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To cite this article: Théo Rouhette *et al* 2024 *Environ. Res. Lett.* **19** 114017

IOP Publishing Environ. Res. Lett. 19 (2024) 114017 https://doi.org/10.1088/1748-9326/ad7748

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OPEN ACCESS

RECEIVED
7 May 2024

REVISED
22 August 2024

ACCEPTED FOR PUBLICATION
4 September 2024

PUBLISHED
24 September 2024

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Limits to forests-based mitigation in integrated assessment modelling: global potentials and impacts under constraining factors

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Keywords: afforestation, AFOLU, climate change mitigation, deforestation, IAM, land-based mitigation, Paris Agreement

Supplementary material for this article is available online

Abstract

Forests-based measures such as afforestation/reforestation (A/R) and reducing deforestation (RDF) are considered promising options to mitigate climate change, yet their mitigation potentials are limited by economic and biophysical factors that are largely uncertain. The range of mitigation potential estimates from integrated assessment models raises concerns about the capacity of land systems to provide realistic, cost-effective and permanent land-based mitigation. We use the Global Change Analysis Model to quantify the economic mitigation potential of forests-based measures by simulating a climate policy including a tax on greenhouse gas emissions from agriculture, forestry, and other land uses. In addition, we assess how constraining unused arable land (UAL) availability, forestland expansion rates, and global bioenergy demand may influence the forests-based mitigation potential by simulating scenarios with alternative combinations of constraints. Results show that the average forests-based mitigation potential in 2020–2050 increases from 738 $MtCO_2.yr^{-1}$ through a forestland increase of 86 Mha in the fully constrained scenario to 1394 $MtCO_2.yr^{-1}$ through a forestland increase of 146 Mha when all constraints are relaxed. Regional potentials in terms of A/R and RDF differ strongly between scenarios: unconstrained forest expansion rates mostly increase A/R potentials in northern regions (e.g., +120 $MtCO_2.yr^{-1}$ in North America); while unconstrained UAL conversion and low bioenergy demand mostly increase RDF potentials in tropical regions (e.g., +76 and +68 $MtCO_2.yr^{-1}$ in Southeast Asia, respectively). This study shows that forests-based mitigation is limited by many factors that constrain the rates of land use change across regions. These factors, often overlooked in modelling exercises, should be carefully addressed for understanding the role of forests in global climate mitigation and defining pledges towards the Paris Agreement.

1. Introduction

Achieving ambitious climate targets and limiting global mean temperature increase to below 2 °C requires strong mitigation efforts from all sectors responsible for greenhouse gas (GHG) emissions. According to the Intergovernmental Panel for Climate Change (IPCC) Sixth Assessment Report, the agriculture, forestry, and other land use (AFOLU) sector emitted 11.9 ± 4.4 $MtCO_{2eq}.yr^{-1}$ on average over the period 2010–2019, representing 21% of total global net anthropogenic GHG emissions (Nabuurs *et al* 2022). The sector is also a carbon sink, annually sequestering −12.5 ± 3.2 $GtCO_2$ on average in

2010–2019 (Friedlingstein *et al* 2020). In the context of the Paris Agreement goals, most national determined contributions (NDCs) rely on the potential of the AFOLU sector to meet countries' mitigation pledges (Griscom *et al* 2017), expecting its net removals to compensate GHG emissions from other sectors considered more costly to abate (shipping, aviation, iron and steel, chemicals, cement).

Among land-based mitigation measures, forests-based measures are often considered to offer large emission reduction potentials at low costs (Busch *et al* 2019). However, recent analyses have challenged this assumption, as high upfront costs and variable cash-flows remain obstacles to landholders (Sinacore *et al* 2023). The rising interest in forest conservation and tree planting for climate mitigation has again sparked an intense debate on the scale, effectiveness and pitfalls for forests-based mitigation since the Kyoto negotiations (Nabuurs *et al* 2022). Criticism highlights the potential negative consequences of considering these measures as silver bullets able to solve the climate crisis, pointing out multiple environmental, socio-cultural and institutional barriers (Naudts *et al* 2016, Seddon *et al* 2019, Perkins *et al* 2023). An over-reliance on the AFOLU sector could both reduce the mitigation efforts in other hard-to-abate sectors with more costly mitigation measures (Grant *et al* 2021, Carton *et al* 2023) and lead to negative side-effects (Boysen *et al* 2017).

In view of these challenges, integrated assessment models (IAMs) have proven useful tools to quantify GHG emissions and removals from different strategies, considering future GHG concentration scenarios as well as socioeconomic developments (Popp *et al* 2017). Compared to sectoral models, IAMs are able to capture the economy-wide outcomes and trade-offs of multi-sectoral interactions (Ohrel 2019). However, the IAM framework is also subject to multiple sources of uncertainty. These models remain limited by the highly aggregated representation of biophysical and agronomic characteristics affecting land use systems at the desired spatial and temporal scales (Schmitz *et al* 2014). Land use modules in IAMs are also highly diverse in terms of their spatial resolution, land classification, land allocation methodologies and technological change assumptions, which explain the large uncertainties in land cover projections (table S1) (Prestele *et al* 2016, Alexander *et al* 2017). Additionally, the ways in which IAMs represent the patterns of international trade, bioeconomy developments and future demand for bio-based products also determine land use competition and associated carbon stock dynamics (Humpenöder *et al* 2014, Escobar *et al* 2018).

Synthesizing outcomes from different IAMs to estimate and compare the climate mitigation potentials of 7 land-based measures in 2020–2050, Roe *et al* (2021) found that forests-based measures contribute the largest share of land-based mitigation (44% of the total land potential). The study estimates a weighted median of 475 $MtCO_2.yr^{-1}$ for afforestation/reforestation (A/R) and of 2562 $MtCO_2.yr^{-1}$ for reducing deforestation (RDF). For both measures, the IPCC AR6 reports higher estimates of their global mitigation potential: 1.6 –$GtCO_2.yr^{-1}$ for A/R and 3.4 (2.3–6.4) $GtCO_2.yr^{-1}$ for RDF and forest degradation, both by 2050 and with a carbon price of $100US.$tCO_2{}^{-1}$ (Nabuurs *et al* 2022). Top-down analyses based on satellite-derived estimates were even more optimistic: Mo *et al* (2023) report a total deficit of global forest carbon storage of 226 Gt, of which 39% lies in regions where forests were removed or fragmented.

These wide ranges highlight the implications of modelling assumptions of land dynamics on estimates of forests-based mitigation, which are also affected by the multiple risks and competing demands for land (Dooley *et al* 2018). Specifically, a deeper understanding is required on the rates of land use change (LUC) realistically achievable within the AFOLU sector. Forest expansion can occur on land uses with low economic value, such as unused arable land (UAL), that is deemed broadly 'available' for conversion. However, specific real-world regulations or drivers that are not represented in IAMs may reduce the availability of such unused or abandoned land areas (Gvein *et al* 2023). Additionally, the rate of forest expansion onto agricultural land is one of the key limitations to the mitigation potential of A/R measures, with direct consequences on sustainability trade-offs (Doelman *et al* 2020). Increasing demand for biomass to produce bioenergy can also pose additional pressures on land, causing trade-offs between forests-based and bioenergy measures (Humpenöder *et al* 2018). The Global Change Analysis Model (GCAM) is a well-suited IAM to study these land dynamics since it combines a recursive dynamic approach and a logit-based land allocation with spatially explicit carbon stock data and land productivity information. In this context, the goal of this study is to assess the implications of alternative assumptions affecting forestland expansion on the global carbon mitigation potential of forests in GCAM. The results provide evidence on the speed and viability of long-term forests-based mitigation, with the ultimate objective to support GHG abatement policies and future NDCs.

2. Methodology

2.1. GCAM modelling framework

GCAM v7.0 is a dynamic recursive model representing the complex interactions between five major systems—energy, water, land, climate, and the economy (Calvin *et al* 2019). GCAM has been widely used for studying climate change mitigation from agriculture and land use (Zhao *et al* 2021, Di Vittorio *et al* 2023). The land and water systems are subdivided into 235 water basins and 32 geopolitical regions structure the economic and energy systems, resulting in a total of 384 distinct land-water regions (called land use units, LUTs).

Land conversion is simulated based on a logit model allocating the land use classes according to their relative expected profit in each LUT, considering underlying costs and land productivity (McFadden 1974, Wise *et al* 2014). This land allocation system has a distribution of preference-adjusted profit behind each competing land use. An option with a higher average profit will get a higher share of allocated land than one with a lower average profit (Zhao *et al* 2020). The GCAM economic framework does not endogenously account for albedo effects when allocating forestland.

GCAM aggregates all commodities considered by the Food and Agriculture Organization. The model includes 21 distinct crop types (table S3 in Supplementary Material—SM), 6 livestock sectors and a managed forestry sector. GCAM uses the primary roundwood data from FAOSTAT for forestry representation. Future production is modelled using the Leontief production function with production coefficients connecting roundwood production with managed forest land cover (Zhao *et al* 2024). The model represents price-induced agricultural intensification through fertilization and irrigation options. Bioenergy demand is met through purpose-grown biomass, residues and municipal solid waste (MSW). The model includes technologies with carbon capture and storage as an important driver of energy demand. Agricultural commodities are traded using the Armington style distinction between imported and domestic goods, which assumes that goods produced in different regions are imperfect substitutes (Zhao *et al* 2022).

GCAM calculates CO_2 emissions from LUC based on changes in carbon stocks (vegetation and soil) between initial and final land use (equation (1) in SM). LUC emissions vary over time based on the carbon stocks in each time step, considering spatially heterogenous vegetation maturity age and soil time scales (e.g. number of years for soil carbon changes to occur). The vegetation growth function follows a sigmoidal curve when the land area expands, while vegetation carbon is released immediately when the land area decreases. In both cases, soil carbon changes follow a region-specific exponential function. GCAM mitigation measures for LUC emissions include land protection and valuing land carbon. For agriculture, the abatement of non-CO_2 emissions is not modelled at the process level but through marginal abatement cost (MAC) curves (EPA 2019) which determine the percent of agricultural emissions abated as a function of the emission price.

2.2. Scenario design

GCAM is used to simulate a climate policy over the period 2020–2050. In this study, the reference scenario follows the Shared Socioeconomic Pathway 2 (SSP2) 'middle-of-the-road' scenario (Riahi *et al* 2017). Beyond SSP2, it is assumed that global biomass demand increases from 51 Exajoules (EJ) in the base year to 76.4 EJ per year by 2050, based on an extrapolation of the historic rate.

For the mitigation scenarios, a global GHG tax on AFOLU emissions is implemented with an annual growth rate of 5% to reach $\$100/tCO_{2eq}$ by 2050. The policy fosters forests-based mitigation by creating both the incentive to retain existing carbon stocks (e.g. RDF) and increase terrestrial carbon stocks (e.g. A/R). A global cap on CO_2 emissions from energy and industrial processes (EIP) is added to ensure a relevant mitigation context. EIP CO_2 emissions follow a trajectory in line with the successful achievement of NDCs and long-term targets (LTTs), translating into 9.8 $GtCO_2$ in 2050 (van de Ven *et al* 2023). The combination of these two policies is jointly referred to hereafter as the 'climate policy'.

We define one constraint for each of the major uses of the AFOLU sector (agriculture, forestry and bioenergy) to represent potential limits to forests-based mitigation (table 1). When constraints become binding, they make the land system less responsive to the climate policy and thus limit its implementation. The constraints are defined as follows:

1. **UAL conversion constraint**: to limit the annual rate at which UAL can be converted to other land uses. The maximum conversion is based on the average annual rate between 1990 and 2015, determined per LUTs (5th to 95th percentiles being −5.15% to −0.03%, with a median value of −1.03%). In LUTs with positive historic rates (where UAL increased in time), conversion of UAL is not allowed. The constraint represents less optimistic assumptions compared to an unconstrained case since UAL is covering a range of land categories. It includes fallow land which is often required from the agronomic point of view to ensure soil productivity and should not be seen as simply available arable land. It may also reflect historical drivers that are not endogenously represented by GCAM, which can lead to large conversion of UAL. Hence, this constraint reflects a conservative case in which there are no major changes in historical classifications or drivers. The expansion/conversion of cropland is not subject to any constraint.
2. **Forestland expansion constraint**: to limit the change in forestland areas in each LUTs with a maximum annual afforestation rate. The rate is based on estimates of historic rates of forest expansion in regions with the largest forest gains

Table 1. Scenario design.

Scenario	Climate policy	Constraints		
	Carbon price up to \$100/tCO_{2eq} by 2050 with 5% annual growth rate for land use CO_2 and agriculture CH_4 and N_2O + High mitigation target with 9.8 Gt CO_2 from EIP globally emitted per year by 2050 (NDCs + LTTs)	*Unused arable land conversion*—Maximum rate of unused arable land conversion (determined from historic rates from 1990 to 2015 for the 384 LUTs)	*Forestland expansion*—Maximum rate of A/R (0.38% relative to agricultural land in each of the 384 LUTs)	*Biomass demand*—Biomass consumption of 113.9 EJ in 2050 (+49% compared to historic trend)
Reference scenario	No (54.3 GtCO_2 globally emitted per year by 2050)	No	No	No
Scenario 1. Fully constrained (*CP_SlowFOR + LowARA + HighBIO*)	Yes	Yes	Yes	Yes
Scenario 2. Constrained without unused arable land conversion constraint (*CP_SlowFOR + HighBIO*)	Yes	No	Yes	Yes
Scenario 3. Constrained without forestland expansion constraint (*CP_LowARA + HighBIO*)	Yes	Yes	No	Yes
Scenario 4. Constrained without biomass demand constraint (*CP_SlowFOR + LowARA*)	Yes	Yes	Yes	No
Scenario 5. Unconstrained (*CP_NoConstraint*)	Yes	No	No	No

between 1992 and 2021, based on FAOSTAT data (China, USA, Russia, India and EU-15). The weighted average rate across the regions is +0.38% relative to total agricultural area (arable land as well as pasture and meadows). Applied to each LUTs, the median maximum rate is 18.8 kha.yr^{-1} (5th and 95th percentiles being 0.07 and 222.3 kha.yr^{-1}, respectively) (section 1.3 in SM). This rate represents projections of forestland expansion within historically observed limits, preventing unrealistically fast conversion of agricultural land even under high CO_2 prices. The constraint acts as an alternative to a better representation of land conversion costs and feasibility challenges (Perkins *et al* 2023).

3. **Biomass demand constraint**: to increase the global consumption of biomass for energy purposes to 64.7 EJ in 2030 and 113.9 EJ in 2050. This is in line with what IAMs estimate to be the average bioenergy demand of scenarios compatible with achieving the Paris targets of 1.5 °C–2 °C in the IPCC AR6, in contrast with the bioenergy demand of 76.4 EJ in 2050 for scenarios without the constraint. It does not specify the proportions of the primary biomass sources, which include purpose-grown bioenergy crops, residues, and MSW, nor which end-use sectors should increase their demand in order to absorb the supply of biomass for bioenergy.

These three constraints are combined into a set of five alternative mitigation scenarios:

1. *CP_SlowFOR + LowARA + HighBIO* or ‘Fully Constrained’: implements the three constraints simultaneously;
2. *CP_SlowFOR + HighBIO*: a scenario combining the forestland expansion and biomass demand constraints;
3. *CP_LowARA + HighBIO*: a scenario combining the UAL conversion and biomass demand constraints;
4. *CP_SlowFOR + LowARA*: a scenario combining the forestland expansion and UAL conversion constraints;
5. *CP_NoConstraint* or ‘Unconstrained’: applies the climate policy alone, without constraints.

The fully constrained scenario is considered the least optimistic and most representative of the limits to the mitigation potential of the climate policy. By comparing results with the unconstrained case, the scenario design aims to quantify the risks of overestimating the potential when constraints are not considered. The three scenarios between the fully constrained and the unconstrained scenario illustrate intermediate cases. Section 1.3 of SM provides further details on the scenario design.

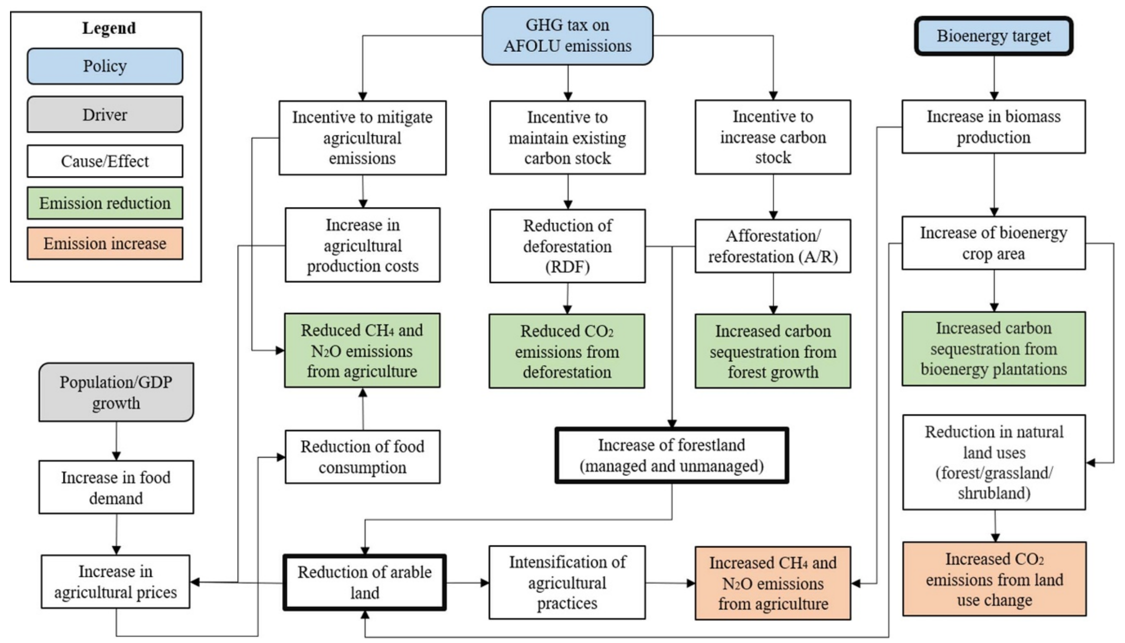

Figure 1. Representation of the climate policy, the mitigation measures and their potential effects across forestry, agricultural and bioenergy systems of the AFOLU sector and associated GHG emissions. Bold boxes represent constrained policies and causes/effects.

2.3. Indicators on LUC, mitigation potential and agricultural impacts

GCAM outcomes are used to quantify changes in land allocation, CO_2 emissions from LUC, agricultural non-CO_2 emissions, net trade balances, and agricultural intensification. Figure 1 summarizes the causal responses triggered by the climate policy. Outcomes in terms of area changes across land uses compared to the reference by 2050 are used to calculate the mitigation potential of forests for each LUT. GCAM estimates land allocation in 5 year time steps for 43 land uses per LUT. Here, land uses are aggregated into the following categories: forestland, cropland, UAL, pasture, grassland and shrubland, biomass, and others. Forestland includes managed and unmanaged (protected and unprotected) forests. Four possible outcomes are distinguished, i.e. A/R if net forestland areas increase in the scenario more than in the reference; avoided A/R (AAR) if net forestland areas increase less; RDF if forestland areas decrease less than in the reference; and deforestation (DEF) if forestland areas decrease more (see equations (2) and (3) and figure S7 in SM).

The four possible transitions result in CO_2 emissions through carbon stock changes in soils and vegetation (above- and below-ground biomass). CO_2 emissions arising from forestland areas are referred to as *first-order* emissions (equation (4) in SM); while CO_2 emissions from other land uses are referred to as *second-order* emissions. The latter capture emissions from land uses in competition with forests, either replaced uses where A/R takes place or uses that would have replaced forests after deforestation in the case of RDF (equations (10)–(12) in SM). In LUTs where two transitions occur simultaneously (e.g. A/R and RDF), the emissions are allocated to each based on their respective areas in the LUT and their global mitigation intensities (equations (5)–(9) in SM). Net A/R is calculated as the potential of A/R minus the emissions of AAR, and net RDF as the potential of RDF minus the emissions of DEF (equations (13)–(17) in SM). Final estimates of the mitigation potentials of forests-based measures account for both first-order and second-order emissions while fluxes beyond 2050 are not included in the results (see SM for further information). The mitigation intensity of the measures is calculated as the cumulative mitigation potential between 2020 and 2050 divided by the total land area, following Roe *et al* (2021). Mitigation from bioenergy use in substitution for fossil fuel across sectors is not considered. Regional consumption and trade balances for agriculture, forestry and bioenergy products are estimated as the amount of consumed and traded areas per commodity. Section 1.4 of SM provides further details on the additional indicators estimated for agricultural systems (non-CO_2 emissions, agricultural prices and agricultural intensification).

3. Results

3.1. Land allocation and LUCs

In the reference scenario, global food demand increases by 2739 $\mathrm{Pcal.yr^{-1}}$, driving an increase of 174 Mha of cropland between 2020 and 2050. Bioenergy demand leads to an increase of dedicated

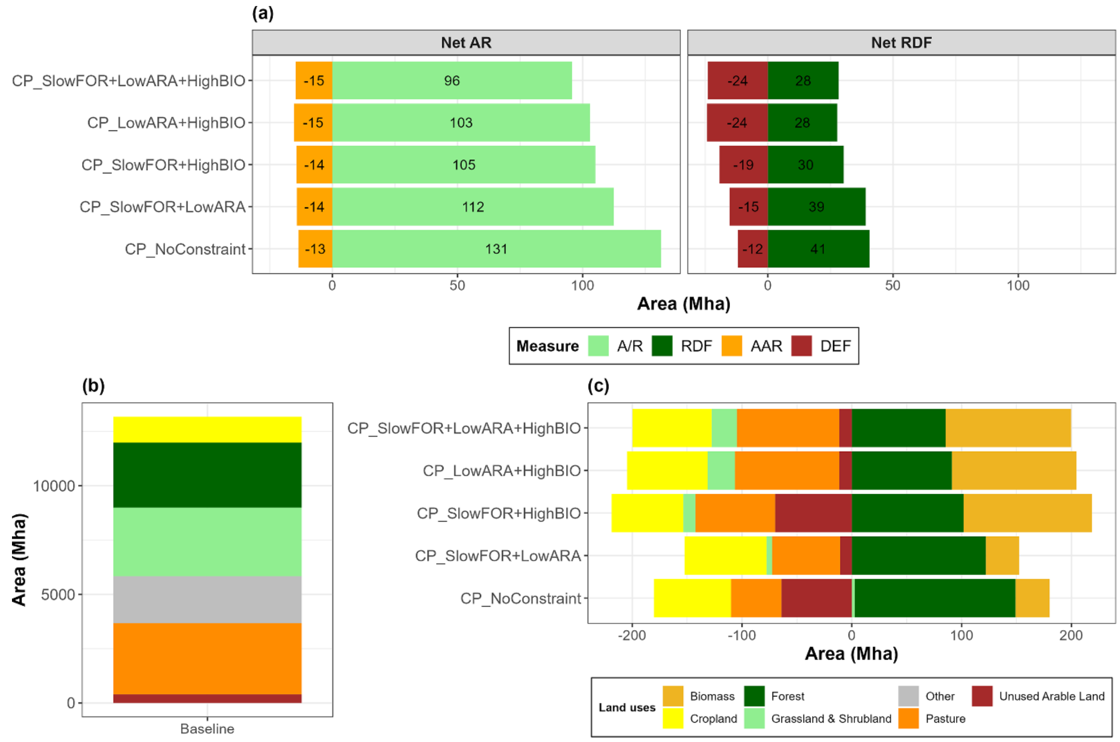

Figure 2. (a) Area change of forests-based measures per mitigation scenarios relative to reference by 2050. (b) Land allocation at baseline year. (c) Area change of land uses per mitigation scenarios relative to reference by 2050. Values are reported in million hectares (Mha).

biomass crop area of 128 Mha by 2050. Forestland areas decrease by 11 Mha, UAL by 75 Mha, pasture by 24 Mha, and grassland and shrubland by 192 Mha between 2020 and 2050 (figure S8).

The climate policy affects land allocation by increasing the profitability of the land uses with relatively large carbon stocks at the expense of other uses (figure S9). In the fully constrained scenario (*CP_SlowFOR + LowARA + HighBIO*), forestland increases globally by 86 Mha compared to reference (81 Mha and 4 Mha from net A/R and net RDF, respectively) (figure 2(a)). Europe has the highest net A/R (34 Mha) while the lowest net RDF is observed in Rest_Asia (Indonesia and Southeast Asia) (−9 Mha) (figure S12). Globally, biomass plantations expand by 114 Mha while UAL is reduced by 11 Mha (figures 2(b) and (c).

The intermediate scenarios illustrate the impacts of each constraint relative to the fully constrained case. In *CP_LowARA + HighBIO*, forestland increases globally by 91 Mha compared to the reference by 2050. Without the forestland expansion constraint, net A/R reaches 88 Mha (+7 Mha compared to fully constrained), with the largest regional increase relative to fully constrained occurring in North America (NAM) (+6 Mha). In *CP_SlowFOR + HighBIO*, removing the constraint on UAL conversion increases the global reduction of UAL, from 11 to 70 Mha. As a result, forestland increases globally by 102 Mha compared to the reference. Net RDF reaches 11 Mha (+7 Mha compared to fully constrained) driven by reductions of DEF in Latin America (LAM, including South, Central America and the Caribbean) and Rest_Asia. In *CP_SlowFOR + LowARA*, forestland increases globally by 122 Mha compared to the reference. Without the biomass demand constraint, net RDF reaches 24 Mha (+20 Mha compared to the fully constrained scenario). Globally, the increase in dedicated biomass crop area drops from 128 to 30 Mha compared to the reference.

In the unconstrained scenario (*CP_NoConstraint*), forestland increases by 146 Mha relative to the reference (+70% more than in the fully constrained). Net A/R and net RDF account for 118 Mha and 29 Mha, respectively. Large areas for net A/R are observed in northern latitudes (up to 42 Mha in Europe). Net RDF in tropical regions (LAM and Rest_Asia) remains limited by high DEF in some regions, such as Kalimantan in Indonesia. Globally, biomass plantations increase by 31 Mha and UAL is reduced by 64 Mha.

3.2. Trade flows and agricultural intensification

The constraints also affect the impact of the climate policy on regional consumption and trade balances of forest, bioenergy and agricultural products, which mediate the regional patterns of LUC and associated GHG emissions. Expansions of forestland and biomass cropland reduce exports of agricultural commodities in several regions, as the climate

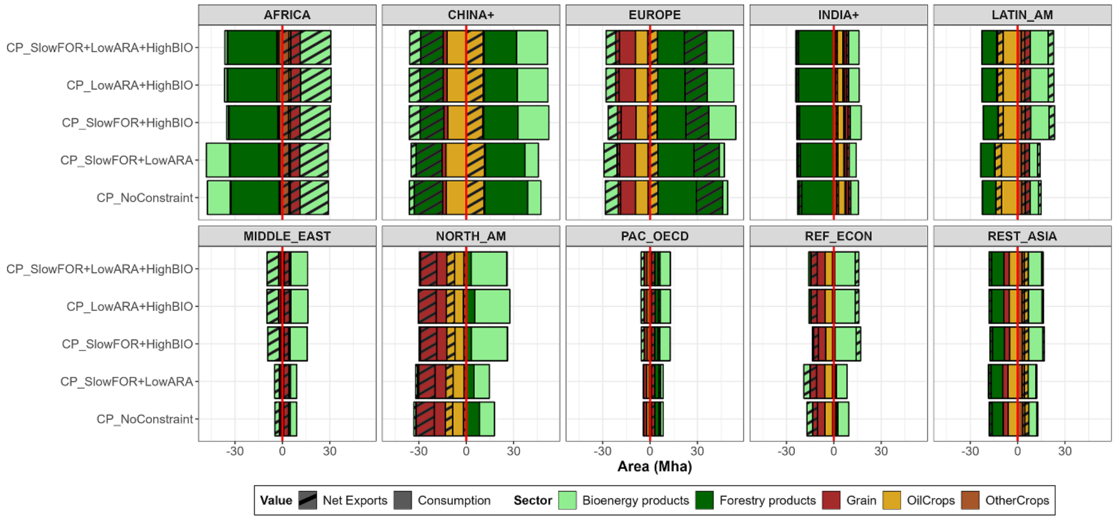

Figure 3. Area dedicated to net exports/imports and regional consumption for the main agricultural commodities: bioenergy products, forestry products, grain, oil crops and other crops. All values are relative to the reference scenario by 2050 and reported in Mha. The hatched bars represent the values of net exports/imports: positive values indicate increased exports and/or reduced dependence on imports relative to reference. The plain bars represent the regional consumption: positive values indicate a higher consumption relative to the reference. Production in physical units (EJ, billion m^3 and Mt) were converted into Mha using regional yields and conversion efficiencies for each commodity (equations (22) and (23) in SM).

policy optimizes the use of carbon-rich soil through trade adjustments. In the fully constrained scenario, regions with the largest changes in areas of forests-based measures reduce their exports or increase their imports of agricultural commodities, as production is displaced to other regions. For instance, area dedicated to exports of oil crops from LAM are reduced by −3.5 Mha and imports decrease by 10.7 Mha in China; while area dedicated to exports of grains from NAM are reduced by −10.3 Mha and imports decrease by 6.1 Mha in Africa (figure 3). Across scenarios, the highest increase in forest products consumption is observed in China and Europe, since forest plantations become more profitable due to higher land protection levels and smaller areas of unmanaged native forests compared to other regions. In both regions, the increase is linked to reduced regional consumption of oil crops and grains.

The constraints also have direct implications for agricultural intensification. While the average crop yield increases by 34% in the reference scenario, it increases by 29% in the unconstrained one as cropland is displaced to less productive regions (figure S24(a)). Yields are higher under constraints, with a maximum increase of 31% in the fully constrained scenario. Across scenarios, agricultural intensification is mostly driven by increased irrigation intensity, which increases up to 8% and 9% in the unconstrained and fully constrained scenario, respectively, in contrast to 5% in the reference (figure S24 (b)).

3.3. GHG mitigation potentials

In the reference scenario, global forest emissions are 457 $MtCO_2.yr^{-1}$ in 2030 and 324 $MtCO_2.yr^{-1}$ in 2050 (figure S14). In the fully constrained scenario (*CP_SlowFOR + LowARA + HighBIO*), the average total mitigation potential between 2020 and 2050 is 738 $MtCO_2.yr^{-1}$, with potentials of 537 $MtCO_2.yr^{-1}$ and 201 $MtCO_2.yr^{-1}$ for net A/R and net RDF, respectively (figures 4(a) and (b). The highest regional mitigation potentials for net A/R are achieved in NAM (198 $MtCO_2.yr^{-1}$). Net RDF is the highest in LAM (95 $MtCO_2.yr^{-1}$) but net RDF emits 69 $MtCO_2.yr^{-1}$ in Rest_Asia (figure 4(c)). Hence, the climate policy has a limited mitigation potential when combined with the three constraints.

Removing the forestland expansion constraint (*CP_LowARA + HighBIO*) leads to a total mitigation potential of 912 $MtCO_2.yr^{-1}$ (+24% compared to the fully constrained scenario). Without restrictions of the rate of forest expansion, the global potential of net A/R reaches 702 $MtCO_2.yr^{-1}$ (+31% compared to the fully constrained scenario). The effect is stronger in northern latitudes with readily available land areas, posing limited competition with agriculture. The net A/R potential increases by 61% in NAM and by 33% in Ref_Econ (Russia, Pakistan, and Central Asia). Relaxing the constraint can thus significantly increase A/R potentials in northern regions.

Removing the UAL conversion constraint (*CP_SlowFOR + HighBIO*) leads to a total mitigation potential of 932 $MtCO_2.yr^{-1}$ (+26% compared to fully constrained scenario). Net A/R and net RDF account for 590 and 342 $MtCO_2.yr^{-1}$, respectively. Globally, this scenario increases the net RDF by 70% compared to the fully constrained one. The sharpest impact is observed in Rest_Asia, where the scenario increases the regional potential of net RDF by 76 $MtCO_2.yr^{-1}$, but this pattern is also observed in LAM. Without the constraint, UAL is preferred to

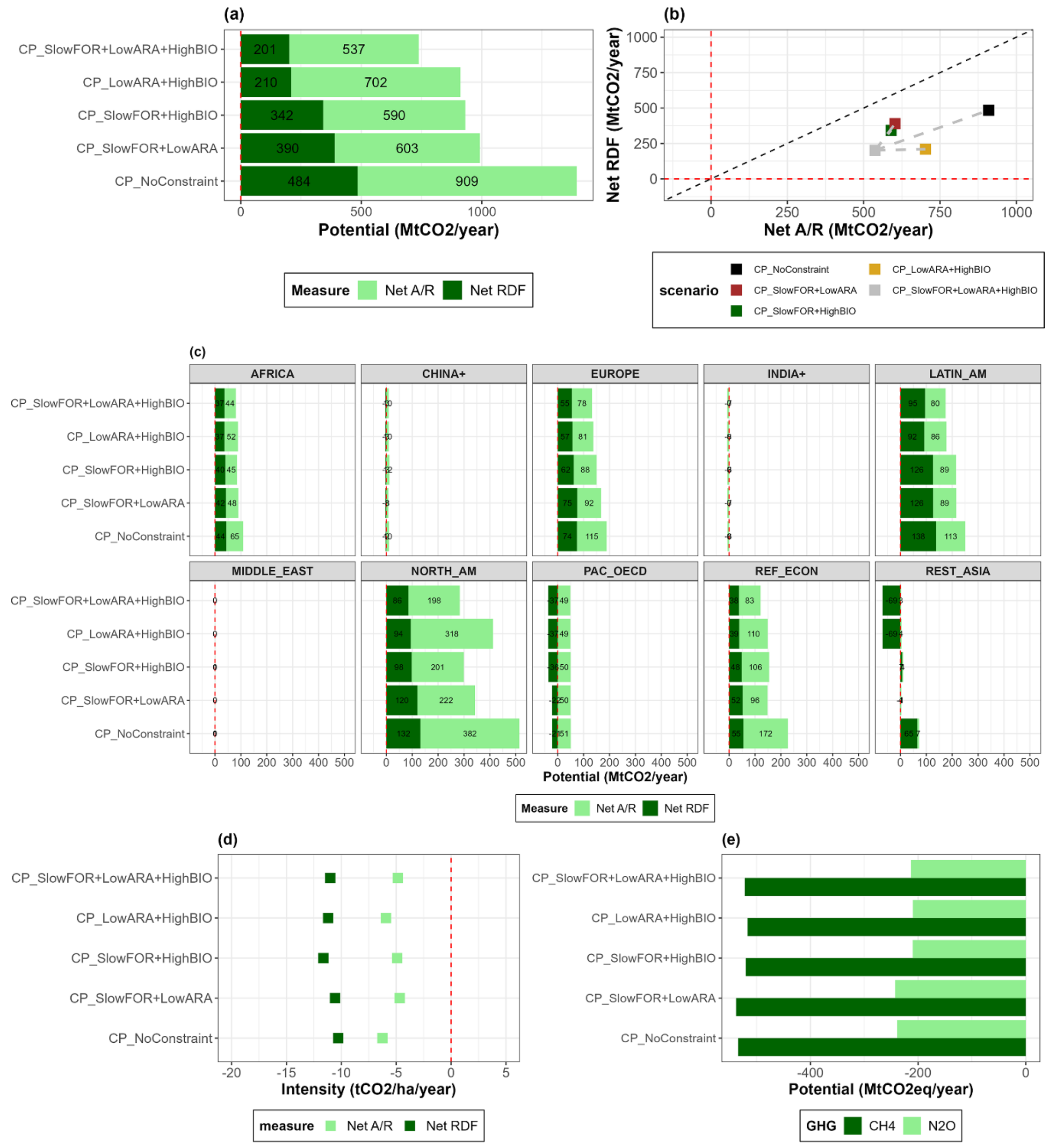

Figure 4. Mitigation potentials for forests-based measures (CO_2) and agricultural activities (CH_4 and N_2O). (a) Global mitigation potentials of net afforestation/reforestation (Net A/R) defined as A/R minus avoided A/R (AAR) and net reducing deforestation (Net RDF) defined as RDF minus deforestation (DEF) per measures and mitigation scenarios. (b) Scatterplot of global mitigation potentials of net A/R and net RDF. The black dotted line is the 45 degrees line and the grey dotted lines are the vectors from each mitigation scenarios to the fully constrained scenario. (c) Regional results, in $MtCO_2.yr^{-1}$. Negative values for net AR indicate that AAR is higher than AR, the same applying to net RDF with DEF and RDF. Regional scatterplots are shown in figure S17. (d) Mitigation intensities per forests-based measures, aggregated into net A/R and net RDF, in tCO_2.ha-1.yr^{-1}. Disaggregated intensities (A/R, RDF, AA/R and DEF) are shown in figures S18 and S19. (e) Mitigation potential of CH_4 and N_2O emissions from agricultural activities per scenario ($MtCO_{2eq}.yr^{-1}$).

forestland for biomass expansion, which ultimately reduces DEF rates.

Removing the biomass demand constraint (*CP_SlowFOR + LowARA*) leads to a total mitigation potential of 992 $MtCO_2.yr^{-1}$ (+34% compared to the fully constrained scenario), as less bioenergy is consumed globally. The global potentials of net A/R and net RDF reach 603 and 390 $MtCO_2.yr^{-1}$, respectively. As in *CP_LowFOR + HighBIO*, the sharpest increase of the net RDF potential is mainly driven by Rest_Asia due to the reduced production of bioenergy in carbon-rich basins. The same pattern is observed in other regions with rapid biomass expansions, such as Ref_Econ and NAM. Lower biomass demand reduces the incentive to deforest, which results in higher net RDF potentials when the constraint is removed.

In the unconstrained scenario (*CP_NoConstraint*), the total mitigation potential is 1394 $MtCO_2.yr^{-1}$ (+89% compared to the fully constrained scenario), with net A/R and net RDF contributing with 909 and 484 $MtCO_2.yr^{-1}$, respectively. The mitigation potential of net A/R increases by 69% relative to the fully constrained scenario, driven by gains in northern regions (NAM and Ref_Econ). LAM and

NAM show the greatest mitigation potentials from net RDF, i.e. 138 and 132 $MtCO_2.yr^{-1}$, respectively. Without constraints, net RDF increases from −69 to 65 $MtCO_2.yr^{-1}$ in Rest_Asia. Hence, the climate policy has a significantly stronger impact when combined with high availability of UAL, unlimited forestation speed, and low global bioenergy demand.

Across all the scenarios, 32% of mitigation potentials occur in boreal regions (section 2.2 in SM). Scenarios without the forest expansion constraint show higher proportions (up to 39% for *CP_LowARA + HighBIO*). Results for changes of carbon stocks in forest vegetation demonstrate similar dynamics to mitigation potentials, ranging from +3.7 GtC in the fully constrained scenario to +7.6 GtC in the unconstrained scenario, compared to the reference by 2050 (figure S22).

Disaggregating first-order and second-order effects illustrate the extent to which the forests-based mitigation potentials are partially offset by emissions from non-forests LUC following conversion. In the unconstrained scenario, the first-order potential of net A/R is 2018 $MtCO_2.yr^{-1}$ while the second-order emission is −1109 $MtCO_2.yr^{-1}$, leading to the final potential of 909 $MtCO_2.yr^{-1}$ (−55%). For net RDF, the second-order effect reduces the first-order potential from 734 $MtCO_2.yr^{-1}$ to 484 $MtCO_2.yr^{-1}$ (−34%) (figure S16). Across scenarios, accounting for the second-order emissions reduces the first-order potentials of A/R and RDF by 61% and 45%, respectively. New forest plantations can be established on land uses with high carbon content like pasture or mature grasslands, which explain the higher offset values of A/R compared to RDF.

RDF shows the strongest mitigation intensity with an average of −13.6 $tCO_2.ha^{-1}.yr^{-1}$, while the average of A/R is −6 $tCO_2.ha^{-1}.yr^{-1}$ (figure S18). Factoring in AAR and DEF, net RDF and net A/R show average intensities of −10.9 and −5.3 $tCO_2.ha^{-1}.yr^{-1}$ across scenarios, respectively (figure 4(d)). Removing the forestland expansion constraint increases the net A/R mitigation intensity by 1.1 $tCO_2.ha^{-1}.yr^{-1}$ in *CP_LowARA + HighBIO* compared to the fully constrained scenario, as carbon removal is maximized through relatively more forestland expansion on carbon-rich basins.

The climate policy also applied a GHG tax on CH_4 and N_2O emitted from agriculture, resulting in additional GHG mitigation abatement. On average, the mitigation scenarios mitigate 526 $MtCO_{2eq}.yr^{-1}$ of CH_4 and 223 $MtCO_{2eq}.yr^{-1}$ of N_2O (figure 4(e)). Scenarios with the biomass demand constraint provide lower mitigation of N_2O and CH_4, as increased area dedicated to purpose-grown biomass production increases agricultural emissions. In the fully constrained scenario, biomass production increases N_2O emissions by 17 $MtCO_{2eq}.yr^{-1}$ compared to the reference through increased N fertilisation, which partially compensates the emission reductions in the other sectors. CH_4 mitigation is reduced in the most emitting sectors (beef, dairy and rice) under the biomass demand constraint: removing it (*CP_SlowFOR + LowARA*) increases the CH_4 mitigation potential by 30 $MtCO_{2eq}.yr^{-1}$ compared to the fully constrained case.

4. Discussion

4.1. Implications and limitations

Our results suggest that the speed and viability of forests-based mitigation are highly sensitive to constraints on forestland expansion rates, UAL availability, and biomass demand. With a constant climate policy, mitigation potentials vary from 738 $MtCO_2.yr^{-1}$ when all constraints are implemented to 1394 $MtCO_2.yr^{-1}$ in an unconstrained scenario. Constraining the rate of forestland expansion prevents fast conversion and an optimal allocation of forestland driven by the economic incentive of the climate policy. Up to 24% of the A/R potential is conditional on expansion rates onto agricultural land superior to rates observed in the past three decades. While policies fostering A/R beyond these historic rates would significantly increase their mitigation potentials, the past forest expansions were mostly driven by China's unprecedented financial investment in long-running forestation programs (Zhang *et al* 2022). Achieving these rates in other regions would thus face significant political, economic and social challenges undermining the feasibility of such large-scale deployment (Turner *et al* 2018, Perkins *et al* 2023). Additionally, the removal benefits occurring in boreal regions (32% of total mitigation potentials across scenarios) could be partially offset by albedo effects (Weber *et al* 2024). However, recent research has demonstrated that forestation could also produce large albedo-induced warming effects in dryland regions (Rohatyn *et al* 2022), suggesting that climate-smart forestry accounting for these effects should be promoted in regions beyond the boreal biome. Then, limiting the rate of UAL conversion to historic rates intensifies DEF. Reaching the full potential of forests-based measures while achieving ambitious bioenergy targets would require conversion of UAL beyond historic rates, with potential agronomic and ecological consequences (Ingalls and Dwyer 2016, Gvein *et al* 2023, Vongkhamho and Ingalls 2023). Our findings highlight the need to improve the representation of drivers and practices that determine the availability of UAL in IAMs in order to better assess their potential impacts on land-based mitigation.

High global demand for biomass adds pressure on the land system, reducing the effectiveness of the land carbon tax to reduce DEF, while also limiting the non-CO_2 mitigation potential of agricultural activities. Thus, while our results do not estimate the additional CO_2 mitigation in the energy sector, they confirm that its decarbonisation through bioenergy poses multiple trade-offs (Humpenöder *et al* 2018) and risks to disproportionally affect the forests of key tropical regions, even under a high land carbon price. Last, forests-based measures displace cropland to less productive regions and global yields decrease despite higher irrigation intensity, which leads to increasing agricultural prices (section 2.3 in SM). Because yield improvements through sustainable intensification (Rockström *et al* 2017) are key to secure adequate food supply within the planetary boundaries (Henry *et al* 2018), the findings confirm the potential trade-offs between forests-based mitigation and the productivity and sustainability of food systems (Fujimori *et al* 2022).

This study has some limitations. First, it has not differentiated managed and unmanaged forests, the carbon dynamics of which differ significantly (e.g. GCAM assumes that the vegetation density of managed forest is 50% of unmanaged forests). Unmanaged forests could also expand through assisted natural regeneration, which would face different drivers and constraints compared to conventional forestation methods (Shono *et al* 2007). While GCAM includes more land use types than most IAMs (table S1), its forestry sector remains highly aggregated and does not include forest management options. Model improvement should include these sectoral practices as mitigation options (Austin *et al* 2020) since they are first-order responses by landowners to a carbon tax (Lintunen *et al* 2016, Baker *et al* 2019). Other relevant constraints have not been considered either, which include socio-cultural, macro-economic, financial and governance constraints (Nolan *et al* 2021). Their integration in land-use modelling is however required to quantify feasible potentials, defined by the IPCC AR6 as the economic potential 'constrained by environmental, socio-cultural, and/or institutional barriers' (Perkins *et al* 2023). In addition, while GCAM v7.0 does not currently capture future climate change impacts on the AFOLU sector, these will have major implications for the permanence of carbon sequestration even in a well-below 2 °C context (Anderegg *et al* 2020). Last, demand-side interventions, socio-economic assumptions and international trade policies are key drivers of LUC that were not captured in the study. These drivers could be integrated in future work by looking at land use impacts of post-growth scenarios within the IAM framework (Hickel *et al* 2021, Bodirsky *et al* 2022).

4.2. Results set into context

Previous studies that quantified forests-based mitigation potentials have implemented a wide variety of constraints: for instance, Griscom *et al* (2017) established maximum mitigation potential with safeguards which did not allow for reductions of existing cropland area and afforestation where forests were not the native cover type; while Busch *et al* (2019) reported estimates spatially restricted to the tropical regions.

Our results are within the range of previous studies for A/R but lower for RDF. Roe *et al* (2021) and Austin *et al* (2020) obtained higher potential for both measures in tropical regions while we find larger mitigation potentials in temperate and boreal regions for A/R and highlight the risk of DEF that bioenergy demand poses in tropical regions. The differences in forest-based mitigation potentials reflect large variations of forestation rates, both for A/R and RDF (table 2). The lower estimates of our study can be explained by the low DEF in the SSP2 reference scenario of GCAM, a lower carbon price by 2050 compared to other studies and the IAM framework itself. IAMs could indeed produce lower estimates than forest sector models like the Global Timber Model or economic approaches like MAC curves since they capture dynamic competition between AFOLU sectors (Ohrel 2019).

The mitigation intensity values of this study (10.9 and 5.3 $tCO_2.ha^{-1}.yr^{-1}$ for net RDF and net A/R, respectively) are similar to the estimates of Roe *et al* (2021) for RDF (10.5 $tCO_2.ha^{-1}.yr^{-1}$), for A/R (5.5 $tCO_2.ha^{-1}.yr^{-1}$) and of median values for LULUCF in AR6 pathways (5.7 $tCO_2.ha^{-1}.yr^{-1}$) (Zhao *et al* 2024). Net RDF sequesters between 1.9 and 2.1 times more carbon than net A/R, which is in line with previous studies (Weber *et al* 2024). RDF could also be more effective than A/R over the long-run, since the marginal mitigation intensity of A/R is generally assumed to decline as forests mature (Zhao *et al* 2024).

Still, the role of the reference scenario assumptions (Nabuurs *et al* 2022), along with large uncertainties in historical data and structural differences in the land modules, explain why land outputs of scenarios driven by the same SSP often differ between IAMs (Popp *et al* 2017, Krause *et al* 2018) and forest sector models (Daigneault *et al* 2022). Future work should harmonize and improve the granularity of key assumptions, while integrating other types of constraints, in order to identify robust and cost-effective portfolios of mitigation policies and associated regional distributions (Diniz Oliveira *et al* 2021).

5. Conclusion

This study demonstrates the importance of improving the representation of the mechanisms shaping global LUC in order to provide realistic estimates of the forests contribution towards achieving net-zero emissions by 2050. The development of future NDCs would benefit from broader assessments of factors constraining land conversion and expansion rates, since they significantly impact the speed and viability of forest-based mitigation. Specifically, climate policies should ensure that the use of purpose-grown

Table 2. LUC and mitigation potentials from recent sectoral studies and from two scenarios of the present study.

Study	Forests-based measures	Model & Scenario information	Carbon price ($\$/tCO_2$)	Study period	LUC (Mha)	Annual LUC ($Mha.yr^{-1}$)	Mitigation potential ($MtCO_2.yr^{-1}$)
Griscom *et al* (2017)	Forestation	Maximum potential	NA	By 2030	678	NA	10 100
	Forestation	<2 °C 'Cost-effective'	$100 in 2030	By 2030	NA	NA	3000
	Avoided forest conversion	Maximum potential	NA	By 2030	NA	9.00	3600
	Avoided forest conversion	<2 °C 'Cost-effective'	$100 in 2030	By 2030	NA	NA	2900
Busch *et al* (2019)	A/R	MACC restricted to tropics	$20	2020–2050	32	1.07	190
	A/R	MACC restricted to tropics	$50	2020–2050	84	2.80	503
	RDF	MACC restricted to tropics	$20	2020–2050	71	2.37	1837
	RDF	MACC restricted to tropics	$50	2020–2050	150	5.00	3610
Austin *et al* (2020)	A/R + RDF	$100@1% (GTM)	$150 in 2055	2015–2055	599	14.98	4000
	A/R + RDF	$100@3% (GTM)	$326 in 2055	2015–2055	777	19.43	4300
Zhao *et al* (2024)	LULUCF	2 C Main & 50%-LCP (GCAM v6.0)	$75 in 2050	2020–2050	91	3.03	800
	LULUCF	2 C Main & 100%-LCP (GCAM v6.0)	$145 in 2050	2020–2050	177	5.90	2600
This study	Net A/R	Fully Constrained (GCAM v7.0)	$100 in 2050	2020–2050	81	2.70	537
	Net A/R	Unconstrained (GCAM v7.0)	$100 in 2050	2020–2050	118	3.93	909
	Net RDF	Fully Constrained (GCAM v7.0)	$100 in 2050	2020–2050	4	0.13	201
	Net RDF	Unconstrained (GCAM v7.0)	$100 in 2050	2020–2050	29	0.97	484

bioenergy production does not counteract efforts to reduce forest loss. Promising avenues to avoid these trade-offs include reducing global energy consumption and the share of bioenergy in the energy mix, increasing the output of bioenergy from residues, along with voluntary environmental actions and regulatory frameworks reducing the induced LUC emissions of bioenergy. Policy-makers should also consider both the territorial and international emissions associated with national policies in order to minimize the risks of displaced deforestation. Furthermore, this study confirms the potentially negative effects of the climate policy on food security. Other trade-offs with biodiversity conservation and water security should also be carefully considered when implementing forests-based mitigation measures. Therefore, while the global forests bear the potential to help mitigate climate change and contribute to countries' Paris Agreement pledges, additional policies may be required to overcome constraining factors affecting land conversion and expansion rates in the AFOLU sector and to avoid that forests-based mitigation translates into negative sustainability outcomes.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

We thank two anonymous reviewers for their constructive comments. The authors acknowledge the funding from EU's Horizon 2020 project 'NDC ASPECTS' (GA #101003866) and from Horizon Europe Project 'CLEVER' (GA. #101060765). Neus Escobar also acknowledges the funding from the European Commission through the MSCA–IF project 'Global Interlinkages in Food Trade Systems' (GIFTS) – GA. #101029457. The research is also supported by María de Maeztu Excellence Unit 2023–2027, Ref. CEX2021-001201-M, funded by MCIN/AEI/https://doi.org/10.13039/501100011033; and the Basque Government through the BERC 2022–2025 program. This work also contributes to the 'ICTA-UAB' María de Maeztu Programme (CEX2021-001201-M) for Units of Excellence of the Spanish Ministry of Science and Innovation.

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