive-meat consumption diet) would worsen the land-use competition and cause additional loss of NCS mitigation potential. Under SSP 1 scenario (shifting to low-meat diet), the reduced pasture demand due to dietary change and low population growth would in turn compensate for cropland demand or even create more land available for implementing NCS (e.g., forest restoration). This also suggests that even though it may increase crop demand, global efforts on shifting away from meat-intensive diets are still critical. In addition to future changes in pasture demand and dietary, cropland for Bioenergy with Carbon Capture and Storage (BECCS) might also influence NCS mitigation potential (Heck et al., 2018). Cropland expansion for BECCS would intensify land-use competition against natural areas usable for NCS, e.g., exacerbating deforestation, and thereby lead to additional NCS mitigation potential loss (Melnikova et al., 2021). The climate change mitigation potential of BECCS remains debatable (Shukla et al., 2019; Yang et al., 2020). Growing bioenergy crops for climate change mitigation is less efficient in land-use (i.e., low production per unit of land) than forest restoration (one of the key NCS) and other key land-based climate change mitigation solutions (Meyfroidt et al., 2022; Yang et al., 2018). At last, it should be noted that SSP scenarios only cover several typical futures rather than all of possibilities. Considering the uncertainties and variability of factors embedded in SSP narratives, further scrutiny is necessary to better illustrate how the variation of certain key factors (e.g., future diet change and yield growth) affects land-use change and NCS mitigation potential.

Nevertheless, our study provides a relative and comparative understanding of how socioeconomic development competes with the climate mitigation potential of NCS under various future development scenarios. Albeit with a conservative estimation, we still find that if socioeconomic development continues without substantial improvement in agricultural productivity and shifts towards sustainable development, up to 39 % of the expected NCS climate change mitigation potential will be less capable. In future studies, our results on the land-use constraint to NCS can be incorporated into barriers from other sectors to give a more holistic picture of the attainable NCS mitigation potential. We also call for new avenues of NCS by either expanding areas available for existing NCS or identifying new solutions, which can help to create additional NCS gain and offset the potential risks in NCS loss.

As we are approaching the milestones of global climate-relevant strategies, such as the 2030 Agenda, NDCs of the Paris Agreement and UNFCCC, more effective implementation of these policies is beneficial to avoid the world leaning towards climate tipping points (Lenton et al., 2019). Having more realistic projections of mitigation potential of NCS by considering the constraints by land-use competition helps to inform the decision-makers a better picture about the potential barriers to translating NCS into grounded actions. Our findings provide essential information to further guide international initiatives and climate mitigation strategies, investment opportunities and local decision-makers to better spatially prioritize their efforts to ensure the long-term success and integrity of NCS.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156409.

Data availability

The 1-km land-use projection data and the baseline land-use map are available from http://geosimulation.cn/download/GlobalSimulation/. The 1-km urban extent projection data is available from https://doi.pangaea.de/10.1594/PANGAEA.905890. The land-use demand of SRES and SSP scenarios are available from http://sres.ciesin.org/final_data.html and https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about, respectively. Climate zone map is obtained from Global ecological zones for FAO forest reporting (2010) at http://www.fao.org/docrep/017/ap861e/ap861e00.pdf. Other datasets and parameters could be found in the corresponding references and links presented in the above Supplementary Information. The output data are presented in the article and Supplementary datasets 1–2.

CRediT authorship contribution statement

Q.Z. and L.P.K. conceived the study. Q.Z. designed the research methods and conducted the analysis. Q.Z. wrote the initial draft. All the authors contributed to manuscript writing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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