



NDC ASPECTS

Mitigation potential of forest-based measures under constraining factors (Deliverable D3.1-A.2 Report)

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Executive Summary

The Agriculture, Forestry, and Other Land Use (AFOLU) sector plays a crucial role towards climate change mitigation. It is particularly important for generating 'negative emissions' — that is, net carbon dioxide removals (CDR). Such relevance is reflected in national climate policies, as AFOLU-related NDC actions make up about 25% of planned GHG reductions in 2030. Globally, the cost-effective potential, limited to \$100 per ton of CO₂ equivalent, is estimated at a median value of 6.9 Gt (with a range spanning from 0.4 to 11.3 Gt) for AFOLU (comprising agriculture and land-use change) and a median value of 8.0 Gt (with a range of 0.8 to 16.5 Gt) for AFOLU combined with Bioenergy with Carbon Capture and Storage (BECCS).

Forests and other ecosystems contribute the largest share of land-based mitigation, particularly through afforestation/reforestation (A/R) and avoided deforestation (AVD). However, the mitigation measures simultaneously face a number of barriers, risks and trade-offs that remain difficult to account for in global potential estimates. Failing to account for these risks in modelling estimates could potentially lead to overestimating the mitigation potential of forestry-based measures, with serious consequences on the climate policy agenda.

The study aims to refine the estimates of forestry-based mitigation measures by simulating a climate policy limiting global CO₂ emissions to the levels that would be reached if NDCs and long-term targets (LTT) were successfully met in addition to implementing a GHG tax on AFOLU emissions of \$100/tCO_{2eq}. Based on the Global Change Analysis Model (GCAM), three constraining factors are considered in addition to the climate policy: a high biomass demand, and limiting both forest expansion and fallow land conversion to historic rates. A set of five scenarios assesses the implications of these constraints on their mitigation potentials, along with land use change, non-CO₂ emissions and food prices.

Results show that considering these constraints could reduce the combined potential of A/R and AVD measures from 1335 to 305 MtCO₂.yr⁻¹ between 2020 and 2050. Under high global biomass demand, deforestation could become positive compared to reference in tropical regions, such as Western Africa and Indonesia, and cause emissions of 44 MtCO₂.yr⁻¹. To minimise this impact on forests, the conversion of other land uses, such as fallow land, beyond historic rates would be required. Under constraints, A/R mitigates 349 MtCO₂.yr⁻¹ through annual land use change of 31 Mha.yr⁻¹. Mostly located in the northern latitudes, the A/R potential is strongly reduced by constraining forest expansion to maximum rates of change observed in historic market-driven land conversions. The mitigation policies translate into a sharp expansion of forestland at the cost of cropland and grassland areas globally. This has important implications on food prices: across mitigation scenarios, food prices increase due to increased pressure on production systems, especially for livestock products.

On the year of the Global Stocktake, the analysis exposes the high uncertainty regarding the mitigation potential of forestry-based measures as well as their interactions with bioenergy policy and food security. It demonstrates the need for a holistic view of the interactions of the AFOLU sector with Sustainable Development Goals (SDGs) beyond climate action in order to foster synergies and minimize trade-offs. Furthermore, land-based mitigation options should not be conceived as silver bullets solutions diverting the required efforts from phasing out of fossil fuels: rather, they are complementary to deep decarbonization of all emitting sectors. Future NDCs could strengthen their coordination with national policies regulating land uses to promote a nexus approach to the land sector capturing interactions between climate mitigation, biodiversity conservation, as well as food and water security.

1. Introduction

The Agriculture, Forestry, and Other Land Use (AFOLU) sector play a crucial role in the complex web of climate change mitigation efforts. As human activities continue to release significant amounts of greenhouse gases (GHGs) into the atmosphere, understanding and effectively managing the AFOLU sector's impact on climate change is essential to limit global temperature to well below 2 degrees.

The agriculture component of the sector is only concerned with emission reductions, while the FOLU components (forest and other land uses) encompasses both emissions and removals, including sequestration potentials in forests, croplands, grasslands, and wetlands. Driven by the estimates from the scientific community, large volumes of net removals are expected from the FOLU sector.

Time scales to observe changes are much longer in forestry and land uses than in other heavily-emitting sectors of the economy. This implies higher uncertainties and longer time lags between policy decisions and the materialisation of their impacts. What is considered speedy change in climate change and forestry – years and decades – would be considered too slow to be transformational in other economic sectors, such as transport or industry.

According to bookkeeping models, total global net anthropogenic GHG emissions from AFOLU were $11.9 \pm 4.4 \text{ GtCO}_{2\text{eq}}\cdot\text{yr}^{-1}$ on average over the period 2010–2019, around 21% of total global net anthropogenic GHG emissions (Nabuurs et al., 2022). CO_2 contributed $5.9 \pm 4.1 \text{ GtCO}_{2\text{eq}}\cdot\text{yr}^{-1}$ (50%), CH_4 $4.2 \pm 1.3 \text{ GtCO}_{2\text{eq}}\cdot\text{yr}^{-1}$ (35%) and N_2O $1.8 \pm 1.1 \text{ GtCO}_{2\text{eq}}\cdot\text{yr}^{-1}$ (15%) of the total global net GHG emissions from the sector. The sector of LULUCF (Land use, land use change and Forestry) is responsible for 51% of the emissions, followed by enteric fermentation (23%), managed soils and pasture (11%), rice cultivation (8%), manure management (3%), synthetic fertiliser application (3%) and biomass burning (1%).

The natural sink of land to atmospheric CO_2 removed $-12.5 \pm 3.2 \text{ GtCO}_2\cdot\text{yr}^{-1}$ (medium confidence) from the atmosphere during 2010–2019 according to global dynamic global vegetation model (DGVM) models (Friedlingstein et al., 2020) which represents 31% of total anthropogenic net emissions of CO_2 from all sectors. Net land use emissions are the difference between CO_2 emissions and CO_2 removals. Net emissions were $4.5 \pm 2.6 \text{ GtCO}_2\cdot\text{yr}^{-1}$ for 2012–2021 and showed a negative trend in the last two decades, but estimates remain highly uncertain.

Deforestation is the main driver of land-use emissions, reaching $6.7 \pm 1.5 \text{ GtCO}_2\cdot\text{yr}^{-1}$ for 2012 – 2021. The global forest area declined by about 178 Mha in the 30 years from 1990 to 2020 (Nabuurs et al., 2022). Forest fluxes from afforestation/reforestation (A/R) and wood harvest emissions and removals counterbalance approximately half of these emissions ($-3.5 \pm 1.0 \text{ GtCO}_2$). Emissions from deforestation are particularly high in the tropics, whereas net sinks occur in regions with a net increase in forest land such as Europe and China. Indonesia, Brazil, and the Democratic Republic of Congo contributed together 58% of the global net land-use emissions.

Given its unique characteristics, the AFOLU sector is vitally important for generating ‘negative emissions’ — that is, more carbon dioxide removals (CDR) than emissions. As of March 2019, 186 countries had included AFOLU measures in their Nationally Determined Contributions

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(NDCs) under the Paris Agreement: AFOLU-related NDC actions make up about 25% of planned GHG reductions in 2030 (Roe et al. 2021).

Land-based mitigation measures largely fall into the following four categories: supply-side interventions in 1. forests and other ecosystems (to protect, manage, and restore), 2. agriculture (to reduce emissions and enhance carbon sequestration), and 3. bioenergy (to reduce fossil fuel emissions and sequester carbon), as well as 4. demand-side interventions on food waste, diets, and resource use. Roe et al. (2021) have estimated the climate mitigation potentials for 20 land-based measures in 2020–2050 by region. IAM estimates (range and median, up to 100 USD.tCO_{2eq}⁻¹) are provided for the seven measures from scenarios in the ENGAGE database (Riahi et al., 2021).

Between 2020 and 2050, the cost-effective mitigation potential of land-based measures from a sector-specific perspective hovers at around 13.8 ± 3.1 GtCO_{2eq}.yr⁻¹. This figure accounts for approximately 42% of the technical potential. This cost-effective potential represents a more practical and attainable level of deployment, slightly surpassing the average annual emissions from Agriculture, Forestry, and Other Land Use (AFOLU) between 2007 and 2016, which stood at 12 ± 2.9 GtCO_{2eq}.yr⁻¹ (Jia et al. 2019).

When utilising the Integrated Assessment Model (IAM) approach, the cost-effective potential, limited to \$100 per ton of CO₂ equivalent, is estimated at a median value of 6.9 Gt (with a range spanning from 0.4 to 11.3 Gt) for AFOLU (comprising agriculture and land-use change) and a median value of 8.0 Gt (with a range of 0.8 to 16.5 Gt) for AFOLU combined with Bioenergy with Carbon Capture and Storage (BECCS) (Table 1). IAMs indicate that the overall cost-effective land-based mitigation potential is equivalent to 58% of the sectoral potential.

Table 1: Mitigation potential of AFOLU measures estimated by IAMs as reported in Roe et al. 2021

Mitigation measures (units in MtCO ₂ .yr ⁻¹)	Global weighted median	Global minimum	Global maximum
Agriculture, Forestry and Other Land Uses (AFOLU)			
AFOLU	6869	403	11300
AFOLU + BECCS	8016	806	16587
Forestry and Other Land Uses (FOLU)			
A/R	475	27	4136
BECCS	721	9	7713
Enhance land sequestration (manage + restore)	952	152	4136
Reduce land use change (protect)	2562	1256	3833
A/R + Reduced land use change ¹	3037	1283	7969
Agriculture			
Enteric fermentation	966	-20	1809

¹ Category added by the authors, corresponding to the sum of the mitigation potential of the forestry-based measures modelled in the report.

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Mitigation measures (units in MtCO ₂ .yr ⁻¹)	Global weighted median	Global minimum	Global maximum
Manure management total	241	-7	593
Manure management CH ₄	170	-8	413
Manure management N ₂ O	47	1	312
Nutrient management	306	-32	644
Rice cultivation	195	11	569
Agriculture total	2661	-45	4090
Agriculture CH ₄	2014	-15	3564
Agriculture N ₂ O	468	-31	824

Divided by sectors, the cost-effective potential within land-based mitigation is structured as follows: approximately 50% comes from forests and other ecosystems, 35% from agriculture, and the remaining 15% from demand-side measures. Thus, forests and other ecosystems contribute the largest share of land-based mitigation. According to IAMs, the cost-effective potential arising from land-use changes in forests and other ecosystems for the year 2050 is estimated at a median value of 3.5 Gt (with a range spanning from 1.4 to 8.0 Gt) of CO₂ equivalent per year. This accounts for 44% of the total land-based mitigation potential. Agriculture represents the second-largest contributor to land-based mitigation. The cost-effective potential in agriculture (excluding CO₂ emissions) for the year 2050 is calculated to be a median value of 2.7 GtCO_{2eq}.yr⁻¹ (with a range from 0 to 4.1 Gt), constituting approximately 33% of the total land-based potential. Demand-side measures contribute 3.1 GtCO_{2eq}.yr⁻¹ in technical potential and 1.9 GtCO_{2eq}.yr⁻¹ in cost-effective potential, accounting for 10% and 14% of the total land-based potential, respectively. In contrast, the estimated mitigation potential from Bioenergy with Carbon Capture and Storage (BECCS) is relatively modest. In the sectoral estimate, BECCS is projected to offer technical and cost-effective potential of 2.5 GtCO_{2eq}.yr⁻¹ and 0.5 GtCO_{2eq}.yr⁻¹, respectively. Across the IPCC regions, the highest cost-effective potentials are found in Asia and developing Pacific with 4.8 ± 1 GtCO_{2eq}.yr⁻¹ (34%), followed by Latin America and Caribbean (3.4 ± 1.2 GtCO_{2eq}.yr⁻¹; 25%), then Africa and Middle East (2.5 ± 0.7 GtCO_{2eq}.yr⁻¹; 18%), Developed countries (2.5 ± 0.1 GtCO_{2eq}.yr⁻¹; 18%), and Eastern Europe and West-Central Asia (0.8 ± 0.1 GtCO_{2eq}.yr⁻¹; 5%).

Forestry-based measures can further be subdivided into three categories: “protect”, “restore” and “manage”. “Protect” measures include reducing deforestation, reduce mangrove loss, reduce peatland degradation and makeup 20% and 28% of the total technical and cost-effective potential, respectively. “Manage” measures include improved forest management and grassland and savanna fire management and make up 6% and 7%, respectively. “Restore” measures include A/R, coastland wetland restoration and peatland restoration and make up 30% and 13%, respectively. The forestry-based measures included in the modelling estimates of this report were restricted to “Restore” (e.g., A/R) and “Protect” (e.g., AVD) measures (Figure 1).

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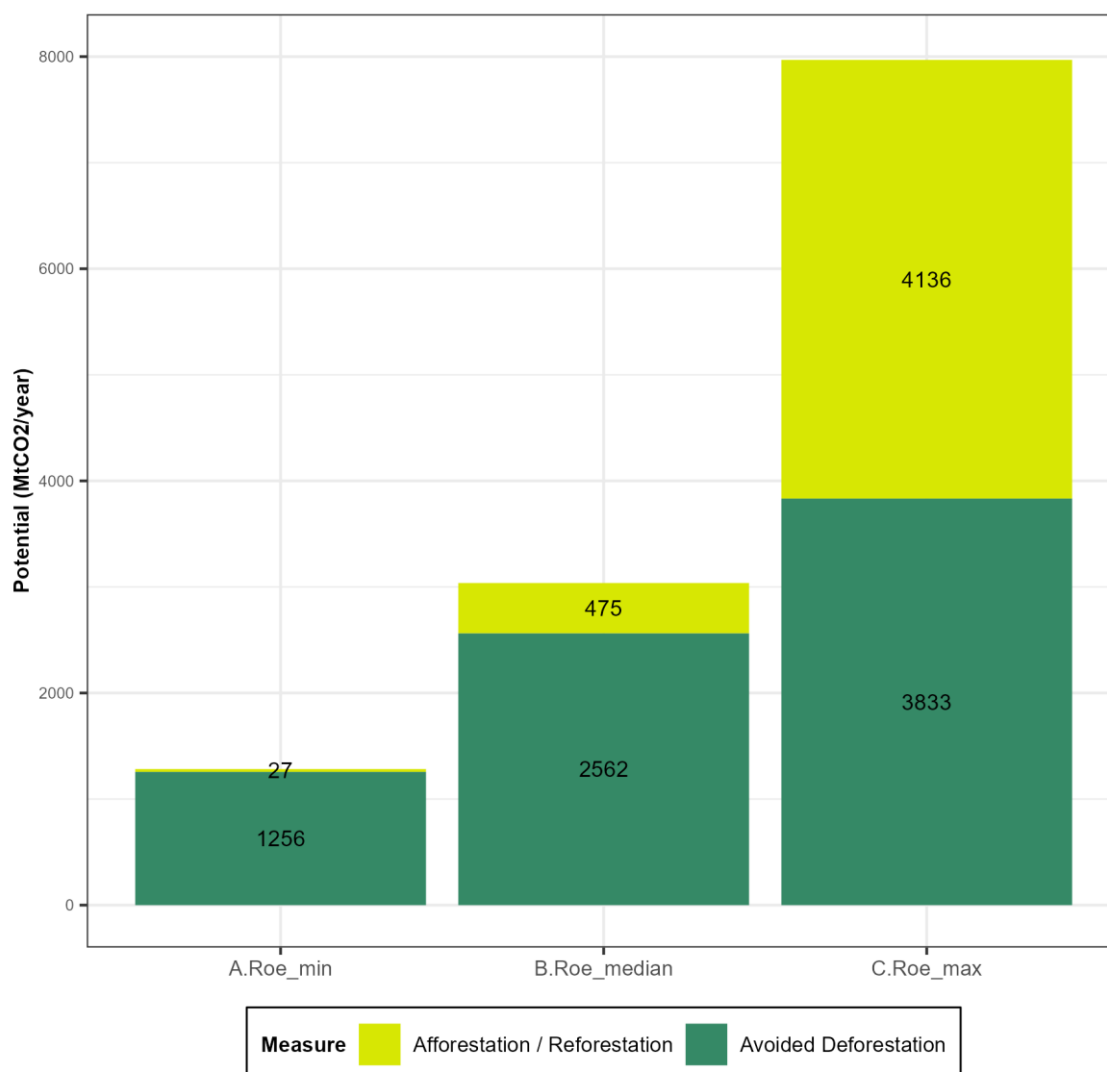


Figure 1: Global minimum (A. Roe_min), median (B. Roe_median), and maximum (C. Roe_max) values of mitigation potential (MtCO₂.yr⁻¹) of A/R (“restore measures”) and AVD (“protect measures”) from IAMs estimates (Roe et al. 2021).

These forestry-based measures can bring a large panel of co-benefits, but simultaneously imply trade-offs with other sustainability dimensions. The planning, design and implementation of these measures determine to a large extent these benefits and trade-offs (Smith et al., 2020). First, in addition to providing the highest mitigation potential of the AFOLU sector, these measures can deliver multiple benefits which include enhancing biodiversity, ecosystem services and connectivity, enhancing adaptation, microclimatic regulation, enhancing soil quality and reducing erosion, degradation and desertification, regulating hydrological cycle and providing renewable resources, and increasing incomes and livelihoods.

However, these measures simultaneously face a number of barriers and risks that remain difficult to account for in global potential estimates. Protection of forests and other ecosystems, particularly of primary ecosystems, present high mitigation efficiency, high provision of co-benefits, and relatively lower costs. Yet, it simultaneously limits the land used for farming and

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food production, representing an opportunity cost for landowners. The restoration of forest ecosystems could improve the carbon sink of land at medium costs but could put additional pressure on other land uses by increasing land competition, especially at a very large scale. Forest plantations could cause loss of biodiversity and reduced water availability. The resulting changes in albedo could further counterbalance the mitigation impact of carbon removals due to the resulting warming effect (Luyssaert et al., 2018).

Furthermore, estimates such as the ones reported in Roe et al. (2021) do not account for climate change impacts on terrestrial ecosystems. These climate impacts will reduce future potential for land-based mitigation and turn residual land sinks into sources. They are marked by strong geographic variability: fires are particularly important in regions like the western United States, Australia, Mediterranean type climates, and boreal forests in North America and Asia (Anderegg et al., 2020). These impacts raise additional concerns on the permanence of realised land-based potential over time. Such permanence is further undermined by factors such as investment risks and weak governance, which tends to be higher in regions with high mitigation potentials from forestry (e.g., tropics).

Thus, while these forestry-based measures are presented as major solutions to limit climate change, these risks in global mitigation policy and the negative trade-offs with other environmental objectives could drastically limit their contribution to global mitigation targets. Such lack of consideration could potentially lead to overestimating the mitigation potential of forestry-based measures, with serious consequences on the climate policy agenda. Indeed, over-reliance on and negative emissions from the AFOLU sector could reduce the level of ambition in other sectors, when they are taken as cost-effective alternatives to policies such as electrification of industry, decarbonisation of transport and large-scale deployment of renewable energy sources.

2. Objectives

In this context, the primary objective of the modelling is to refine the estimates of forestry-based mitigation measures. Based on existing data and methodologies, it seeks to estimate the impacts on discrete alternative scenarios on the sector's contributions to climate change mitigation. To achieve this objective, the study simulates an ambition climate policy with a GHG tax of AFOLU emissions and estimates the impacts of main constraints associated with forestry-based mitigation strategies. By understanding the challenges and risks posed by the processes that can limit the mitigation potential of forests, policymakers can develop robust policies able to minimise adverse impacts while capitalising on opportunities for land-based mitigation.

Furthermore, this modelling will provide actionable measures that counter the trade-offs associated with forestry-based mitigation. The proposed measures aim to align forestry-driven climate actions with the overarching objectives of Nationally Determined Contributions (NDCs), ensuring a harmonious integration of forestry-related efforts into broader climate policy frameworks. The sectoral modelling will compare the impact of the climate policy defined for the AFOLU sector on the mitigation potential of forestry-based measures under different biophysical and energy constraints. The goal is to estimate the extent to which forested ecosystems could contribute to global climate mitigation under these constraints. By improving the knowledge on the mitigation potential of these measures, the study ultimately aims to provide science-based support to policy-making towards more ambitious future NDCs and climate policies.

The analysis focuses only on both A/R and AVD for several reasons. First, they are the only two forestry-based measures which were included in the study of Roe et al. (2021), which is the reference study against which the results of the analysis are compared. In addition, both measures can be modelled by implementing a tax on land carbon while forest management and soil carbon sequestration in grassland and cropland would have required measure-specific modelling approaches. This would have reduced the comparability of the impact of the constraints on the mitigation potential of the assessed measures. Last, A/R and AVD are the AFOLU measures with the highest mitigation potential.

The analysis focuses only on both A/R and avoided deforestation for several reasons. First, they are the only two forestry-based measures which were included in the study of Roe et al. (2021), which is the reference study against which the results of the analysis are compared. In addition, both measures can be modelled by implementing a tax on land carbon. This would have reduced the comparability of the impact of the constraints on the mitigation potential of the assessed measures. Last, A/R and avoided deforestation are the AFOLU measures with the highest mitigation potential. Additional mitigation options (i.e., forest management and soil carbon sequestration in grassland and cropland), could have been considered but these entailed additional modelling challenges and requirements, such as a better representation of the forestry sector.

3. Methodology

3.1. Modelling framework

Overview of the GCAM model

A number of modelling tools and frameworks have been established to explore the multiple interactions among human and Earth systems and the impact of mitigation policies on GHG emissions. The modelling framework of this study is based on Global Change Analysis Model (GCAM) v7.0. GCAM represents the complex interactions between five major systems – energy, water, land, climate, and the economy – at global and regional scales. GCAM is a dynamic recursive model, i.e., decision-makers base their decisions only on currently available information rather than optimising over the full future, as is the case in inter-temporal optimisation models (Calvin et al., 2019).

Various systems are depicted within this framework, each operating at different spatial scales. Specifically, economic and energy systems are portrayed through 32 geopolitical regions. In contrast, the land and water system are further subdivided into water basins, resulting in a total of 384 distinct land-water regions. This level of granularity is necessary to establish meaningful connections between water and agriculture systems, facilitating the accurate representation of their interactions. These interactions can encompass factors such as the consequences of forthcoming droughts or the hydrological impacts of agricultural production. Figure 2 provides a visual representation of these spatial levels.

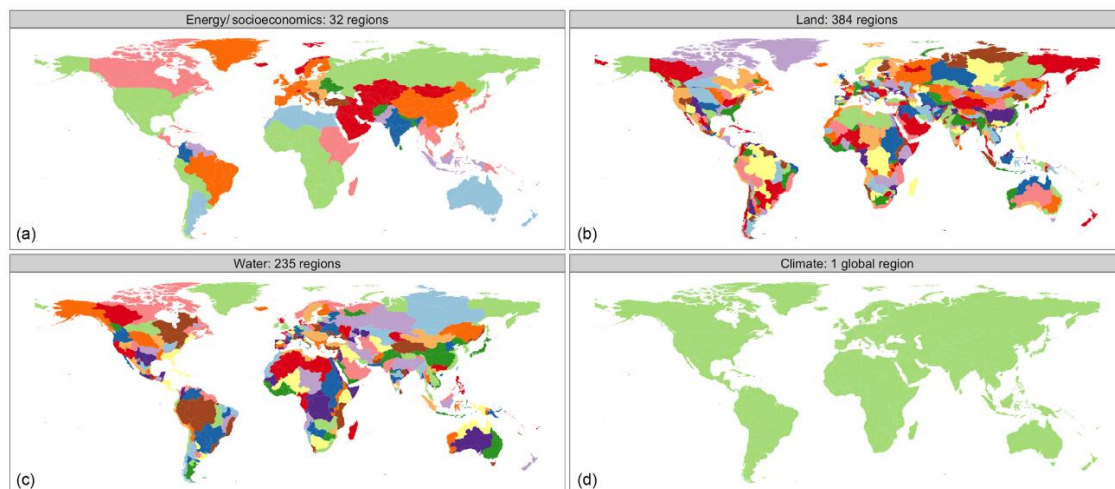


Figure 2: GCAM regional mapping for energy and economy (a), land (b), water (c), and climate (d). (Calvin et al. 2019)

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Land system

The land component of GCAM computes supply, demand, and land utilisation in various sectors, encompassing food, feed, fiber, forestry, and bioenergy production. Additionally, it tracks the land cover for different types of natural ecosystems. The land nesting approach of GCAM structures the land uses as shown in Figure 3. Within each land node, it is generally assumed to be easier to substitute products which implies a tighter competition. Substitution across land nodes is also allowed but is assumed to be more difficult than within land nodes.

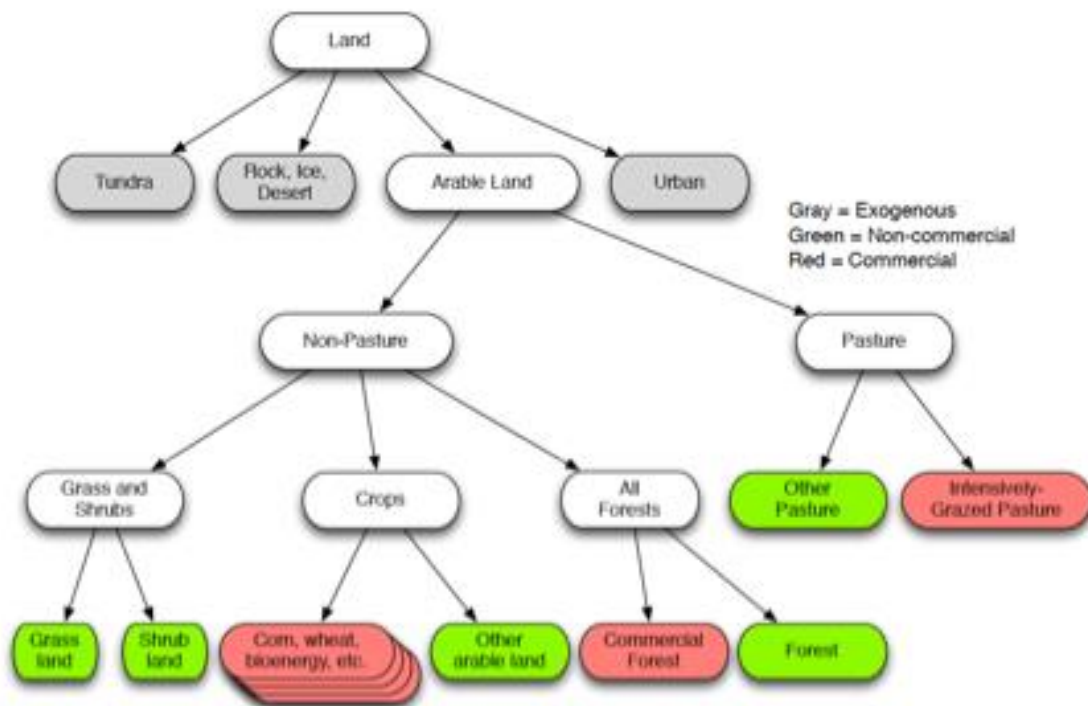


Figure 3: Land nesting structure of GCAM. Crops are further divided into categories accounting for irrigation (irrigated/rainfed) and fertilization (high/low).

Land conversion in GCAM is simulated based on a logit model to allocate the several land uses (cropland, forest, grassland, shrubland, pasture, fallow land, others) according to their relative expected profit in each LUT, considering underlying costs and land productivity. The interpretation of this land allocation system in GCAM is that there is a distribution of profit behind each competing land use within a LUT, so that an option with a higher average profit will get a higher share of allocated land than one with a lower average profit.

In its determination of the economic allocation of crop production and land use across regions of the globe, GCAM follows the basic economic principle of comparative advantage. While each land subregion makes its own independent allocation, the subregions communicate these decisions with each other through economic markets. The global markets for agricultural and forest products react to these allocations by comparing global supplies to demands and adjusting prices to equilibrate supplies and demands. The resulting prices are sent back to each land subregion as signals as to how its land allocation should be changed. The process of allocation and price adjustment continues until the markets are in equilibrium.

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Agriculture and crop representation

GCAM accounts for all commodities that are reported by the Food and Agriculture Organization (FAO), consolidating them into 15 distinct commodity classes such as wheat, sugar crops, oil crops, forests, pastures, and more. The demands for food, fiber, and forestry products within GCAM are influenced by several factors, including the size of the population, their income levels, and the prevailing commodity prices. Food demand, in particular, is sensitive to price changes but exhibits relatively low-price elasticities, with values of -0.08 for crops and -0.25 for meat and dairy. These values were however modified to better model the response of food demand to changes in the supply of food products: all elasticities for agricultural commodities were set to -0.25.

The inclusion of multiple management types for each crop within each subregion of GCAM allows the model to represent price-induced intensification. That is, we can increase yields via increased fertiliser or irrigation if economic conditions favour those options. Like for land allocation, the share of each management practice depends on relative profitability. As profits of one option increase, more land will be allocated to that option. In general, GCAM will intensify when there is a lot of land competition (like when carbon in land is valued). The agriculture productivity growth is based on projected yields through 2050 for agricultural commodities from FAO which are then endogenously adjusted by the process of intensification through irrigation and fertilisation.

Land use change emissions

The GCAM model calculates emissions from agriculture and land-use changes at each time step using a methodology that resembles an accounting-style approach, similar to the one employed in Houghton's work from 1995. In this process, GCAM estimates the equilibrium change in carbon resulting from alterations in land use or land cover and then allocates this change across different time periods.

The emission profiles over time can vary based on several factors, including which specific carbon stock (above or below ground), whether there is an increase or decrease in carbon stocks, and the user-defined parameter of time to maturity. If the carbon stock increases the emissions are spread out over time using a sigmoid function. Soil carbon emissions follow an exponential approach. The "time to maturity" essentially represents the period it takes for the carbon stocks to reach their peak standing levels, with regions that have slower-growing conditions at higher latitudes requiring more time to achieve this maturity.

3.2. Scenario design

GCAM includes the ability to represent multiple different types of land-related policies, including afforestation, protected lands, bioenergy constraints (e.g., lower or upper bounds on total bioenergy consumption or the share of bioenergy in liquid fuels), and bioenergy taxes (Calvin et al., 2014). We use GCAM to simulate a GHG tax on land use emissions of \$100/tCO_{2eq}, which applies to both forest-related CO₂ emissions and agriculture-related CH₄ and N₂O emissions. It is implemented progressively to reach the full price in 2050. In the mitigation scenarios, the land tax is implemented in addition to a cap on CO₂ emissions limiting global CO₂ emissions to 8997

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in 2030 and 2671 MtCO₂ in 2050. The values are taken from Van de Ven et al., (2023) which modelled the global CO₂ emissions in scenarios where both short term (current policies and NDCs) and long-term targets (LTTs) were fulfilled. With such mitigation ambition, temperature increase will stabilize around 1.7–1.8°C, which is arguably in line with a future ‘well below 2 °C’. In other words, the mitigation scenarios implement a tax on land GHG emissions in addition to global CO₂ emission reduction corresponding to the achievement of all existing short term and long-term targets in the energy and industry sectors.

The carbon pricing applied in the scenario enables the comparison with Roe et al. 2021 whose scenarios include the range between \$50 and \$150/tCO_{2eq} in 2050 to best represent mitigation at \$100/tCO_{2eq} (approximate median) across IAMs. It is implemented as a carbon rent to credit landowners for holding carbon stocks: the land rental profit is increased by factoring in the annualized land carbon storage rent. The policy creates both the incentive to retain existing carbon stocks (e.g., AVD) and increase terrestrial carbon stocks (e.g., A/R). Incentivising forestry-based measures by a price on CO₂ emissions from the land system is among the main method to estimate their economic mitigation potentials and has been applied in numerous previous studies (Calvin et al., 2014; Humpenöder et al., 2014; Kreidenweis et al., 2016).

The reference follows the shared socioeconomic pathway 2 (SSP2) "middle-of-the-road" scenario. Global population peaks around 2070, and per-capita incomes increase in all regions throughout the course of the century, with particularly high rates of growth assumed in currently developing nations. Furthermore, our study assumes that purpose-grown second-generation bioenergy crop demands increase from 0 in the base year to between 50 and 70 EJ per year by mid-century (Kc & Lutz, 2017). For biophysical yield growth in the GCAM reference scenario, a linear interpolation based on the Food and Agriculture Organization (FAO) of yield projections in 2030 and 2050 is deployed (Zhao et al., 2021).

Five mitigation scenarios are considered (Table 2) based on combinations of three constraints applied to the climate policy described above. The unconstrained climate policy scenario (*Uncons*) introduces the climate policy, which provides incentives for enhancing terrestrial carbon stocks, without considering constraints (Calvin et al., 2014). The second scenario, thereafter referred to as ‘constrained’, implements all the three constraints in addition to the climate policy (*Cons_All*). To test the impact of individual constraints, three intermediate scenarios are implemented where one constraint is removed from the constrained scenario: a constrained scenario where the biomass demand constraint is removed (*Cons_NoBiomass*), a constrained scenario where the forest expansion constraint is removed (*Cons_NoForest*) and a constrained scenario where the fallow land conversion constraint is removed (*Cons_NoFallow*). The following sections describe successively the constraint applied in the scenarios.

Constraint 1: Biomass demand

The first constraint implemented increase the global consumption of biomass to produce bioenergy. While bioenergy combined with carbon capture and storage (CSS) figures among the main strategies for carbon removal, the demand for land from growing demand puts additional pressure on land systems and enters in direct competition with forestry-based measures. Under this constraint, the consumption of biomass increases from 28.6 EJ in 2015 to 57.8 EJ in 2030 and 117.4 EJ in 2050, which is in line with the IPCC Sixth Assessment Report. In contrast,

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scenarios which are not constrained by this production target have a consumption of biomass extrapolating the historic rate, where consumption reaches 43.6 EJ in 2030 and 63.6 EJ in 2050.

Constraint 2: Fallow land conversion

The second constraint limits the rate to which fallow land can be converted into other land uses in each of the 384 land units of the land system. While it is generally assumed that fallow land is readily convertible to other land uses because of its poor profitability, fallow land is often regulated by specific policies which are poorly accounted for in the land use modelling. This is particularly relevant in developed countries where such legislation is most developed. Under this constraint, we set a maximum conversion rate determined by historic values between 1990 and 2015 for all the land units. Fallow land cannot be converted at a rate higher than the maximum rate observed during that period (these rates range between 0% to -9.85%). Yet, we allow for conversion beyond these constrained rates if higher rates are observed in the reference scenario. In this case, the area of fallow land follows the reference trajectory, which allows to isolate the impact of the climate policy on fallow land allocation dynamic.

Constraint 3: Forest expansion

The third constraint limits the change in forestland areas in each of the 384 land units with a maximum annual afforestation rate of 0.4% relative to total agricultural land. The constraint will test the impact on the mitigation potential of limiting land use change to historic rates and preventing unrealistic conversion of agricultural land to forests. This maximum afforestation rate is based on estimates for palm oil in Indonesia and of soy in Brazil, which are assumed to be good historical examples for strongly market-driven land use change (Doelman *et al.*, 2020). Like for the second constraint, we allow for expansion rates beyond these constrained rates if higher rates are observed in the reference scenario. In this case, the area of forests follows the reference trajectory.

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Table 2: Alternative scenarios simulated to estimate the global potential for forestry-related carbon mitigation.

Scenario	Climate policy	Biomass demand	Fallow land conversion	Forest expansion
Reference	None	Biomass consumption increased to 63.6 EJ in 2050 (historic rate)	None	None
Unconstrained (<i>Uncons</i>)	High mitigation target with 2.7 GtCO ₂ globally emitted per year by 2050 + Carbon price up to \$100/tCO _{2eq} by 2050 for land use CO ₂ and agriculture CH ₄ and N ₂ O	Biomass consumption increased to 63.6 EJ in 2050 (historic rate)	None	None
Constrained (<i>Cons_All</i>)	High mitigation target with 2.7 GtCO ₂ globally emitted per year by 2050 + Carbon price up to \$100/tCO _{2eq} by 2050 for land use CO ₂ and agriculture CH ₄ and N ₂ O	Biomass consumption increased to 117.4 EJ in 2050 (nearly doubling historic rate)	Maximum rate of fallow land conversion (determined from historic rates from 1990 to 2015 for the 384 land units)	Maximum rate of A/R (0.4% relative to agricultural land in each of the 384 land units)
Constrained without biomass constraint (<i>Cons_NoBiomass</i>)	High mitigation target with 2.7 GtCO ₂ globally emitted per year by 2050 + Carbon price up to \$100/tCO _{2eq} by 2050 for land use CO ₂ and agriculture CH ₄ and N ₂ O	Biomass consumption increased to 63.6 EJ in 2050 (historic rate)	Maximum rate of fallow land conversion (determined from historic rates from 1990 to 2015 for the 384 land units)	Maximum rate of A/R (0.4% relative to agricultural land in each of the 384 land units)
Constrained without fallow land constraint (<i>Cons_NoFallow</i>)	High mitigation target with 2.7 GtCO ₂ globally emitted per year by 2050 + Carbon price up to \$100/tCO _{2eq} by 2050 for land use CO ₂ and agriculture CH ₄ and N ₂ O	Biomass consumption increased to 117.4 EJ in 2050 (nearly doubling historic rate)	None	Maximum rate of A/R (0.4% relative to agricultural land in each of the 384 land units)
Constrained without forest constraint (<i>Cons_NoForest</i>)	High mitigation target with 2.7 GtCO ₂ globally emitted per year by 2050 + Carbon price up to \$100/tCO _{2eq} by 2050 for land use CO ₂ and agriculture CH ₄ and N ₂ O	Biomass consumption increased to 117.4 EJ in 2050 (nearly doubling historic rate)	Maximum rate of fallow land conversion (determined from historic rates from 1990 to 2015 for the 384 land units)	None

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3.3. Indicators on carbon mitigation potential, land use change and food price index

Outcomes from the GCAM model are used to estimate the mitigation potential of forestry sector as the difference of emissions from forests between the reference scenario and each mitigation scenario. Here, A/R and AVD are defined as the mitigation measures resulting from the climate policy: as increases and avoided decreases in forest area, respectively. In this analysis, forest land includes both natural forests and managed forests (plantations). All land uses of GCAM are aggregated per LUTs in the following categories: forests, grassland and shrubland, cropland, fallow land, pasture, biomass and others (urban, tundra and rock/ice/desert).

In order to be able to quantify the contribution of A/R and AVD separately, an accounting procedure was established, since GCAM does not provide results for each mitigation options. For each of the 384 LUTs, the presence/absence of each measure is determined by comparing the area change of forests between reference and mitigation scenario and between calibration year (2015). If forest increases in both reference and mitigation scenarios, the potential from the LUT is labelled A/R-only. On the contrary, if forest decreases in both, the potential is labelled AVD-only. In many cases, the sign of land use change is different between reference and mitigation: the mitigation scenario leads to increases in forests while reference leads to decreases. In other words, the potential of the LUT is split between the two measures, as the mitigation scenario both avoids the deforestation that would occur in reference and leads to the expansion of forestland. Then, the emissions from forest loss in the reference relative to calibration year are attributed to AVD, while the carbon sequestration from forest growth in the mitigation scenario relative to calibration year are attributed to A/R.

The emissions from the *first-order* LUC emissions corresponding to changes in forestland areas are completed by estimating *second-order* LUC emissions, referring to indirect emissions from land uses being replaced by A/R or that would have replaced forests after deforestation. GCAM does not specify at the expense of which land uses forestland expansion (or contraction) takes place. Thus, the second-order LUC emissions are determined by estimating a single aggregated emission factor ($\text{MtC} \cdot \text{ha}^{-1}$) for the non-forest land uses with opposite sign of area change relative to forestland. For each non-forest land use, the emission factor captures the aggregate CO_2 released/absorbed by unit of area increase/decrease. The weighted average across non-forest land uses is multiplied by the areas of A/R and/or AVD in each LUT to estimate the CO_2 emissions from second-order LUC. Complete LUC emissions are obtained by subtracting second-order LUC emissions from first-order LUC emissions.

CO_2 sequestration between 2050 and 2100 resulting from the growth of vegetation planted in the modelling period which did not reach maturity by 2050 is also reported. Because sequestration in vegetative biomass is associated with planted forests (e.g., A/R) or with the land uses growing post-deforestation, these absorptions are not assigned to specific measures and are reported for informative purposes.

Land use change (Mha) associated with the forestry measures is estimated for each land use units. GCAM outputs land allocation for 43 land uses which are aggregated. In our analysis, forestland aggregates managed forests, unmanaged forests and protected unmanaged forests. Same as for the mitigation potential, an area assignment protocol determines the hectares of

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each measure in each land use units. The areas are used to estimate the mitigation intensity of the measures, calculated as the cumulative technical mitigation between 2020 and 2050 divided by the total land area used (Roe et al. 2021).

As an additional metric to interpret effects on food prices, we estimate a food price index (FPI) derived from the Laspeyres index. We report FPI for all agricultural commodities, and for crops and animal products separately. The equation is based on the FAO methodology (Eq. 1).

$$FPI_t = \sum_{i=1}^n S_{i0} \frac{P_{it}}{P_{i2020}}$$

Where S_{i0} is the share of each commodity's global export value in the total export value of the agricultural commodities reported by GCAM, P_{it} is the price for the commodity at time t and P_{i2015} is the price for the commodity in 2020.

3.4. Data and inputs to the modelling

GCAM is based on a set of tabular data which serve as input to the land system. There are three primary types of input data for the land component: historical data used for calibration, information related to competition, and future driver data. The historical data include the following: supply, demand, prices, and variable costs of production for agriculture and forestry products; land use and land cover; the value of unmanaged land; carbon cycle parameters; and emissions and/or emissions factors for non-CO₂ emissions. The competition information includes the logit exponents dictating the competition between various land types. The future driver data include income and price elasticities for demand, agricultural productivity growth rates, and MAC curves. The detailed inputs to the land modules are summarized in Table 3, with the units that GCAM requires.

Table 3: Detailed inputs required for the land module of GCAM

Name	Description	Resolution	Unit
Historical land use and land cover	Land area by region, land type and year. Land cover data is provided beginning in 1700 in order to spin-up the carbon cycle within GCAM.	By GLU, land type, and year	thousand km ²
Vegetation carbon density	Inputs include potential vegetation and soil carbon density (i.e., carbon density if the land grew to equilibrium), and mature age for vegetation carbon.	By GLU and land type	kg per m ²
Soil carbon density		By GLU and land type	kg per m ²
Mature age		By GLU and land type	years
Soil time scale	Inputs include the number of years for soil carbon changes to occur.	By geopolitical region and land type	years
Value of unmanaged land	GCAM requires profit rates for all land types in the historical period for calibration. Managed land profit is calculated in the supply model. For	By GLU	1975\$ per thous. km ²

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	unmanaged land, the value is input into the model.		
Profit rate of managed land		By GLU	1975\$ per thous. km ²
Logit exponents	GCAM requires the user to specify the logit exponents that determine the substitutability between different leaves and nodes in the land model.	By GLU and land node	Unitless

GCAM also requires tabular inputs for the supply module of food, feed, and forestry, as detailed in Table 4.

Table 4: Detailed inputs required for the supply module of food, feed and forestry of GCAM

Name	Description	Resolution	Unit
Historical harvested area (used to calculate historical yield)	Harvested area for agricultural commodities by country in the historical period; used for initialisation/calibration of GCAM	By GLU, crop, management practice, and year	thousand km ²
Historical production (used to calculate historical yield)	Production of agricultural commodities by country in the historical period; used for initialisation/calibration of GCAM	By GLU, crop, management practice, and year	thousand km ²
Agriculture productivity growth (used to calculate future yield)	Projected yields through 2050 for agricultural commodities from FAO	By GLU, crop, management practice, year	% per year
Non-fertiliser, non-water, non-land variable cost of production	Based on historical cost of crop production in the USA (used in all regions)	By GLU, crop, management practice, and year	1975\$/kg
Fertiliser coefficients		By GLU, crop, management practice, and year	1975\$/kg
Water coefficients		By GLU, crop, management practice, and year	1975\$/kg
Commodity prices	Based on historical prices of agriculture and livestock commodities	By region, commodity, and year	1975\$/kg
Fertiliser prices		By region, commodity, and year	1975\$/kg

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Water prices		By basin and year	1975\$/m3
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Furthermore, GCAM builds upon a Land Data System called Moirai which is a modular system that can be updated and customised through replacement and addition of source data. The advantage of Moirai is to enable the use of spatially explicit input data (e.g., raster images) with tabular input data (e.g., crop price table) to generate spatially-referenced tabular data of crop production, crop harvested area, land value, irrigated and rainfed crop area, water footprint, soil and vegetation carbon density of unmanaged land, and historical land use/cover. Moirai takes a given set of Geographic Land Unit (GLU) boundaries and generates 10 production output files for use by a global land use model, as well 5 raster files containing the final country, region, and GLU boundaries as determined by the intersection of the input data.

4. Mitigation options (MO)

4.1. Afforestation/reforestation (A/R)

According to the IPCC AR6, afforestation and reforestation (A/R) are activities that “convert land to forest, where reforestation is on land that has previously contained forests, while afforestation is on land that historically has not been forested”. A/R activities aim to improve biomass stocks and hence the carbon sequestration of the newly forested land. Native mixed-species plantings effectively sequester and stabilize carbon within decades while providing a range of other social, economic, and environmental benefits. Regrowth and regeneration historically occurred in Europe, Eurasia, and North America. Globally, the declining rate of net forest loss during the last decade was due mainly to forest gains through afforestation and the natural expansion of forests.

A/R activities can take place in a variety of land types including naturally regenerated forests, forest plantations, arable crops, permanent crops, pastures, and grasslands. They are however limited by biophysical factors which include soil, climate, and slope. Scaling up A/R depends on carbon capture potential and sequestration rates, based on trees lifetime and growth. Removal occurs at faster rates in young- to medium-aged forests and declines thereafter such that older forest stands have smaller carbon removals but larger stocks, with net uptake of carbon slowing as forests reach maturity (Jia et al., 2019).

Specific mitigation potential is very dependent on local conditions and species chosen. The IPCC SRCCL reports that afforestation/reforestation (A/R) and forest restoration can increase carbon sequestration in both vegetation and soils by 0.5–10.1 GtCO₂.yr⁻¹. The higher bound estimates the potential with reforestation of all areas where forests are the native cover type, constrained by food security and biodiversity concerns (Griscom et al., 2017). Climate change will affect the mitigation potential of reforestation due to impacts in forest growth and composition, as well as changes in disturbances including fire. However, none of the mitigation estimates included in the SRCCL account for climate impacts. The land intensity of afforestation and reforestation has been estimated at 0.0029 km² tC⁻¹.yr⁻¹ (Smith et al., 2016). It is estimated that to sequester about 100 GtC by 2100 would require 13 million km² of abandoned cropland and pastures (Boysen et al., 2017).

A/R activities have a wide variety of co-benefits and improve ecosystem services. Beyond carbon sequestration, A/R can increase water quality, soil protection against erosion, improve biodiversity and provide timber, fuelwood and non-timber forest products (NTFPs) as secondary commodities (Nabuurs et al., 2022). Forested land also offers benefits in terms of food supply, especially when forest is established on degraded land and other land that cannot be used for agriculture. For example, food from forests represents a safety-net during times of food and income insecurity (Jia et al., 2019).

Yet, A/R can also have various trade-offs which depend on the context and the scale of implementation. Poorly planned deployment of A/R for carbon sequestration may conflict with environmental and social dimensions of sustainability. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people (Jia et al., 2019).

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Afforestation can also impact land surface albedo, decreasing the amount of short-wave radiation reflected back to space. The reduced albedo results in a warming effect with important consequences, especially in the boreal zone. Such biophysical warming effects are indeed estimated to offset the cooling effect from carbon sequestration (Kreidenweis et al., 2016). On the contrary, afforestation in the tropics have demonstrated a cooling effect (Perugini et al., 2017). Next, the use of non-native species and monocultures may have adverse impacts on ecosystem structure and function, and water availability, particularly in dry regions. Reversal of carbon removal through wildfire, disease, pests may also occur (Anderegg et al., 2020). Reduced catchment water yield and lower groundwater level if species and biome are inappropriate have been observed (Schwärzel et al., 2020).

The IPCC AR6 estimates the cost of A/R to be 0-240 USD.tCO₂⁻¹. A recent global assessment of the aggregate costs for afforestation and reforestation suggests that at 100 USD.tCO₂⁻¹, 1.6 GtCO₂.yr⁻¹ could be sequestered globally for an annual cost of USD 130 billion (Austin et al., 2020). The operational costs of A/R are divided into conversion and monitoring costs. Conversion costs included site preparation, planting, maintenance (e.g., mowing, weeding, herbicides, tilling, herbivore control), and replanting.

Afforestation and reforestation, including reclamation of degraded or desertified lands, offer a great scope for job creation, particularly where rural unemployment or underemployment is high and vast tracts of degraded land are available. Land preparation, production of planting material and planting and maintenance, adapted to the specific local conditions, knowledge and skills, could be important sources of employment. Since a major share of a worker's income goes to the purchase of goods and services, mainly at the local level, every job created in forestry generates an additional 1.5 to 2.5 jobs in the economy (Nair & Rutt, 2009).

Additionally, the provision of fuelwood in the long term could reduce time spent in its collection and diversify women livelihood activities (as they traditionally assume this task), as well as reducing associated risks on the way (violence and assaults) and the use of more toxic fuel alternatives (e.g. dung) (Aguilar et al., 2007). The gender dimension of the mitigation options is described in depth in the Section 6.4 of this report.

4.2. Avoided deforestation (AVD)

Reducing deforestation and forest degradation amounts to conserving existing carbon pools in forest vegetation and soil by avoiding tree cover loss and disturbance. It implies avoiding the conversion of forest to non-forest land use, often produced by clearing land for agricultural purposes (to grow crops like palm oil or to create pasture for livestock), but also for extractive industries, infrastructures, or urban settlements. The rate of net forest loss has decreased since 1990, a result of reduced deforestation in some countries and forest gains in others.

As such, the mitigation measure is particularly relevant for naturally regenerated forests and forest plantations subject to conversion due to a variety of drivers. The drivers can include commercial and subsistence agriculture, mining, or urban expansion. Through the drivers mediated by international trade and globalisation, reducing deforestation can be scaled up not only by protecting existing forest but also through measures regulating the demand of products originating from areas prone to deforestation. Traditional approaches have included activities such as conservation policies, establishment of protected areas, law enforcement, improved

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land tenure, REDD+², sustainable commodity production, improved supply chain transparency, procurement policies, commodity certification, cleaner cookstoves, etc. A meta-analysis has revealed that higher agricultural prices were a key driver of deforestation, while law enforcement, area protection, and ecosystem services payments were found to be important drivers of reduced deforestation (Busch & Ferretti-Gallon, 2017).

Establishing the full potential of reducing deforestation depends on the baseline deforestation dynamic, which partially explains why potential estimates can vary substantially. According to the IPCC SRCCL, reducing deforestation and forest degradation have an estimated technical mitigation potential of 0.41–5.80 GtCO₂.yr⁻¹ which is the largest potential for reducing AFOLU emissions (Jia et al., 2019).

The land use impact of reducing deforestation is directly influenced by its complex and non-linear interactions with agriculture. The competition between the two land uses implies an opportunity cost of conversing forests related to the crops that would have been grown in the area. Furthermore, reducing deforestation can have leakage effects, as an improved regulation in a country could lead to a displacement of the deforestation to a neighbouring territory (Ingalls et al., 2018). Studies have shown that transboundary displacement emerges as a structural limitation in the REDD+ framework. This has also been observed in the case of supply chain management, in particular for the Amazon Soy Moratorium where deforestation was displaced from the Amazon to the Cerrado (Moffette & Gibbs, 2021). Similarly, very high leakage rates (60% to 100%) have been observed in Norway, where the change in the national roundwood harvest were offset by opposite change in the rest of the world (I. Kallio & Solberg, 2018).

Reducing deforestation provides numerous and substantial co-benefits, preserving biodiversity and ecosystem services (e.g., air and water filtration, water cycling, nutrient cycling, soil protection against erosion) more effectively and at lower costs than afforestation/reforestation (Jia et al., 2019). It also allows for the continued provision of timber, fuelwood, and non-timber forest products (NTFPs) which contribute to economic security and livelihood. Yet, reducing deforestation also implies trade-offs. For instance, if safeguards are not adequately implemented, it could cause conflicts regarding property and tenure rights, inequitable distribution of benefits, negative livelihood impacts, and the expansion of other socioeconomic conflicts (Löv, 2020). When deforestation and degradation are halted, it may take many decades to fully recover the biomass initially present in native ecosystems. The measure also faces barriers to implementation such as unclear land tenure, weak environmental governance, insufficient funds, and increasing pressures associated to agriculture conversion, resource exploitation and infrastructure development.

The cost of AVD ranges from 0-100 USD.tCO₂⁻¹ (Nabuurs et al., 2022). Most of the mitigation potential lies within the 0-20 USD.tCO₂⁻¹, including through payment for ecosystem services (PES) schemes and REDD+. Analyses of the costs of REDD+ have focused on the opportunity costs of foregone alternative uses of forest land. However, a pan-tropical study which explored patterns in implementation costs revealed that many organisations involved in the

² The **REDD+ Framework** (Reducing emissions from deforestation and forest degradation in developing countries) is a voluntary climate change mitigation framework established by the United Nations Framework Convention on Climate Change (UNFCCC) aiming to encourage developing countries to reduce emissions and enhance removals of greenhouse gases through a variety of forest management options (reducing emissions from deforestation and forest degradation, conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks).

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implementation of REDD+ are bearing implementation costs not covered by the budgets of the REDD+ initiatives. Thus, while reduced deforestation is often seen as a cheap mitigation measure, implementation bears higher transaction and implementation costs than expected (Luttrell et al., 2018).

Forest conservation activities could provide 2–3 million potential jobs at global level (Nair & Rutt, 2009). However, job creation in forests directly compete with other sectors, as employment in mining sector or in agriculture for instance are still dependent on forest clearing and deforestation in many regions. Payment for ecosystem services schemes attempt to internalize natural resources that have been externalised from the accumulation economy. The market-based instruments that have been deployed to avoid deforestation have been associated with social risks and impacts. A market-based approach could exclude local communities by restricting their non-market livelihood activities (Löw, 2020). The accumulation of interventions and the anticipated arrival of REDD+ benefits may amplify the land grabbing and provoke new conflicts. The REDD+ Framework can favour the emergence of private actors and diminish the State's responsibility for the preservation of its forests and its support to communities. This trend modifies the conditions of access to the land and contributes to the dispossession of lands, creating a "green-grabbing" phenomenon.

5. Sectoral pathways

The mitigation options included in the sectoral modelling exercise cover both afforestation/reforestation and avoided deforestation. This section presents the main results of the scenarios, focusing on the mitigation potential, land use change (LUC) emissions, land allocation, non-CO₂ emissions and food price evolutions associated with the scenarios.

5.1. Forest emissions

In 2015, the calibration year, the forest is a net source of CO₂ with 1183 MtC emitted. In historical series, a high peak is observed in 2015, caused by the shifts of vast areas of unmanaged forests and unmanaged pasture to managed forests and managed pasture, respectively. The average emissions from forests between 1990 and 2015 is 899 MtC. The climate policy is initiated in 2020. In the reference scenario, the forest emissions continue the trend of a historical decrease but remain positive from 2020 to 2050 with an average value of 263 MtC.yr⁻¹ (Figure 4). From 2025 onwards, a declining trend is observed. The forest emissions decline from 313 in 2030 to 186 MtC.yr⁻¹ in 2050, explained by the carbon sequestration from the forest gains.

In the unconstrained scenario (*Uncons*), the implementation of the land tax increases the competitiveness of land uses with high carbon stocks which pushes down LUC emissions. They become negative with an average value of -418 MtC.yr⁻¹ from 2020 to 2050, the lowest average across all scenarios. By the first period of the time period, in 2020, emissions drop to -719 MtC.yr⁻¹. In the scenario constrained by all constraints (*Cons_All*), the introduction of the land tax has the lowest impact on LUC emissions. The forest emissions are higher compared to other mitigation scenarios with an average value of 109 MtC.yr⁻¹ from 2020 to 2050. In other words, the constraints of *Cons_All* lead to forest emission levels closer to the reference scenario than to the *Uncons* scenario, causing a large reduction of the impact of the climate policy of LUC emissions.

In the scenario without the constraint on biomass energy production (*Cons_NoBiomass*), the climate policy results in a decrease in forest emissions, with a lower average value of 32 MtC.yr⁻¹ from 2020 to 2050. In the scenario without the constraint on fallow land conversion (*Cons_NoFallow*), the land tax implementation leads to a reduction in LUC emissions with an average value of 19 MtC.yr⁻¹ from 2020 to 2050. In the scenario without constraint on forestland expansion (*Cons_NoForest*), the implementation of the land tax has a significantly reduced impact on the decrease in LUC emissions. These emissions have an average value of -19 MtC.yr⁻¹ from 2020 to 2050. Thus, *Uncons* and *Cons_NoForest* are the only scenarios where forests are global sinks of CO₂, with a negative average emission level between 2020 and 2050.

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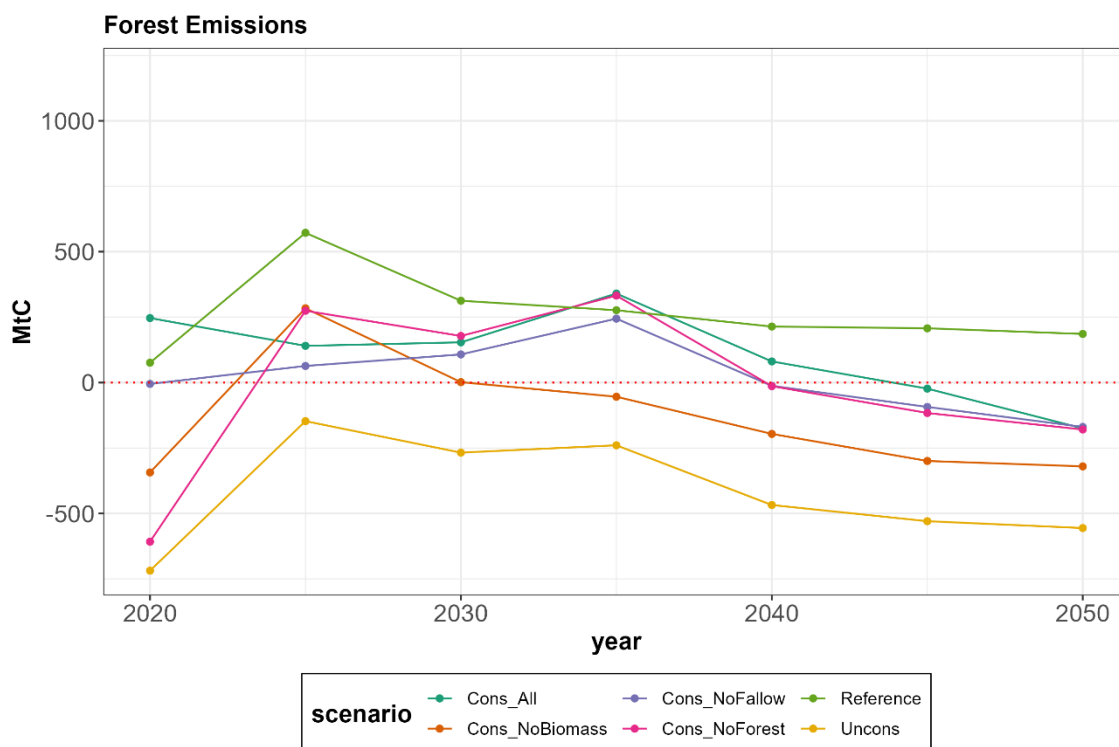


Figure 4: Forest carbon emissions (MtC) from 2020 to 2050 for the reference (Reference), unconstrained (Uncons) and constrained (Cons_All, Cons_NoBiomass, Cons_NoForest, Cons_NoFallow) scenarios

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5.2. Mitigation potential

Our results show the mitigation potential of the climate policy through its effects on the forestry sector (A/R and AVD) under different constraints. The mitigation potential is estimated by comparing the forest emissions of the mitigation scenario with the reference scenario and differentiating between A/R and AVD. For each scenario, the section first shows the global mitigation potentials before reviewing the regional results for each scenario. The mitigation potential of each measure for the five mitigation scenarios, as illustrated in Figure 5, demonstrates the following main results:

- The scenario with the lowest mitigation potential is *Cons_All* with 305 MtCO₂.yr⁻¹. This scenario has a negative potential of -44 MtCO₂.yr⁻¹ for AVD, meaning that under all constraints, deforestation is higher than in the reference scenario.
- The scenario with the fourth greater mitigation potential is *Cons_NoFallow* with 502 MtCO₂.yr⁻¹ where 77% comes from A/R and 23% from AVD.
- The scenario with the third greater mitigation potential is *Cons_NoForest* with 571 GtCO₂.yr⁻¹. Like in *Cons_All* the scenario has a negative potential for AVD of -51 MtCO₂.yr⁻¹.
- The scenario with the second highest mitigation potential is *Cons_NoBiomass* conversion with 759 MtCO₂.yr⁻¹ where 53% comes from A/R and 47% from AVD.
- The scenario with the highest mitigation potential is *Uncons* with 1335 MtCO₂.yr⁻¹, where 59% comes from A/R and 41% from AVD.

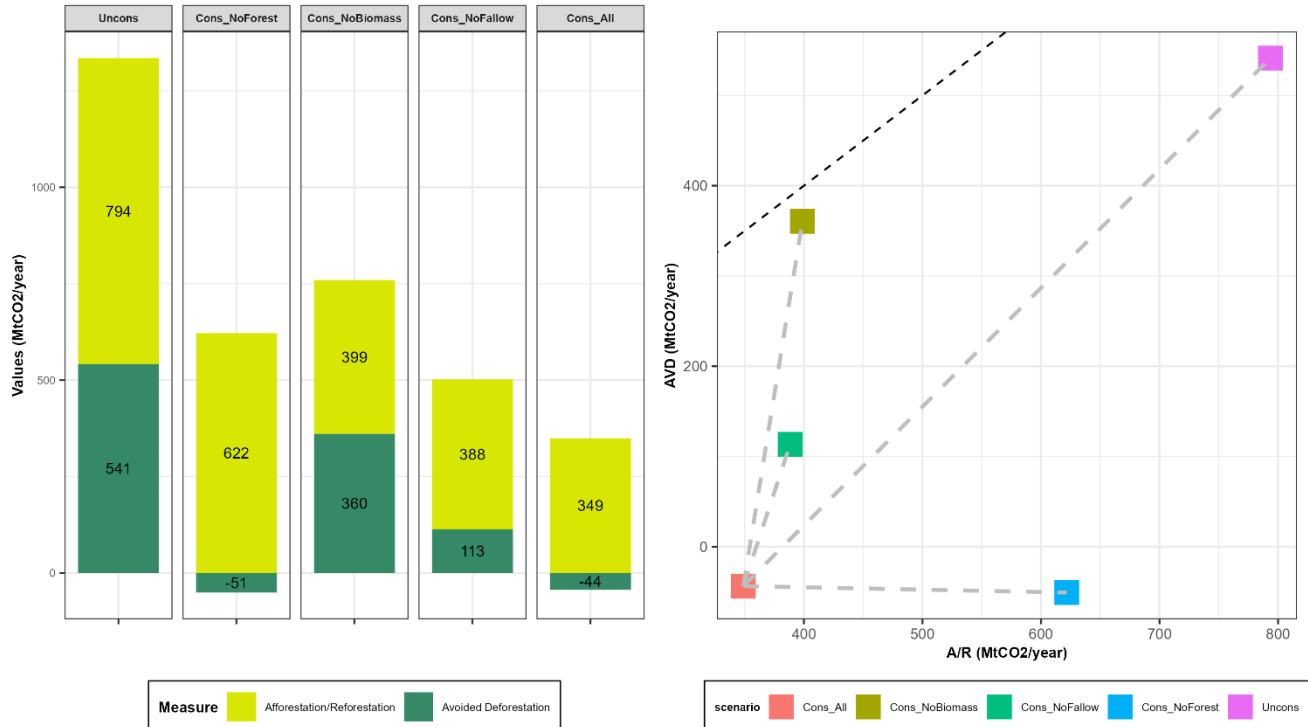


Figure 5: Average annual mitigation potential of 2020 to 2050 for the reference, the unconstrained and constrained scenarios.

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In order to estimate the mitigation potential from forests while accounting for the carbon emissions from land use replaced by forests (in the case of A/R) and of land uses that would have replaced forests (in the case of AVD), we subtracted from the first-order LUC the potentials of the second-order LUC (see Section 3.3 for methodological details) (Figure 6). These results demonstrate for A/R that in all mitigation scenarios, a large proportion of the mitigation potential from forest growth is offset by the carbon dynamic of the land uses that they replace. This can be explained by the high carbon content of the replaced land, such as grasslands and pasture, which can hold important stocks of below ground soil carbon. For AVD, similarly the potentials are reduced by accounting for the carbon absorptions of the land uses that would have replaced forests in the reference scenario. In mitigation scenarios with negative potentials for AVD (under high biomass demand, *Cons_All* and *Cons_NoForest*), the potentials are almost entirely compensated by the fast growth rates and high yields of bioenergy crops.

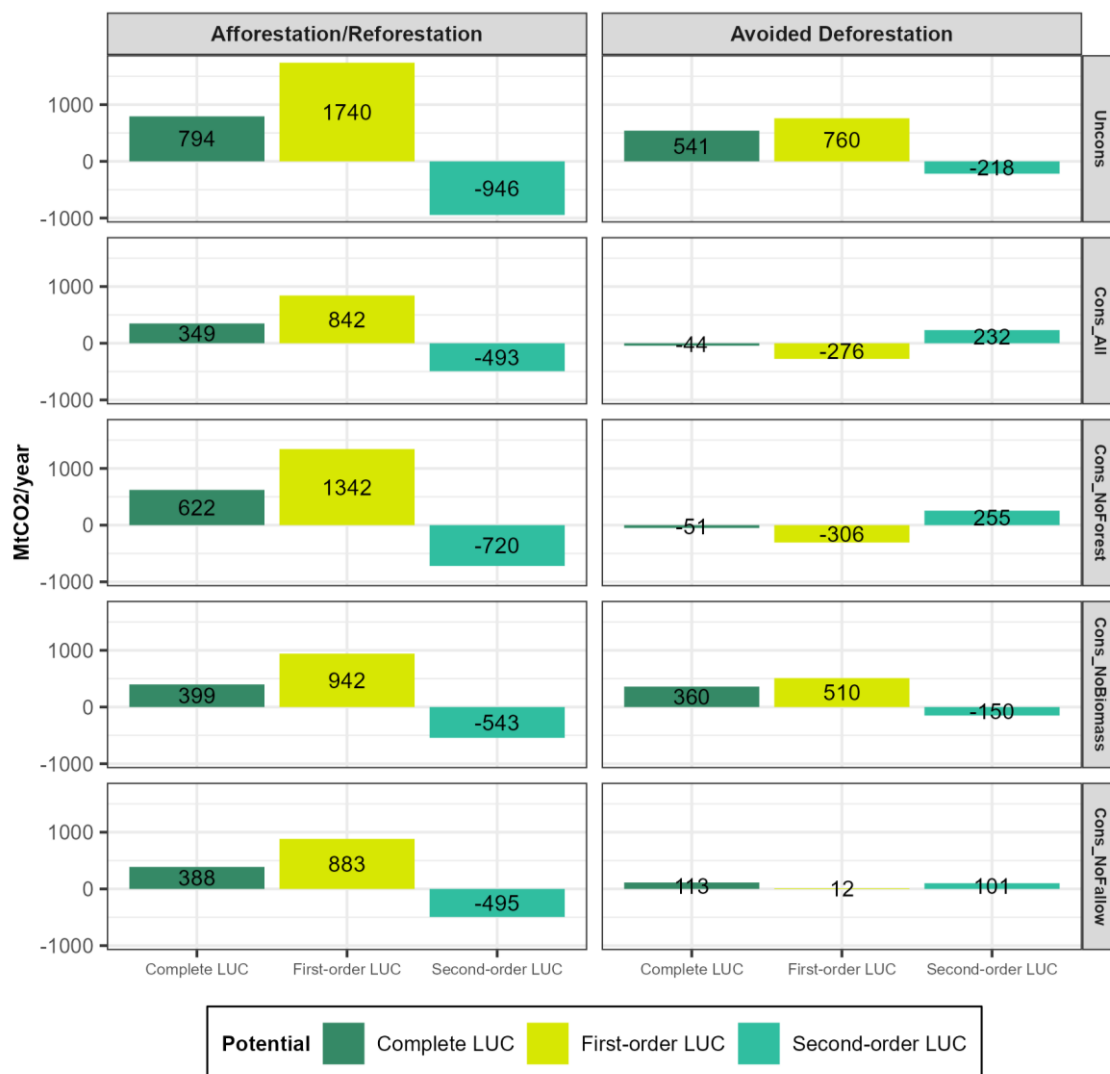


Figure 6: Mitigation potential from first-order LUC emissions, second-order LUC emissions and all land uses (Complete LUC) per mitigation measures and per scenarios

Mitigation potential of forest-based measures under constraining factors

While accounting for emissions from replaced or replacing land uses allows for a *spatial* completeness of the estimates, reporting the potentials beyond 2050 up to 2100 ensures the *temporal* completeness. Vegetation planted prior to 2050 which did not reach maturity by then will continue to sequester carbon while soils also follow non-linear carbon dynamics spanning several decades. Yet, because the resulting absorptions could originate both from newly planted forests (A/R) or from forests which were not deforested (AVD), we do not differentiate between the mitigation options (Figure 7) and report these emissions for informative purposes.

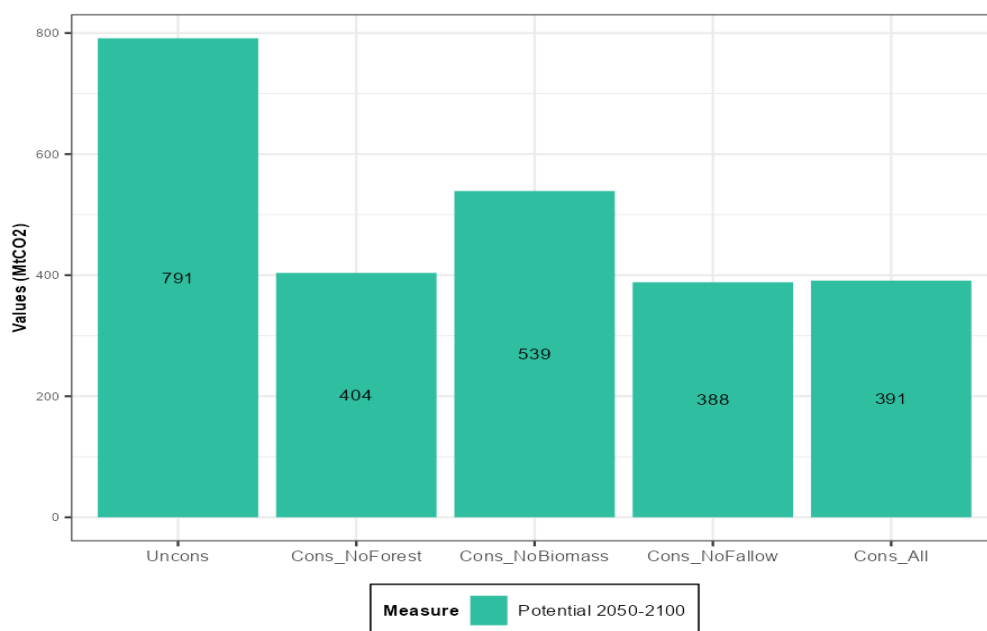


Figure 7: Mitigation potential from residual vegetation growth and soil absorptions from 2050 to 2100 per scenarios

The global results aggregate the values from the ten IPCC regions. Figure 8 illustrates the mitigation potentials of A/R and AVD in each of these regions, exposing the high variability both in absolute values and in the impacts of the constraints. The following sections summarize the main findings for each mitigation scenario.

Mitigation potential of forest-based measures under constraining factors

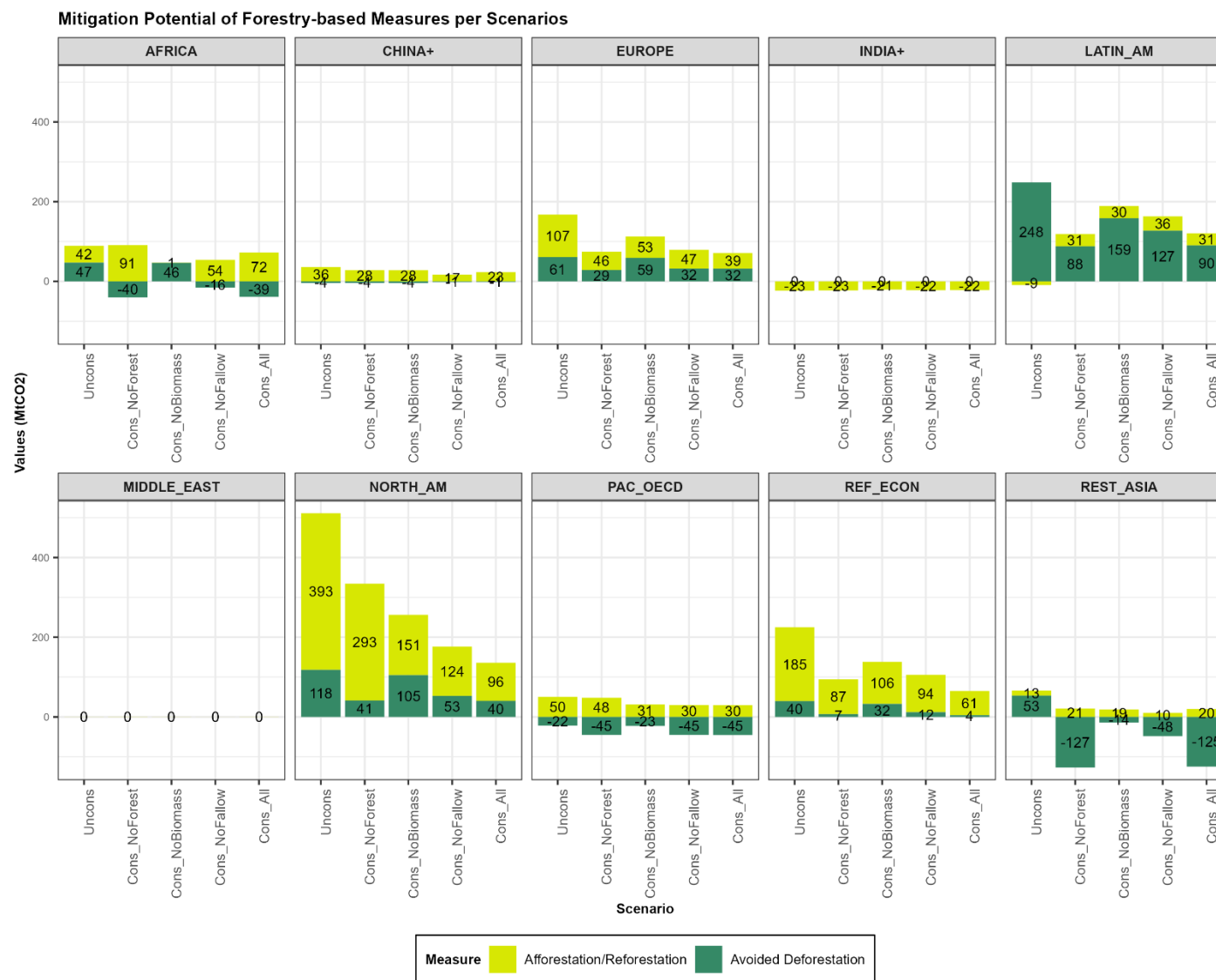


Figure 8: Mitigation potential per scenarios in the IPCC +10 Regions

Mitigation potential of forest-based measures under constraining factors

5.2.1. *Cons_All: Scenario with all constraints*

The *Cons_All* scenario has the lowest mitigation potential due to cumulative impact of constraints on land expansion/conversion rates and bioenergy policy (Figure 9). Concerning A/R, the scenario shows that most of the potential is geographically located in high latitudes: Europe, North America and Russia (Ref_Econ). The results show that under these multiple constraints, regions like India and Latin America could have reduced A/R potentials compared to the reference scenario. Concerning AVD, Latin America provides the highest potential due to the high deforestation occurring in the Amazon basin in the reference scenario. However, in Indonesia (Rest_Asia), the scenario causes high level of deforestation, mostly driven by the allocation of large areas for biomass production.

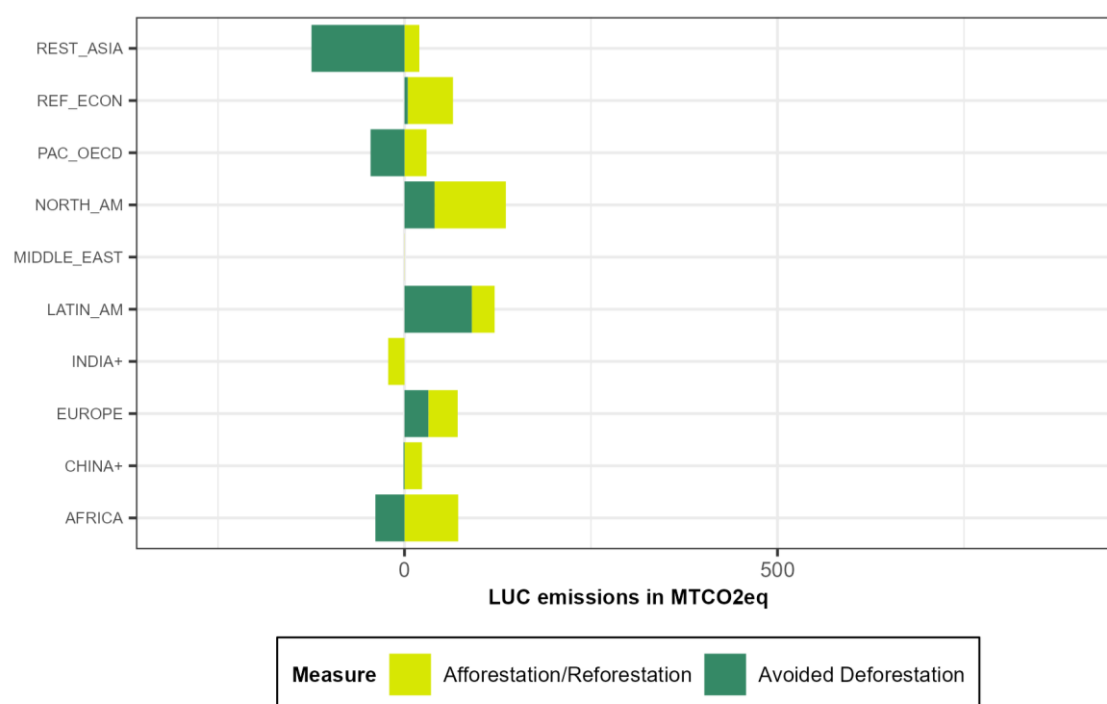


Figure 9: Average annual mitigation potential of *Cons_All* from 2020 to 2050 per IPCC region

Mitigation potential of forest-based measures under constraining factors

5.2.2. *Cons_NoBiomass: Removing the biomass demand constraint*

In the *Cons_NoBiomass*, all the constraints are applied except the high global demand for biomass to produce bioenergy (Figure 10). In this scenario, the land competition is lower than in the *Cons_All*, with marked regional implications. The results show that releasing the constraint increases the potential of AVD, demonstrating how biomass production could lead to high levels of deforestation in specific regions. The four regions with highest potentials are also impacted, as we see important potential increases in North America, Latin America, Russia and Europe. The case of Indonesia further demonstrates the trade-off: from a region with net deforestation in *Cons_All* with $-125 \text{ MtCO}_2\text{yr}^{-1}$, the potential of AVD reduces this negative potential to $-14 \text{ MtCO}_2\text{yr}^{-1}$ in *Cons_NoBiomass*. In Africa, only *Cons_NoBiomass* and *Uncons* have positive mitigation potentials from AVD. Natural forests with high carbon stocks spatially coincide with regions with high biomass productivity, suggesting that these trade-offs should be carefully addressed in the future NDCs and sectoral climate policies.

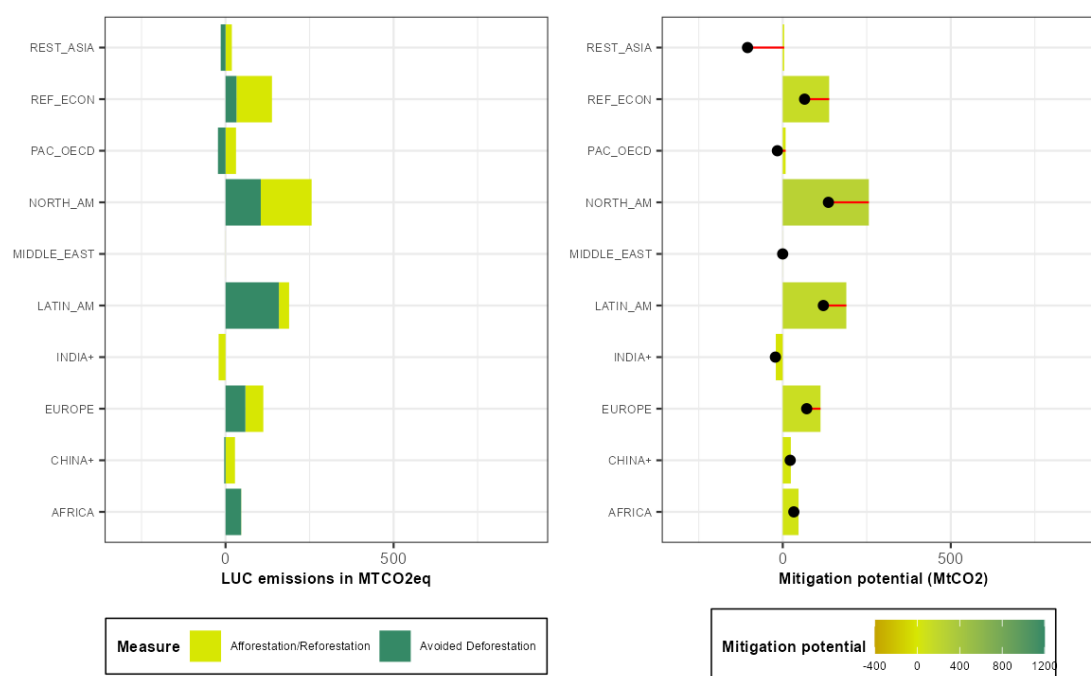


Figure 10: Average annual mitigation potential of *Cons_NoBiomass* from 2020 to 2050 per IPCC region (left panel) and difference with the mitigation potential of *Cons_All* (right panel; block dots are the potential of *Cons_All* and red lines represent the change between the two scenarios).

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5.2.3. *Cons_NoForest: Removing the forest expansion constraint*

The *Cons_NoForest* illustrates the impact of allowing for rates of forestland expansion higher than historically-observed expansion rates of palm oil in Indonesia and soybean in Brazil (0.4% of agricultural land per year). In that scenario, forest expansion is driven by their increased profitability due to the climate policy without encountering limits to how fast agricultural land is converted to forests. Thus, vast areas of agricultural land are converted to forests as landowners are incentivised to increase the stock of carbon on their parcels. North America is the region with the highest forest expansion and hence highest mitigation potential from A/R, followed by Russia (Ref_Econ) and Africa (Figure 11). North America is also the region most impacted by the release of the constraint: in water basins like Nelson in Canada, the extensive forest expansion compared to *Cons_All* explains the differences. In such basins, the proportion of forest related to agriculture land is large and hence, the limited rate of 0.4% of agricultural land per year is stricter in relative terms compared to other basins with more balanced proportion of forests and agricultural land.

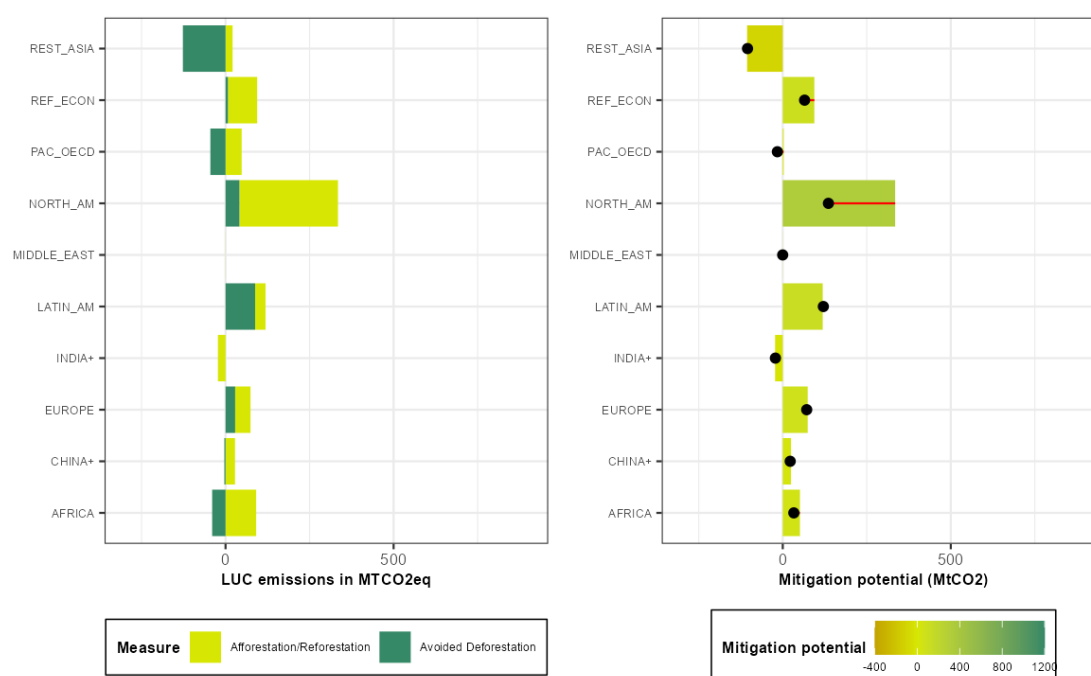


Figure 11: Average annual mitigation potential of *Cons_NoForest* from 2020 to 2050 per IPCC region (left panel) and difference with the mitigation potential of *Cons_All* (right panel; block dots are the potential of *Cons_All* and red lines represent the change between the two scenarios).

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5.2.4. *Cons_NoFallow: Removing the fallow land conversion constraint*

In the *Cons_NoFallow*, the constraint on fallow land conversion is removed which enables a larger proportion of fallow land to be used by the model for the expansion of forest every year (Figure 12). While fallow land is sometimes assumed to be readily available land for land use policies such as A/R, fallow land is often used in crop rotations or regulated by specific policies which prevent high rates of conversions to other land uses. While the high biomass demand and the limited forest expansion impacted AVD and A/R disproportionately, the fallow land conversion has a smaller but more balanced impact on the mitigation potential of the two forestry-based measures. Removing the constraint increases the potential in North America, Latin America and Russia. The strongest impact is in Indonesia (Rest_Asia) where fallow land has historically increased rather than decreased. This suggests that, on the one hand, fallow land can provide an important proportion of the land uses which are afforested, and on the other hand, that fallow land availability for biomass and other crops is an important factor influencing deforestation in scenarios with high land competition.

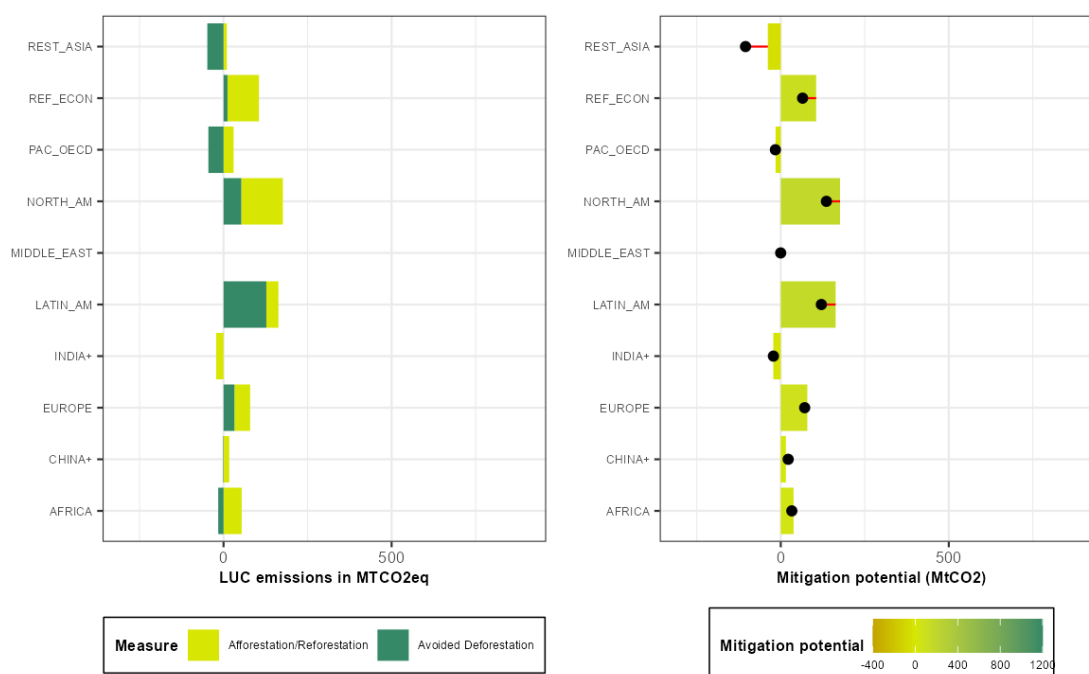


Figure 12: Average annual mitigation potential of *Cons_NoFallow* from 2020 to 2050 per IPCC region (left panel) and difference with the mitigation potential of *Cons_All* (right panel; block dots are the potential of *Cons_All* and red lines represent the change between the two scenarios).

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5.2.5. *Uncons: Removing all constraints*

In the *Uncons* scenario, the results show the impact of removing all the constraints on the mitigation potential of both A/R and AVD. Both measures have greater potential, but the causes and the spatial distribution of these increases are highly differentiated (Figure 13). First, the diminished land competition caused by the lower global demand for biomass prevents high levels of deforestation observed in Indonesia. Second, unconstrained rates of forestland expansion increase the potential of A/R in northern latitudes, but also in Latin America and Africa where the constraints prevented an increase in forest area compared to reference scenario. As a consequence, the potentials are higher in almost all regions except India and China, where the climate policy has a limited impact on the land use change of forests.

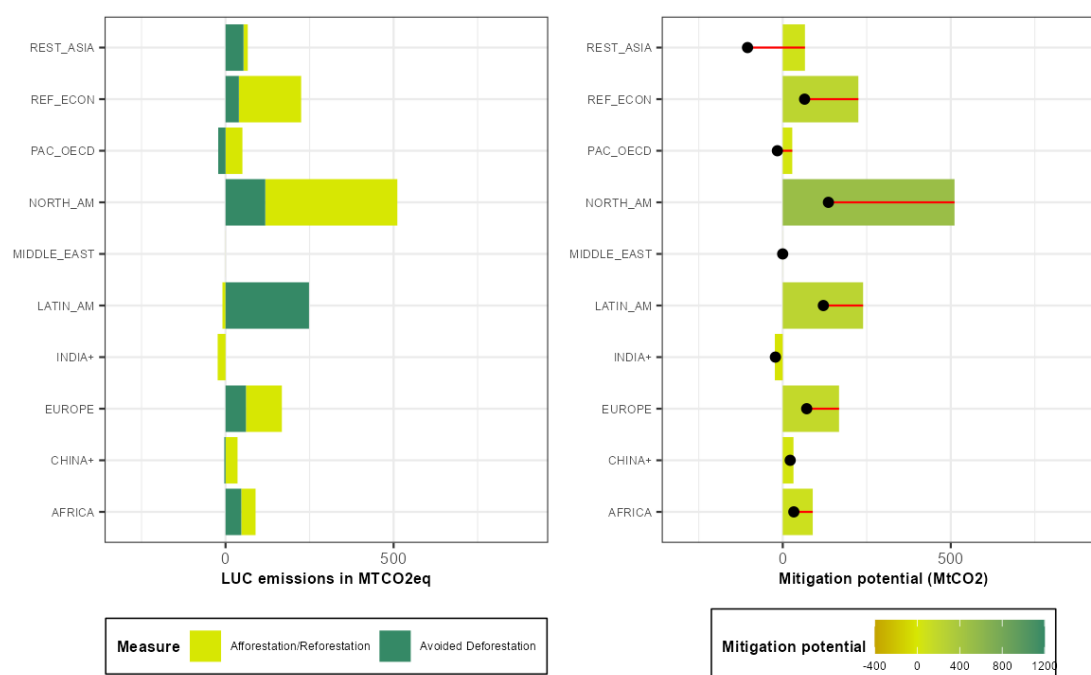


Figure 13: Average annual mitigation potential of Uncons from 2020 to 2050 per IPCC region (left panel) and difference with the mitigation potential of Cons_All (right panel; block dots are the potential of Cons_All and red lines represent the change between the two scenarios).

Mitigation potential of forest-based measures under constraining factors

5.3. Land allocation

5.3.1. Area per MO and mitigation intensity

Land use change emissions are directly driven by changes in land allocation. The differences between the mitigation potentials described above are thus determined by changes in the total area and spatial distributions of the forestry-based measures. Figure 14 shows the average annual areas of A/R and AVD for all the mitigation scenarios.

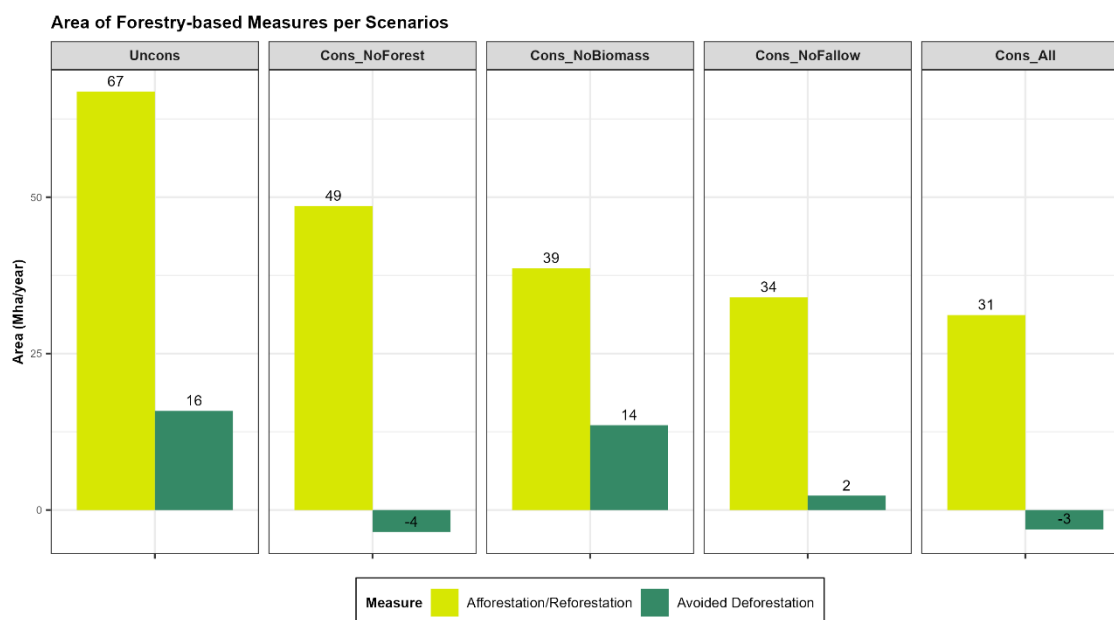


Figure 14: Annual area of forestry-based measures per mitigation scenario

Compared to the patterns observed for mitigation potential, the results for total area change illustrate a similar impact of the constraints: the area under each measure is larger for *Uncons*, lowest for *Cons_All*. The constraint with the greater impact on area of AVD is the high biomass demand (*Cons_NoBiomass*) while the constraint with the highest impact on the area of A/R is the limited rate of forest land expansion (*Cons_NoForest*). The fallow land constraint has smaller impacts but is relevant for both forestry measures (*Cons_NoFallow*).

The results also explain the negative potentials from AVD in *Cons_All* and *Cons_NoForest*. In these scenarios, the constraints cause enough pressure on land systems, especially in Indonesia, to cause higher deforestation than in the reference, of 3 Mha.yr⁻¹ and 4 Mha.yr⁻¹ respectively. As discussed before, while basins like the Brazilian Amazon remain key locations for AVD in these two scenarios, their mitigation potentials are more than compensated by forest loss in other basins, first and foremost Kalimantan and Sumatra, in Indonesia.

Beyond the spatial differences of the constraints' impacts, A/R and AVD also imply different carbon dynamics which explains differences in the mitigation potential per unit of area, an indicator commonly referred to as 'mitigation intensity' or 'mitigation density' (Roe et al. 2021). Our results confirm the higher mitigation intensity of AVD compared to A/R. Figure 15 demonstrates that AVD has in all scenarios a higher capacity to mitigate forestry emissions. It also shows a higher variation around the mean value of 195 tCO₂.ha⁻¹ compared to the mitigation intensity of A/R with mean value of 81 tCO₂.ha⁻¹. While these estimates are lower

Mitigation potential of forest-based measures under constraining factors

than in Roe et al, (2021) which report 316 and 166 tCO₂.ha⁻¹, they confirm that AVD can preserve between 1.9 and 2.4 times more carbon than A/R can sequester.

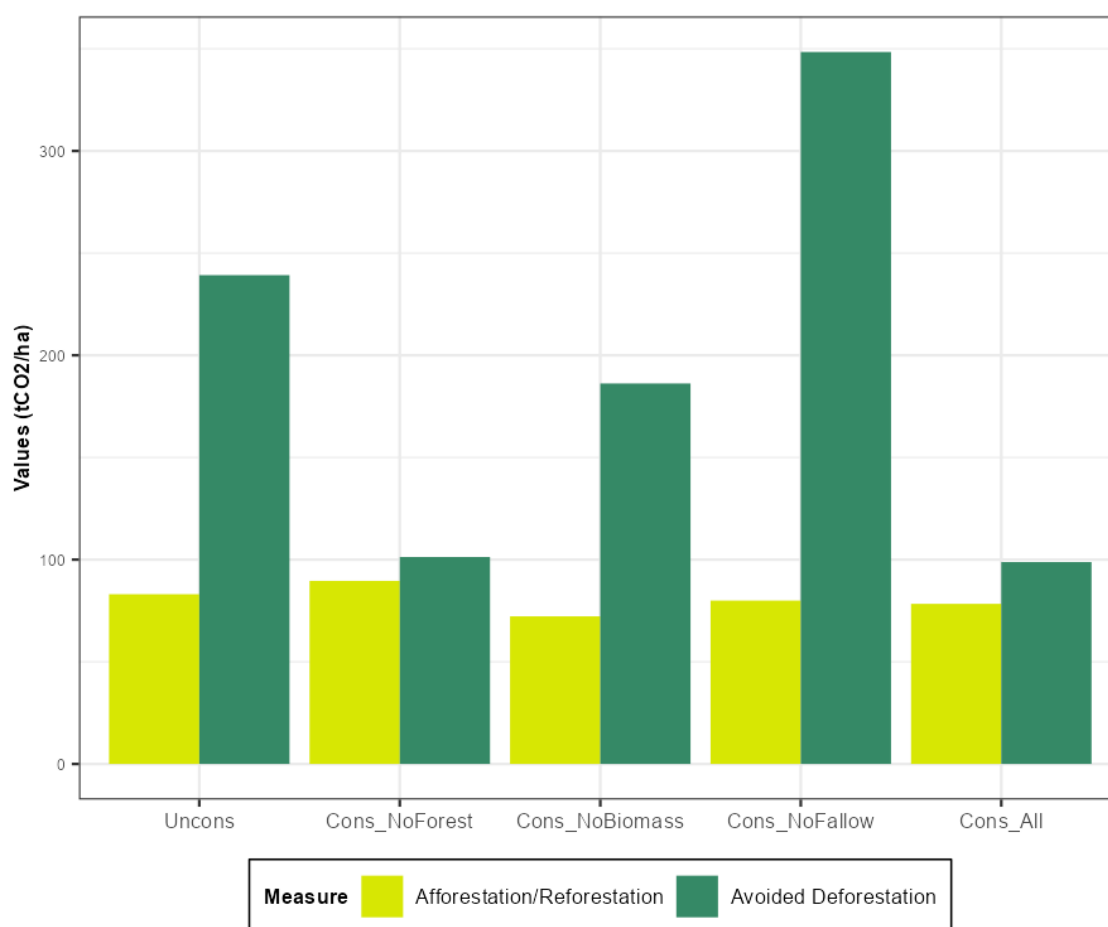


Figure 15: Mitigation intensity (MtCO₂/ha) of measures per scenarios

5.3.2. Global land use change

Globally, the climate policy drives land use changes away from the land use developments of the reference scenario. In the reference, driven by the socio-economic assumptions of SSP2, an expansion of arable land and tree plantations used for biomass is observed. While total forest land also increases to a lesser extent, it is worth noting that unmanaged or natural forests globally decrease, but that the decrease is inferior to the expansion of managed forests. These expansions come at the cost of grassland, shrubland and pasture. Figure 16 illustrates the land use changes for all the mitigation scenarios, estimated as the difference in the area of the land use in 2050 compared to the baseline value in 2020.

Mitigation potential of forest-based measures under constraining factors

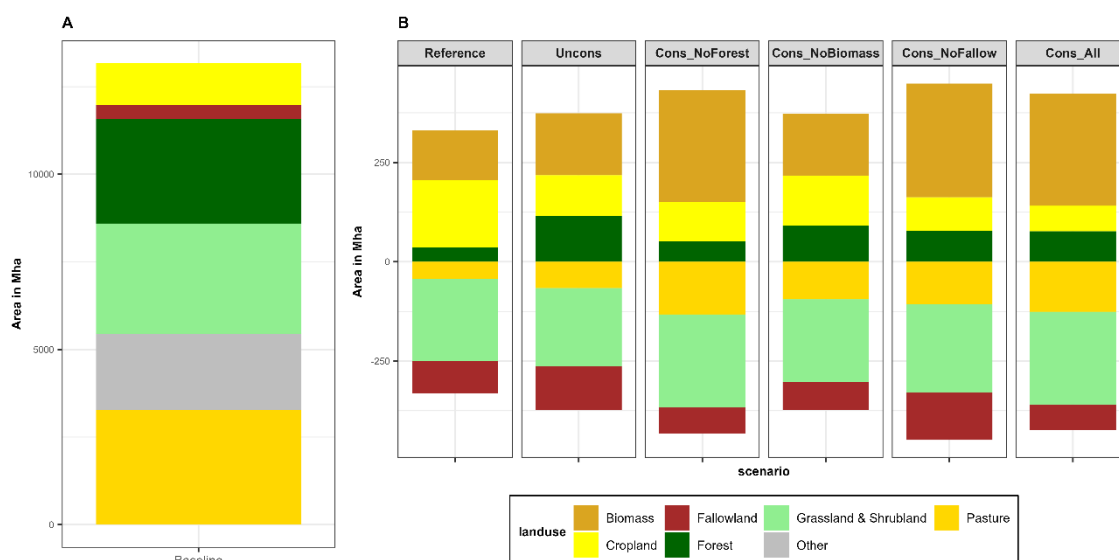


Figure 16: Land allocation in 2020 (A) and land use change relative to 2020 by 2050 for all scenarios (B)

The result shows an increase in forest land in the reference under the SSP2 assumptions. This explains the lower values obtained for AVD compared to other IAMs models, where SPP2 assumptions lead to net forest loss at global scale. One explanation is that GCAM does not fully capture key drivers of deforestation. The land allocation also demonstrates the large rise of biomass production, which starts to develop in the model from 2025 onwards. Scenarios where forestry mitigation is constrained by high biomass demand have a markedly higher expansion of biomass production than scenarios with historic rate of development of bioenergy. The increases in biomass and in forest areas limit the expansion of cropland relative to reference scenario. Across scenarios, the expansion of these three land uses come at the expense of grassland and shrubland, fallow land and to a lesser extent grazed pasture, which is used for livestock production. Loss of grazed pasture can partially explain the rise of livestock product prices, as explained below, along with the GHG tax applied to CH₄ emissions, despite productivity gains from technological improvements. Figure 17 illustrates in more details the temporal evolution of the areas of each land uses for each scenario. The figure clearly exposes the differentiated pathways of forest expansion across scenarios, as well as the marked impact of higher biomass demand and limited fallow land conversion on the global land allocation dynamic.

Mitigation potential of forest-based measures under constraining factors

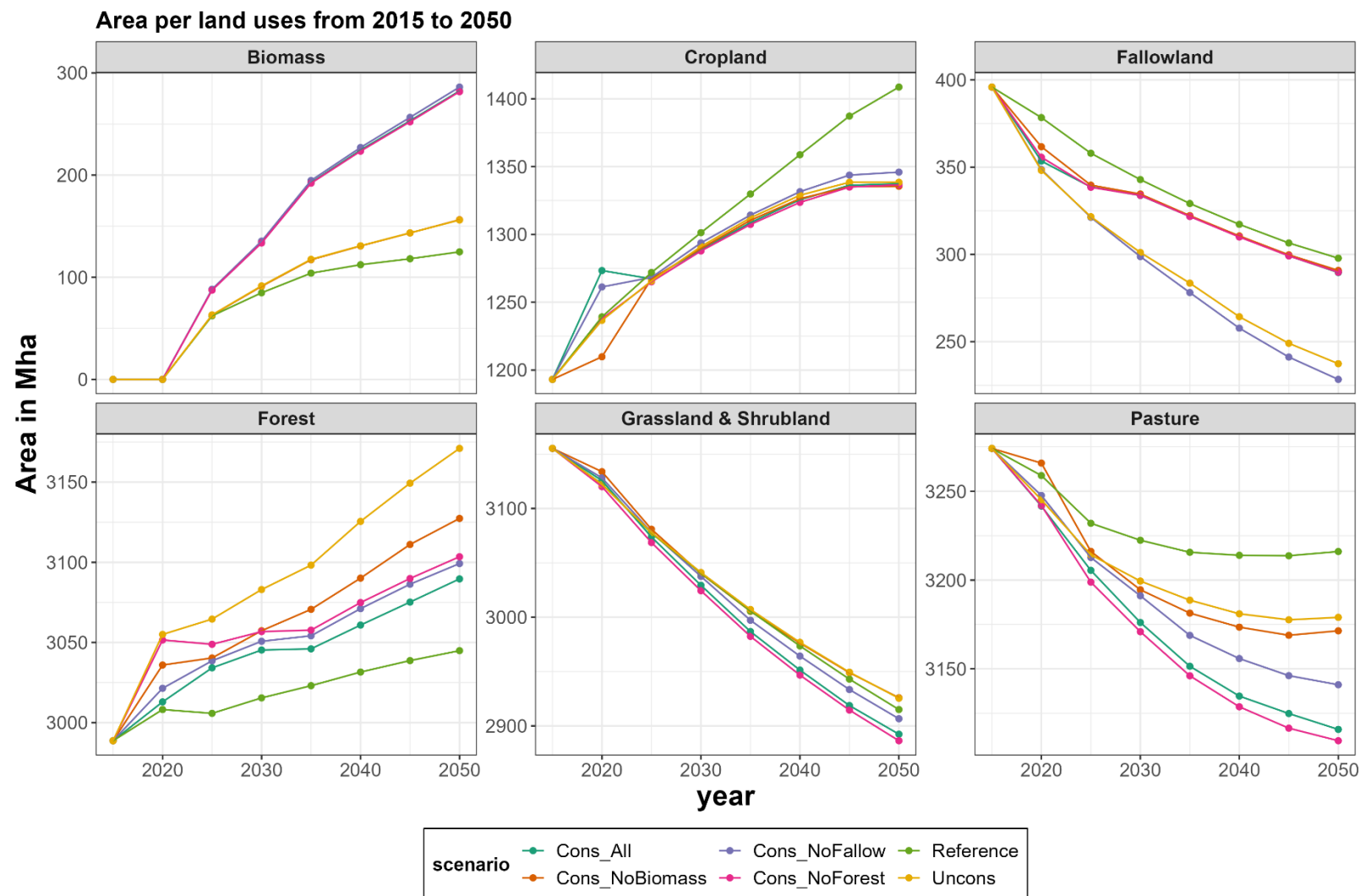


Figure 17: Land allocation of major land uses from 2015 to 2050 for all scenarios

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5.3.3. Land use change in focus regions

Looking at the regional scale reveals the great spatial heterogeneity between the IPCC regions. In absolute terms, Africa is the region that experiences the highest land use changes across scenarios, including in the reference. Mitigation scenarios increase the conversion of pasture, especially under high biomass demand. Africa, China+ and India+ are the three regions where forest increase in the reference scenario, which explains their relatively small mitigation potentials. Europe and North America, however, shifts from a net forest loss to net forest gains thanks to the climate policy in all mitigation scenarios. In Latin America, Indonesia and Southeast Asia, the climate policy, even without constraints, does not change the regional trend of net forest loss.

Indonesia

The land allocation results for Indonesia, which along with Southeast Asia make up the Rest_Asia IPCC region, are marked across scenarios by forest loss, particularly in the basins of Kalimantan and Sumatra. Figure 19 illustrates these land use changes, considering Indonesia only. In the reference scenario, large deforestation and fallow land conversion are caused by rapid expansion of cropland and to a lesser extent of pasture. The climate policy does change substantially the dynamic in the region except for the bioenergy land use. The reference scenario and *Uncons* have the same global bioenergy targets by 2050 (63.6 EJ). Yet, in *Uncons*, substantially more land is allocated to biomass production in Indonesia than in the reference. This suggests that in other regions, bioenergy production is outcompeted by land uses benefiting from the climate policy, first and foremost forest. This leads to a higher allocation of bioenergy in Indonesia, due to its comparative advantage for bioenergy crops like palm oil, and hence a higher proportion of the global demand being met by the land resources of the country.

Europe

A deep dive into the land use change patterns in Europe explain the reasons why the region has a high mitigation potential (Figure 20). In the reference scenario, the conversion of close to 40 Mha of land to produce bioenergy leads to a return of forest loss in Europe, reversing the historic trend of forest growth mentioned in the introduction. Unlike Indonesia, the mitigation scenarios systematically reverse the trend through large-scale implementation of A/R, leading to loss of cropland across the scenarios. However, the results expose the impact of the competition between forests and bioenergy. When global biomass demand is limited to historic rates (*Uncons* and *Cons_NoBiomass*), both land uses grow in similar proportion. Yet, all scenarios with high bioenergy demand provides a comparative advantage to bioenergy which increases the net total land use change in Europe but also limits the expansion of forests and hence their terrestrial carbon stocks.

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Figure 18: Regional land use change by 2050 for the IPCC+10 region

Mitigation potential of forest-based measures under constraining factors

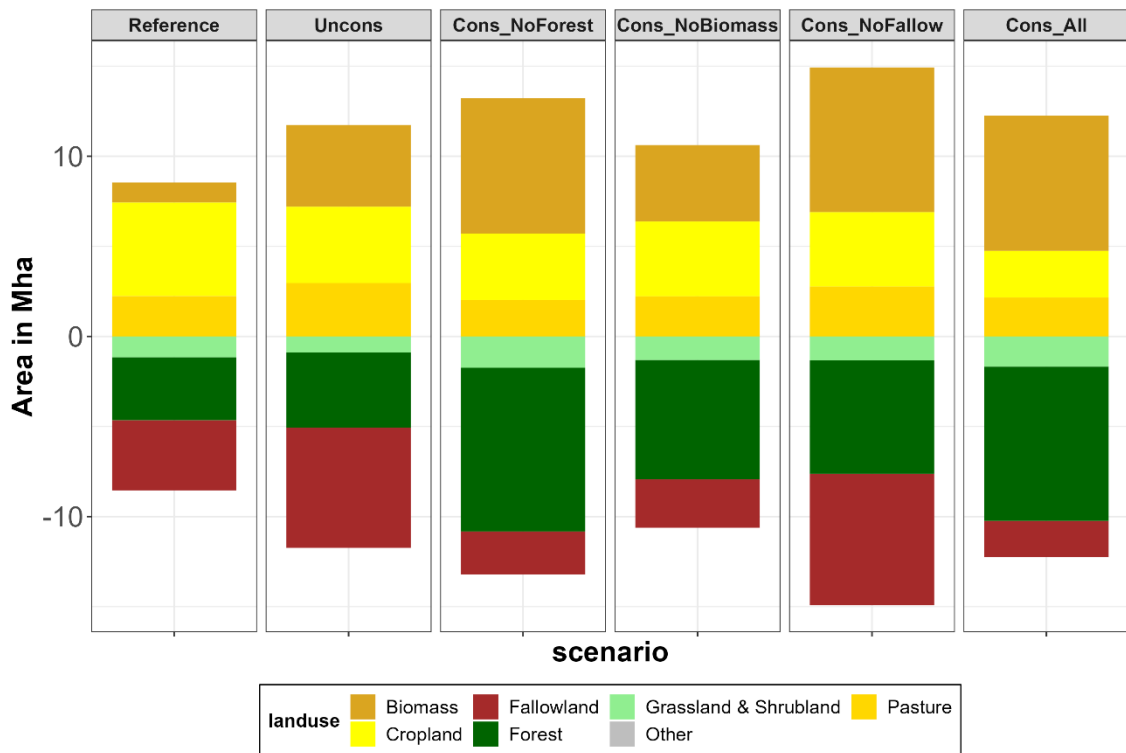


Figure 19: Land use change for all scenarios in Indonesia by 2050

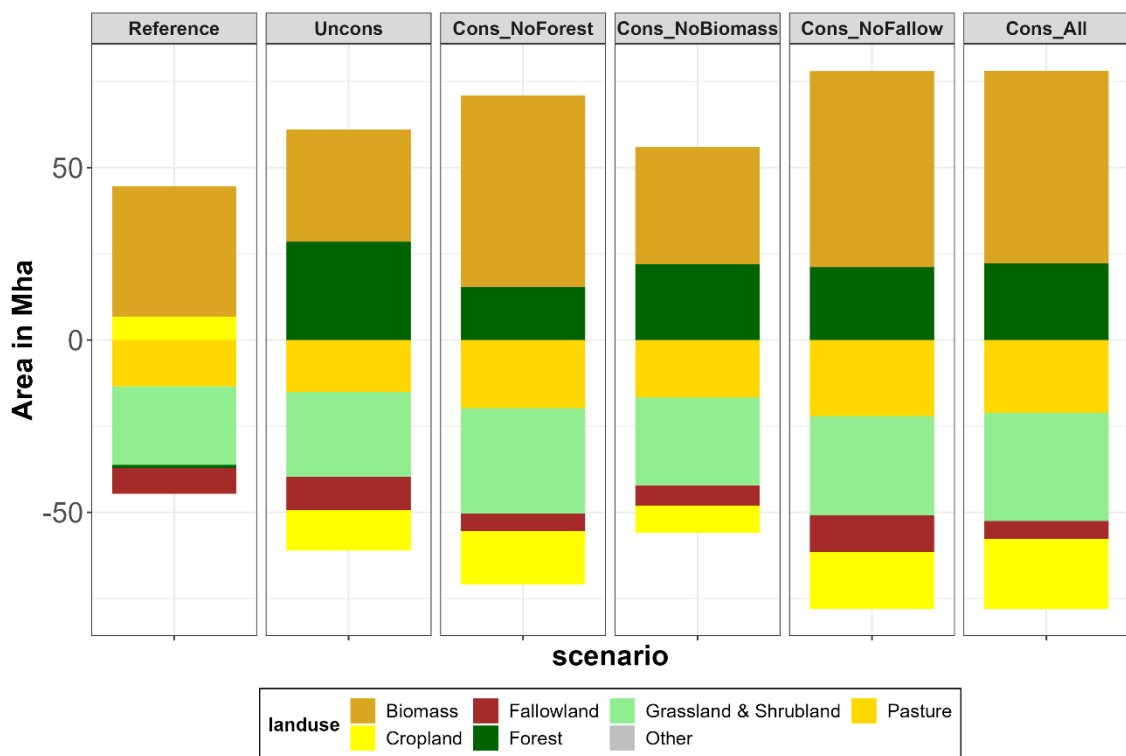


Figure 20: Land use change for all scenarios in Europe by 2050

5.4. Non-CO₂ emissions from agriculture

The climate policy applied the same price to land use CO₂ and to CH₄ and N₂O emitted from agriculture, which results in GHG mitigation from the agricultural sectors (Figure 21). Our results show that the policy has implications for both CH₄ and N₂O emissions from agricultural production, partially driven by the land use changes explained below. On average, the scenarios with the climate mitigation policy mitigates 532 MtCO_{2eq}.yr⁻¹ of CH₄ and 198 MtCO_{2eq}.yr⁻¹ of N₂O. All scenarios with high biomass demand provide lower mitigation of N₂O and CH₄, as fertilisation of biomass production partially compensates the emission gains in the most emitting sectors (soybean, rice, and beef production).

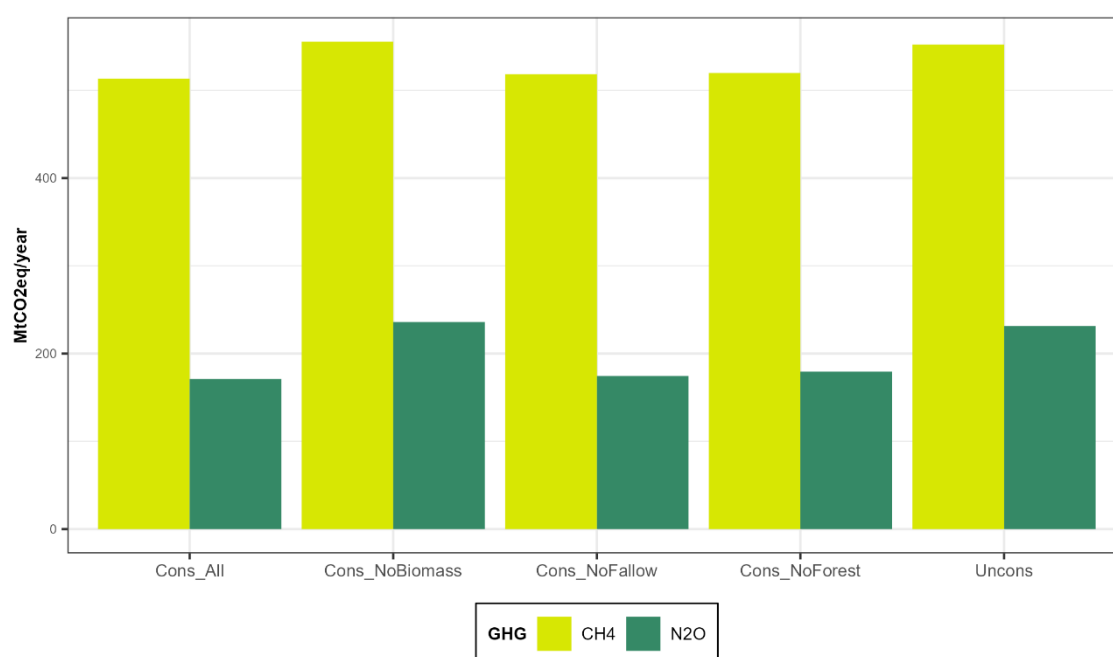


Figure 21: Mitigation potential of CH₄ and N₂O from agriculture per scenarios

The regional impacts are however highly differentiated, marked by the differences in the emitting sectors of each region. Figure 22 shows that despite important variations between regions of the mitigation potential of each GHG, the impacts of the constraints reproduce the patterns observed globally.

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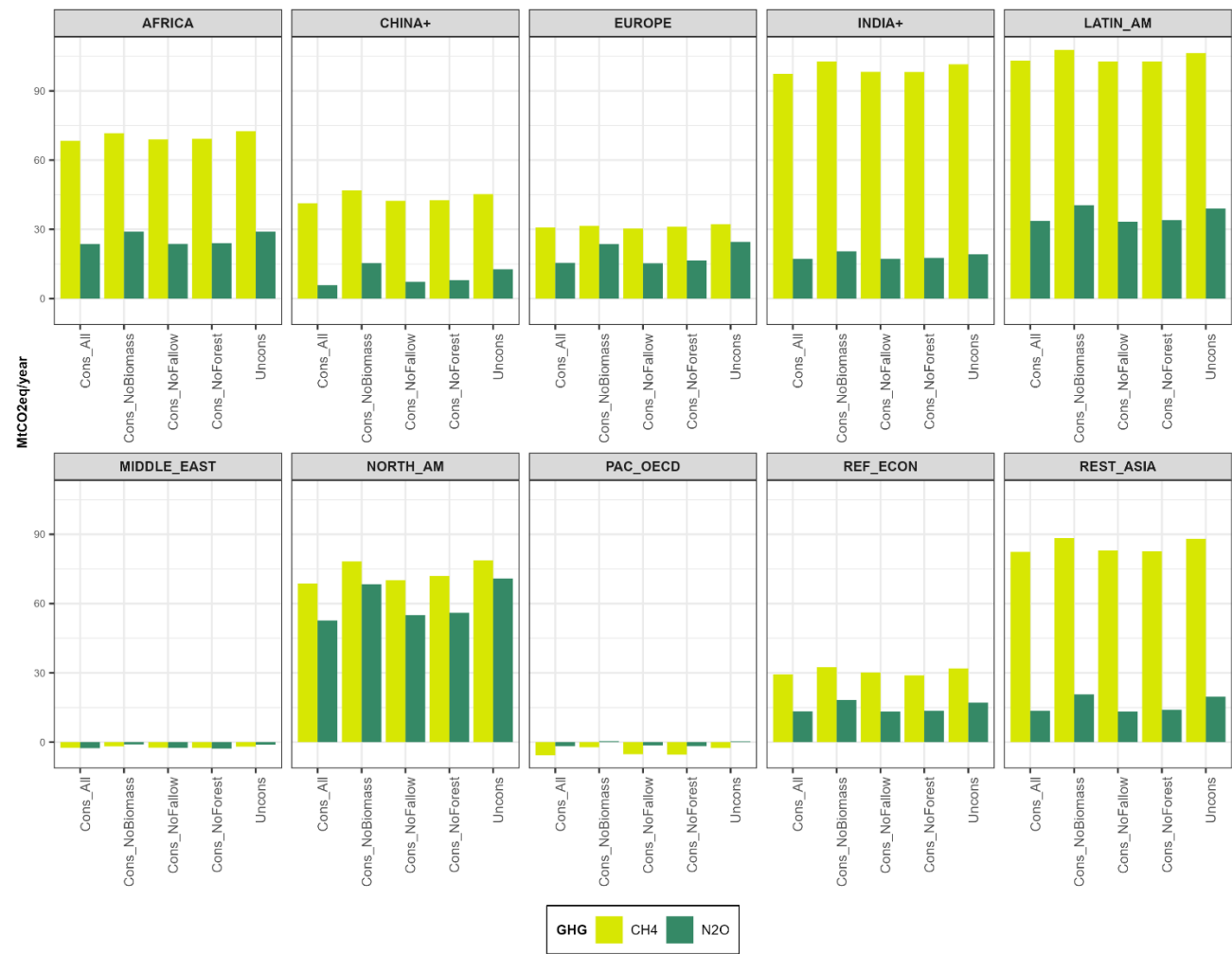


Figure 22: Mitigation potential of CH4 and N2O across the mitigation scenario per IPCC+10 Region

5.5. Food price index

In the reference scenario, global average food price captured FPI increases moderately for agricultural commodities with 102.4 (2020 corresponding to the 100-value of the dimensionless-index) by 2050. The growing demand for food driving prices up is compensated by an expansion of cropland and increases in technological improvement. Under the climate change mitigation scenarios, the land competition of forests limits the potential for cropland expansion, driving down the supply of food and hence increases food prices in all scenarios (Figure 23).

The livestock products are most affected by the climate change policy, with an index of 131 as opposed to 117 for crops in the unconstrained scenario by 2050. The impact can be explained by two processes: first by the large loss of grazed pasture across scenarios, due to the competition from forests and bioenergy; and second by the GHG tax which would penalize the activities with high CH₄ emissions which includes beef and dairy products from livestock.

Constraints marginally increase the impact on food prices. By 2050, for all agricultural commodities, *Uncons* has the minimum value (118), followed by *Cons_NoBiomass* (119), *Cons_NoFallow* (120) and lastly *Cons_NoForest* and *Cons_All* (121). Thus, under the climate policy, high biomass demand and limited fallow land conversion are the constraints with the highest impacts on the food system, through the price transmission from the carbon to the food market. The results hold for both crop and livestock commodities and can have direct consequences on food demand and calorie intake, mediated by price-induced dietary changes.

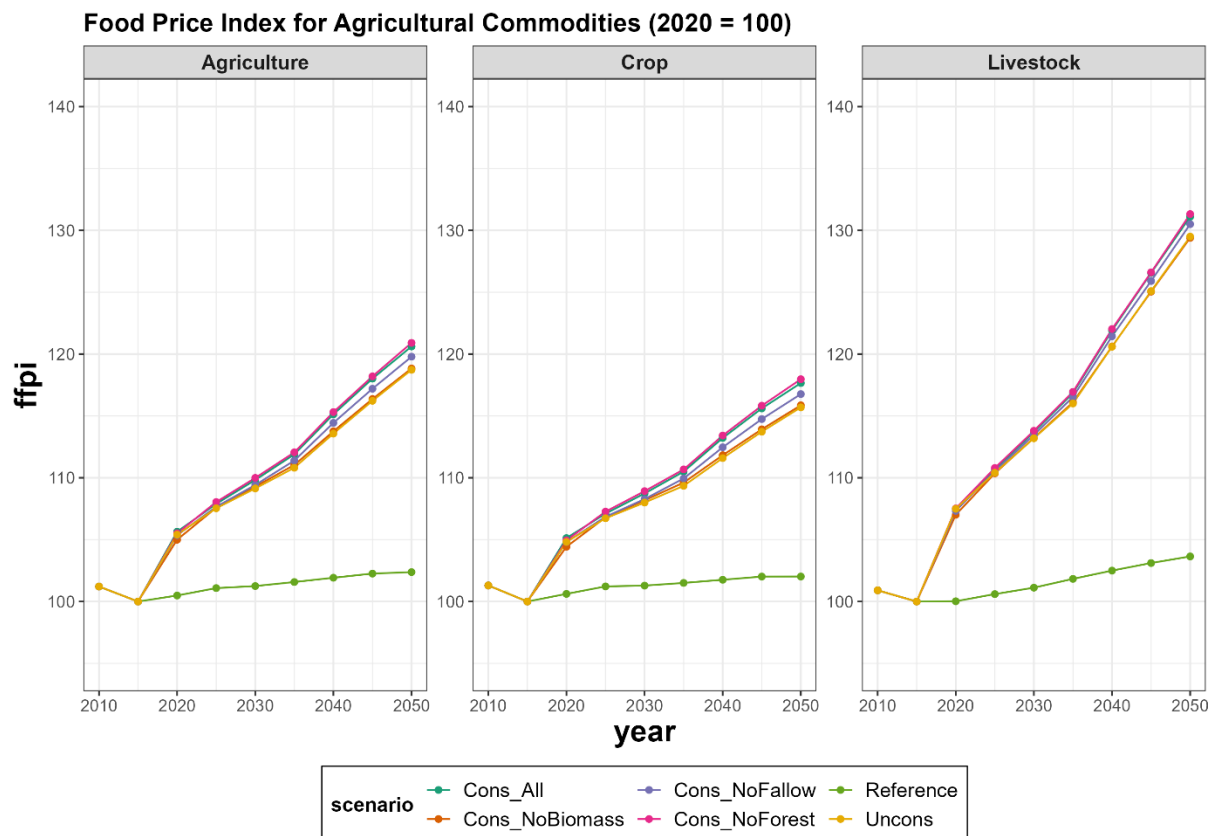


Figure 23: Food price index for agricultural commodities, with differentiation of crops and livestock products

6. Implications for NDCs and other sectors

This section discusses the implications of the results presented above for future NDCs. As shown, while the forestry sector is characterised by high mitigation potential, it also presents high uncertainties which must be considered in NDCs and climate policies. These potentials were obtained through a climate policy including ambitious CO₂ emission reduction in energy and industry as well as a global carbon tax on land emissions. The following sections discuss the implications of the modelling results in light of the complex and non-linear interactions that must be considered for the AFOLU sector in future NDCs.

6.1. Role of A/R and AVD in forestry-based mitigation

The study has focused on A/R and AVD, which are the measures with the greatest mitigation potential of the AFOLU sector. The results have demonstrated the range of mitigation potentials under a set of constraints. Under the three constraints implemented, the mitigation potential from LUC emissions between 2020 and 2050 is 305 MtCO₂.yr⁻¹. Removing the fallow land constraint increases the potential to 501 MtCO₂.yr⁻¹, the forest expansion constraint to 571 MtCO₂.yr⁻¹, and the biomass demand to 759 MtCO₂.yr⁻¹. Removing all constraints increases to mitigation potential to 1335 MtCO₂.yr⁻¹. Thus, considering the constraints can reduce the mitigation potential by more than 77%, global biomass demand being the most impactful factor of the analysis presented above.

The analysis has demonstrated how each constraint impact the measures differently, with great spatial heterogeneity. In our study, while high biomass production mostly limited AVD, constrained forest expansion limited A/R. In previous studies (Griscom et al. 2017; Roe et al. 2021), the potential of A/R is more variable than the potential of AVD. Here, we show that while this might be true in specific regions (e.g., Latin America, where AVD is relatively 'resilient' to the constraints), this finding does not hold on the global scale, where the pressure from bioenergy production contributes to high levels of deforestation (e.g., Indonesia) despite the climate policy applied, especially under limited conversion rates of fallow land. While the literature acknowledges that uncertainty in A/R is due to the large range in existing constrained of potential forest expansion, we show the importance of improved representation of the drivers of deforestation, which is highly conditioned by the evolutions of energy policies (e.g., biomass demand) and land use regulations (e.g., fallow land availability).

However, the modelling did not cover all the interactions and feedbacks between these two measures because of the lack of distinction between different types of forests. Yet, research has shown that reforestation could contribute to offset emissions from deforestation: in the Brazilian Amazon, it was found that secondary forest regrowth offset 9 to 14% of gross emissions due to deforestation (Aragão et al., 2018). However, the regrowth rate of the secondary forests could be reduced by 8% to 55% due to disturbances such as fire and repeated deforestation cycles (Nabuurs et al., 2022). In addition, as high potentials from A/R would occur in northern latitudes, afforestation could cause net warming due to a reduction in albedo (Prevedello et al., 2019). Net climate effects figure among the constraints which are not captured in the results. Recent studies are moving in this direction, such as Jäger et al. (2023) which modelled the impact of fire on forest - climate change feedbacks with five IAMs.

Furthermore, we confirm that AVD has a higher mitigation intensity compared to A/R. On top of conserving a higher carbon stock per unit of area than A/R can sequester, protecting intact ecosystems delivers ecosystem services beyond carbon sequestration and has lower risks of impermanence (Seddon, 2022), as opposed to large-scale A/R projects where monocultures of productive species could hamper biodiversity. According to the "Natural Climate Solutions hierarchy", "protect" measures

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such as AVD have the highest potential for mitigation, followed by land management and lastly restoration, which includes reforestation activities. Future NDCs should therefore account for the climatic, economic and ecological differences between the measures of the forestry sector, accounting for the additional benefits of protecting and conserving existing ecosystems.

6.2. Feedbacks between agriculture and forestry sectors

Expanding the scope to the AFOLU sector as a whole, the results highlight the multiple interactions between forestry and agriculture. The results first demonstrate the importance of considering second-order LUC when estimating mitigation potential from the forestry sector. The carbon densities of land uses replaced by A/R or replacing forest post-deforestation have important implications. The analysis showed that more than half of the potential of A/R could be offset by the carbon lost from the land use transition, suggesting that A/R is projected to occur in land parcels with relatively high amounts of carbon, typically natural grasslands. However, AVD was only partially affected by second-order LUC, suggesting that the replacing land uses have on average lower carbon stocks, such as annual crops. The results thus reveal the importance of considering these indirect land use changes when planning for large-scale deployment of A/R and/or forest protection policies to reduce deforestation.

Furthermore, the results show the impact of protecting and restoring forests on land competition dynamic, as cropland expansion slows down across the mitigation scenarios. The market-mediated effects lead to higher food prices, especially for livestock products. However, there is a broad agreement that actions towards one SDG (e.g., Goal 13: Climate action) should not compromise the efforts on others (e.g., Goal 2: Zero hunger). At the same time, increasing food prices is a main driver of deforestation (Busch & Ferretti-Gallon, 2017) and estimates suggest that between 29 and 39% of emissions from deforestation in the tropics resulted from the international trade of agricultural commodities (Pendrill et al., 2019).

Managing and minimising these unintended consequences across forestry and agriculture sectors highlighted in this study remain major policy challenges. Solutions could come from sustainable intensification of agriculture (SIA), defined by the IPCC as “suggested means of pursuing increased overall production, reducing associated environmental externalities, and potentially releasing agricultural land for alternative uses, such as forestry or rewilding” (Nabuurs et al., 2022). While what constitutes sustainable intensification remains debated, Rockström et al. (2017) summarises it as the task to “produce more food with fewer resources”. SIA has to be contrasted to unsustainable intensification, where the “productivity first” paradigm prevails. Production gains come from additional phytochemical inputs such as fertilisers and pesticides or from increased irrigation, both of which could result in negative cascade effects on natural and agricultural ecosystems. Improving the management of existing working land, for example through agroforestry, and incorporating ecological landscape approaches making use of natural functionalities could thus enable win-win solutions in land systems, through the deployment of nature-based measures that minimizes the competition with other land uses. Achieving positive outcomes for both climate action, food security and biodiversity conservation thus requires strong stakeholder engagement and appropriate regulations to ensure these multiple and interrelated goals are considered in an integrated manner.

6.3. Bioenergy: the link between AFOLU and the energy sector

The study also assessed the link between the AFOLU and the energy sector through the potential of land to produce biomass for bioenergy. The findings confirm a trade-off that is well-identified in the literature: the production of energy crops and the increase biomass demand could hamper mitigation

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measures such as reduced deforestation and degradation (Hanssen et al., 2020; Nabuurs et al., 2022). The trade-off impacts disproportionately specific regions: in our results, large areas of forests are deforested to produce purpose-grown energy crops (e.g., Indonesia), while other regions with similar carbon densities and productivities do not have such increase in biomass expansion (e.g., Latin America). The ill-deployment of bioenergy could have negative impacts beyond climate mitigation: as natural land and agricultural land (cropland and pasture land) are converted to bioenergy cropland, potentially severe consequences for various sustainability dimensions such as biodiversity (Hof et al., 2018) and food security (Fujimori et al., 2019) could also materialise. Stenzel et al., (2021) further demonstrated that due to the irrigation of biomass plantations, the global area and population living under severe water stress would double in a BECCS scenario, which could be reduced with sustainable water management.

In addition, comparing the land-use dynamics of the Illustrative Mitigation Pathways (IMPs) illustrates the impact of large-scale renewable energy deployment on land-based carbon dioxide removal (CDR) technologies like bioenergy. The high share of renewable energy in *IMP Ren* strongly reduces the need for large-scale land-based CDR even with ambitious mitigation targets. This leads to smaller bioenergy and afforestation area increases by 2100 and hence smaller decreases of pasture, cropland, and other land. Considering these dynamics demonstrates the importance of not considering purpose-grown bioenergy and more broadly CDRs which include A/R as silver bullets that will solve the climate crisis without requiring major investments in the energy transition away from fossil fuels. Mitigation from land-based CDRs such as BECCS can complement other mitigations options but should not divert from the deep decarbonisation of all emitting sectors. Thus, if bioenergy and BECCS do develop at a large-scale in the coming decades, policy efforts must ramp up to substantially value, encourage, and protect terrestrial carbon stocks and ecosystems in order to avoid outcomes inconsistent with many SDGs.

6.4. Gender in the AFOLU sector

Considering the policy relevance of the results means going beyond technical and sectoral implications in order to account for social and cultural factors which could hamper the capacity to realize the mitigation potential of the forestry sector. Gender inequality figures among these structural social factors, as women often lack de-jure and de-facto access to land or forest resources which limits their opportunities to benefit from other kinds of land investments, such as through REDD+ (Manfre & Rubin, 2012). The gender inequality is not limited to economic dimensions, where market economies can lead to lack of consideration of care work, unequal incomes and wages and unbalanced economic recognition. It also expands to the institutional arena where masculine models set the standards and influence the power distribution within political and social institutions.

Within the forestry sector, policy implementation would need to explicitly acknowledge these structural dimensions on gender in order to provide social and economic benefits beyond climate mitigation, if they are to succeed at all. Reforestation projects in India and Nepal that lacked a gender perspective indeed faced problems when replanting, protecting the forests and implementing rules that protect the reserves (Agarwal, 2001).

Yet, worldwide, women labour and care are a major contributor to the preservation of tropical forests. Positive examples have also been identified where a gender perspective has contributed to the success of forestry projects. Several afforestation/reforestation initiatives are acknowledged to successfully deliver environmental benefits while integrating gender perspectives, securing women participation and their inclusion in the benefits, like the Mama Watoto Women's group in Kenya or the Chipko Movement in the Uttarakhand region of the Himalayas (Aguilar et al., 2007).

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Beyond these specific positive cases, policymaking faces the challenge to ensure positive outcomes are met in a systematic manner. The benefits from activities such as REDD+ and payments for ecosystem services (PES) should be shared equally among members of a household. Widespread information program would further ensure women have access to the required information on these programs and are enabled to make the most appropriate decisions for their household and communities. Women empowerment also requires equal participation and equal decision-making capacity when designing and implementing forestry projects, to ensure they feel ownership of the policies.

Integrating a gender perspective is thus an important opportunity towards the decarbonization of the AFOLU sector. Yet, modelling the gender implications within the IAMs structure remains a challenge. While ensuring a just transition requires climate research to consider inequalities across various groups, the structure of IAMs based on a representative agent implies that societal inequalities are not easily captured. The SSPs do include scenarios accounting for gender, along with age and education, yet despite the relevance of gender the IAMs are not yet able to endogenously model this dimension of inequality (Emmerling & Tavoni, 2021). Income inequalities are captured through within-country quintiles of income distribution, mostly due to the data availability and the strong linkages with other socio-economic dimensions. For gender, the current situation arises from various difficulties, including a structural deficit in research dedicated to identify, quantify and model the drivers of gender inequalities. Such drivers are however required to be able to assess the distributional impacts of climate policies on the gender dimension. The inherent difficulties in modelling labour and activities occurring outside of the market, leading to a lack of data, can also explain why capturing it in current modelling frameworks is challenging.

In order to better integrate and consider the necessary improvements and policies to reduce gender inequalities, modelling improvements could be realized through three entry points: first, improving the representation of drivers of gender inequality in reference scenarios; second, integrate within the model equations these dynamics so that they are captured endogenously; and third, represent the interactions between the differentiated social agents. The first entry point requires to compile and integrate in IAMs the existing economic data on the (unpaid) care economy which make gendered divisions of labour visible in the models. The last two steps represent major challenges for IAMs, which could therefore benefit from increased linkages with models able to capture these dynamics at the micro-level, such as Agent-based models (ABMs). These entry points require improvements not only limited to mathematical representation and modelling tools, but also in the conceptual frameworks of economic representations. Given the gender-biased valuation of societally relevant economies, models should work towards a better representation of the care economy, as opposed to the market-oriented economies.

Beyond a better representation of gender in AFOLU modelling, gender perspective can be better integrated in climate mitigation policy-making from the AFOLU sector on multiple levels (Aguilar et al., 2007). On the project level, participation and integration of women should be ensured and the socially-defined differences between men and women explicitly recognised. In addition, beyond providing equal access, projects could ensure that the public space of forests and related activities are free from masculine violence and provide safe space for care-giving practices such as community forestry. Nationally, appropriate regulations need to guarantee equitable distribution of economic benefits from forest services as well as equal access to land ownership and other natural resources. Policymaking should promote gender mainstreaming in all key regulations for the AFOLU sector that recognize women as key agents of climate change processes. Reforms could also target deeply entrenched institutionalised androcentrism which maintains the dominance of masculine models and

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values within institutions. Internationally, REDD+ program developed indicators and a gender marker rating system facilitating the mainstreaming of gender in forestry projects. Beyond monitoring the gender dimension, compliance with international commitments on gender equality and equity should be ensured in programs and regimes in relation to REDD+.

7. Opportunities and constraints in the sector

The modelling of the potential of A/R and AVD has shed light on the scientific and policy debate presented in the introduction. With the rising interest for natural-based solutions (NBS) or natural climate solutions (Griscom et al. 2017), discussions have focused on the scale, effectiveness, and pitfalls of land-based mitigation measures with a particular emphasis on CDRs, including A/R and BECCS. Among the measures covered in this study, AVD has received less attention within this debate suggesting a broad consensus on its high mitigation potential, large environmental benefits beyond carbon sequestration and least concerns about potential trade-offs with agricultural production and food security. Our findings contribute to the debate by quantifying the impact of key modelling assumptions and parameters on the potential of A/R and AVD. These modelling decisions have focused on constraints, understood as processes that limit and control the extent to which the measures could contribute to climate mitigation. The constraints have assessed the implications of global biomass demand, forest expansion onto agricultural land, and fallow land conversion. Other studies have similarly modelled the forestry-based potential through constraints and safeguards, whose impacts are generally reported in the form of sensitivity analysis. Compared to the constraints applied here, a safeguard can be defined as a specific type of constraint which prevents something that is undesirable: for example, negative impacts on biodiversity of afforestation projects.

These previous studies have similarly used IAMs to quantify land-based mitigation potentials. Despite a coarser resolution compared to sectoral studies, IAMs are well suited to capture interactions and trade-offs between measures and sectors and thus to test the implications of different biophysical, economic, and agronomic processes across sectors and regions, such as emission leakages. The large range of estimates reflect the differences in studies' methods and assumptions: high estimates consider few constraints, include a wide range of ecosystems and do not differentiate between afforestation and reforestation; while low estimates usually have stricter biophysical and socioeconomic limits and have a low carbon price per tonne (Seddon, 2022). Using the IMAGE framework, Doelman et al. (2020) report for A/R a potential comprised between $1.5 \text{ GtCO}_2\text{.yr}^{-1}$ at USD 50/tCO₂ and $4.9 \text{ GtCO}_2\text{.yr}^{-1}$ at USD 200/tCO₂ by limiting the forest expansion based on examples of rates of crop expansions historically observed. Griscom et al. (2017) have established a maximum mitigation potential with safeguards which did not allow for reductions of existing cropland area and afforestation where forests are not the native cover type. Kreidenweis et al. (2016) have applied spatial restrictions to the areas that can be afforested, testing for restrictions in temperature/boreal regions and tropical regions. The analysis presented here contributes to this analysis by comparing the implications of these modelling decisions and assumptions on global and regional mitigation potentials, land use change, non-CO₂ emissions and food prices.

The results confirm the high spatial specificities of the mitigation potential of A/R and AVD and of the impact of the constraints. They confirm that the most important region for AVD is Latin America, through the contribution of the Amazon basin. However, they also highlight the risk of bioenergy demand to drive increased deforestation in Indonesia, potentially compensating the emission reduction enabled in the energy sector. The analysis warrants further analysis in that regard. Still, the results are in line with the broad conclusion that the protection of forests and other ecosystems is the dominant source of mitigation potential in tropical regions. While the IPCC reports that restoration and management of forests and other ecosystems is more geographically distributed, with all regions having significant potential, our results find that developed regions, mostly North America and Europe, provide a large proportion of the potential from A/R.

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Beyond their respective mitigation potential, the analysis confirms that forestry-based measures can increase land competition and add pressure to agricultural production systems. The land use implications in <1.5°C, <2°C and <3°C mitigation pathways are shaped by land-demanding mitigation options such as bioenergy and afforestation, in addition to the demand for other agricultural and forest commodities. Beyond these concerns, policies promoting biodiversity conservation through land-intensive measures such as protected areas could further increase demand for land (Di Vittorio et al., 2023). However, an estimate of the contributions of protected areas to mitigation between 2000 and 2012, showed that in the tropics, protected areas reduced carbon emissions from deforestation by 4.88 PgC, or around 29%, when compared to the expected rates of deforestation (Bebber & Butt, 2017). These examples illustrate how land governance should seek complementarity and integration between these land-intensive objectives to better capitalize on the possible synergies.

Results confirm that land for A/R displace agricultural land for food production (cropland and pasture) while AVD prevents the continued expansion of agriculture onto forests. Combined with increasing demand for bioenergy, the IPCC AR6 report estimates that in the <1.5°C mitigation pathway in Asia, bioenergy and forest area together increased by about 2.1 million km² between 2020 and 2100, mostly at the cost of cropland and pasture (median values). However, large-scale transformations of land use have repercussions on biogeochemical cycles (e.g., fertiliser and water) but also on the economy (e.g., food prices), a finding confirmed by our analysis of food price indices. Socio-political conditions could be affected by these environmental and economic impacts (Nabuurs et al., 2022).

While in line with previous estimates and studies, the results and insights of the analysis should be taken in light of its multiple limitations. The potential future climate change impacts on the agriculture and forestry sectors have not been considered. Particularly under high warming scenarios, these impacts would have direct and indirect implications for carbon sequestration. Special concerns on forest mitigation potential have been expressed on permanence risks (Anderegg et al., 2020) due to vulnerability to heat stress, wild fires, pest and pathogens. Climate impacts could thus reduce the mitigation potential of the measures covered by the study.

Also, while IAMs are well equipped to study in conjunction multiple mitigation measures from different sectors, the study did not include land-based mitigation measures beyond the forestry sector. Bioenergy was indirectly included, but the mitigation potential for biomass was not captured in the results. Complementary measures could further include agriculture and demand-side measures. Past studies have assessed the complementarity between forestry-based measures and changes in diet, showing how the latter could mitigate the food security implications of the former (Prudhomme et al., 2020).

Then, the study has not differentiated between managed and unmanaged forests. GCAM assumes that in each water basin the vegetation density of managed forest is 50% of unmanaged forests, while soil carbon density is 13% lower. The difference partly explains the higher mitigation intensity of AVD, which protects unmanaged forests as opposed to A/R which mostly incentivizes forest plantations with lower carbon content. Model improvements would further include forest management as a mitigation option within the sector, as well as differentiating between afforestation and reforestation. This would contribute to minimize the risks mentioned above and to improve the representation of permanence and leakage, which remain major concerns for mitigation effectiveness (Murray et al., 2007).

Potential mitigation, however, will be influenced by barriers, challenges and opportunities that are not considered by IAMs or by studies reviewed here. They include policy, regulation, finance, innovation and behavioural and social dimensions (e.g., gender equality) which are governed by fragmented and

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often conflicting policy frameworks (Nolan et al., 2021). The most common and crucial challenges range from lack of investments for transformation actions to weak land tenure regimes. These challenges can be further enhanced by lack of coordination across administration levels with distributed competencies and different capacities. Successful implementation would also require a secure finance to the communities along with appropriate land ownership and access. A study has shown that accounting for financial, land use and operational constraints towards reforestation in Southeast Asia could reduce by more than 80% the mitigation potential (Zeng et al., 2020).

In terms of policy implementation, implementing policies like a global GHG tax would bring significant challenges to effectively reward or penalize landowners, with the transfer of potentially large sums of money being involved (Calvin et al. 2014). In addition, policymakers would have to choose between different options to operationalize these carbon sequestration policies (carbon purchase policy vs. carbon rent policy, see Lintunen et al., (2016)). These policies rewards land use types and tree species that generate the highest amount of carbon sequestration, which could come at the expense of other land uses and species which generate other important and non-valued ecosystem services (Hashida & Lewis, 2019).

These final considerations imply that the implementation of the mitigation measures analysed in this study will vary significantly according to socio-cultural, political and economic contexts, as they depend on much more than the inputs and parameters that can be covered by IAMs. Yet, they confirm that NDCs should avoid the 'carbon tunnel' reducing the goal of AFOLU policies to the maximization of mitigation potentials from land systems. Rather, integrative policy planning and implementation should ensure that policies such as carbon pricing do not generate unintended negative externalities on other key ecosystem services and SDGs.

8. Conclusion: future NDCs and the Global Stocktake

About one-quarter of the 2030 mitigation pledged by countries in their nationally determined contributions (NDCs) under the Paris Agreement is expected to come from land-based mitigation options (Jia et al., 2019). Furthermore, high profile initiatives have been launched with global restoration objectives which will shape future land use dynamics, such as the UN Decade on Restoration announced in 2019, the Bonn challenge on 150 million ha of restored forest in 2020 and the one trillion trees campaign launched by the World Economic Forum in 2020. On the year of the Global Stocktake of the Paris Agreement, this analysis has assessed the mitigation potential of two key measures from the AFOLU sector, A/R and AVD, along with their implications for land use change and food security. The key conclusions with direct relevance for future NDCs and climate targets from the AFOLU sector are the following:

- ❖ As illustrated through the forestry sector, the mitigation strategies from land systems require a holistic view of their interactions with other Sustainable Development Goals (SDGs) in order to foster synergies and minimize trade-offs;
- ❖ The mitigation measures from AFOLU needs to be placed within the broader framework of deep decarbonisation of all emitting sectors, so that land-based CDRs are not portrayed as silver bullets solutions to the climate problem diverting the required efforts from phasing out of fossil fuels;
- ❖ The implications of large-scale bioenergy development on land use systems should be carefully assessed to ensure that ramping up the ambition of future NDCs in the energy sector does not hamper the mitigation from the forestry sector and do not cause additional stress on food systems;
- ❖ International markets create potential for complementarity but also leakages between mitigation options, which calls for broader coordination between countries and regions when designing AFOLU mitigation measures of future NDCs;
- ❖ Sustainable intensification in agriculture and demand-side measures could enhance efficiencies and reduce the need for agricultural land, and are therefore critical for enabling supply-side measures from the forestry sector and for decreasing CH₄ and N₂O emissions from agricultural production;
- ❖ Future NDCs could strengthen their coordination with national policies regulating land uses (e.g., National Biodiversity Strategies and Action Plans) to improve the integration of measures with indirect benefits for land-based climate mitigation (e.g., protected areas).

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