Terrestrial systems' impact on and response to climate change

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Dissertation Abstract

Terrestrial systems are both a source and a sink of carbon emissions and play a fundamental role in regulating climate change. To deliver on the Paris Agreement goal of limiting warming to 1.5°C or 2°C, clarifying terrestrial systems' mitigation potential and their response to climate change is critical. The goal of my dissertation was to investigate terrestrial systems' potential contribution to the Paris Agreement mitigation pathway (Chapter 2), the impact of climate change on forest sequestration potential (Chapter 3), and the effect of climate on tropical forest litter carbon turnover and consequent impacts on the tropical forest sink (Chapter 4). The meta-analysis of land-based mitigation and roadmap to 2050 developed in Chapter 2 showed that deploying measures in agriculture, forestry, wetlands, and bioenergy could feasibly and sustainably contribute ~30% (14-15 $GtCO_2e\ yr^{-1}$) of the global mitigation needed in 2050 to deliver on the 1.5°C target. Land-based emissions would need to decline by ~50% per decade (85% gross reductions by 2050) and carbon removals would need to increase ten-fold by 2050 to make the land sector net zero emissions by 2050. Both 2°C and 1.5ºC temperature targets require steep emission reductions from tropical deforestation, yet the 1.5ºC goal will require earlier and deeper reductions in agricultural and demand-side emissions, and enhanced carbon removals from reforestation, soil carbon sequestration, agroforestry and forest management.

Land-based measures that enhance carbon removals are likely to be affected by future climate change. However, very few studies that estimate land-based sequestration potential consider climate impacts. My study on biophysical sequestration potential for afforestation, reforestation and forest enhancement (A/R/E) under two climate futures in Chapter 3 is one of the first to do so. A/R/E has the potential to sequester 3.8-7.3 $GtCO_2\ yr^{-1}$ in 2050 depending on future agricultural expansion, with ~45% from afforestation, ~33% from reforestation, and ~21% from forest enhancement. High levels of future agricultural expansion (+650 Mha) not only

reduces the A/R/E sequestration potential by 41%, it also substantially reduces (by 62%) the natural capacity of land to act as a carbon sink. Reforestation and forest enhancement in the tropics and sub-tropics have higher mitigation densities than afforestation, higher potential to deliver multiple benefits, and are most aligned with countries' restoration pledges. In a 4°C climate future (7.0 W/m^2 forcing), sequestration potential is ~20% greater, with 15-30% higher gains in the tropics compared to temperate and boreal regions. Productivity increases outweighed carbon losses from ecosystem respiration and fire, largely due to CO_2 fertilization. However, the strength of carbon–concentration and carbon–climate feedbacks over land is highly uncertain. Responses in tropical forest soils in particular, including impacts on decomposition and carbon turnover, are poorly represented in models and are a critical source of uncertainty.

In Chapter 4, I evaluated the effects of sustained 4°C warming on *in-situ* litter decomposition in a tropical forest and then compared the experimental field results to the earth system model results from Chapter 3. I found that warming reduced mass loss by an average of 7% across four different substrates. Warming decreased litter moisture by an average of 36%, relative humidity by 4%, and soil moisture by 1.2%, which appear to have limited microbial activity and decomposition. However, the effect of warming on reduced mass loss varied among the substrates, with a stronger response in lower quality (higher C:N) substrates. These results suggest that temperature increases with concomitant drying could significantly slow carbon and nutrient turnover from lower quality litter to soil. In the model experiment, we also found reduced litter carbon turnover rates in tropical forests that experienced drying, but with lower sensitivity. Although litter carbon turnover decreased across most dry tropical forests with reduced precipitation, it only decreased in wet tropical forests that experienced higher levels of drying than occurred in our field experiment. The Chapter 4 findings suggest carbon turnover with future climate change could depend more strongly on moisture regimes in wet tropical forests than currently captured in models.

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Chapter 1: Introduction to the dissertation

Background

Anthropogenic climate change has warmed the Earth about 1°C (0.9-1.3 °C) in 2010-2019 above pre-industrial levels (1850-1900) (Gillett et al. 2021). If we continue business as usual (pathways between 6.0– 8.5 W/m^2 of radiative forcing), carbon dioxide (CO_2) concentrations are projected to rise to greater than 700 ppm, causing 3.7-4.8°C of warming by the end of the century (IPCC 2014). Terrestrial systems play a fundamental role in regulating climate change through biogeochemical and biophysical processes that affect atmospheric greenhouse gas (GHG) concentrations and the Earth's energy balance and hydrologic cycle (Bonan 2008). Importantly, land is both a major source of GHGs and a sink of carbon dioxide (CO_2) (Friedlingstein et al. 2020).

About half of all anthropogenic CO_2 emissions remain in the atmosphere, while the other half are incorporated into the land and ocean carbon pools (Le Quéré et al. 2009; Friedlingstein et al. 2020). Human activity in agriculture, forestry and other land uses account for 10-12 $GtCO_2e$ (~25%) of net anthropogenic GHG emissions per year (Smith et al. 2014; Jia et al. 2019). Approximately half of land-based anthropogenic emissions are from net land-use changes including deforestation, conversion and degradation of forests, mangroves, grasslands and savannas, draining of peatlands, as well as regrowth on managed lands (Smith et al. 2014; Jia et al. 2019). Agriculture, through livestock and crop production, generates the other half of land-based emissions, primarily methane (CH_4) and nitrous oxide (N_2O) (Smith et al. 2014; Jia et al. 2019). In addition to the net emissions and removals from managed lands, unmanaged, or natural lands (referred to as the residual terrestrial carbon sink) act as an important carbon sink, sequestering about 12.5 $GtCO_2$ (~30%) of anthropogenic emissions annually (between 2010-2019), in addition to the ocean sink of about 9 $GtCO_2$ (~25%) (Friedlingstein et al. 2020).

Improved stewardship of land to reduce GHG emissions, enhance carbon removals and protect the residual sink will be critical to delivering on the Paris Agreement goal of limiting warming to 1.5°C or 2°C above pre-industrial levels, and avoiding the worst impacts of climate change (Jia et al. 2019; Rogelj et al. 2018; Hoegh-Guldberg et al. 2018). Land-based mitigation measures include interventions to protect, manage, and restore forests and other ecosystems, reduce emissions and enhance carbon sequestration in agriculture, capture carbon through bioenergy, as well as demand-side interventions on food waste, diets, and resource use (Jia et al. 2019). Unlike mitigation measures in the energy and industrial sectors, improved land management (also referred to as nature-based solutions or natural climate solutions) also have the potential to enhance food security, biodiversity, resilience to climate change and other ecosystem services, and contribute to international sustainable development goals (Smith et al. 2020; Seddon et al. 2020). As countries and practitioners develop climate strategies, policies and investments to deliver on the Paris Agreement targets of limiting warming to 1.5°C and 2°C, it is helpful to understand what level of mitigation is needed for each sector, what mitigation potential individual measures can deliver, and what the trade-offs are, particularly in the land sector where many opportunities for environmental and social co-benefits exist.

In addition to examining the mitigation potential and co-benefits of land management measures, better understanding how their potentials may be affected by future climate change is critical for developing adaptive and more resilient plans and policies (Hurlbert et al. 2019; de Coninck et al. 2018). The ecological functions and processes of terrestrial systems will be affected by climate change, which in turn can affect the amount of mitigation delivered from managed systems as well as the carbon sequestration capacity of the residual terrestrial sink (Jia et al. 2019). Increases in temperature and atmospheric CO_2 concentration, and changes in precipitation and disturbance regimes will affect primary production and decomposition which in turn will affect CO_2 concentration in the atmosphere (Knorr et al. 2005; Keenan et al. 2014; Crowther et al. 2016; Sakalli et al. 2017). Climate change is expected to alter plant physiology including photosynthesis, autotrophic respiration and evapotranspiration (Boisvenue and Running 2006; Latta et al. 2010; Keenan et al. 2013). It will also affect microbial activity, altering litter decomposition, heterotrophic respiration, and carbon retention in soils (Davidson and Janssens 2006; Cornelissen et al. 2007; Frey et al. 2013; T. Walker et al. 2018). To more fully understand the potential for land management to mitigate future warming, we must therefore account for the changing climate itself. Climate impacts are particularly important for carbon sequestration measures, like afforestation /reforestation (A/R), which have among the highest mitigation potential of natural climate solutions (Griscom et al. 2017) and rely on stable carbon storage.

Understanding the impact of future climate change on both managed and unmanaged lands, and potential feedbacks on the climate system is critical for projecting and managing the effort needed to meet Paris Agreement targets. Earth System Models (ESMs) project an increase in total land carbon uptake through the end of the century (Arora et al. 2020; Ciais et al. 2013), with the strongest effect in the tropics (Arora et al. 2020). However, the strength of terrestrial carbon feedbacks (carbon–concentration and carbon–climate feedbacks) over land varies substantially among models (Arora et al. 2013; Friedlingstein et al. 2014; Friedlingstein 2015; A. P. Walker et al. 2020) and represents one of the largest sources of uncertainty in climate change projections (Ciais et al. 2013). The dominant sources of uncertainty in terrestrial carbon cycle responses in ESMs include climate control on net primary productivity (NPP), changes to carbon turnover, and soil respiration (decomposition) (Koven et al. 2015; Aerts et al. 2015; Todd-Brown et al. 2014; Nishina et al. 2014).

Climate responses in tropical forest soils in particular, including impacts on decomposition and carbon turnover, are poorly represented in models and contribute to the high uncertainty (Cavaleri et al. 2015; Bradford et al. 2016; Wood et al. 2019). Tropical forests are an important carbon sink, accounting for ~2/3 of live terrestrial plant biomass (Pan et al. 2013) and ~1/3 of the world's soil carbon (Jobbágy and Jackson 2000). Tropical forests also have the highest carbon turnover rates (Carvalhais et al. 2014) and exchange more CO_2 and water with the atmosphere than any other terrestrial ecosystem (Foley et al. 2003; Beer et al. 2010; Townsend et al. 2011). Model results and field experiments in temperate forests suggest temperature increases will increase carbon inputs from litter to the soil, and carbon fluxes from the soil (litter, roots and soil organic matter) to the atmosphere due to increased decomposition and microbial respiration, potentially accelerating climate change (Conant et al. 2011; Crowther et al. 2016). However, a dearth of evidence limits extending these findings to tropical forests (Wood, Cavaleri, and Reed 2012; Cavaleri et al. 2015; Wood et al. 2019). Improving our understanding and representation of tropical forest litter and soil responses to climate will enhance our ability to predict global carbon cycle dynamics and feedbacks to future climate.

Objectives, Approach and Structure

This dissertation has three main objectives: 1) explore terrestrial systems' potential contribution to climate mitigation pathways, 2) examine the impact of climate change on forest sequestration potential, and 3) assess the impact of climate on tropical forest litter carbon turnover on the tropical forest sink. I addressed these objectives in three chapters, each written and formatted in this dissertation for peer-reviewed journals.

In **Chapter 2**, titled “The contribution of the land sector in a 1.5°C world” (*published in Nature Climate Change, 2019*), I conducted a meta-analysis of land-based mitigation (land-use change, agriculture, and bioenergy) from integrated assessment models (IAMs) and literature to address Objective 1. The study investigates how much terrestrial systems can contribute to climate change mitigation, identifying relevant land-based measures and geographies, and providing a roadmap of priority measures and regions to help achieve the Paris Agreement temperature target of 1.5°C. The findings in this study complement and provide an update to land-based mitigation estimates in the IPCC Fifth Assessment Report (WGIII, Ch11) and the IPCC Special Report on Climate Change and Land. In a follow-up study, titled “Land-based measures to mitigate climate change: potential and feasibility by country” (**Annex 1,** *in review in Global Change Biology*), I updated mitigation potentials for 20 land-based measures identified in Chapter 2 and regionally disaggregated into >200 countries, compared sectoral estimates to results from integrated assessment models, and assessed country-level feasibility.

In **Chapter 3**, titled “Mitigation potential of afforestation, reforestation and forest enhancement, considering impacts from climate change, agricultural expansion, and biodiversity prioritization” (*in review in Global Change Biology*), I used Earth System Modeling to address Objective 2. The study modelled the biophysical sequestration potential for afforestation, reforestation and forest enhancement in two climate futures, 2°C (2.6 W/m2 forcing) and 4°C (7.0 W/m2 forcing), and two agricultural land futures, and assessed the changes in sequestration potential, and in vegetation, litter and soil carbon pools and fluxes by region between 2015 and 2100.

In **Chapter 4,** titled “ In-situ warming effects on litter decomposition and carbon cycling in a wet tropical forest” (*in preparation for submission*), I addressed Objective 3 by evaluating the effects of sustained warming on *in-situ* litter decomposition across four substrates in a tropical forest and comparing the results to the Earth System Model outputs from Chapter 3. The field experiments were part of The Tropical Responses to Altered Climate Experiment (TRACE) in Puerto Rico, the first field-scale warming experiment which investigates how tropical forest ecosystems will respond to increased temperatures of 4°C above ambient temperatures.

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Chapter 2: Contribution of the land sector to a 1.5°C World

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Abstract

The Paris Agreement introduced an ambitious goal to limit warming to 1.5°C above pre-industrial levels. Here, we combine a review of modelled pathways and literature on mitigation strategies, and develop a land-sector roadmap of priority measures and regions that can help to achieve the 1.5°C temperature goal. Transforming the land sector and deploying measures in agriculture, forestry, wetlands, and bioenergy could feasibly and sustainably contribute about 30%, or 15 billion metric tons of carbon dioxide equivalent ($GtCO_2e$) per year of the global mitigation needed in 2050 to deliver on the 1.5°C target, but it will require substantially more effort than the 2˚C target. Risks and barriers must be addressed, and incentives will be necessary to scale up mitigation while maximizing sustainable development, food security, and environmental co-benefits.

Introduction

The Paris Agreement marked the conclusion of many years of negotiations, setting a global temperature target of "well below 2°C" and encouraging efforts to "limit increase to 1.5°C above pre-industrial levels." However, submitted Nationally Determined Contributions (NDCs), countries' pledges to implement emissions reductions, fall short of the goal (Rogelj et al. 2016). Current commitments are more compatible with 2.5°C to 3°C of warming by 2100 (Rockström et al. 2017; Schleussner et al. 2016; Rogelj, Shindell, et al. 2018). To limit warming to 1.5°C (and 2°C), countries will need to plan for a more rapid transformation of their national energy, industry, transport, and land-use sectors (Peters and Geden 2017; Rockström et al. 2017; Rogelj et al. 2016).

The land sector, commonly referred to as 'agriculture, forestry, and other land uses' (AFOLU) is responsible for 10-12 $GtCO_2e$ (~25%) of net anthropogenic GHG emissions per year, with approximately half from agriculture and half from 'land use, land use change, and forestry' (LULUCF) (Le Quéré et al. 2018; Smith et al. 2014). LULUCF emissions represent the net balance between emissions from land-use change and carbon sequestration from the regeneration of vegetation and soils (Le Quéré et al. 2018; Smith et al. 2014). Although the AFOLU sector generates considerable emissions, the residual terrestrial sink (accumulation of carbon in the terrestrial biosphere excluding land sinks from LULUCF) also currently sequesters about 30% of annual anthropogenic emissions, making land vitally important for generating "negative emissions" – that is, more carbon dioxide removals (CDR) than emissions (Le Quéré et al. 2018). In addition to GHG impacts, land-use generates biophysical impacts that affect the climate by altering water and energy fluxes between the land and the atmosphere (Alkama and Cescatti 2016). Furthermore, the AFOLU system provides significant ecosystem goods and services such as air and water filtration, nutrient cycling, habitat for biodiversity, and climate resilience (Smith et al. 2014).

Of the countries that ratified and submitted NDCs, a majority included land-sector mitigation providing 10-30% of all planned emissions reductions in 2030 (Forsell et al. 2016; Grassi et al. 2017). Land-based mitigation measures largely fall into four categories: reduced land-use change, CDR through enhanced carbon sinks, reduced agricultural emissions, and reduced overall production through demand shifts. Most countries included reduced land-use change, afforestation and forest restoration, a few included soil carbon sequestration and reduced agricultural emissions, yet none mentioned demand-side shifts. As countries submit new or revised NDCs by 2020 and prioritize climate strategies and investments, it is helpful to take stock of the scientific and technological advancements in key sectors, particularly in the land sector where there are many opportunities for environmental and social co-benefits.

Building on existing studies of mitigation pathways (Rogelj, Popp, et al. 2018; Rogelj, Shindell, et al. 2018; Popp et al. 2017; Riahi et al. 2017; van Vuuren et al. 2018) and mitigation potentials (Dickie et al. 2014; Frank et al. 2017; Fuss et al. 2018; Griscom et al. 2017; Smith et al. 2013, 2014, 2016; Wollenberg et al. 2016) in the land sector, here we provide a comprehensive assessment of all land-based activities (agriculture, LULUCF, and bioenergy), and their possible contributions to the Paris Agreement temperature target of 1.5°C. We conducted four complementary analyses: 1) review of 1.5°C scenarios across all sectors, 2) comparative analysis of top-down modelled pathways in the land sector, 3) bottom-up assessment and synthesis of land-sector mitigation potential, and 4) a geographically explicit roadmap of priority mitigation actions to fulfil the 1.5°C land-sector transformation pathway by 2050, informed by the first three analyses. The methods are described in each section, and a more detailed description including additional figures and tables are available in the Appendix 2.2.

Pathways for the Paris Agreement

To put the Paris Agreement in context, we reviewed available 1.5°C scenarios to assess viable emissions pathways and required mitigation across all sectors. Recently released 1.5°C (1.9 W/m^2) scenarios in the Shared Socio-economic Pathway (SSP) Database (Rogelj, Popp, et al. 2018) and Integrated Assessment Modelling Consortium (IAMC) Database (Huppmann et al. 2018), as well as individual studies of 1.5°C carbon budgets (Goodwin et al. 2018; Millar et al. 2017; Rockström et al. 2017; Schurer et al. 2018; Tokarska and Gillett 2018; Walsh et al. 2017) agree that aggressive mitigation of total emissions from 2020 until 2050 (approximately 50% reduction per decade, approximately 90% total reduction) coupled with substantial carbon removals increase the chance (>66% and >90% respectively) of limiting warming to 1.5°C and 2°C by 2100 (detailed methods and analysis in Appendix section 2.1). The 1.5°C scenarios fall into three categories: 'Below 1.5°C' the entire 21st century; 'Low overshoot' in mid-century (50-66% chance of exceeding 1.5°C) before temperatures decrease to below 1.5°C by 2100; and 'High overshoot' risk (> 67% chance of overshoot) (Rogelj, Shindell, et al. 2018). Current research thus defines three significant milestones to deliver on the Paris agreement targets: peak emissions around 2020, net zero emissions (balance between sources and sinks) by 2040-2060, and net negative emissions (sinks are greater than sources) thereafter (**Figure 2.1**)

Achieving the 1.5°C and 2°C targets requires huge transformations of the energy, industry, transportation and land sectors (emission reductions across all sectors), and substantial deployment of CDR (to achieve negative emissions) (Rogelj, Shindell, et al. 2018) – with 1.5°C scenarios requiring much earlier and more pronounced action. Net zero emissions for the 1.5°C target must be achieved about 10-40 years before the 2°C scenario, with the earliest mitigation for Below 1.5°C and 1.5°C Low overshoot scenarios (**Figure 2.1**). The early action contributes to making 1.5°C pathways costlier , with a median of (in 2010 prices) US$480 per tCO_2e in 2050 and US$2400 in 2100, compared with the 2°C pathways (median of US$365 per tCO_2e in 2050 and $1505 in 2100) (Huppmann et al. 2018). Pathways to 1.5°C also rely on about 40% (median) more CDR annually than 2°C scenarios, primarily from bioenergy with carbon capture and storage (BECCS), but also afforestation and reforestation (A/R), and CCS of fossil fuels (Smith et al. 2016). Substantial CDR was incorporated in 17 of the 18 2°C scenarios and all 13 of the 1.5°C scenarios in the SSP Database (Riahi et al. 2017; Rogelj, Popp, et al. 2018), and all 90 scenarios for the 1.5°C scenarios in the IAMC Database (Huppmann et al. 2018) (range of -1 to -27 $GtCO_2\ yr^{-1}$ (95% confidence interval) with a median of -15 $GtCO_2\ yr^{-1}$ by 2100) (Rogelj, Shindell, et al. 2018), because of the sizable and speedy emissions reduction needed. A 1.5°C pathway without negative emissions would need to achieve net zero emissions by about 2040, given a post-2018 median carbon budget of 420 $GtCO_2$ (Rogelj, Shindell, et al. 2018) (**Figure 2.1**). Emissions reductions in the next two decades are therefore critical to limiting warming to 1.5°C. The longer mitigation is delayed, the lower the probability of delivering on the Paris Agreement targets, and the higher the reliance on negative emissions.

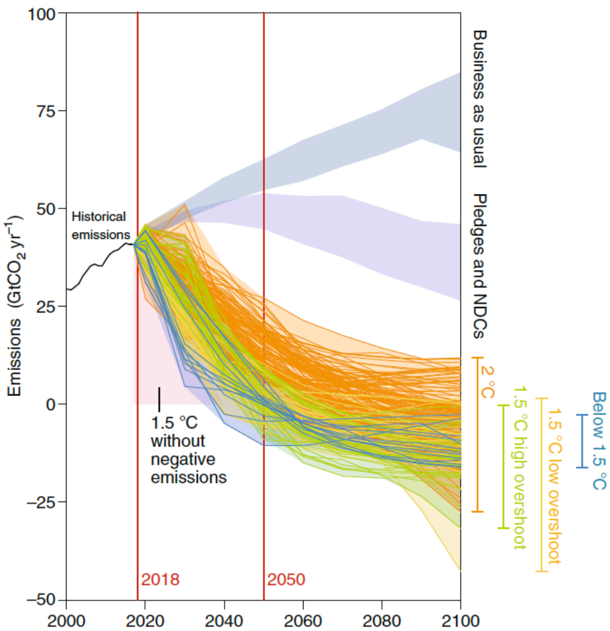


Figure 2.1. Global net anthropogenic CO_2 emission pathways in BAU, 2°C and 1.5°C model scenarios. The 2°C (132 model runs, orange lines), 1.5°C high overshoot (37 model runs, green lines), 1.5°C low overshoot (44 model runs, yellow lines) and Below 1.5°C (9 model runs, blue lines) pathways from the IAMC 1.5°C Database (Huppmann et al. 2018), present values at a >66% probability threshold (2°C and 1.5°C high overshoot) and 50-66% probability threshold (1.5°C low overshoot and below 1.5°C scenarios) (Rogelj, Shindell, et al. 2018). More details on these emission trajectories, comparisons with other carbon budgets in the literature, and a variant of the figure including all greenhouse gases in CO2e can be found in Appendix section 2.1. The scenario of mitigation for 1.5°C without negative emissions scenario (pink wedge) represents the range of remaining allowable emissions from the carbon budget of 420 GtCO2 from 2018 in the IPCC SR1.5°C (Rogelj, Shindell, et al. 2018). NDC numbers are adapted from Climate Action Tracker, 2018, removing non-CO2 emissions. Business as usual numbers represent the range of SSP2 baseline scenarios from the SSP Database (Rogelj, Popp, et al. 2018). Historical emissions data are from the Global Carbon Project (Le Quéré et al. 2018).

What the land sector can deliver

*Across top-down 1.5°C models, land-based activities (AFOLU and BECCS) provide 0.9 – 36.6 (median 13.8) $GtCO_2e\ yr^{-1}$ of economic mitigation potential in 2050, about 4 – 40% (median 25%) of the total mitigation required for a 1.5°C pathway (***Figure 2.2c***). AFOLU delivers 0.9 – 20.5 (median 9.1) $GtCO_2e\ yr^{-1}$ of mitigation potential and BECCS delivers 0 – 16.1* *(median 4.7) $GtCO_2e$ yr^{-1}. In the bottom-up assessment, supply-side AFOLU and BECCS measures provide 2.4 – 48.1 (median 14.6) $GtCO_2e$ yr^{-1} of mitigation potential in 2020-2050. AFOLU provides 2 – 36.8 (median 10.6) $GtCO_2e$ yr^{-1} of mitigation spanning technical and economic potentials, while BECCS provides 0.4 – 11.3 (median 4.0) $GtCO_2e$ yr^{-1} (***Figure 2.4***).*

Top-down modelled pathways

To evaluate the contribution of the land sector in 1.5°C and 2°C pathways, we reviewed model assessments of net CO_2, CH_4, and N_2O emissions trajectories in AFOLU and BECCS using the IAMC Database (Huppmann et al. 2018) (Appendix section 2.2). We then compared the emission pathways of specific mitigation activities in the AFOLU sector and land cover changes using the updated SSP Database with 1.5°C scenarios (1.9 W m^{-2}) (Rogelj, Popp, et al. 2018). Both databases include outputs from integrated assessment models (IAMs) which incorporate the coupled energy–land–economy–climate system and quantify GHG emissions pathways across sectors based on cost optimization (Rogelj, Shindell, et al. 2018).

Of the 2°C and 1.5°C scenarios in the IAMC Database (Huppmann et al. 2018), projected emissions reductions in AFOLU (CO_2 reductions in LULUCF and N_2O and CH_4 reductions in agriculture) were similar in the 2°C and 1.5°C High overshoot pathways before 2050, with deeper mitigation and higher BECCS in the 1.5°C High overshoot pathways after 2050 (**Figure 2.2a**). Mitigation is earlier and more pronounced in the 1.5°C Low overshoot and Below 1.5°C (no overshoot) scenarios until 2050 in LULUCF, and through 2100 in agriculture. The similarities between the 2°C and 1.5°C pathways in LULUCF after 2050 are due to the lower cost of reducing deforestation compared to other land-use activities. Across all 1.5°C scenarios (high, low and no overshoot), net zero CO_2 emissions in LULUCF were achieved around 2030, with net emissions of -0.6 to -4.7 $GtCO_2e$ yr^{-1} (interquartile range, IQR) in 2050 compared with 0.9 – 3.2 $GtCO_2e$ yr^{-1} in the business as usual (BAU) scenario. In agriculture, non-CO_2 emissions were 3.9 – 6.8 $GtCO_2e$ yr^{-1} (IQR) in 2050, down about 40% from BAU (7.7 – 10 $GtCO_2e$ yr^{-1} IQR). The deployment of CDR from BECCS across all 1.5°C scenarios is 3.4 – 7.9 $GtCO_2e$ yr^{-1} (IQR) in 2050 compared with about 0 in BAU (**Figure 2.2a**), although the Below 1.5°C scenarios had approximately 50% lower CDR because of earlier and deeper mitigation. Although there were a few pathways where BECCS was not deployed at all(van Vuuren et al. 2018; Grubler et al. 2018; Holz et al. 2018), BECCS provided a majority of land-based mitigation after 2050 across the 1.5˚C scenarios (**Figure 2.2c**).

From all 1.5°C scenarios in the SSP Database (Rogelj, Popp, et al. 2018), the largest share of emissions reductions from AFOLU were from forest-related measures. CO_2 emissions from deforestation decreased by about 40% by 2050 (1.6 – 2.9 $GtCO_2e$ yr^{-1} IQR compared with 2.5 – 5.4 $GtCO_2e$ yr^{-1} in BAU) (Figure 2b). Increased A/R and forest management produced negative emissions of -0.5 to -5.3 $GtCO_2e$ yr^{-1} (IQR) by 2050 compared with -0.9 to -2.3 $GtCO_2e$ yr^{-1} in BAU. In agriculture, the largest reduction was from CH_4 emissions from enteric fermentation (1.6 – 4.5 $GtCO_2e$ yr^{-1} (IQR) in 2050 compared with 3.4 – 5.3 $GtCO_2e$ yr^{-1} in BAU), primarily owing to intensification in the livestock sector and related GHG efficiency gains. Additional CH_4 reductions came from changing irrigation and fertilization practices in rice cultivation with smaller N_2O reductions from cropland soils and pastures. CO_2 and CH_4 decline more rapidly and prominently than N_2O, implying the difficulty in reducing N_2O in agriculture (Rogelj, Shindell, et al. 2018).

AFOLU and BECCS yielded 21%-30% (IQR) of the total mitigation required by 2050 to achieve the 1.5°C target, and 23%-32% (IQR) in 2100 (**Figure 2.2c**). Despite the limited portfolio of land-based mitigation measures in IAMs (Popp et al. 2017; Rogelj, Shindell, et al. 2018), the large share of total mitigation highlights the importance of the land sector in achieving the 1.5°C target. The inclusion of additional land-based mitigation measures (for example, wetland conservation and regeneration, soil carbon management, biochar, food and feed substitutes) may increase the land sector's importance in modelled pathways (Rogelj, Shindell, et al. 2018).

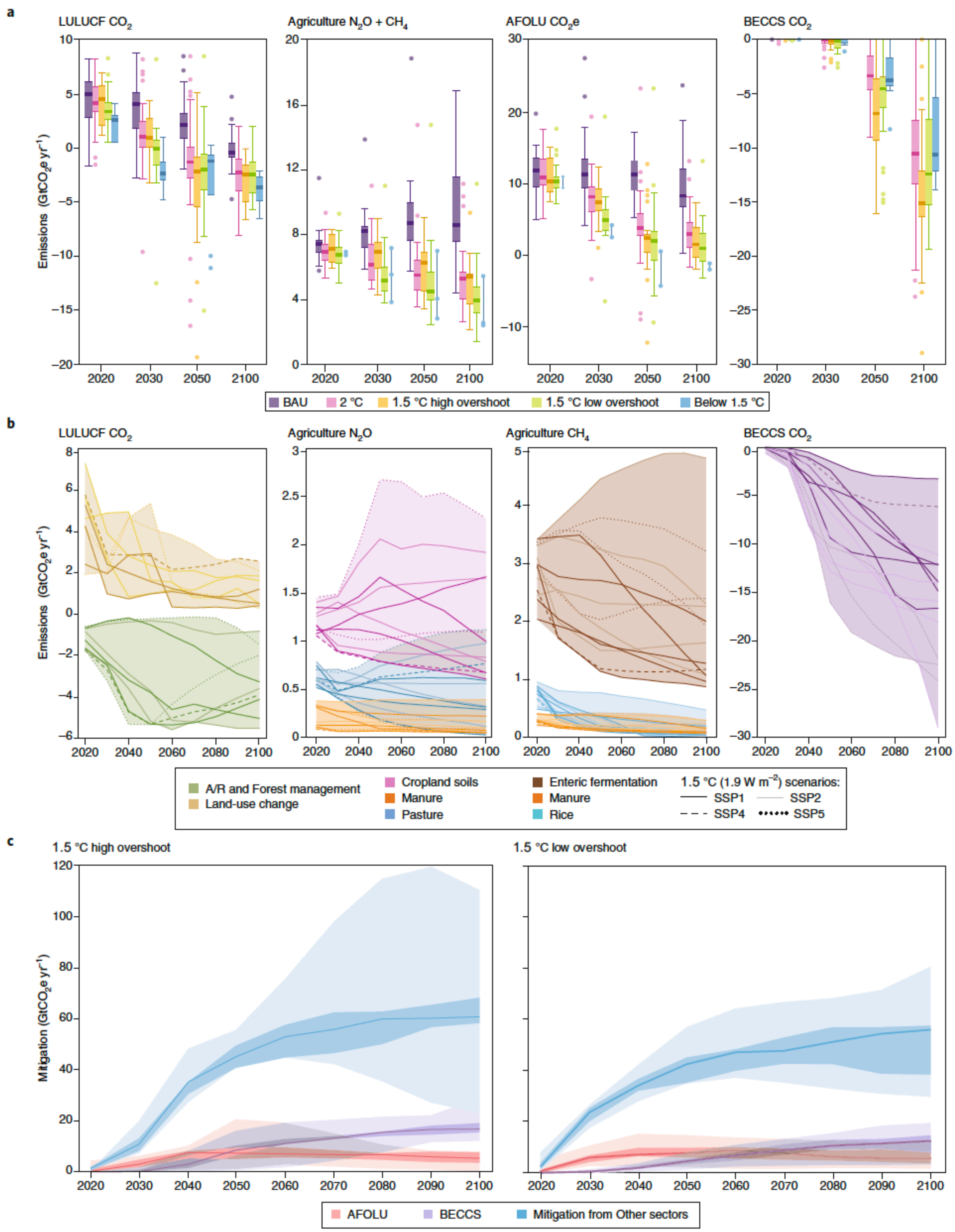


Figure 2.2. GHG emission pathways in the land sector across model scenarios.
(a) Emission pathways in LULUCF, Agriculture, AFOLU (LULUCF +Agriculture) and BECCS in BAU, 2°C, 1.5°C high overshoot, 1.5°C low overshoot and below 1.5°C scenarios. Boxplots show the median, interquartile range, and minimum-maximum range of pathways. In scenarios with fewer than 5 data points (below 1.5°C in agriculture and AFOLU), only the minimum-maximum range and single data points are shown. Data is from the IAMC Database (Huppmann et al. 2018). (b) 1.5°C Mitigation pathways of land-based activities in LULUCF, agriculture and BECCS from the SSP Database (Rogelj, Popp, et al. 2018; Riahi et al. 2017). Shaded areas show the minimum-maximum range across the SSPs per activity. Single pathways are lines, styled according to the SSP scenario in the legend. Single pathways are lines, styled according to the SSP scenario in the key. (c) Total mitigation of AFOLU, BECCS and Other sectors (total global mitigation minus AFOLU and BECCS) in 1.5°C high and low overshoot scenarios. Below 1.5°C scenarios are not illustrated due to too few data points. Total mitigation is calculated as the reference scenario minus 1.5°C for each model and scenario, then summed for AFOLU, BECCS and Other sectors. Shaded areas show the minimum-maximum range (light shading), interquartile range (dark shading) and median (dark line). Data is from the IAMC Database (Huppmann et al. 2018). The GHG flux of bioenergy plantations is accounted for in the land sector until harvest (i.e., part of the AFOLU flux), then bioenergy, processing, use and carbon removal through CCS is accounted for in the energy sector (BECCS). Additional energy and industry sector mitigation falls under all Other sectors.

Measures taken to achieve the 1.5°C target drove vast land-use changes (**Figure 2.3**). Across SSPs in the 1.5°C scenario, average pasture and cropland area for food, feed and fibre decreased (in 2050: -120 to -450 Mha IQR compared with 2020 in pasture, and -70 Mha to -250 Mha IQR in cropland). Simultaneously, average natural forests and energy cropland area increased (in 2050: -10 to +730 Mha IQR compared with 2020 in natural forests, and +170 to +550 Mha in energy croplands) (Appendix Table 2.1). However, the full range for natural forest change is large, from about 300 Mha decrease to about 1,000 Mha increase in 2050 compared with 2020, primarily due to the inclusion or exclusion of A/R in natural forests by some models (Appendix Table 2.2). The substantial land-use changes were largely driven by BECCS deployment, the scale of which is influenced by the SSP scenario and model assumptions on biomass feedstock (trees, energy crops or residues), agricultural yields, and conversion efficiencies (Popp et al. 2017; Rogelj, Shindell, et al. 2018). Land-use changes were also driven by carbon-price-induced shifts in agricultural systems and consumption of GHG-intensive ruminant meats and crops.

CDR and BECCS in modelled pathways. CDR is deployed widely in models because, owing to political and economic inertia, achieving the 1.5° and 2°C targets is generally considered infeasible without removing large amounts of CO_2 from the atmosphere (Rogelj, Popp, et al. 2018; Peters and Geden 2017). However, models make implicit assumptions about

CDR availability in the future, with some using an amount of CDR comparable to the remaining carbon budget (Rogelj, Shindell, et al. 2018; Peters and Geden 2017). IAMs also optimize for least cost and often make idealized assumptions about a global carbon price and effective land governance which promote measures like BECCS as the predominant CDR technology used (as energy and negative emissions are produced at relatively low cost) (Rogelj, Shindell, et al. 2018).

Various studies, however, question the feasibility and sustainability of large-scale BECCS deployment. Feasibility concerns include 1) bioenergy crops yields and available land in IAMs are higher compared to ecological studies (Creutzig 2016; Dooley and Kartha 2018; Fajardy and Mac Dowell 2017; Haberl et al. 2010); and 2) the technical, economic and political requirements of establishing adequate BECCS plants and storage basins may not materialize (Fajardy and Mac Dowell 2017; Creutzig et al. 2015; Fuss et al. 2018; Turner et al. 2018; Haberl et al. 2010; Peters and Geden 2017; Dooley and Kartha 2018). Sustainability concerns include: 1) the extensive amount of land (31-58 Mha per $GtCO_2e$ (Smith et al. 2016)), water (60 km^3 per $GtCO_2e$ (Smith et al. 2016)), and fertilizer required by BECCS could cause deforestation, biodiversity loss and GHG emissions, and risk food security (Heck et al. 2018; Humpenöder et al. 2018; Turner et al. 2018; Fuss et al. 2018; Dooley and Kartha 2018; Fajardy and Mac Dowell 2017; Creutzig et al. 2015; Creutzig 2016; Smith et al. 2016); and 2) the emissions from production and potential deforestation, biophysical changes to surface energy fluxes, and high yield assumptions that may not materialize could make BECCS less effective in removing CO_2 (Fajardy and Mac Dowell 2017; Creutzig et al. 2015; Creutzig 2016; Heck et al. 2018; Dooley and Kartha 2018). Although some models are developing sustainable development pathways that limit the negative effects of BECCS and/or CDR deployment (Obersteiner et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018; Holz et al. 2018; Rogelj, Popp, et al. 2018), social and environmental safeguards are typically not addressed by IAMs, resulting in some undesirable scenarios like large-scale conversion of forests and croplands into BECCS plantations. The sustainable pathways include increased emission reductions, increased energy and material efficiency, and reduced pressure on land through dietary change, lower population growth, and alternative CDR like using algae for BECCS.

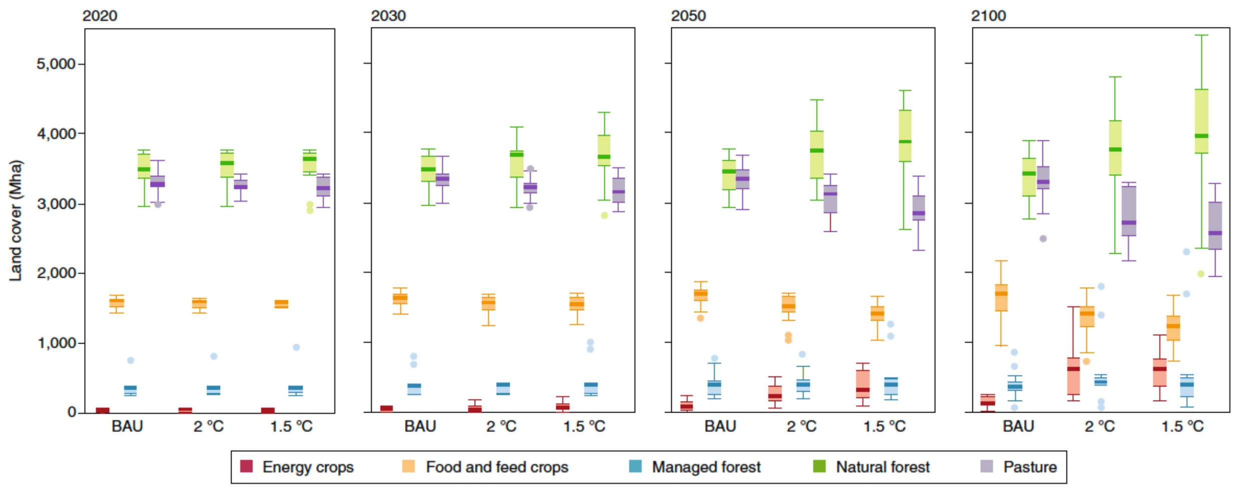


Figure 2.3. Land cover balance in million hectares (Mha) in BAU, 2°C and 1.5°C model scenarios. Natural forests (unmanaged forests) are primary, secondary, and protected forests with no planned timber production and tree felling either for wood extraction or for silvicultural purposes such as pre-commercial thinnings. Some models account for afforestation and reforestation (A/R) under natural forests, which is why natural forests increase over time in certain models and scenarios (the treatment of A/R in each of six models is outlined in Appendix Table 2.2, and detailed in Appendix section 2.2). Managed forests are forests that are managed for timber production and/or carbon sequestration, in some models, including BECCS. Energy Crops are short rotation plantations and other feedstocks for bioenergy including BECCS. Data from the SSP Database. Boxplots show the median, interquartile range and minimum–maximum range.

Bottom-up assessment of mitigation potential

To complement the top-down modelled scenarios and gauge how a larger portfolio of land-sector measures could contribute to a 1.5°C pathway, we conducted a bottom-up synthesis of mitigation potential, updating the IPCC-AR5 (Smith et al. 2014) framework with new categories and more recent literature (methods and additional analysis of land-sector measures in Appendix section 2.3). We assessed the range of technical, economic and sustainable mitigation potential of 24 land-based activities in both the supply- and demand-side, and developed new estimates of country-level mitigation potential.

The total mitigation potential of supply side measures from reduced land-use change, CDR through enhanced carbon sinks, and reduced agricultural emissions amounted to 2 – 36.8 (median 10.6) $GtCO_2e\ yr^{-1}$ in 2020-2050 (**Figure 2.4**). When BECCS was included, the estimate increased to 2.4 – 48.1 (median 14.6) $GtCO_2e\ yr^{-1}$. Demand-side measures yielded 1.8 – 14.3 (median 6.5) $GtCO_2e\ yr^{-1}$ of mitigation potential from reducing food loss and waste, shifting diets, substituting cement and steel with wood products, and switching to cleaner cookstoves. Our upper range from supply-side measures is higher than the IPCC-AR5 economic mitigation potential of 7.18 – 10.60 $GtCO_2e\ yr^{-1}$ in 2030, as it reflects technical potential that does not consider cost or feasibility. We also consider a wider scope of previously unaccounted for AFOLU activities including wetlands and bioenergy (Smith et al. 2013, 2014). For the same reasons, our estimates are higher than the economic mitigation potential of AFOLU activities in our intermodel analysis (0.9 – 20.5 $GtCO_2e\ yr^{-1}$ (median 9.1) across 1.5°C scenarios in 2050). Our estimate is more consistent with a recent study by Griscom et al. 2017 of 23.8 $GtCO_2e\ yr^{-1}$ in 2030 which represents technical mitigation potential constrained by biodiversity and food security safeguards. About half of their technical mitigation potential (11 $GtCO_2e\ yr^{-1}$) is considered "cost effective" (<US$100 per tCO_2e), similar to our median estimate.

Carbon dioxide removal. CDR measures provided the largest land-based mitigation potential. Of the biological solutions, A/R (0.5 – 10.1 $GtCO_2e\ yr^{-1}$) accounted for the highest, followed by soil carbon sequestration (SCS) in croplands (0.3 – 6.8 $GtCO_2e\ yr^{-1}$), agroforestry (0.1 – 5.7 $GtCO_2e\ yr^{-1}$) and converting biomass into recalcitrant biochar (0.3 – 4.9 $GtCO_2e\ yr^{-1}$) (**Figure 2.4**). Although the restoration of peatlands and coastal wetlands (0.2 – 0.8 $GtCO_2e\ yr^{-1}$ for both) have more moderate potentials, they have among the largest sequestration potentials per unit area (Hooijer et al. 2010; Pendleton et al. 2012). The higher range of potentials are largely theoretical, as many estimates do not consider economic and political feasibility, contain uncertainty related to carbon gains and permanence, and require locating available, suitable land that limits food insecurity and biodiversity concerns. Measures such as A/R (particularly, ecosystem restoration) and agroforestry could deliver considerable co-benefits if managed sustainably (e.g., enhanced biodiversity, soil fertility, water filtration, and income from agroforestry) (Budiharta et al. 2014; Ellison et al. 2017). Soil carbon and biochar measures can increase soil fertility and yields at lower cost than to A/R (Griscom et al. 2017; Smith 2016). However, below-ground carbon potentials have higher uncertainty compared with above-ground, specifically on issues of permanence (Paustian et al. 2016; Smith 2016). Recent mitigation potential estimates for A/R provide "plausible" figures of 3.04 $GtCO_2e\ yr^{-1}$ by 2030 with environmental, social and economic constraints (<US$100 per tCO_2) (Griscom et al. 2017), and 3.64 $GtCO_2e\ yr^{-1}$ between 2020 and 2050 based, on a conservative scenario of restoration commitments and smaller scale afforestation (Hawken 2017). Feasible estimates also exist for other activities based on varying economic and socio-political assumptions (indicated as "economic potential" in **Figure 2.4**). In the top-down modelled results, A/R (0 – 3.1 $GtCO_2e\ yr^{-1}$ across all SSPs in 2050) are at the lower range of the bottom-up mitigation potential, owing to higher cost compared with BECCS. The BECCS mitigation potential is 0.4 – 11.3 $GtCO_2e\ yr^{-1}$ (0.4 – 5 $GtCO_2e\ yr^{-1}$ "sustainable potential"), lower compared to the IAMC model results (0 – 16.1 $GtCO_2e\ yr^{-1}$ in 2050). The feasibility and sustainability of BECCS is discussed in "*Modelled pathways.*"

Land-use change. Measures that reduce land-use change (reduced deforestation, forest degradation, peatland conversion and coastal wetland conversion) also provided large mitigation potentials: 0.6 – 8.2 $GtCO_2e\ yr^{-1}$. Reducing the conversion and degradation of natural ecosystems is an important land-based measure because of its large climate mitigation effect from avoided emissions, continued sequestration (Houghton and Nassikas 2018) and biophysical effects

(Lawrence and Vandecar 2015), and the many co-benefits from ecosystem services provided by intact forests. Maintaining tropical and peatland forests are particularly critical because both store a large fraction of terrestrial carbon per unit area and have high biodiversity (Houghton and Nassikas 2018; Hooijer et al. 2010). The top-down modelled mitigation potential for reduced deforestation (0 – 4.7 $GtCO_2e\ yr^{-1}$ across all SSPs in 2030 and 0 – 3.8 $GtCO_2e\ yr^{-1}$ in 2050) is in line with the bottom-up mitigation estimate (0.4 – 5.8 $GtCO_2e\ yr^{-1}$) due to low mitigation costs.

Agriculture. Among agriculture measures, the largest potential for non-CO_2 reductions include reduced enteric fermentation from better feed and animal management (CH_4 reduced by 0.1 – 1.2 $GtCO_2e\ yr^{-1}$), improved rice cultivation (CH_4 reduced by 0.1 – 0.9 $GtCO_2e\ yr^{-1}$) and management of cropland nutrients (N_2O reduced by 0.03 – 0.7 $GtCO_2e\ yr^{-1}$). Recent studies suggest "feasible" agricultural non-CO_2 reductions in 2030 from 0.4 $GtCO_2e\ yr^{-1}$ (Wollenberg et al. 2016) at a carbon price of \$20/tCO_2e to 1.0 $GtCO_2e\ yr^{-1}$ (Frank et al. 2017) at US\$25 per tCO_2e. The modelled economic mitigation potential for agriculture in all 1.5°C pathways is 3.3 – 4.1 $GtCO_2e\ yr^{-1}$ in 2050, consistent with our bottom-up estimates of 0.3 – 3.4 $GtCO_2e\ yr^{-1}$. Since agriculture accounts for 56% of methane emissions, and 27% of potent short-lived gases, reducing CH_4 emissions from livestock and rice cultivation would reduce global warming effects sooner and may offset delays in reducing emissions (Montzka, Dlugokencky, and Butler 2011).

Consumer behavior. On the demand side, shifting diets and reducing food waste have potential to mitigate 0.7 - 8 $GtCO_2e\ yr^{-1}$ (range of "healthy diet" to vegetarian diet) and 0.8 – 4.5 $GtCO_2e\ yr^{-1}$ respectively. A recent study finds "plausible" mitigation potential of 2.2 $GtCO_2e\ yr^{-1}$ (0.9 $GtCO_2e\ yr^{-1}$ excluding emissions from land-use change) if 50% of the global population adopted diets restricted to 57g of meat protein per day, and 2.4 $GtCO_2e\ yr^{-1}$ (0.9 $GtCO_2e\ yr^{-1}$ excluding emissions from land-use change) if food waste is reduced by 50% in 2050 (Hawken 2017). Decreasing meat consumption and food waste reduces land used for feed, water use and soil degradation, thereby increasing resources for improved food security (Tilman and Clark 2014; Bajželj et al. 2014). Improving wood fuel use by increasing clean cookstoves provides moderate mitigation potential (0.1 – 0.8 $GtCO_2e\ yr^{-1}$), and also delivers high co-benefits of improved air quality and health (Bailis et al. 2015). The mitigation potential of increasing wood products to replace energy-intensive building materials like steel and concrete is moderate (0.3 - 1 $GtCO_2e\ yr^{-1}$), and wood sourcing would need to be managed sustainably to avoid negative impacts to biodiversity and natural resources.

Regional mitigation potential. Brazil, China, Indonesia, the European Union, India, Russia, Mexico, the United States, Australia and Colombia represent 54% of global AFOLU emissions (Tubiello et al. 2013), and are the 10 countries/regions with the highest mitigation potential in the land sector (**Figure 2.5**). In tropical countries, the highest mitigation potential is from carbon removals (A/R and forest management) and reduced land-use change. Brazil and India also have substantial mitigation potential in reducing enteric fermentation. Mitigating emissions from rice cultivation is important in Asian countries. Large emerging countries, China, India, and Russia, as well as developed countries in the European Union, the United States and Australia have large mitigation potential from A/R and forest management, as well as reduced emissions from enteric fermentation, synthetic fertilizer and manure.

The regional mitigation potentials do not include demand-side potential. However, based on current consumption of beef and food losses and waste (Appendix section 2.3), the highest diet shift potential lies in the United States, European Union, China, Brazil, Argentina and Russia. The largest food waste potential from consumers is in the United States, China and the European Union. Southeast Asia and Sub-Saharan Africa have the greatest avoided food loss potential from production. The European Union and China also have high potential to reduce the consumption of commodities associated with deforestation (palm oil, soy, beef, timber) (Henders, Persson, and Kastner 2015).

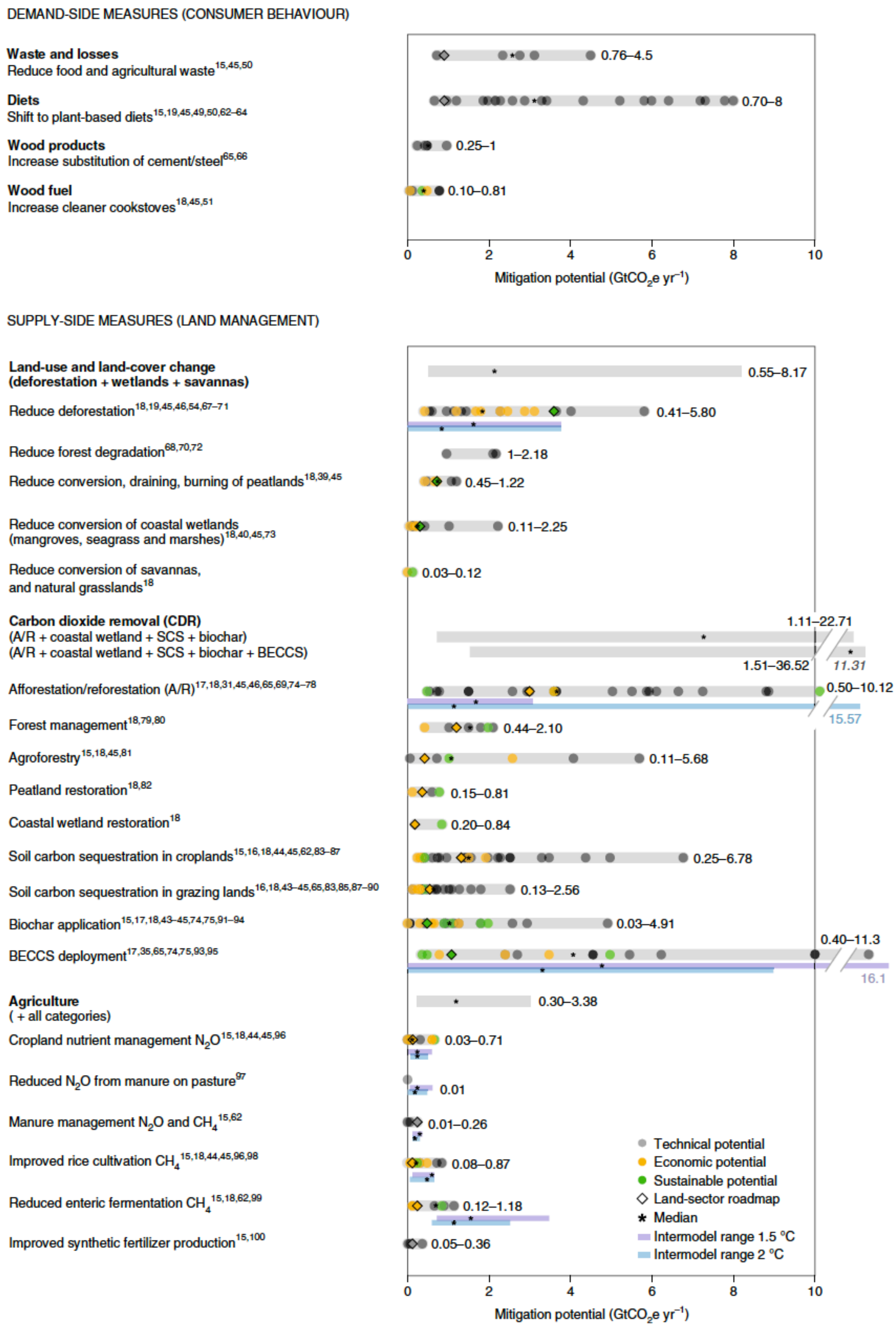


Figure 2.4. Global land-based mitigation potential in 2020-2050 by activity type from bottom-up literature review. Mitigation potentials reflect the full range of low to high estimates from studies published after 2010, and are differentiated according to technical (possible with current technologies), economic (possible given economic constraints) and sustainable

potential (technical or economic potential constrained by sustainability considerations). Medians are calculated across all potentials in categories with more than four data points. We only include references (cited after each category title) that provide global mitigation potential estimates in CO_2e yr^{-1} (or similar derivative) by 2050. Supply-side measures (activities that require a change in land management) and demand-side measures (activities that require a change in consumer behavior) are treated separately as these two categories are not additive. The analysis was designed to avoid potential double-counting of emissions reductions. The summed categories are highlighted in the supply-side measures (for example, total land-use change "deforestation+wetlands+savannas" excludes forest degradation and peatlands as these categories are included in many estimates). For Agriculture, all categories are summed ('+ all categories'). More information on the methods and description of activities are in Appendix section 2.3. To compare with bottom-up potentials, top-down intermodel ranges and medians are included in available categories from the 2°C and 1.5°C scenarios in the SSP Database, and in the IAMC Database for BECCS. The models reflect land management changes, yet in some instances, can also reflect demand-side effects from carbon prices, so may not be defined exclusively as "supply-side." Estimates used for the Land-sector Roadmap are given more context in Figure 2.6.

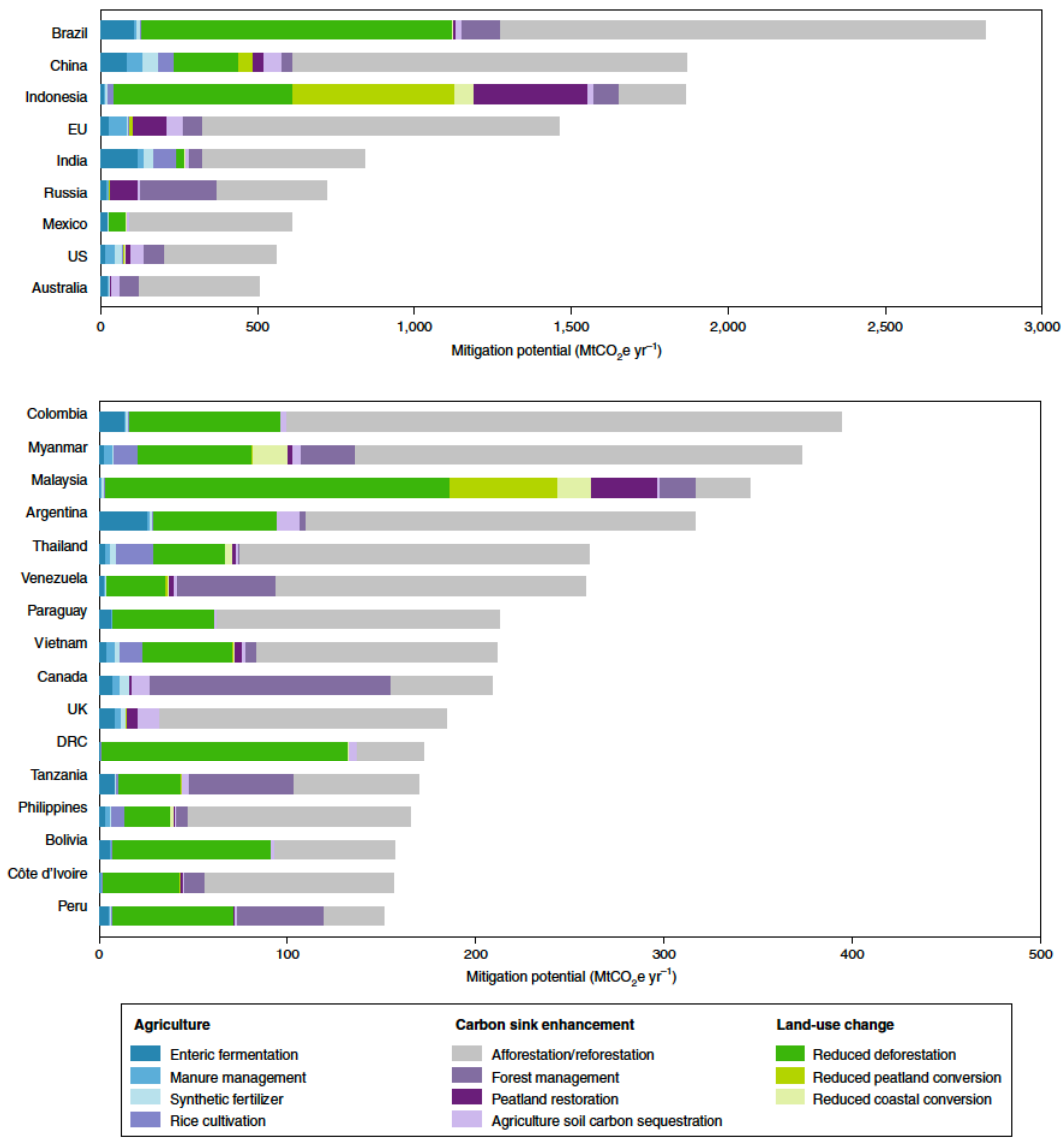


Figure 2.5. Land-based mitigation potential in 2020-2050 by region.
The top 25 countries with the highest mitigation potential are presented, nine with over 500 $MtCO_2e$ yr^{-1} (top panel) and 16 with 100 - 400 $MtCO_2e$ yr^{-1} (bottom panel). Numbers are compiled from country mitigation potentials in Griscom et al. (2017) (Rice cultivation, Forest management, Peatland restoration, A/R, Reduced deforestation, Reduced peatland conversion, and Reduced coastal conversion), as well as percentages of FAOSTAT emissions data calculated for this study (Enteric fermentation, Manure

Management, Synthetic Fertilizer and Agriculture soil carbon enhancement. Additional detail and data available in Appendix section 2.3 and Appendix Table 2.4.

Land-sector roadmap for 2050

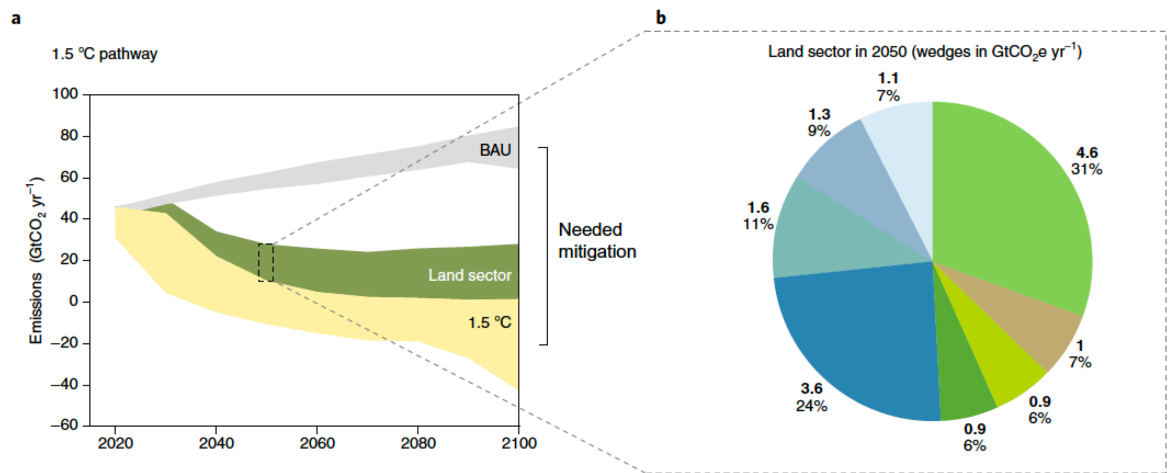
The land-sector transformation characterized in the 1.5°C modelled pathways will require significant investment and action. Given that land interventions have interlinked implications for climate mitigation, adaptation, food security, biodiversity and other ecosystem services, we developed a roadmap of priority activities and geographies through 2050 (**Figure 2.6**) to illustrate a potential path of action for achieving climate and non-climate goals. Reconciling the median top down (13.8 $GtCO_2e$ yr^{-1}) and bottom up (14.6 $GtCO_2e$ yr^{-1}) estimates of mitigation potential, we established a viable mitigation target (sum of emission reductions and removals) for the land sector of approximately 14 $GtCO_2e$ yr^{-1} (15 $GtCO_2e$ yr^{-1} with BECCS) in 2050. We then divided the required effort into priority mitigation measures, or "wedges", by determining mitigation potentials according to their feasibility and sustainability from the bottom-up mitigation analysis (Appendix Table 2.5), qualitatively weighing associated risks and trade-offs and prioritizing activities that maximize co-benefits (Appendix Table 2.6). The resulting eight priority wedges incorporate the 24 activity types from the bottom-up assessment, maximizing emissions reductions from land-use change, and using "sustainable estimates" that are also "cost effective" for carbon removal measures, "plausible" estimates for demand-side measures, and conservative economic potentials for agriculture measures (estimates are highlighted in **Figure 2.4** and detailed in Appendix Table 2.5). For each wedge, we highlighted important regions and activity types based on bottom-up mitigation potentials and a political feasibility analysis. Finally, we produced GHG reduction trajectories by region consistent with the modelled emissions trajectories pathway (full analysis and methods in Appendix section 2.4).

The 15 $GtCO_2e$ yr^{-1} roadmap mitigation target delivers about 30% of global mitigation, reducing gross emissions by 7.4 $GtCO_2e$ yr^{-1} (4.6 $GtCO_2e$ yr^{-1} from reduced land-use change, 1

$GtCO_2e$ yr^{-1} from agriculture, and 1.8 $GtCO_2e$ yr^{-1} from diet shifts and reduced food waste) and increasing carbon removals by 7.6 $GtCO_2e$ yr^{-1} (3.6 $GtCO_2e$ yr^{-1} from restored forests, peatlands and coastal wetlands, 1.6 $GtCO_2e$ yr^{-1} from improved plantations and agroforestry, 1.3 $GtCO_2e$ yr^{-1} from enhanced soil carbon sequestration and biochar, and 1.1 $GtCO_2e$ yr^{-1} from the conservative deployment of BECCS) (**Figure 2.6a**). Carbon removals of 1.1 $GtCO_2e$ yr^{-1} through BECCS requires 34-180 Mha of land (Turner et al. 2018; Smith et al. 2016) and is within the lower range of "sustainable potential" (Fuss et al. 2018). Each mitigation wedge is associated with a wide portfolio of activities and countries, illustrating that no single strategy or region will be sufficient to deliver on the mitigation target (**Figure 2.6b**). Near-term priorities include avoided deforestation, peatland burning and mangrove conversion in the tropics, CDR in developed and emerging countries (restoration, forest management, agricultural soils), and reduced food waste and a shift in diets in developed countries and China (Appendix section 2.4). The roadmap translates to a needed reduction of land-based emissions by about 50% per decade (85% decrease by 2050) compared to BAU, and about a tenfold increase in carbon removals over two decades 2030–2050 (cumulative 184 $GtCO_2e$ by 2050) to make the land sector net zero emissions by 2040 and a net carbon sink of approximately 3 $GtCO_2e$ yr^{-1} by 2050 based on current AFOLU emissions of 12 $GtCO_2e$ yr^{-1}.

Our illustrative roadmap diverges with some 1.5°C modelled pathways. Seeking to avoid undesirable impacts from larger-scale deployment of BECCS (detailed in *"Modelled pathways"*), our roadmap relies on deeper emissions reductions from lifestyle changes such as reducing food waste and shifting diets, which have various economic, environmental and health co-benefits (Tilman and Clark 2014; Bajželj et al. 2014), and on higher removals from ecosystem-based sequestration including forest, peatland and coastal mangrove restoration, forest management and agricultural soils, which enhance vital ecosystem services (Budiharta et al. 2014; Ellison et al. 2017) (Appendix sections 2.3 and 2.4). The roadmap, similar to other sustainable pathways that limit BECCS and improve food consumption (Obersteiner et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018), will require additional efforts in the energy sector (for example, lower energy demand and more aggressive emissions reductions). Thus, our roadmap may be more expensive than a cost-optimized model pathway. However, the trade-offs illustrated in our roadmap (Appendix Tables 2.5 and 2.6) increase the likelihood of limiting warming to 1.5°C (or 2°C) and improve our ability to deliver on other social and environmental goals, potentially offsetting additional costs (damages from climate change and adaptation costs) not captured in the models.

The roadmap described here was designed to meet the targets of the Paris Agreement, enhance co-benefits (biodiversity, water, air, soil, resilience, food security and livelihoods) and also deliver on other international commitments and policies including the Sustainable Development Goals (SDG) 2, 6, 12, 14, 15, the New York Declaration on Forests (NYDF) goals 1 and 5, and the United Nations Convention on Biological Diversity (UNCBD) Aichi Targets 5 and 15 (Appendix Table 2.6). The roadmap reduces deforestation by 95% by 2050, contributing to the NYDF, SDG and Aichi Targets of halving deforestation by 2020 and halting deforestation by 2030. Our restoration wedge (3 $GtCO_2e\ yr^{-1}$ of reforestation, 0.4 $GtCO_2e\ yr^{-1}$ of peatland restoration and 0.2 $GtCO_2e\ yr^{-1}$ of coastal mangrove restoration) would restore forests on more than 320 Mha of land (Smith et al. 2016) by 2050 – an area consistent with the NYDF and Bonn Challenge targets of 350 Mha by 2030. Our mitigation wedges also contribute to the 2030 SDG goals of sustainably managing forests, conserving biodiversity, reducing water and air pollution, increasing agricultural productivity, and promoting sustainable consumption and production.



c

Implementation roadmap to 2050 (% emissions reductions [green] or cumulative $GtCO_2$ increase in carbon removals [blue])

Wedge	Priority regions for mitigation	Activity types	2020	2030	2040	2050
Reduce emissions from deforestation and degradation, conversion of coastal wetlands, and peatland burning[18] (95% emissions reduction by 2050 compared to 2018)	Tropical countries, particularly countries with high overall loss: Brazil, Indonesia, DRC, Myanmar, Bolivia, Malaysia, Paraguay, Colombia, Peru and Madagascar	Conservation policies, establishment of protected areas, law enforcement, improved land tenure, REDD+, sustainable commodity production, improved supply chain transparency, procurement policies, commodity certification, cleaner cookstoves	25%	70%	90%	95%
Reduce emissions from agriculture[16,21] (25% emissions reduction by 2050 compared to BAU)	Developed and emerging countries (China, India, Brazil, EU, US, Australia, Russia)	Reduce CH_4 and N_2O emissions from enteric fermentation, nutrient management, synthetic fertilizer production, manure management	0%	0%	15%	25%
	Asia (India, China, Indonesia, Thailand, Bangladesh, Vietnam, Philippines)	Reduce CH_4 emissions by improving water and residue management of rice fields, and manure management				
	Latin America (Brazil, Argentina, Mexico, Colombia, Paraguay, Bolivia)	Reduce CH_4 emissions from enteric fermentation and manure management				
Shift to plant-based diets[45] (50% adoption in global population by 2050)	Developed and emerging countries (US, EU, China, Brazil, Argentina, Russia, Australia)	Reduce production of GHG-intensive foods through public health policies, consumer campaigns, development of new foods	5%	20%	35%	50%
Reduce food waste[45] (50% reduction in total food waste by 2050 compared to BAU)	China, Europe, North America, Latin America	Reduce food waste: consumer campaigns, private sector policies, supply chain technology, improved food labelling, waste to biogas	20%	30%	45%	50%
	Southeast Asia, Sub-Saharan Africa	Reduce food loss: improve handling and storage practices through training, investment and technology	10%	30%	45%	50%
Restore forests, coastal wetlands and drained peatlands[18]	Brazil, Indonesia, China, EU, India, Mexico, Australia, US, Russia, Colombia, Malaysia	Invest in restoration, national and local policies, payment for ecosystem services	0	9	45	90
Improve forest management and agroforestry[18]	Russia, Canada, Brazil, Indonesia, US, EU, Australia, Tropical countries	Optimizing rotation lengths and biomass stocks, reduced-impact logging, improved plantations, forest fire management, certification; integration of agroforestry into agricultural and grazing lands	0	4	20	40
Enhance soil carbon sequestration in agriculture and apply biochar[17,45]	China, EU, US, Australia, Brazil, Argentina, India, Indonesia, Mexico, Sub-Saharan Africa	Erosion control, use of larger root plants, reduced tillage, cover cropping, restoration of degraded soils, biochar amendments	0	3	16	32
Deploy BECCS[17,35]	USA, Russia, China, Canada[35]	BECCS R&D, investment and deployment	0	0	11	22

Figure 2.6. Land-sector roadmap for 2050.
(a) The land sector makes up 21 – 30% interquartile range (median 25%, approximately 14 $GtCO_2e$ yr^{-1}) of the total mitigation in 2050 in modelled 1.5°C pathways (data from Fig 2.2c). In the bottom-up assessment, the median land-sector mitigation potential is about 15 $GtCO_2e$ yr^{-1} in 2020-2050, or about 30% of the total mitigation needed. (b) The needed mitigation is translated into eight priority land-based measures (wedges), combining the 24 land-based activities from the bottom-up assessment, and based on an analysis of co-benefits and risks, feasibility and sustainability to deliver mitigation of about 15 $GtCO_2e$ yr^{-1} by 2050 (detailed in Appendix Tables 2.5 and 2.6). The green wedges represent emission reduction measures (7.4 $GtCO_2e$ yr^{-1}), and the blue wedges represent carbon removal measures (7.6 $GtCO_2e$ yr^{-1}). Each wedge is individually accounted for with the intent of avoiding double counting (Appendix section 2.4). **(c)** The implementation roadmap to 2050 details each wedge and related priority regions, activity types and implementation trajectories in percent for emission reduction activities and cumulative $GtCO_2e$ for carbon removal activities starting in 2020. The baseline and trajectory numbers in 2050 are based on the source used for each wedge (Appendix Table 2.5). The 2020-2050 trajectories were developed through a political feasibility assessment

combined with an expert assessment weighing tradeoffs. Additional details on priority regions and trajectories are provided in Appendix sections 2.3 and 2.4.

Discussion: Challenges and Opportunities

Our analysis, similar to other studies (Rogelj, Shindell, et al. 2018; Rogelj, Popp, et al. 2018; Rockström et al. 2017), shows that delivering on the Paris Agreement's target of 1.5˚C is daunting, yet still within reach if ambitious mitigation is implemented and substantial negative emissions are deployed. Limiting warming to 1.5˚C will require more effort than the 2˚C target and current NDCs. Although both targets require steep emission reductions from tropical deforestation, the 1.5˚C goal will require earlier and deeper reductions in agricultural and demand-side emissions, and enhanced carbon removals in the land sector. We show that model results and bottom-up analysis differ on types of mitigation measures included and their relative mitigation contributions, and that additional considerations are needed to account for feasibility and sustainability. In our roadmap, the land sector can deliver 15 $GtCO_2e\ yr^{-1}$ (about 30% of climate mitigation) by 2050 while contributing to various sustainable development goals. However, top-down and bottom-up mitigation estimates do not yet reflect biophysical changes nor show how potentials will be affected by future climate change, so more research is needed. Furthermore, implementing the roadmap comes with important challenges.

Negative emissions and BECCS

The impacts associated with large-scale deployment of BECCS on natural ecosystems and agricultural land, and the risks from high CDR reliance later in the century, are discussed in this Review and recent literature (Fajardy and Mac Dowell 2017; Rogelj, Shindell, et al. 2018; Fuss et al. 2018; Smith et al. 2016; Creutzig 2016; Dooley and Kartha 2018; Peters and Geden 2017; Haberl et al. 2010; Creutzig et al. 2015; Turner et al. 2018; Heck et al. 2018; Humpenöder et al. 2018; Obersteiner et al. 2018). Better incorporating environmental and social safeguards in IAMs and scenario setting, and emphasizing alternative pathways of early carbon removal and lifestyle changes in climate policy discussions may help to address some of these risks. Despite the risks from BECCS, negative emissions will be necessary to limit warming to <2˚C. Counterintuitively, halting the development of carbon removal technologies like BECCS without a replacement could yield more detrimental effects on land and climate, due to the potential for increased use of bioenergy as a cheap energy source without the benefit of sequestration (Rogelj et al. 2016; Schleussner et al. 2016; Rogelj, Shindell, et al. 2018). Research, development, and investment in negative emissions technologies today could assist their sustainable deployment in the future (Obersteiner et al. 2018; Smith et al. 2016).

Scaling up action in the land sector

Our 1.5˚C land-sector roadmap shows a pathway to reduce emissions by about 85% by 2050 and increase carbon removals tenfold between 2030-2050. However, there is a large gap between progress so far and the desired pathway.

Despite efforts to reduce deforestation over the past decade, emissions from land-use change have increased because of surging tropical deforestation (Zarin et al. 2016; NYDF Assessment Partners 2019). Between 2014 and 2018, more than 26 Mha of tree cover was lost every year, a 43% increase since 2001–2013 year (NYDF Assessment Partners 2019), yet deforestation must decline 70% by 2030 and 95% by 2050 to align with the 1.5˚C roadmap. Commitments toward ecosystem restoration have been increasing, with a majority of countries (122 of 165 that submitted) including forest restoration pledges in their NDCs(NYDF Assessment Partners 2019). However, only 20% of countries included quantifiable targets, amounting to 43 Mha (NYDF Assessment Partners 2019), and our roadmap suggests more than 320 Mha of new or restored forests will be needed. Empirical evidence is lacking on progress in addressing emissions in agriculture (non-CO_2 emissions and soil carbon) and demand-side measures.

Major barriers to delivering AFOLU mitigation include political inertia, weak governance and lack of finance. Addressing agricultural emissions is limited by concerns about negative trade-offs, such as food security, economic returns, and adverse impacts on smallholders (Wollenberg et al. 2016). Demand-side measures – reducing food waste and shifting diets – have proceeded slowly because of limited awareness and political support, in addition to the difficulties of eliciting behavioural change (Bajželj et al. 2014). Similarly, development of negative emissions technologies is stymied primarily because of low awareness, low prioritization, and concerns about negative trade-offs (Fuss et al. 2018). Increased dialogue between scientists and policymakers is important for bridging the knowledge gap in "no-regret" options for mitigation and catalysing political action. Key areas of necessary research include breakthrough technologies and approaches in behavioural science, meat substitutes, livestock production systems including new feed, peatland restoration, improved fertilizer, seed varieties, CCS, and advanced biofuels.

Governance issues related to illegality and a lack of enforcement have been major challenges for addressing land-use change, particularly deforestation and peatland fires in the tropics (Lambin et al. 2018; NYDF Assessment Partners 2019). Effectively reducing deforestation and scaling up restoration depends on understanding local dynamics at the forest frontier and coordinated action among private and public actors – exemplified by the successes in Brazil (Lambin et al. 2018; NYDF Assessment Partners 2019). Agricultural intensification combined with forest restoration on spared land holds significant potential when accompanied by stringent land policies and enforcement and demand-side measures (for example, reduced meat consumption) (Lamb et al. 2016). Less intensive forestry systems have also shown success in avoiding deforestation if land tenure security is combined with best practices in forest management (Griscom et al. 2018).

Efforts to reduce emissions from deforestation and degradation and promote A/R often have higher transaction and implementation costs than expected, and existing finance for forest protection is inadequate (Luttrell et al. 2018). Climate finance for forests accounts for 1.5% (US$3.2 billion) of global public climate funding (US$256 billion), and 0.1% of total public and private land-sector funding in countries with high levels of deforestation (US$1,495 billion) (NYDF Assessment Partners 2019). A lack of finance, high transition costs and low expected returns from changed practices are the main challenges for farmers (Rodriguez et al. 2009; Scherer and Verburg 2017; Wollenberg et al. 2016). A large shift from traditional investments in the land sector (for example, intensified commodities with no environmental benefits) to financing that promotes sustainable land-use and capacity building at the farm level will be needed to scale up action.

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Chapter 3: Mitigation potential of afforestation, reforestation and forest enhancement, considering impacts from climate, agricultural expansion, and biodiversity prioritization

In review in *Global Change Biology, 2021*

Abstract

Afforestation, reforestation and forest enhancement (A/R/E) activities have gained significant traction as a response to climate change. However, few studies consider the impact of climate change itself on sequestration potential. Here, we assess the biophysical sequestration potential for A/R/E in two climate futures, 2°C (2.6 W/m^2 forcing) and 4°C (7.0 W/m^2 forcing). We also consider land competition tradeoffs by evaluating potential in two land futures, no land-use change, and high agricultural expansion. We then assess areas with greatest potential for multiple benefits, and compare to existing country restoration commitments. With 2.6 W/m^2 forcing, we find A/R/E could cumulatively remove 300-510 $GtCO_2$ from the atmosphere using 710-935 Mha of land by the end of the century. In 2050, the annual mitigation potential for A/R/E is 3.8-7.3 $GtCO_2$ yr^{-1}, with ~45% from afforestation, ~33% from reforestation, and ~21% from forest enhancement. Large agricultural expansion (+650 Mha) not only reduces the A/R/E sequestration potential by 41% (lower end of the ranges), it also substantially reduces the natural capacity of land to act as a carbon sink by 62%. Tropical regions capture a majority of potential (80%), with 65% of afforestation, 90% of reforestation and 92% of forest enhancement. With 7.0 W/m^2 forcing, sequestration potential is ~20% greater, with 15-30% higher gains in the tropics compared to temperate and boreal regions. Productivity increases outweighed carbon losses from ecosystem respiration and fire, largely due to CO_2 fertilization. Priority areas for biodiversity and ecosystem services overlap on 42% of A/R/E area, with the highest synergies in forest enhancement (58%), then reforestation (43%), then afforestation (34%). Our results show

reforestation and forest enhancement in the tropics and sub-tropics have higher mitigation densities than afforestation, higher potential to deliver multiple benefits, and are most aligned with countries' restoration pledges, indicating where efforts should be prioritized.

Introduction

Forests currently cover ~30% of the Earth's terrestrial surface and store ~45% of terrestrial carbon (Pan et al. 2011; Grace, Mitchard, and Gloor 2014). A large majority of climate scenarios that limit warming to the Paris Agreement targets of 1.5°C and 2°C rely on substantial carbon dioxide removals (CDR) from increasing forest cover through afforestation and reforestation (A/R) (Rogelj et al. 2018; Roe et al. 2019). A/R is a set of anthropogenic activities that convert non-forested land into forest, where reforestation is on land that was once a forest ecosystem, and afforestation is on land that historically has not contained forest (P. Smith, Nkem, and Calvin 2019). Forest restoration, which could include the enhancement of tree density in degraded forests, is sometimes considered part of A/R activities and/or forest management (P. Smith, Nkem, and Calvin 2019). Based on current literature, A/R has among the highest climate mitigation potential of land-based measures (Roe et al. 2019).The biophysical (and technical) potential estimates of A/R range from about 2 $GtCO_2$ yr^{-1} (154 $GtCO_2$ cumulatively) on 350 million hectares (Mha) of land between 2020-2100 (Lewis et al. 2019) to about 10 $GtCO_2$ yr^{-1}on 678 Mha in 2030 (Griscom et al. 2017) with a median potential of 3.6 $GtCO_2$ yr^{-1} between 2030-2050 (calculated from (Lenton 2014; Houghton, Byers, and Nassikas 2015; Kreidenweis et al. 2016; Sonntag et al. 2016; Griscom et al. 2017; Houghton and Nassikas 2018; Bastin et al. 2019). The large range is due to different assumptions (e.g. timeline, only focusing on reforestation, considering future land-use change) and carbon pools considered. Estimates of economic potentials (available at a carbon price of $20-200/$tCO_2$) have a lower range of 0.2 to 5 (median 2) $GtCO_2\ yr^{-1}$ between 2030-2050 (Humpenöder et al. 2014; Griscom et al. 2017; Busch et al. 2019; Doelman et al. 2020; Favero, Daigneault, and Sohngen 2020; Austin et al. 2020).

A/R is also considered a nature-based solution, an action that enhances nature to help address societal challenges (Cohen-Shacham et al. 2016). Depending on the management, location, and scale, A/R, particularly reforestation and restoration of degraded forest ecosystems, has the potential to deliver significant co-benefits beyond global climate mitigation (Smith et al. 2019). Benefits include enhancing biodiversity and multiple ecosystem services such as regulating water supply and quality, air quality, nutrient cycling, providing agroforestry products, as well as building resilience to climate impacts like floods and landslides (Locatelli et al. 2015; Ellison et al. 2017; Seddon et al. 2019), and stabilizing local climate (Bright et al. 2017; Devaraju et al. 2018). Environmental and social benefits have gained forest restoration and tree-planting initiatives significant attention in both the public and private sector. These activities have been promoted in country pledges under the UN Framework Convention on Climate Change (UNFCCC), Sustainable Development Goals (SDGs), Bonn Challenge, New York Declaration on Forests, the UN Convention on Biological Diversity (UNCBD), and the UN Convention to Combat Desertification (UNCCD) (Seddon et al. 2020).

While A/R has significant potential benefits, it also has some potential risks and trade-offs. If poorly implemented, A/R could have negative impacts on and localized trade-offs with resource availability (e.g. water, nutrients, land), biodiversity and food security (P. Smith et al. 2020). A/R, and in particular, afforestation of natural grasslands and other non-forest ecosystems with non-native species and monocultures, could have negative impacts on ecosystem structure and function, nutrient use, and water availability, particularly in dry regions (Veldman et al. 2015; Zhang et al. 2016; Schwärzel et al. 2020). Deploying A/R at a large-scale can also increase food prices through land competition and present a risk for food insecure regions (Kreidenweis et al. 2016; Doelman et al. 2020).

Furthermore, the mitigation benefit of A/R is likely to be impacted by future climate change. Changes in atmospheric CO_2 concentrations, temperature and precipitation are expected to alter plant physiological responses such as photosynthesis, respiration and evapotranspiration in trees (Boisvenue and Running 2006; Latta et al. 2010; Keenan et al. 2013). In addition, species dominance, the prevalence of pests and diseases, and the frequency and intensity of disturbances like fire are likely to change (Colwell et al. 2008; Pretzsch et al. 2014; Ma et al. 2016). The response of individual trees and the entire forest ecosystem will affect total carbon sequestration and emissions. To estimate the potential for A/R to mitigate future warming, we must account for the warming itself. However, few studies of A/R mitigation potential consider the effects of warming. Also, few studies break out the mitigation effect of different A/R activities, afforestation, reforestation and forest restoration through density enhancement (from now on, referred to as A/R/E).

In this study, we assess the impact of future climate change on the global and regional biophysical potentials of carbon sequestration from A/R/E in 2015-2100. We examine these potentials under low warming (2°C or 2.6 W/m^2 in 2100; Paris Agreement target) and high warming (4°C or 7.0 W/m^2 in 2100; Business as usual). To consider potential trade-offs related to land competition from agriculture, we limit A/R/E expansion to non-agricultural and non-urban lands. We assess two land-use scenarios, a 'Max Forest' scenario based on the current agricultural extent, and a 'Constrained forest' scenario where future agricultural expansion is high. We also overlay the various scenarios on biodiversity priority areas to assess areas of highest co-benefit. Finally, we compare our potentials to existing reforestation and forest restoration pledges made by countries as part of national and international commitments, to highlight possible complementarities and gaps between biophysical potential and policy goals.

Methods

Model set up and scenarios

Community Land Model (CLM)

Our A/R/E modeling experiment used the Community Land Model (CLM5), the land model for the Community Earth System Model (CESM2) that examines the physical, chemical, and biological processes by which terrestrial ecosystems affect and are affected by climate (D. Lawrence et al. 2019). In CLM, the land surface is divided into grid cells which are represented by six primary sub-grid land cover types (glacier, lake, wetland, urban, vegetated, crop). CLM is capable of variable resolutions; we ran our simulations at a resolution of 0.25° (a grid cell roughly 25 km across in the tropics). The vegetated grid cells are assigned to 15 plant functional types including bare soil. The model was run with active land biogeochemistry where the distribution of plant functional types is prescribed annually but all plant and soil, carbon and nitrogen, pools and fluxes are explicitly simulated. The model simulations generate the physical representations of plant leaf area and canopy height, as well as all of the carbon, energy and water exchanges between the land and atmosphere (see D. Lawrence et al. 2019).

A/R/E Scenarios

We developed four A/R/E scenarios, across two land futures (‘Max Forest’ and ‘Constrained forest’) and two climate futures (2.6 W/m^2, representative of 2°C warming and 7.0 W/m^2, representative of 4°C warming) (**Table 3.1**).The ‘Max Forest’ scenario is based on current (2015) land cover and land-use (NoLUC), where crops, pasture and urban land are held constant from 2015-2100 (**Figure 3.1**) and forests are added incrementally to targeted areas with forest-supporting climates, according to the process described in *‘Implementing A/R/E in CLM’* below.

This scenario is intended to represent the theoretical biophysical maximum amount of forested land given plausible constraints on the rate of reforestation and current land use. This theoretical maximum is an upper limit on the ability of A/R/E to mitigate climate change.

Table 3.1. A/R/E and baseline (reference) scenarios in two land-use futures and two climates.

	Scenario name	Land future	Climate future (radiative forcing)
Baseline	NoLUC 2°C	Current land cover (no change in agriculture from 2015)	2.6 W/m^2 (2°C)
	NoLUC 4°C	Current land cover (no change in agriculture from 2015)	7.0 W/m^2 (4°C)
	SSP3 2°C	SSP3 (high agriculture expansion)	2.6 W/m^2 (2°C)
	SSP3 4°C	SSP3 (high agriculture expansion)	7.0 W/m^2 (4°C)
A/R/E	Max Forest 2°C	NoLUC 2°C + Afforestation NoLUC 2°C + Reforestation NoLUC 2°C + Forest enhancement	2.6 W/m^2 (2°C)
	Max Forest 4°C	NoLUC 4°C + Afforestation NoLUC 4°C + Reforestation NoLUC 4°C + Forest enhancement	7.0 W/m^2 (4°C)
	Constrained Forest 2°C	SSP3 2°C + Afforestation SSP3 2°C + Reforestation SSP3 2°C + Forest enhancement	2.6 W/m^2 (2°C)
	Constrained Forest 4°C	SSP3 4°C + Afforestation SSP3 4°C + Reforestation SSP3 4°C + Forest enhancement	7.0 W/m^2 (4°C)

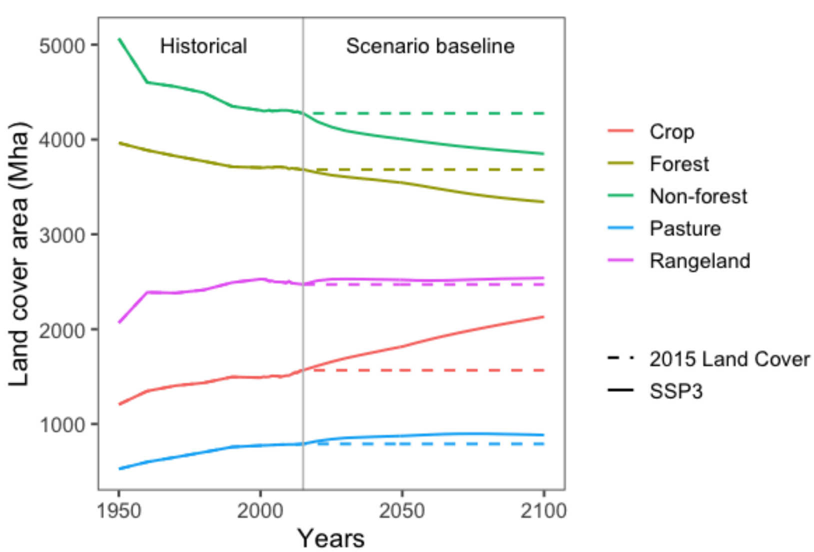

Figure 3.1. Land cover area (Mha) baselines for A/R/E scenarios.
Between 2015-2100, the 'Max Forest' scenario uses 2015 land cover, held constant, and the 'Constrained Forest' uses the SSP3 land future. Historical land cover change is included from 1950-2014 for comparison. The definitions of the landcover types are from (Hurtt et al. 2020), where 'Crop' is croplands, 'Forest' (primary and secondary) is an area with natural vegetation of

aboveground standing stock of >2 kgCm-2 , 'Non-forest' (primary and secondary) is an area with natural vegetation below the 'Forest' threshold of >2 kgCm-2 (including shrublands, natural grasslands, some wetlands), 'Pasture' is managed grazing land, and 'Rangeland' is unmanaged grazing land.

In contrast, the 'Constrained forest' scenario represents the theoretical biophysical contribution of A/R/E constrained by very high needs for agricultural land. In this scenario, we use the Shared Socio-economic Pathway 3 (SSP3, 'Regional rivalry') land future (**Figure 3.1**). This world sees continued deforestation and natural land conversion at high historical rates due to large increases in croplands and pasturelands to meet the food demands of a rapidly growing population (Fujimori et al. 2017; Popp et al. 2017). SSP3 has the highest levels of agricultural expansion across all five SSP scenarios and is characterized by regional conflicts, strongly constrained international trade, resource-intensive consumption, low technology development, limited regulation, and heavily delayed international cooperation on climate change (Popp et al. 2017). In an SSP3 world, countries increasingly focus on national food and energy security, however, rates of global crop yields decrease due to low agricultural technology transfer to developing countries (Popp et al. 2017). We see this as a scenario in which land used for agriculture is maximized and agricultural production is the main limiting factor in land use decisions.

Implementing A/R/E in CLM5

Beginning with the land surface baseline scenarios (**Table 3.1, Figure 3.1**) we systematically added tree cover, starting in 2015 and increasing according to the methods described in '*Deploying A/R/E in 2015-2100'* below. The baseline scenarios began in 2015 using the CLM land surface created during the sixth phase of the Coupled Model Intercomparison Project (CMIP6) land-use harmonization, a process that entails linking records of historic land use with remote sensing data to create the land surface for input into earth system models (P. Lawrence, Lawrence, and Hurtt 2018; Hurtt et al. 2020).

What we term ‘Reforestation’ is adding tree plant functional types on land where current climate (temperature and precipitation), defined by the Whittaker Biomes (Whittaker 1975) (**Figure 3.2a**), would allow for tropical, temperate or boreal forests to persist and the land was not already in use for crops, pasture or urban development. We chose the Whittaker classification as it uses climate (temperature and precipitation) to create biome boundaries, can be applied globally and is used widely. In this classification, reforestation was implemented on abandoned agricultural land and rangelands where forests could occur naturally regardless of whether forests had been present within the past 50 years or more, as long as the land was not occupied by agriculture or urban area. The definitions of land cover are from the CMIP6 land harmonization (Hurtt et al. 2020), where ‘abandoned lands’ had previously been used for cropping, pasture or urban development but had returned back to rangeland, secondary forest or secondary non-forest. The tree cover density and types of tree added to reforested land were determined by the average density and plant functional types found in the grid cell being forested (if existing forests were still remnant) or the closest remnant forest (if no forests existed in the grid cell).

‘Forest Enhancement’ adds tree cover on land already considered forest in the CMIP6 land surface, but where tree cover density was less than the potential. The current tree cover density of remnant forests in land surface baseline scenarios was determined from the MODIS Vegetation Continuous Fields data, as detailed in P. Lawrence et al. (2012). Tree cover density is increased to the average tree cover fraction for each Whittaker Biome (**Figure 3.2b**), using the same plant functional types from the grid cell.

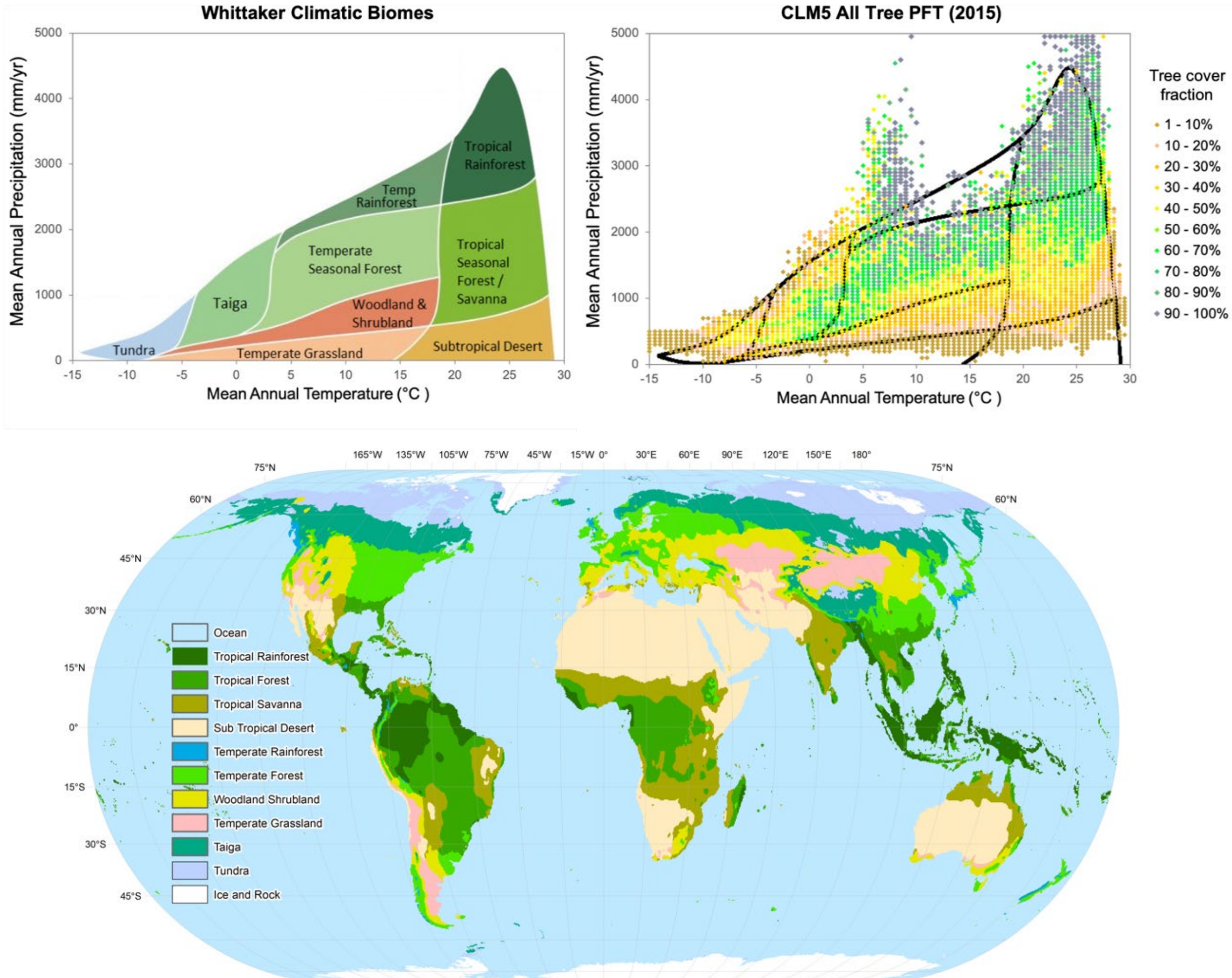

Figure 3.2. Suitability for forest expansion based on Whittaker biomes
(a) Whittaker climatic biomes (Whittaker 1975). (b) CLM5 grid cells (0.25° resolution) mapped onto the Whittaker climate space, with fraction of tree cover indicated by color. (c) Geographic extent of Whittaker biomes across the globe in present day climate. The map illustrates the temperature and precipitation data from CRU 3.1 (Harris et al. 2014), using thresholds based on the Whittaker biome diagram (Whittaker 1975).

Unlike reforestation and forest enhancement, 'Afforestation' was implemented where current climate would not indicate a Whittaker forest biome, but tree cover was currently or historically over 10%. In practice, these areas would be categorized by Whittaker as woodlands and shrublands, temperate grasslands, and savannas (**Figure 3.2c**). As with reforestation, afforestation could only occur on land that was not in use for crops, pasture or urban development, and tree cover density and plant functional types were based on the remnant forests in the grid cell being afforested or extrapolated from the nearest remnant forest. Tree cover in afforestation was added in rangelands, non-forests (e.g. shrublands and woodlands), and abandoned agricultural land using the definitions from the CMIP6 (Hurtt et al. 2020). In the SSP3 baseline scenario, agricultural land expanded substantially at the expense of existing forest. Afforestation and reforestation did not occur in newly deforested lands.

Deploying A/R/E in 2015-2100

Based on our analysis of the land surface in CLM in 2015, excluding cropland, pasture and urban area, and constrained according to Whittaker-based suitability as noted above (**Figure 3.2**), just over 9 million km^2 (935 Mha) were suitable for A/R/E. Because mitigation potential increases as a forest grows, A/R/E will be most effective the sooner trees are put into the ground. Therefore, we rapidly increased forest area starting in 2015, and the rate of implementation declined exponentially over the 85-year experiment. To account for likely limitations on the speed of implementation, we limited the amount of A/R/E occurring in a given year at both the global scale and the grid cell. In 2015, we transformed 5% of our ultimate area target, which declined to 2.3% in 2030, 0.9% in 2050 and 0.2% in 2080. At the grid cell level, 10% of a given grid cell could be changed in one year. This rate of A/R/E deployment was based on the historical rate of land conversion, reflecting the amount of area per year that could be feasibly transformed. In the first five years (highest A/R/E deployment), about 0.05-0.40% of the total land area by region was transformed annually.

We transformed areas in the order that would maximize tree and carbon sequestration performance, first transforming areas with the most suitable climates then moving into less suitable climates when the former areas were full of trees. To determine and prioritize areas with the most suitable climates, we assigned each grid cell a climate index score (**Equation 1**):

$$\text{Climate index} = \left(\frac{\text{annual precip} - 700}{2500} - \frac{\text{annual temp} - 25}{100} \right) \times 100 \qquad \textbf{(1)}$$

The index reflects the relationship between precipitation and temperature in current day, and prioritizes areas with higher tree density, those above woodland and shrubland in the Whittaker diagram (**Figure 3.2a-b, Figure A3.1**). Therefore, areas with the highest climate index score (highest priority), represented higher humidity or 'wetness' areas like tropical forests and temperate forests. In the index, a grid cell with warmer temperature would require more precipitation than a grid cell with cooler temperature to have the same wetness, and therefore the same climate index score. Because forests currently exist where they are best suited, grid cells partially covered by existing forest were the first to be reforested or enhanced, followed by grid cells that once had forests. Grid cells were added in order of descending climate index until the global area suitable for reforestation and forest enhancement was met for a given year. A similar procedure was followed to allocate grid cells for afforestation, starting close to existing forested grid cells and transforming up to 5% of suitable area based on climate index until the total suitable area was met. The climate index does not change over time as the climate warms to more effectively isolate the effect of land-use change and climate.

Testing the effect of climate on A/R/E mitigation potential

To run multiple scenarios with lower computing time and higher resolution, we ran CLM in a land-only configuration with prescribed atmospheric forcing data as described in Lawrence et al. 2019. In this configuration, CLM is uncoupled from the rest of the earth system model (CESM), therefore land-atmosphere feedbacks are not part of these experiments. The future climate of these simulations was prescribed through anomaly forcing, where the last 20 years of standard CLM meteorology from the Global Soil Wetness Project (GSWP3) is used to characterize meteorology over decadal scales and grid cell-level monthly climate forcing is imposed on top. Temperature, precipitation, and other atmospheric anomalies were derived from fully coupled runs in CESM2 of RCP2.6 climate (2.6 W/m^2) and SSP1 land use (SSP1-2.6), and RCP7.0 climate (7.0 W/m^2) and SSP 3 land use (SSP3-7.0). This approach allows us to create a future climate with real-world derived and thus realistic daily, weekly, seasonal and annual variability. The climate experienced by the land surface in CLM was thus the combination of a 20-year record of mean half-hourly data, repeated every 20 years, to which scenario-specific climate anomalies were added for the time period 2015-2100. SSP1-2.6 (2.6 W/m^2) results in global warming of about 2°C and atmospheric CO_2 of about 450 ppm by the end of the century, whereas SSP3-7.0 (7.0 W/m^2) results in global warming of about 4°C and atmospheric CO_2 of about 860 ppm (for simplicity, hereafter we refer to the climate scenarios as 2°C and 4°C) (**Figure 3.3**). The anomaly forcing also resulted in changes in global rainfall and relative humidity over land shown in **Figure 3.3** (regional climates are in **Figure A3.3**). Both land use scenarios were forced with both climates. All runs were driven with prescribed atmospheric concentrations of CO_2 and other radiative gases associated with the scenario. The climate forcing allows the terrestrial system to respond, however, because we ran the land model uncoupled from the earth system, there are no feedbacks from the land system to the atmospheric climate or carbon pool.

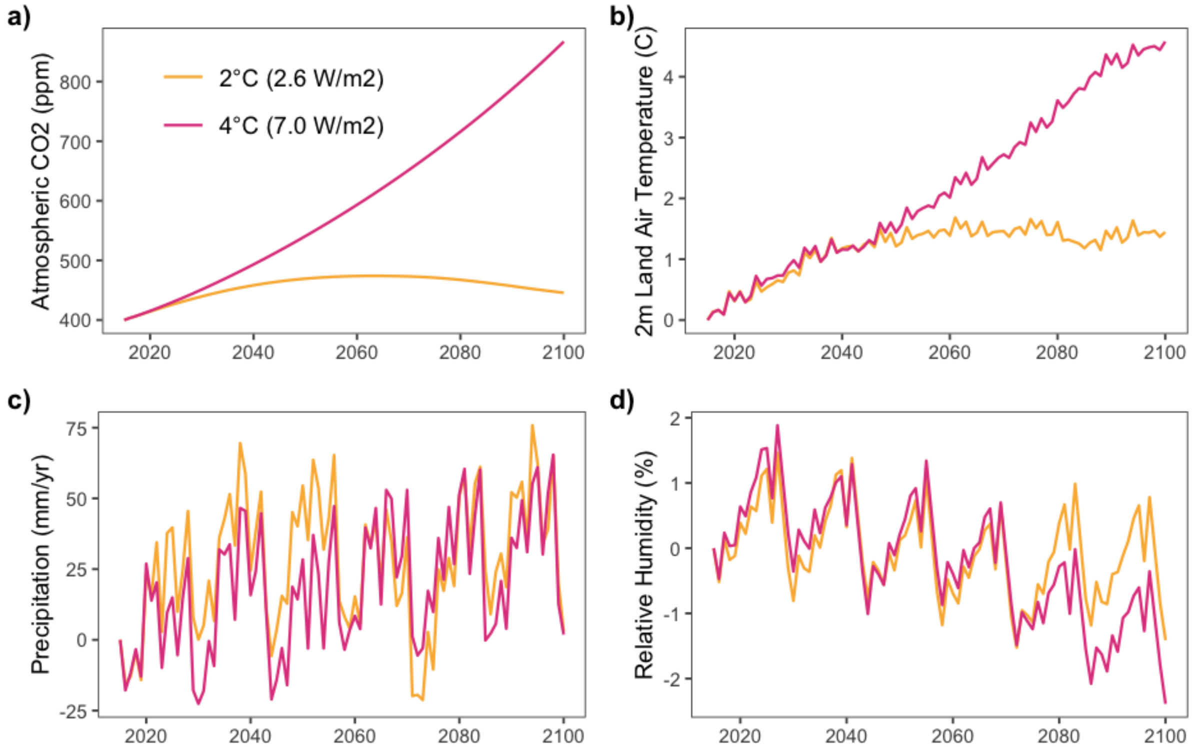

Figure 3.3. Prescribed experimental climate anomalies in A/R/E scenarios.
(a) Annual global atmospheric CO_2 concentration. (b) Change, relative to 2015 in global average 2m land surface air temperature (excluding Antarctica). (c) Change, relative to 2015 in global precipitation over land. (d) Change, relative to 2015 in global average relative humidity over land. Climates represent a combination of a 20-year record of mean half-hour meteorology data, repeated every 20 years, to which anomaly-forced global climate (from fully coupled simulations of RCP 2.6 and RCP 7.0 in CESM5) anomalies were added for the time period 2015-2100.

Analysis

We quantified the annual and cumulative ecosystem carbon sequestration potential associated with A/R/E in 2015-2100, as well as the associated forest area and the density of sequestration potential. Ecosystem carbon includes vegetation carbon, litter carbon, and soil carbon (depth-to-bedrock values with variable depths based on Pelletier et al. (2016)). We calculated mitigation potentials (annual and cumulative) as the difference in carbon sequestered in each A/R/E scenario compared to the reference scenario (**Table 3.1**). For annual mitigation, we used net biome production (NBP) (**Equation 2**) and analyzed 10-year averages to represent values in 2030 (2025-2034), 2050 (2045-2054) and 2100 (2091-2100). For cumulative

$$\textit{Net biome production (NBP)} = \textit{Gross primary production (GPP)} - \textit{Autotrophic respiration (AR)} - \textit{Heterotrophic respiration (HR)} - \textit{Carbon lost to fire (FireC)}$$

(alt)

$$\textit{Net biome production (NBP)} = \textit{NPP (Net primary productivity)} - \textit{HR} - \textit{FireC} \quad \textbf{(2)}$$

mitigation, we used the total ecosystem carbon (TEC) accumulated per time period. NBP is the annual increment in TEC. We then calculated the density of mitigation potential as the cumulative potential (TEC) divided by the cumulative area for A/R/E to get tCO_2 per hectare for 2030, 2050, and 2100. Mitigation potentials for afforestation, reforestation, and forest enhancement were accounted for separately. The units for mitigation potential in this study were converted from C to CO_2 (where $GtCO_2 = PgC * (44/12)$) for ease of comparison to other mitigation studies and country restoration pledges. In addition to A/R/E mitigation potential, we also estimate the sequestration capacity of the residual terrestrial carbon sink (TEC and NBP in the NoLUC [no land-use change] reference scenario).

To assess the effect of future climate on the sequestration potential of A/R/E, we compare the TEC and NBP values from A/R/E in the two radiative forcing scenarios (2°C [2.6 W/m^2] vs 4°C [7.0 W/m^2]). To isolate the climate effect from land-use on the total ecosystem carbon, we then evaluated carbon fluxes in the two climates for the NoLUC reference scenario (no land use change from 2015). Assessing the changes in carbon fluxes, Gross primary productivity (GPP), autotrophic respiration (AR), heterotrophic respiration (RH), fire carbon loss (FireC), and NBP helps to understand the mechanisms driving carbon sequestration under different climate regimes. We assessed global cumulative carbon flux differences (7.0 W/m^2 minus 2.6 W/m^2 per time period, then summed) as well as cumulative differences per region (sum (7.0 W/m^2 minus 2.6 W/m^2 per time period), normalized per area) for the NoLUC scenario in the two climates following P. Lawrence, Lawrence, and Hurtt (2018). For ease of comparison to other carbon flux studies, we kept the units in gC for the climate analysis.

We conducted our analysis of mitigation potential and climate effect at the global and regional scale, dividing the world into the 10 regions based on the IPCC AR6 WGIII regional disaggregation (**Figure A3.1**). The 10 regions are: Africa (AFR), Asia-Pacific Developed (APD), Eastern Asia (EAS), Eurasia (ERA), Europe (EUR), Latin America and Caribbean (LAC), Middle East (MEA), North America (NAM), South-East Asia and developing Pacific (SEA), and Southern Asia (SAS).

Biodiversity priorities

To highlight possible complementarities between areas designated for A/R/E and areas important for biodiversity, we overlaid a biodiversity priority map on the Max Forest and Constrained Forest scenarios under a 2°C climate. Then, we assessed area and mitigation potential overlaps for each A/R/E activity using ArcGIS. Aiming to assess future biodiversity priority areas in the same time frame as the A/R/E scenarios, we used the 'Sharing the Planet' (SP) map for 2050 (Kok et al. 2020). This map optimizes biodiversity (mean species abundance, geometric mean abundance and red list index) while prioritizing ecosystem services. The SP map combines protected areas from the World Database on Protected Areas (UNEP-WCMC and IUCN 2019) and Key Biodiversity Areas (Birdlife International 2019) to identify global conservation priorities, then adds strategic areas to maximize ecosystem benefits including high carbon forests (>100MgC/ha), peatlands, riparian zones, areas functioning as water towers, and urban green spaces to cover about 30% of the global terrestrial area excluding Antarctica. The Aichi Biodiversity Targets of the UNCBD set a goal of increasing protected areas in key biodiversity ecosystems by 20% between 2010 and 2020. With limited progress toward these targets (Bongaarts 2019), calls by civil society and governments to conserve 30% of their land by

2030 (commonly referred to as '30x30') have increased. The SP scenario provides an option for the post-2020 global biodiversity framework that integrates protecting nature with improving social conditions and humans' quality of life (Kok et al. 2020; Ellis 2019).

Comparison to current forest restoration policies and pledges

To see where and to what extent complementarities and gaps exist between biophysical mitigation potentials from A/R/E and policies and initiatives in practice, we compare the regional A/R/E mitigation estimates to summed country pledges on forest restoration. Data on 115 country pledges were adapted from the Global Restoration Commitments (GRC) database (Sewell, van der Esch, and Löwenhardt 2020a, 2020b). The GRC database includes quantitative country commitments for restoration, protection, management and rehabilitation across various ecosystems from plans submitted under at least one of the Rio Conventions (Nationally Determined Contributions under the UNFCCC (NDCs), National Biodiversity Strategy Action Plans under the UNCBD (NBSAPs), and Land Degradation Neutrality (LDN) targets under the United Nations Convention to Combat Desertification (UNCCD)), and/or the Bonn Challenge. Accounting for overlaps between different categories, the total global restoration commitments currently range from around 750 Mha to 1 billion ha (7.5 - 10 Mkm^2), largely in Sub-Saharan Africa (Sewell, van der Esch, and Löwenhardt 2020a). For this study, we only used the categories and available data relevant to A/R/E, 'restore/improve forest land', 'increase forest area', and restore/improve protected area', resulting in a total range of around 350-450 (median 385) million hectares across 98 countries. We then compared the pledged A/R/E areas (in Mha) to the biophysical potentials across the ten regions assessed.

Results

Mitigation potential of A/R/E

Global

In the Max Forest 2°C scenario, the global biophysical mitigation potential in all A/R/E activities increases from 4.2 $GtCO_2\ yr^{-1}$ in 2030 to 7.3 $GtCO_2\ yr^{-1}$ in 2050 before declining to 5.8 $GtCO_2\ yr^{-1}$ in 2100. On average, 47% is derived from afforestation, 32% from reforestation, and 21% from forest enhancement throughout the century (**Figure 3.4a**). Given that our climate index prioritizes activities that maximize tree performance (and thus adding within remnant forests), the proportion of forest enhancement is larger in the first two decades, with the share of reforestation and afforestation increasing in mid- to late century. When averaged between 2020-2050, the total A/R/E annual mitigation potential is 5.2 $GtCO_2\ yr^{-1}$. The cumulative total ecosystem carbon sequestration is about 160 and 510 $GtCO_2$ in 2050 and 2100 respectively (**Figure 3.4b**). A large majority accumulates in vegetation (96%), with much smaller fractions in soil organic matter (3%), and litter (<1%). Carbon sequestration increases substantially after 2050, as trees grow and forest cover expands.

A/R/E mitigation covers about 325 Mha (expanding at an average rate of 17.4 Mha yr^{-1}) in 2030, 610 Mha (11.4 Mha yr^{-1}) in 2050, and 935 Mha (1.7 Mha yr^{-1}) in 2100 (**Figure 3.5a**). By 2100, afforestation and reforestation add about 550 and 230 Mha of forest cover respectively (or 83% of the total A/R/E area) and forest enhancement occurs in 155 Mha of existing forest. Mitigation density (sequestration potential per hectare) for A/R/E is 264 $tCO_2\ ha^{-1}$ in 2050 and 545 $tCO_2\ ha^{-1}$ in 2100, and is highest for reforestation (703 $tCO_2\ ha^{-1}$), then forest enhancement (658 $tCO_2\ ha^{-1}$) and lastly afforestation (447 $tCO_2\ ha^{-1}$) (**Figure 3.5b**). Afforestation therefore has about 36% lower carbon sequestration efficiency than reforestation in our model given its sub-optimal growing conditions compared to reforestation.

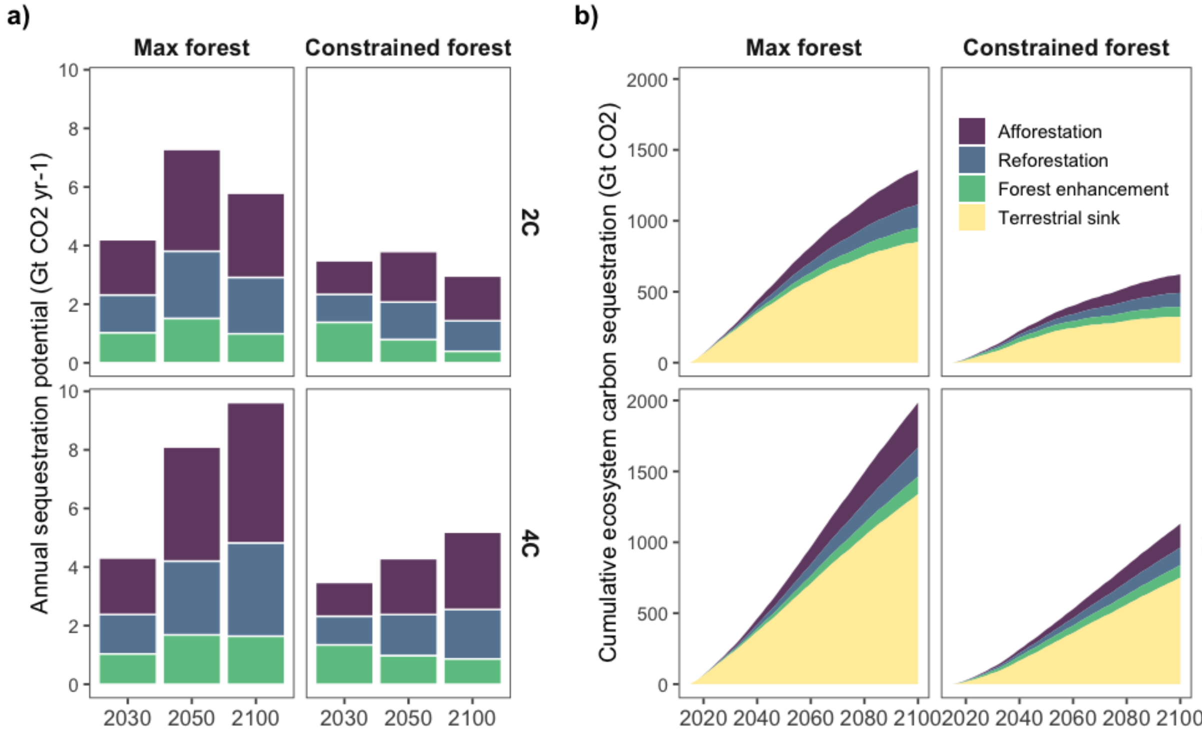

Figure 3.4. Sequestration potentials in the Max Forest and Constrained Forest scenarios.
a) Annual mitigation potential in 2030 (avg 2025-2034), 2050 (avg 2045-2054), and 2100 (avg 2091-2100), in two climates, 2°C and 4°C; b) Cumulative mitigation trajectory in 2°C and 4°C between 2020 and 2100 of A/R/E and the Terrestrial sink (terrestrial carbon pool outside of A/R/E), as indicated by cumulative increases in total ecosystem carbon.

In 2100, the Constrained Forest 2°C scenario has about 60% of the cumulative sequestration potential and 77% of the forest area of the Max Forest scenario (**Figure 3.4a, Figure 3.5a**). The global biophysical mitigation potential for the Constrained Forest scenario across all A/R/E activities in a 2°C climate is 3.5 (80% of Max Forest), 3.8 (52%) and 3.0 (50%) $GtCO_2\ yr^{-1}$ in 2030, 2050, and 2100 respectively. When averaged between 2020-2050, the total A/R/E annual mitigation potential is 3.6 $GtCO_2\ yr^{-1}$. The cumulative total ecosystem carbon sequestration is about 119 $GtCO_2$ in 2050 and 300 $GtCO_2$ in 2100 (**Figure 3.4b**). As in the Max Forest scenario, just under a third of the mitigation is from reforestation (32%) (**Figure 3.4a**). The Constrained Forest scenario has a larger proportion of forest enhancement (24 vs 21%) and smaller share of afforestation (43 vs 47%) compared to Max Forest, as more non-forest land is converted into agricultural land.

Total A/R/E activities in the Constrained Forest 2°C scenario cover about 245 Mha (expanding at an average rate of 14.1 Mha yr^{-1}) in 2030, 470 Mha (9.1 Mha yr^{-1}) in 2050, and 720 Mha (2.0 Mha yr^{-1}) in 2100. Forest area is about 75% of that in the Max Forest scenario across all time periods (**Figure 3.5a**). By 2100, afforestation and reforestation increase forest area by 400 and 175 Mha (80% of the total A/R/E area), and forest enhancement occurs within 135 Mha of forest. These A/R/E activities happen while croplands and pasturelands simultaneously expand by about 565 and 100 Mha respectively, and deforestation continues on a historical path reducing forest cover by about 340 Mha by 2100 (**Figure 3.1**).

Mitigation density (sequestration potential per hectare) for A/R/E in the Constrained Forest scenario is 253 tCO_2 ha^{-1} in 2050 and 416 tCO_2 ha^{-1} in 2100, in a 2°C climate. Similar to the Max Forest scenario in 2100, mitigation density is highest for reforestation (561 tCO_2 ha^{-1}), then forest enhancement (516 tCO_2 ha^{-1}) and afforestation (319 tCO_2 ha^{-1}) (**Figure 3.5b**). However, all densities in the Constrained forest scenario were 20-28% lower in 2100 compared to the Max Forest scenario, with the largest difference in afforestation. This result is due to higher carbon potential areas in the tropics being converted into agricultural lands under SSP3.

In addition to lowering the sequestration potential of A/R/E, we find that the high level of conversion to agriculture also impacts the sequestration capacity of the residual terrestrial carbon sink (total ecosystem carbon accumulation without A/R/E) (**Figure 3.4b**). Between 2030-2100, the terrestrial sink sequesters 62% less carbon in the Constrained Forest compared to the Max Forest scenario.

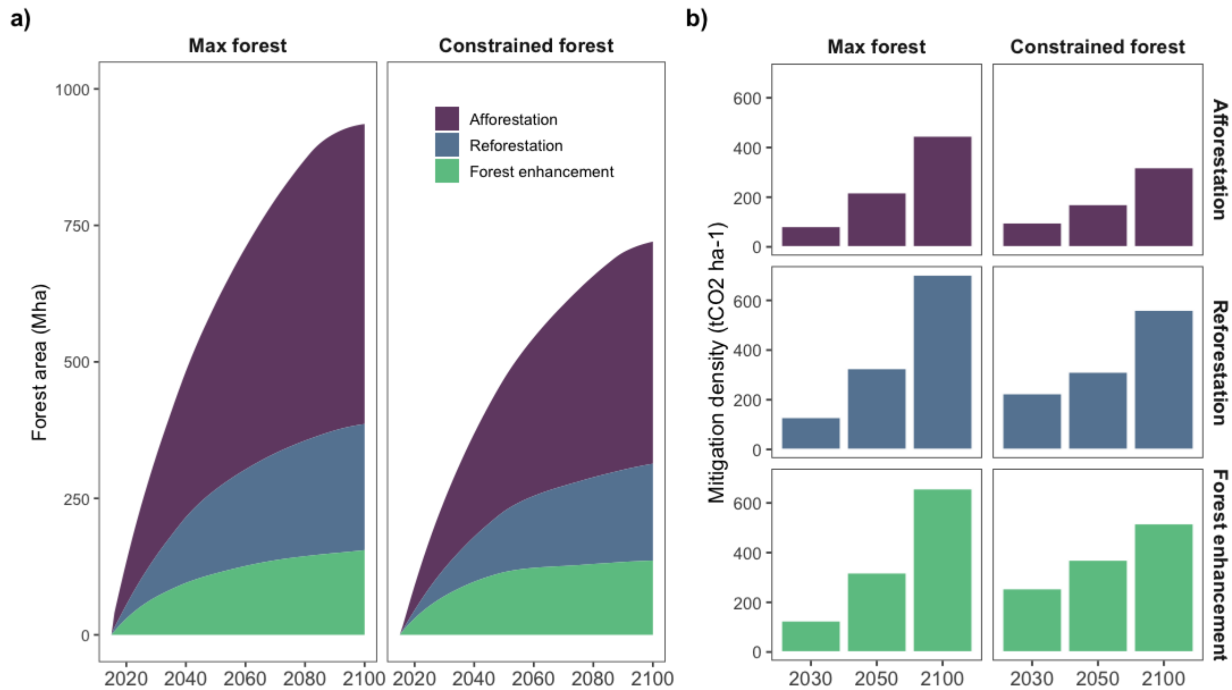

Figure 3.5. Change in forest area and mitigation density (sequestration tCO2 ha^{-1}) in A/R/E scenarios.
a) Cumulative forest area (area graph) and forest area per year (line graph). b) Mitigation density (calculated as the cumulative sequestration potential divided by the cumulative area) in 2030, 2050 and 2100 in a 2°C climate.

Regions

Regionally, the tropics (Latin America and Caribbean [LAC], Africa, Southern Asia and South-East Asia and developing Pacific [SEA]) play an outsized role in A/R/E, making up over 80% of the global sequestration potential in 2050 and about 75% in 2100 in both scenarios. In the Max Forest 2°C scenario, LAC and Africa have the highest A/R/E sequestration potentials, accounting for 73% of the global cumulative potential (64.3 and 52 $GtCO_2$) in 2050 and 70% (180.2 and 169.3 $GtCO_2$) in 2100. Annually, LAC and Africa have the potential to sequester 2.7 and 2.3 $GtCO_2$ yr^{-1} in 2050, respectively (**Figure 3.6**). Regions currently dominated by agricultural and urban landscapes make up a smaller proportion of A/R/E potential, as evident in Europe, Southern Asia and SEA with only 5%, 5% and 3% of global potential respectively. Deserts, arid regions and other climatically unfavorable conditions also have very low potential, with the Middle East seeing no sequestration gains and Eurasia having very modest potential

(1% of global) from A/R/E. Southern Asia, LAC, Africa and SEA have the highest A/R/E sequestration densities (cumulative potential divided by cumulative area in 2100) at 651, 650, 641 and 524 tCO_2 ha^{-1} respectively. Due to favorable climates with carbon rich biomes, they are well above the global average density of 428 tCO_2 ha^{-1}.

In the Constrained Forest 2°C scenario, LAC also has the highest relative A/R/E mitigation potential, accumulating 2.1 $GtCO_2$ yr^{-1} in 2050 and 151.2 $GtCO_2$ by 2100 (50% of the global total) (**Figure 3.6**). However, Africa's cumulative potential, 52 $GtCO_2$ in 2100, is 70% lower in the Constrained Forest scenario, down from a share of 33% in the Max Forest scenario to 17% due to high agricultural expansion. Annually, Africa's potential is 0.3 $GtCO_2$ yr^{-1} in 2050, a decrease of about 85% from the Max Forest scenario, indicative of high agricultural growth in mid-century. Given the vast conversion of forest and natural lands, the difference in the terrestrial carbon sink capacity between Max Forest and Constrained Forest is also largest in Africa. Southern Asia and Europe also experience substantially lower A/R/E potential in the Constrained Forest scenario, with a respective decrease of 94% and 67% in cumulative mitigation potential in 2100 from the Max Forest scenario. The remaining regions saw more moderate decreases of 16-25% under the Constrained Forest scenario.

The largest mitigation gains from reforestation in the Max Forest 2°C scenario are in LAC, predominantly Brazil, Colombia and Venezuela (1.6 $GtCO_2$ yr^{-1} over 104 Mha by 2050, about 80% of global reforestation potential) and Africa, largely in the Congo Basin countries (0.2 $GtCO_2$ yr^{-1} over 15 Mha by 2050, about 10% of global) (**Figure 3.6, Figure 3.9**). Modest reforestation potential (about 3-5% of the global total) is also found in North America (the US),

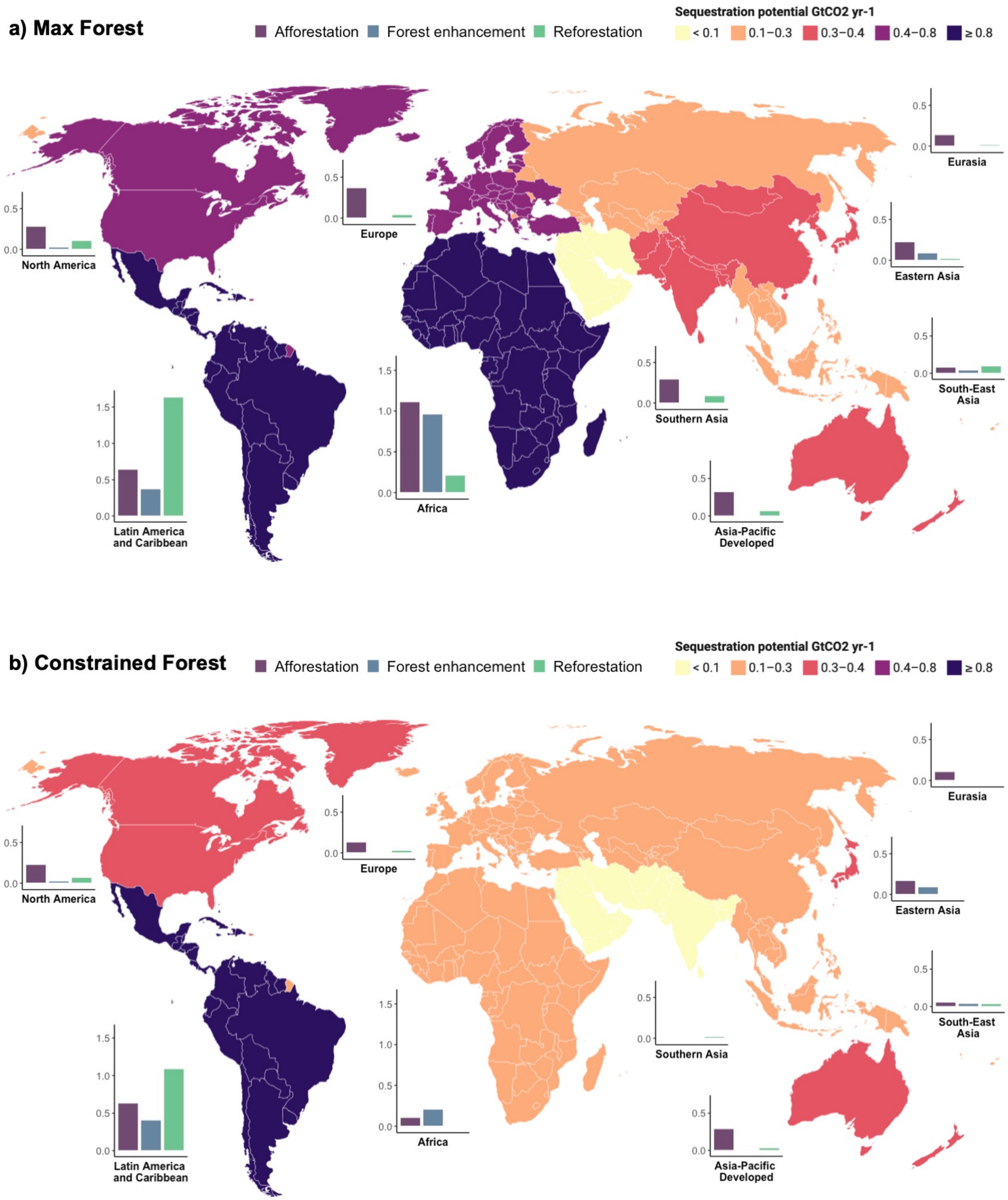

Figure 3.6. Annual mitigation potential (GtCO$_2$ yr^{-1}) by region in 2050 in a 2°C climate.
(a) Max Forest scenario, (b) Constrained Forest scenario. Maps show A/R/E sequestration potential in 2050, summed across the 10 IPCC regions, and bar graphs show annual sequestration potential in 2050 for afforestation, reforestation, and forest enhancement separately.

SEA (Mekong River basin countries) and Asia Pacific Developed (Australia, New Zealand). In the Constrained Forest 2°C scenario, reforestation potential is lower by approximately 30% across all regions, thus the relative proportion of the global reforestation potential generally remained consistent with the Max Forest scenario in 2050. About 90% of reforestation potential occurs in LAC and Africa. However, by the end of the century, reforestation potential is about 30% lower in LAC, North America, SEA and Europe in the Constrained Forest compared to the Max Forest scenario. In Africa and Southern Asia, reforestation potential is lower by 80% and 75%, respectively. Throughout the century, mitigation densities for reforestation (Max Forest 2°C) are highest in Southern Asia and LAC, with 1044 $tCO_2\ ha^{-1}$ and 805 $tCO_2\ ha^{-1}$ respectively by 2100. Southern Asia has a very small area of reforestation (5.5 Mha) relative to global potential (231 Mha), and it is concentrated in high carbon systems. Other tropical regions range between 500-650 $tCO_2\ ha^{-1}$, while temperate regions range between 250-650 $tCO_2\ ha^{-1}$ with Europe and North America at the high end of the range.

For afforestation, sequestration potential is more evenly distributed among regions. In the Max Forest 2°C scenario, through 2100, Africa (with woodland and savanna-rich countries) accounts for 32% of global afforestation potential and LAC (Brazil, Venezuela, Argentina, Paraguay, Peru, Bolivia and Mexico) accounts for 20%. Europe (most central and northern countries) has 11%, Asia Pacific Developed (predominantly Australia), Southern Asia (India), North America (US and Canada) and East Asia (China) each account for about 8%, and Eurasia and SEA have less than 4%. In the Constrained Forest 2°C scenario, afforestation mitigation potentials are 2-20% lower across all regions except for Southern Asia and Africa, where potentials are 99% and 82% lower respectively (**Figure 3.6**). Mitigation densities for afforestation (Max Forest 2°C) also have a smaller range compared to reforestation, 340-585 $tCO_2\ ha^{-1}$ by 2100 across all regions except for Eurasia which has markedly lower densities at

150 tCO_2 ha^{-1}. As with reforestation, tropical regions have the highest afforestation sequestration densities, between 490-585 tCO_2 ha^{-1} by 2100.

Sequestration potential from forest enhancement is similar to reforestation in that a large majority of potential (90% throughout the century) is in Africa and LAC (**Figure 3.6**). However, Africa (Congo Basin countries, Ethiopia and Madagascar) has the highest share of potential from forest enhancement with 0.96 $GtCO_2$ yr^{-1} over 63 Mha (64% of the global total) in Max Forest 2°C. LAC (Colombia, Venezuela, Ecuador and Brazil) has far less, with 0.37 $GtCO_2$ yr^{-1} over 31 Mha and 25% of the total. Eastern Asia (China) has 6% of potential, 0.09 $GtCO_2$ yr^{-1} over 9 Mha, and SEA and North America together have the remaining 5% of potential. The highest sequestration densities are in Africa, with 823 tCO_2 ha^{-1} by 2100. The remaining regions range between 362-555 tCO_2 ha^{-1} by 2100. More detail on area and sequestration potential by region is in the Supplementary Information (**Fig A3.4, Fig A3.5, Table A3.1 and Table A3.2**).

Climate effect on A/R/E mitigation potential

In the model, climate had a notable effect on A/R/E mitigation potential. Across both Max Forest and Constrained Forest scenarios, carbon sequestration potentials for A/R/E in 2100 is 21% higher in 4°C (7.0 W/m^2 forcing) compared to 2°C (2.6 W/m^2 forcing) (646 vs 510 $GtCO_2$ and 379 vs 300 $GtCO_2$, respectively) (**Figure 3.4**). The climate effect is less pronounced in mid-century (3-5% higher under 7.0 W/m^2 forcing) as temperature, rainfall and atmospheric CO_2 diverge later (**Figure 3.3**). Compared to the global average, by 2100, tropical regions – Southern Asia (India), Asia Pacific Developed (Australia), and SEA – saw larger sequestration enhancements for A/R/E of 36%, 30%, and 24% respectively across the two forest scenarios. The climate-induced sequestration enhancement is slightly more pronounced for afforestation than reforestation and forest enhancement (**Figure 3.4**).

Climate had an even greater effect on sequestration in the residual terrestrial carbon sink (total ecosystem carbon not counting A/R/E, NoLUC scenario). By 2100, this pool was 37% greater in Max Forest and 57% greater in Constrained Forest in the 4°C world (**Figure 3.4b**). Similar to the effect in A/R/E sequestration, the climate-induced increase in the terrestrial carbon sink is greater in tropical regions (+44-47%) compared to temperate and boreal regions (+12-32%).

Looking at the NoLUC scenario to isolate the climate effect from land-use change, we see the enhanced sequestration potential in the 4°C climate compared to the 2°C climate is due to the large gains in GPP (**Figure 3.7a**). These gains offset increased carbon losses from AR (autotrophic respiration) and HR (heterotrophic respiration), producing higher NBP (net biome production) or net total ecosystem carbon sequestration (**Figure 3.7b**). Carbon loss from fire increased marginally from 2020-2100 in both climates, with very little difference between the two. As a result of differences in carbon fluxes, by the end of the century, the vegetation carbon pool was 16% greater and litter carbon pool 3% greater in the 4°C than the 2°C climate, and the soil organic carbon pool was marginally lower (<1%) (**Figure 3.7c**). The change in vegetation carbon and litter carbon increases over time, yet soil carbon increases then decreases (**Figure 3.7d**), largely from losses in temperate regions, Eurasia and North America in the 4ºC compared to the 2ºC climate (**Figure A3.6**). Although the terrestrial carbon sink shows continual accumulation (**Figure 3.4b**), the annual rate of increase (NBP) declines over time as the growth in carbon losses increases higher relative to the growth in GPP (**Figure 3.7b**). In the 2°C climate, NBP peaks between 2020-2040, then declines by about 70% by the end of the century until it is almost zero. In the 4°C climate, NBP peaks between 2045-2065 and sees close to 20% reductions by 2100. The higher radiative forcing of 7.0 W/m2 therefore had a later and flatter slope of NBP decline (**Figure 3.7b**). However, the NBP in both climates remains positive throughout the century.

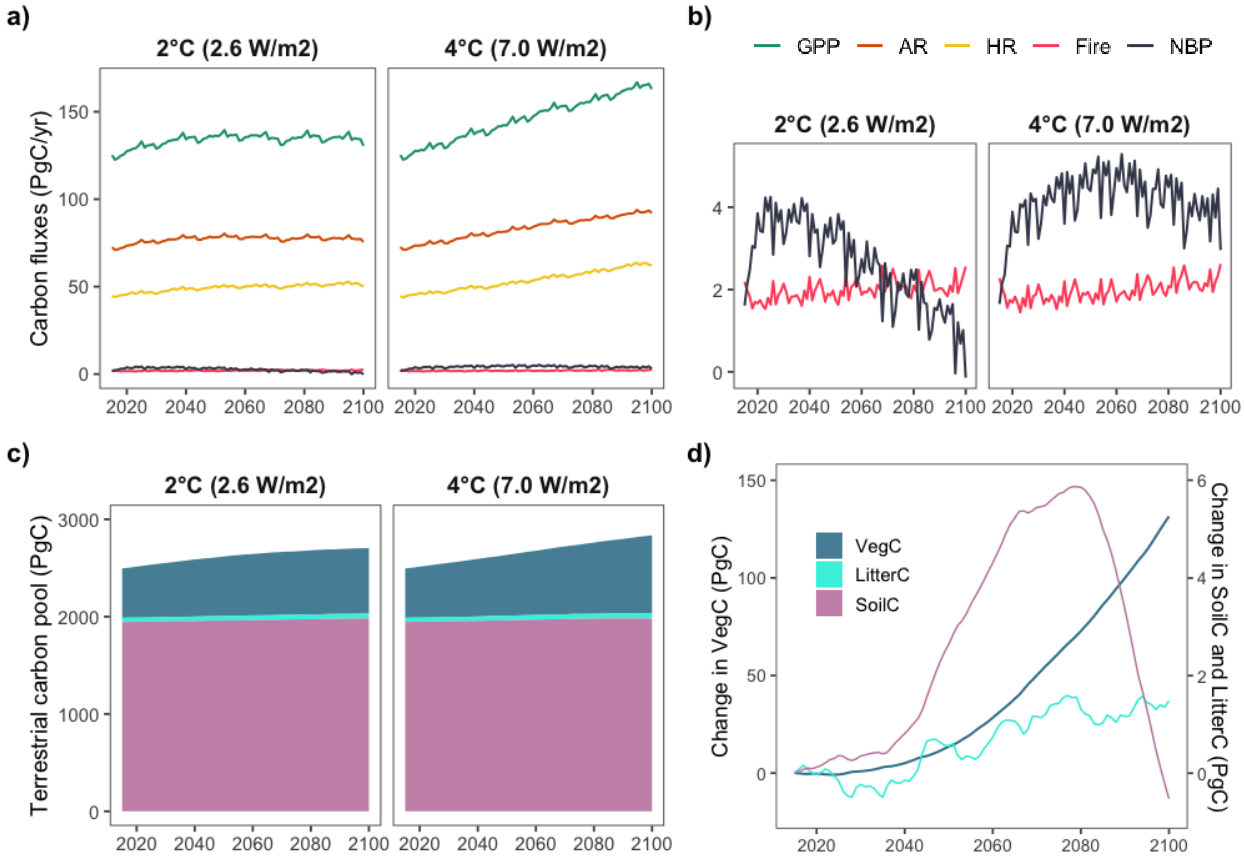

Figure 3.7. Global carbon flux and carbon pool trajectories in NoLUC 2°C (2.6W/m²) and NoLUC 4°C (7.0 W/m²). (a) All global carbon fluxes (PgC/yr). (b) Zoom in to NBP and Fire carbon fluxes (PgC/yr). (c) Terrestrial carbon pools of total ecosystem carbon (PgC). (d) Differences between 4°C and 2°C in carbon pools (PgC). The NoLUC (no land use change from 2015) scenario is used to remove the land-use change effect to isolate the climate effect on the terrestrial sink. The NBP (net biome production) represents the net annual total ecosystem carbon sequestration and results from GPP (gross primary productivity) minus AR (autotrophic respiration), HR (heterotrophic respiration), and FireC (fire carbon loss). The terrestrial carbon pool is the total ecosystem carbon in vegetation, litter and soil.

Productivity (GPP) differences between the two climate scenarios are greatest in regions with humid tropical forests and wetlands, and smallest in xeric regions. SEA and LAC have the largest differences in NBP per hectare, while the smallest are in Eurasia and the Middle East (**Figure 3.8**). The change in AR and HR is also higher in tropical regions, although the proportion of change in AR to change in GPP is similar across regions (45-56%) while the proportion of change in HR compared to GPP is higher in Eurasia, Southern Asia and North America (40-48%; higher than global average of 35%). Changes in fire carbon produce losses in

Europe, North America and Eastern Asia, but the effect on NBP is negligible (**Figure 3.8**). The difference in annual carbon fluxes between the 4°C and 2°C climates do not appear to be directly related to the differences in precipitation, temperature and relative humidity. While SEA and LAC show the largest difference in NBP with a warmer climate, both regions also have the largest reductions in precipitation. SEA has moderately higher relative humidity under 4°C, whereas relative humidity is lower for LAC (**Figure A3.3**). CO_2 fertilization and increased water use efficiency are therefore the likely drivers of productivity gains.

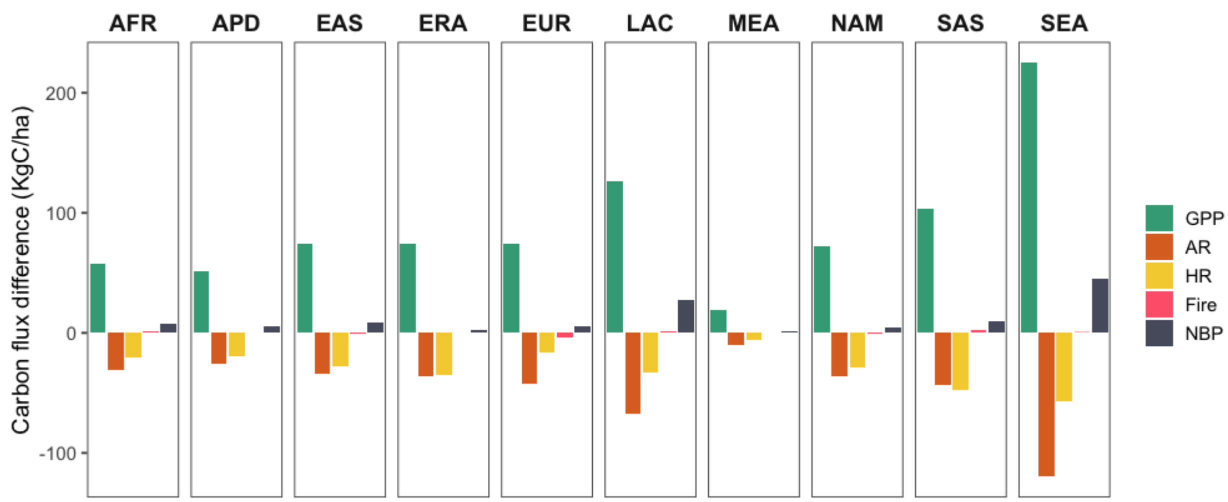

Figure 3.8. Change in annual carbon fluxes per region between 4°C and 2°C in the terrestrial sink (NoLUC scenario). The differences in fluxes are cumulative from 2015-2100 per region for GPP, AR, HR, Fire, and NBP. NBP (net biome production) is the net total ecosystem sequestration, and is the result of GPP minus carbon losses from AR (autotrophic respiration), HR (heterotrophic respiration) and Fire. Carbon losses are illustrated as negative to more clearly show the contribution to NBP. Regions are: Africa (AFR), Asia-Pacific Developed (APD), Eastern Asia (EAS), Eurasia (ERA), Europe (EUR), Latin America and Caribbean (LAC), Middle East (MEA), North America (NAM), Southern Asia (SAS) and South-East Asia and developing Pacific (SEA).

Biodiversity and ecosystem service overlaps with mitigation potential

The priority areas for biodiversity and ecosystem service provision in the 'Sharing the Planet' (SP) scenario encompass about 30% of each eco-region globally, covering about 4,890 Mha, roughly five times as much as the area designated here for A/R/E. In 2050, A/R/E in the Max Forest 2°C scenario overlaps with 254 Mha of priority areas (**Figure 3.9**). With care to species selection and appropriate attention to fire and disturbance regimes, A/R/E could complement efforts to enhance biodiversity and ecosystem service provision on 42% of the total A/R/E areas in 2050 and 5% of the global priority biodiversity areas. Mitigation potential from the area of overlap is a slightly higher proportion than the area, at about 50% of cumulative total ecosystem carbon by 2050 (81 $GtCO_2$), as expected given the priority placed on areas capable of generating higher carbon density in the experiment. In Constrained Forest 2°C, the A/R/E area that overlaps with biodiversity priorities is 30% less (177 Mha) and mitigation is 42% less than in the Max Forest (48 $GtCO_2$).

Forest enhancement overlaps most with biodiversity and ecosystem priority areas (57-58%), then reforestation (42-43%), then afforestation (32-34%) across the Max Forest and Constrained Forest scenarios. The proportion of mitigation potential is similar but slightly higher, 63-65% for forest enhancement, 47-51% for reforestation, and 39-40% for afforestation. Biodiversity and ecosystem priority areas target protected areas, key biodiversity areas, high carbon ecosystems and riparian zones. Thus, the highest overlaps would be expected in intact forests (where forest enhancement occurs) and the lowest would likely be in drier ecosystems (where afforestation occurs).

Regionally, the greatest opportunities to enhance forests in priority areas are in LAC (72% of its area overlaps with SP), SEA (60%) and Africa (55%), and the lowest overlaps are in Eastern Asia (22%) (**Figure 3.9**). In remaining regions, 45-50% of forest enhancement are within priority areas. The proportion of sequestration potential and priority area overlaps across regions have a slightly smaller range for reforestation (21-60%) and afforestation (19-46%). Humid areas in the tropics and sub-tropics including LAC (Amazon basin countries and coastal forests), Africa (Congo basin countries, Ethiopia, Madagascar), SEA, and Asia Pacific Developed (Australia and New Zealand) have the highest share (45-46%) of reforestation opportunities with multiple benefits. Afforestation overlaps most with biodiversity and ecosystem service priority areas in similar regions to reforestation, although in different ecosystem types and at a lower proportion (35-37%).

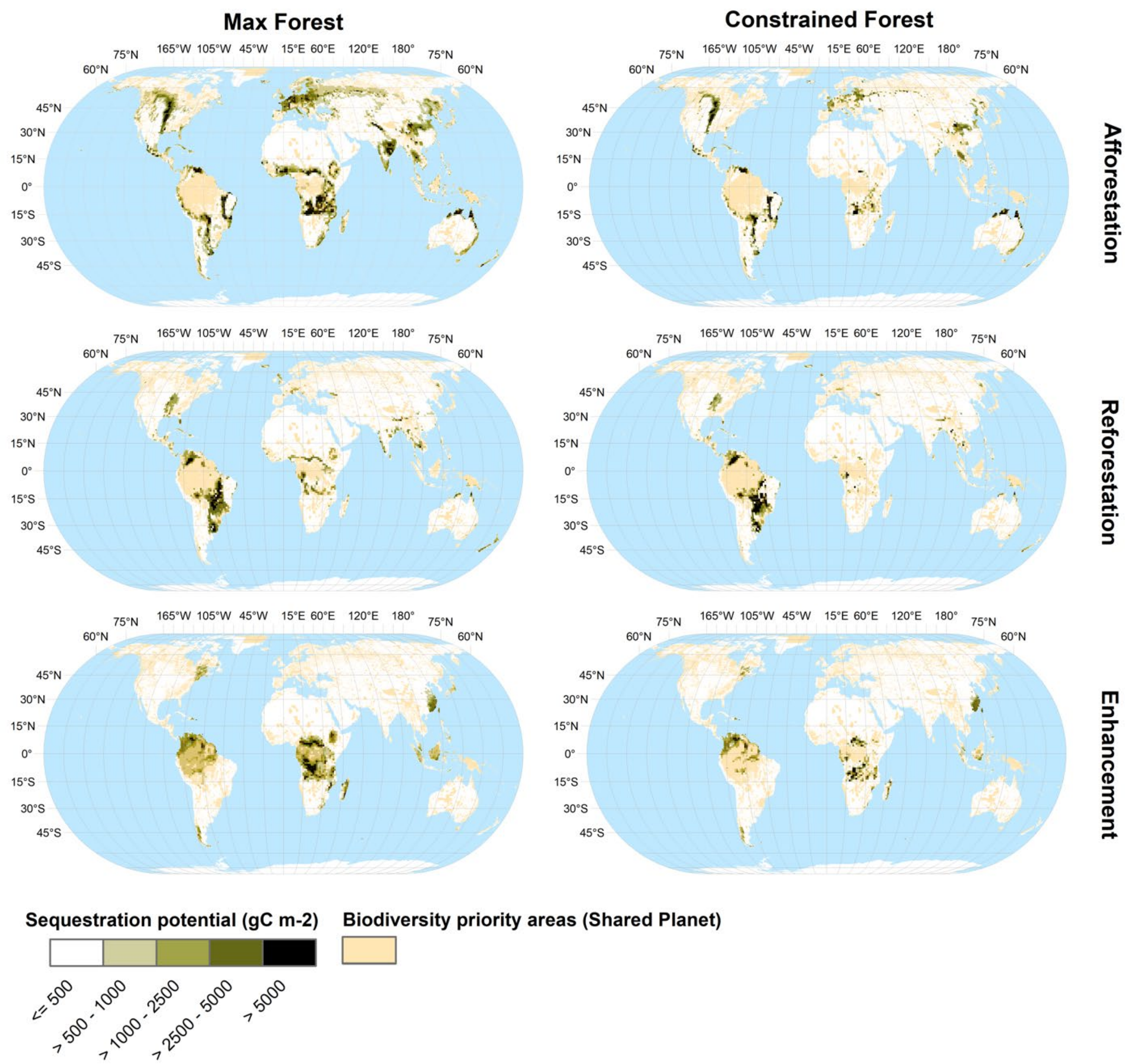

Figure 3.9. Maps of sequestration potential and conservation priority areas in 2050.
The Max Forest and Constrained Forest scenarios are disaggregated by A/R/E activities, and are combined with the biodiversity and ecosystem service priority areas (Sharing the Planet). The A/R/E areas represent the mitigation potential in gC/m^2 (very small to negative potential is not shown), which is the cumulative total ecosystem carbon in 2050.

Synergies between forest restoration pledges and biophysical potentials

Globally, the forest restoration pledges made by countries for 2020-2030 (median estimate) refer to activities that 'restore/improve forest land' (260 Mha), restore/improve protected areas (95 Mha) and increase forest area (30 Mha). Little congruency is initially apparent between the total biophysical potential of A/R/E in 2050 and the country pledges (**Figure 3.10**). However, upon closer inspection, reforestation plus forest enhancement potential (R/E, in green and blue bars in **Figure 3.10**) aligns well with the total areas pledged for forest restoration in LAC, SEA, North America, Europe, and Eurasia, with additional R/E potential in LAC. In Africa and South Asia, we see the median estimate of pledges exceeds the biophysical potential. In these regions, some countries have pledged a high percentage of their total land area for A/R/E, including Burundi (78%) Gambia (50%), Malawi (74%) and Rwanda (91%). In other regions, few hectares have been pledged, despite moderate biophysical potential, including Asia-Pacific Developed (Australia, New Zealand, Japan), and Eastern Asia (China, Korea, Mongolia). A few countries with ambitious targets make up a large proportion of total regional area pledged. For example, Ethiopia, India and Brazil have each made commitments of about 22 Mha to 'restore and improve forest land'.

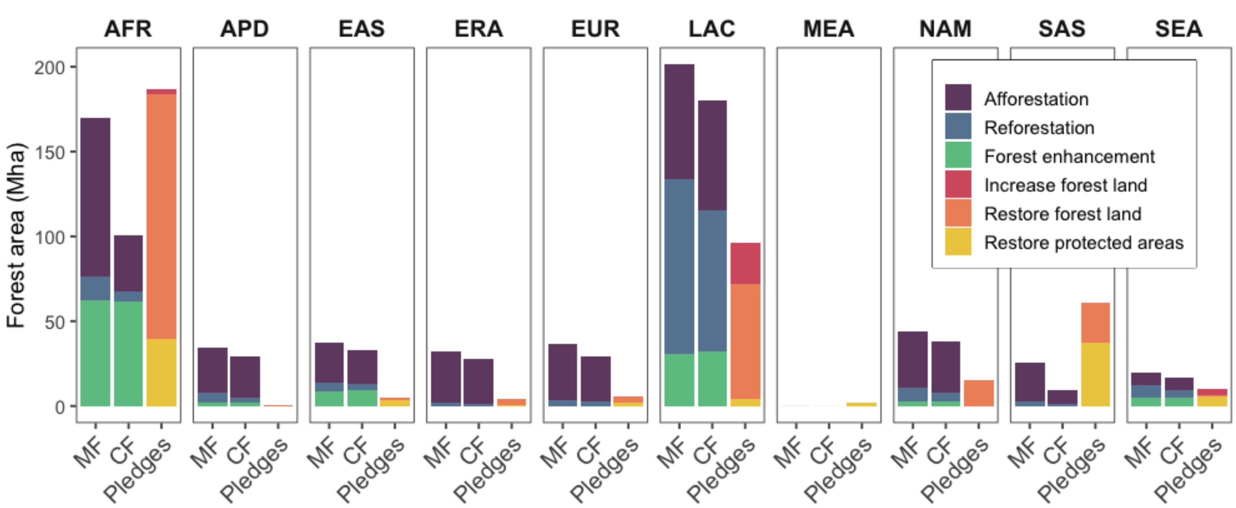

Figure 3.10. Total area (Mha) of A/R/E biophysical potential in 2050 for Max Forest (MF) and Constrained Forest (CF) compared to country Pledges made on forest restoration for 2020-2030, by region.
Total A/R/E in 2050 in Max Forest = 600 Mha, and Constrained forest = 463 Mha. Total pledges equal 385 Mha and incorporate NDCs, NBSAPs, LDN voluntary targets, and Bonn Challenge commitments, and are disaggregated into pledge categories, 'increase forest land' 'restore/improve forest land', and 'restore/improve protected areas.' Regions are: Africa (AFR), Asia-Pacific Developed (APD), Eastern Asia (EAS), Eurasia (ERA), Europe (EUR), Latin America and Caribbean (LAC), Middle East (MEA), North America (NAM), Southern Asia (SAS) and South-East Asia and developing Pacific (SEA).

Discussion and Conclusions

In this study, we confirm a large biophysical potential to sequester additional carbon through A/R/E, in line with previous studies (Roe et al. 2019). In a 2°C world, A/R/E could cumulatively remove 300-510 $GtCO_2$ from the atmosphere using 710-935 Mha of land by the end of the century, depending on the land future. In 2050, the annual biophysical mitigation potential for A/R/E is 3.8-7.3 $GtCO_2$ yr^{-1}, where 1.7-3.5 $GtCO_2$ yr^{-1} is from afforestation, 1.3-2.3 $GtCO_2$ yr^{-1} from reforestation, and 0.8-1.5 $GtCO_2$ yr^{-1} from forest enhancement. Our estimates are somewhat higher than the median from previous studies of A/R technical potential, which range from 2 to 10 (median 3.6) $GtCO_2$ yr^{-1} between 2030-2050 (calculated from Lenton 2014; Houghton, Byers, and Nassikas 2015; Kreidenweis et al. 2016; Sonntag et al. 2016; Griscom et al. 2017; Houghton and Nassikas 2018; Bastin et al. 2019; Roe et al. 2019). However, our estimates include forest enhancement, which is often reported separately as forest management in other studies. Including this additional mitigation potential (0.5-2 (median 1.5) $GtCO_2$ yr^{-1} between 2030-2050 (Roe et al. 2019)) aligns the median estimate of prior studies (5.1 $GtCO_2$ yr^{-1}) with our mean estimate (5.5 $GtCO_2$ yr^{-1}) in a 2°C climate.

Tropical regions contain a majority of the sequestration potential (80%), largely in Latin America and Africa (70%). The tropics account for approximately 65% of afforestation, 90% of reforestation and 92% of forest enhancement. The relatively low A/R/E mitigation potential of 3% in South-East Asia (which includes Indonesia and Papua New Guinea) is striking. Over the past 30 years, SEA has seen high levels of conversion of carbon-rich ecosystems including forests and peatlands to permanent agriculture, making those areas ineligible for A/R/E in our model. The tropics also host a large proportion of the planet's conservation priority areas for biodiversity and ecosystem service provision. About 40% of A/R/E areas and 50% of mitigation potential overlap with the 'Sharing the Planet' conservation priority map, with higher proportions in forest enhancement and reforestation in the tropics. A majority of the country pledges to restore forests are also in tropical regions. The combined area of reforestation and forest enhancement (R/E) biophysical potential has the greatest alignment with pledges, providing an opportunity to optimize the synergies with biodiversity and ecosystem service priority areas.

In addition to sequestration potential from A/R/E, the existing terrestrial carbon sink, which currently absorbs 12.5 ± 3.3 $GtCO_2$ yr^{-1} (~30% of all anthropogenic emissions annually) (Friedlingstein et al. 2020), continues to accumulate throughout the century in our model (additional 135-850 $GtCO_2$ from 2015-2100). The large range in the terrestrial carbon sink capacity is due to the vast differences in future land cover scenarios. The upper bound assumes no agricultural expansion after 2015, and the lower bound assumes very high agricultural expansion (+650 Mha of additional croplands and pastures) at the expense of forests, grasslands and other natural ecosystems. Therefore, the ideal scenario will likely fall somewhere between the Max Forest and Constrained Forest. Some agricultural expansion will be needed in the future to account for increased food demand (and thus food security), even in a sustainable and high-ambition pathway scenario like SSP1 (Popp et al. 2017). Yet, conservation and restoration will also be needed to avoid the substantial negative environmental and social impacts from deforestation and conversion of natural ecosystems. In addition to large losses of biodiversity and vital ecosystem services (water provision, nutrient cycling, enhanced resilience), high levels of natural ecosystem conversion (+650 Mha in SSP3) has a double negative effect on climate. The conversion not only reduces the mitigation potential from A/R/E (by about 40%), it also substantially reduces the natural capacity of land to act as a carbon sink (by about 85%) (**Figure 3.4**).

Climate impacts

In a warmer, CO2-rich world (4°C [7.0 W/m2] compared to 2°C [2.6 W/m2]), the cumulative sequestration capacity of A/R/E increases by about 20% and the terrestrial carbon sink (existing ecosystem carbon without A/R/E) increases by 40% by 2100 (**Figure 3.4**).Tropical regions gain 15-30% more carbon in the 4°C climate than temperate and boreal regions. The higher forcing had a net positive effect on productivity and ecosystem carbon sequestration, likely from CO_2 fertilization (P. Lawrence, Lawrence, and Hurtt 2018), although that effect declined after mid-century (**Figure 3.7b**).

Our findings are in line with other earth system modelling studies of land futures, which find that the positive effect from CO_2 fertilization with higher radiative forcing outweighs the negative effect from warming and other climate-induced disturbances like droughts and fires (Sonntag et al. 2016; Doelman et al. 2020; Arora et al. 2020). Across the 11 earth system models in the Coupled Model Intercomparison Project (CMIP6), and consistent with CMIP5, CO_2 fertilization is the dominant cause for increased land carbon uptake up to 2100, with the strongest effect in the tropics (Arora et al. 2020). Other drivers also contribute, including increased plant water-use efficiency (WUE) due to higher CO_2, increased nutrient availability from mineralization of organic matter and elevated decomposition rates, and a longer growing season in colder climates. WUE is an important driver in drier regions, which could explain the slightly higher carbon gains in afforestation in a 4°C climate (**Figure 3.4**).

CMIP6 models show that removing the CO_2 fertilization effect from a warming climate will lead to net losses of land carbon due to lower photosynthetic uptake, elevated rates of ecosystem respiration, and increased stress, disturbance and plant mortality (Arora et al. 2020). Compared to all 11 CMIP6 models, the positive effect of increased atmospheric CO_2 concentrations on land carbon sequestration (land carbon-concentration feedback) is close to the intermodel mean in our model, CLM, whereas the negative effect of climate warming (land carbon-climate feedback) is weaker (Arora et al. 2020). Therefore, the net carbon and climate feedback effect and total carbon uptake in CLM is slightly higher than the intermodel mean, although it is the model closest to the mean.

Other studies have shown that A/R sequestration potentials are enhanced with higher radiative forcing. In Doelman et al. (2020), cumulative sequestration potential (430 $GtCO_2$ by 2100) from afforestation and reforestation in SSP2-2.6 increased 18% in 3.4 W/m^2 and 30% in 4.5 W/m^2 largely due to CO_2 fertilization. Our estimates are slightly lower, a 20% increase between 2.6 W/m^2 and 7.0 W/m^2 . In Sonntag et al. (2016), expanding global forest cover increased terrestrial carbon in the residual sink and A/R/E by 85% from present day climate to 4.5 W/m^2 forcing. Terrestrial carbon increased by another 5% from 4.5 W/m^2 to 8.5 W/m^2. The weaker net climate and CO_2 feedback effect between 4.5 W/m^2 and 8.5 W/m^2 suggests that climate feedbacks eventually reduce the effect of CO_2.

Although increased CO_2 concentrations are very likely to increase land carbon uptake through the end of the century (Arora et al. 2020; Ciais et al. 2013), the strength of carbon–concentration and carbon–climate feedbacks over land is highly uncertain (Arora et al. 2013; Friedlingstein et al. 2014; Friedlingstein 2015; Walker et al. 2020), and represent one of the largest sources of uncertainty in climate change projections (Ciais et al. 2013). The magnitude of the CO_2 fertilization effect and land uptake is modulated by nutrient and water availability, plant carbon allocation, changes in plant community composition, disturbance, and natural plant mortality (Terrer et al. 2019; Song et al. 2019; W. K. Smith et al. 2020; Reich, Hobbie, and Lee 2014; Green et al. 2019), processes which are poorly represented in models and thus contribute to uncertainty (Arora et al. 2020; Walker et al. 2020; Fatichi et al. 2019). Ongoing debate focuses on whether the land sink will continue to be a sink or eventually turn into a source due to a combination of stressors including land-use change and climate. A number of field-based and empirical studies differ from model projections, demonstrating where some uncertainties lie.

Regional studies show that warming from climate change is already turning or could turn existing global terrestrial carbon sinks into sources by mid- to late century (Duffy et al. 2020; Hubau et al. 2020; Maia et al. 2020; Brienen et al. 2015; Zhou et al. 2014). Wang et al. 2020 find that the CO_2 fertilization effect has been declining (since 1982), with global observations showing larger decreases compared to models. Other studies show earth system models produce higher GPP and NPP per ppm CO2 and do not adequately capture nutrient-carbon interactions when compared to field-based observations (Piao et al. 2013; Friedlingstein 2015). Vegetation models may also underestimate global vulnerability to tree mortality and forest die-off partly due to difficulties in predicting threshold responses to extreme climate events (Allen, Breshears, and McDowell 2015). Furthermore, empirical evidence for CO_2 effects on vegetation mortality and soil carbon stocks is limited and highly uncertain (Walker et al. 2020).

Beyond the large uncertainties associated with the net effect of atmospheric carbon concentration and warming on terrestrial ecosystem carbon, other aspects of this study constrain our assessment of the warming effect on A/R/E. An important limitation is that CLM is not a tree-based model and does not have dynamic vegetation, but rather plant functional types as a fraction of grid cells. Therefore, no mechanism exists to represent climate-induced tree mortalities (e.g. from drought), die-backs or species shifts, which field-based studies and empirical evidence to date show are critical for the land carbon future. Conducting this experiment across multiple models, including those with dynamic vegetation, may better constrain the effect of climate on A/R/E. In addition to the limitations of CLM, we ran this experiment uncoupled from the rest of the Earth system, and therefore cannot account for the feedbacks from the land system to the atmosphere. Including coupled scenario runs across multiple models would provide the most robust assessment. It would, however, require substantial computing resources.

Implications for policies and implementation

To meet the Paris Agreement target of limiting warming to 1.5°C - 2°C above pre-industrial levels with >66% likelihood, emissions need to fall to net zero emissions by mid-century, then become net-negative thereafter (Rockström et al. 2017; Rogelj et al. 2018). If GHG emissions persist at current levels (~50 GtCO_2e), A/R/E could deliver about 8-15% of the mitigation potential in 2050, depending on how much agriculture and forest expansion occur. Deploying just reforestation and forest enhancement (R/E) could provide 4-8% by 2050. By the end of the century, A/R/E could supply 41-70% and R/E could deliver 23-36% of the median carbon dioxide removal (CDR) projected in 1.5°C pathways (Rogelj et al. 2018). However, various factors need to be considered for implementation and scale-up of A/R/E, including timing of sequestration gains, costs, and optimizing benefits and minimizing trade-offs.

<u>Timing A/R/E's contribution to 1.5°C - 2°C pathway</u>

The sequestration potential from A/R/E is a small proportion of the needed mitigation for a 1.5°C - 2°C pathway, and the majority of carbon removal occurs in the longer-term, after 2040. Therefore, if A/R/E is deployed, it will need to be in tandem with, and not a substitute for deep emission reductions from fossil fuels and land-use change. Reducing land-use change (deforestation) will avoid emissions in the near term, and will enable the residual terrestrial sink to continue to accumulate and remove a large amount of anthropogenic emissions. Although our A/R/E scenarios have an aggressive scale up from the first year, trees accumulate and remove carbon at a much slower rate than cutting emissions from sources like fossil fuels and deforestation. The cumulative sequestration potential of A/R/E in 2030 is only 20% of its potential in 2050. So, while A/R/E interventions can be mobilized fairly quickly, the climate effect will be delayed (Baldocchi and Penuelas 2019).

Costs and feasibility

Our estimates represent biophysical potential and do not consider costs or feasibility of implementation. Limiting implementation to costs below \$100/tCO_2 (considered cost-effective as it is on the low end of the range for carbon prices in 2050 for a 1.5°C pathway) could reduce the biophysical potential (also known as technical potential) for A/R/E by about 70-90% (Roe et al. 2019). Feasibility conditions including governance, available funding, socio-cultural conditions and acceptance of policies could create barriers for implementing A/R/E, particularly in the tropical regions that have the highest sequestration potential (**Figure 3.6**) and highest feasibility concerns (Roe et al., n.d.). Focusing A/R/E activities on those areas that create multiple benefits for people and the environment could increase social acceptability and political feasibility, expand the pool of available funding, and reduce downstream costs (Smith et al. 2020).

Delivering multiple benefits and reducing trade-offs

Tree planting initiatives and country pledges on forest and landscape restoration have proliferated in recent years which has prompted significant debate and increasing caution on A/R/E deployment (Holl and Brancalion 2020; Anderegg et al. 2020; Bond et al. 2019; Baldocchi and Penuelas 2019). A/R/E and other land-based mitigation interventions will occur against a backdrop of various land challenges in addition to climate change, including food insecurity, biodiversity loss and ecosystem transformation, desertification and land degradation, land-use change, fresh water shortages, and nitrogen pollution. Given these dynamics, successful A/R/E interventions will need to serve multiple goals and balance carbon sequestration with sustainable development goals. A/R/E interventions have the potential to contribute to 13 of the 17 Sustainable Development Goals and 17 of the 18 Nature's Contribution to People (Smith et al. 2019). However, unintended negative effects of previous large-scale A/R efforts have included reduced water supply in drier regions, conversion of native grasslands and reduced biodiversity, spread of invasive species, displacement of croplands, increased land-use change due to land competition, and increased social inequity (Holl and Brancalion 2020). The mitigation efficacy of A/R/E, as well as its potential co-benefits and possible trade-offs, will depend on the type of A/R/E activity deployed, its scale, method of deployment (natural regeneration vs mixed species planting vs monoculture; top-down or planned with the local community), and location (ecosystem, climate, water availability, disturbances, slope) (Smith et al. 2019; Cook-Patton et al. 2020).

Our map of carbon sequestration potential, biodiversity, and ecosystem service priority overlaps (**Figure 3.9**) can be used to highlight areas with multiple benefits for each type of A/R/E activity. Forest enhancement overlaps most with conservation priority areas, with the highest synergies in large forest basins in South America, South-East Asia and Central Africa (55-72%). Effective strategies in these regions could include natural and/or assisted regeneration, fire management, and sustainable forest management (Cook-Patton et al. 2020). Reforestation also has high synergies with conservation priority areas, and is more geographically heterogenous, with some overlaps buffering intact forests or protected areas, and others buffering agricultural zones. The opportunities to enhance biodiversity and ecosystem services through reforestation will therefore need a diverse set of strategies and methods for implementation. In every region, at least ~20% (North America and Eastern Asia) and at most 60% (Europe, Australia, New Zealand) of reforestation potential overlaps with priority areas, representing areas that could be prioritized for multiple benefits. Afforestation, which overlaps the least with priority areas, may be less complementary with conservation as a large proportion of biodiversity areas occur in natural grasslands and savannas where trees are sparse. Adding trees in non-forest ecosystems, especially natural grasslands may reduce the biodiversity and ecosystem services provided in a way that is at odds with the priorities established for those areas (Veldman et al. 2015; Bond et al. 2019; Schwärzel et al. 2020). Given the larger potential for multiple benefits from forest enhancement and reforestation, and the higher risks and lower carbon density potentials associated with afforestation, a push to focus efforts on reforestation and forest enhancement of the tropics and sub-tropics is increasing (Lewis et al. 2019; Cook-Patton et al. 2020). Agroforestry activities, which add trees in croplands at a lower density than A/R/E, are also gaining support due to their positive impact on livelihoods, food provision and resilience (Mbow et al. 2014; Waldron et al. 2017; Tschora and Cherubini 2020).

In addition to multiple benefits, we consider tradeoffs related to the scale of A/R deployment and its effect on food security needs by providing a lower A/R/E estimate for a future world with very large gains in croplands and pasture (Constrained Forest). However, more land does not necessarily equate to more food and food security. In fact, the high agricultural expansion in SSP3 is due to reduced global crop yields, low agricultural technology transfer and inefficient supply chains and trade (Popp et al. 2017). Increased food security in line with sustainable development could include a combination of land sparing measures including increased crop productivity, lower food loss and waste and lower-meat diets in developed and emerging economies, enhanced nutrition in developing countries, improved infrastructure and supply chains, as well as the continued provision of ecosystem services from forests like water regulation, nutrient cycling, and local cooling (Smith et al. 2020; Charles, Godfray, and Garnett 2014). A food secure world with higher A/R/E mitigation potential than our Constrained Forest scenario is therefore possible.

Scaling up efforts and translating biophysical potential into reality

Our study shows that reforestation and forest enhancement (R/E) combined have the potential to sequester 170-264 $GtCO_2$ cumulatively over 313-386 Mha by 2100 and 2.1-3.8 $GtCO_2$ yr^{-1} in 2050. Optimizing multiple benefits from R/E by targeting efforts in biodiversity and ecosystem service priority areas could provide 1.2- 2.2 $GtCO_2$ yr^{-1} in 2050 over 111-134 Mha. These annual potentials in 2050 are in the range of cost-effective potential (<\$100/tCO_2) of 0.5-2 $GtCO_2$ yr^{-1} (Roe et al. 2019; Roe et al., n.d.). The area range is also in line with the Bonn Challenge and NYDF Goal 5 target of restoring 350 Mha by 2030.

However, translating biophysical potentials that target multiple benefits and reduce tradeoffs into actionable policy and implementation strategies has proved to be challenging. According to Lewis et al. 2019, of the nearly 300 Mha of forest landscape restoration pledges made under the Bonn Challenge and other national schemes, a majority (45%) are committed to plantations (often monocultures), and a lower proportion (34%) are committed to natural regeneration and agroforestry (21%). Sewell, van der Esch, and Löwenhardt (2020a) find that quantitative restoration pledges, in general, do not appear to be coordinated between the UN conventions (climate, biodiversity, land degradation) or restoration outcomes. Our assessment shows that while a few regions' area commitments for restoration align with the biophysical potential for reforestation and forest enhancement (LAC, SEA, Europe), some regions (Africa and Southern Asia) have higher pledges than biophysical potential, in some cases covering more than 50% of their total land area. Other regions have pledges substantially lower than their biophysical potential. Also, many countries have qualitative commitments for restoration that lack specificity and are difficult to measure and, thus, to evaluate or monitor. To deliver on the goals of the various UN conventions and the SDGs and enable monitoring of progress, country commitments and A/R/E strategies should be based on holistic land-use planning, rigorously evaluate the risks and benefits, formulate geographically specific and realistic targets with clear implementation plans, prioritize R/E over A, and be measurable and transparent (Sewell, van der Esch, and Löwenhardt 2020a). This study could help regions as they reconsider and revise their restoration targets.

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Chapter 4: In-situ warming effects on litter decomposition and carbon cycling in a wet tropical forest

Abstract

Litter decomposition is a critical driver of carbon and nutrient cycling at ecosystem and global scales. The paucity of empirical data on how climate change will impact litter decomposition in tropical forests – ecosystems which exchange more carbon dioxide (CO_2) with the atmosphere than any other terrestrial biome – contributes to uncertainties in Earth System Models (ESM) that predict future climate change. In a wet tropical forest in Puerto Rico, we evaluated the effects of 4ºC sustained warming on *in-situ* litter mass loss and nutrient release across four substrates (native litter, green tea, black tea and wood) in the rapid phase of decomposition. We then compared our field results to modelled results using an ESM in a 4°C scenario (7.0 W/m^2). Contrary to our expectation that increased temperatures would increase litter mass loss and nutrient release, we found that warming reduced mass loss by an average of 7% across the four substrates and retained 14% more C:N and 44% more N in the native litter. Warming decreased litter moisture by an average of 36%, relative humidity by 4%, and soil moisture by 1.2%, which appear to have limited microbial activity and decomposition. However, the effect of warming on reduced mass loss varied among the substrates, with a stronger response in lower quality substrates. These results suggest that temperature increases with concomitant drying could significantly slow carbon and nutrient turnover from lower quality litter to soil. In the model experiment, we also found reduced litter carbon turnover rates in tropical forests that experienced drying including Puerto Rico, but with lower sensitivity. Although litter carbon turnover decreased across most dry tropical forests with reduced precipitation, it only decreased in wet tropical forests that experienced higher levels of drying than occurred in our field experiment.

Our study suggests carbon cycling with future climate change could depend more strongly on moisture regimes in wet tropical forests than currently captured in models.

Introduction

Up to 90% of terrestrial primary production is spared from herbivory and is returned to the ecosystem as dead plant material, or leaf, wood and root litter (Cebrian 1999). Dead organic matter is then decomposed through fragmentation, chemical alteration, and leaching, and is ultimately converted into inorganic components (CO_2, mineral nutrients, and water) through mineralization, or transformed into more recalcitrant organic matter (soil organic matter, SOM) (Stuart, Matson, and Vitousek 2012). Decomposition is therefore a critical driver of nutrient and carbon cycling at ecosystem and global scales. The global CO_2 flux from decomposition (as heterotrophic respiration) is estimated at 68 PgC yr-1 (Raich and Schlesinger 1992), about 50% of the CO_2 released from the biosphere to the atmosphere (Stuart, Matson, and Vitousek 2012), and approximately six times more than current annual anthropogenic CO_2 emissions. About half the CO_2 flux from decomposition can be attributed to surface litter fall, while the other half is from soils (M.-M. Coûteaux, Bottner, and Berg 1995). The total soil carbon pool (litter and soil) is thus largely determined by the input and turnover of litter, and turnover and accumulation of SOM (Keenan et al. 2014; Crowther et al. 2016).

Surface litter is decomposed by microinvertebrates and microbes (bacteria and fungi), therefore the controls on the composition and activity of these decomposers affect the rate of decay. A large body of research shows that climate (temperature, water availability) and litter quality (substrate chemical composition) influence decomposer communities and regulate litter decomposition rates (M.-M. Coûteaux, Bottner, and Berg 1995; Hobbie 1996; Aerts 1997; Gholz et al. 2000; Parton et al. 2007; Adair et al. 2008; Cornwell et al. 2008; Wieder, Cleveland, and Townsend 2009; Paudel et al. 2015). Soil temperature and moisture regimes drive chemical reactions and the biological activities of decomposers, which impacts mass loss and CO_2 fluxes (Davidson and Janssens 2006; Knorr et al. 2005; Conant et al. 2011). Decomposition rates are expected to increase with temperature up to a physiological maximum or until decomposers become limited by resources (Davidson and Janssens 2006). At longer time-scales, climate can also affect the composition and abundance of decomposer organisms (González and Seastedt 2001; García-Palacios et al. 2013) as well as litter substrate quality through phenotypic responses and changes in species composition (Cornelissen et al. 2007; Suseela and Tharayil 2018). Measures of litter quality including high nitrogen (N) content, and low lignin content, C:N and lignin:N have been effective in predicting rates of mass loss (Taylor, Parkinson, and Parsons 1989; Vitousek et al. 1994; Aerts 1997; Coq et al. 2011; Hatenschwiler et al. 2011; Talbot and Treseder 2012; Cleveland et al. 2014), exerting a stronger influence on decomposition than climate within individual biomes and ecosystems (Aerts 1997; Cornwell et al. 2008). Litter quality is also positively linked to abundance, diversity and activity of decomposer microorganisms (Fierer and Jackson 2006; Yang and Chen 2009; Nemergut et al. 2010; Handa et al. 2014).

Climate change is projected to increase surface air temperatures by about 3.7-4.8°C under business as usual scenarios, as well as significantly alter moisture and disturbance regimes (IPCC 2014). Given its critical role in the terrestrial carbon cycle, even small modifications in litterfall and litter decomposition rates due to climate change could have large impacts on atmospheric concentrations of CO_2 and the soil carbon pool. Earth System Models (ESMs) use empirically based parameters to predict climate change impacts on the terrestrial carbon cycle. Most ESMs project an increase in gross primary productivity, total litter carbon and soil carbon pool accumulation through the end of the century (Arora et al. 2020; Ciais et al. 2013), with among the strongest effects in the tropics (Arora et al. 2020). However, terrestrial carbon responses to climate change are highly uncertain and (Arora et al. 2013; Friedlingstein et al. 2014; Friedlingstein 2015; Walker et al. 2020) and represent one of the largest sources of uncertainty in climate change projections (Ciais et al. 2013). Responses in tropical forest soils in particular, including impacts on decomposition and carbon turnover, are poorly represented in models and are a critical source of uncertainty (Cavaleri et al. 2015; Bradford et al. 2016; Wood et al. 2019).

Tropical forests are an important carbon sink, accounting for 2/3 of live terrestrial plant biomass (Pan et al. 2013) and ~1/3 of the world's soil carbon (Jobbágy and Jackson 2000). Tropical forests also exchange more CO_2, water and energy with the atmosphere than any other terrestrial ecosystem (Foley et al. 2003; Beer et al. 2010; Townsend et al. 2011). However, there is a paucity of empirical studies in tropical forests that examine the response of tropical litter and soils to a changing climate (Wood, Cavaleri, and Reed 2012; X. Zhou et al. 2013; Cavaleri et al. 2015; Wood et al. 2019). Improving our understanding and representation of tropical forest responses to climate will enhance our ability to predict global carbon cycle dynamics and feedbacks to future climate.

In this study, we tested the effects of *in-situ* warming (+4°C compared to control) on litter decomposition in a tropical forest in Puerto Rico. The experiment was part of the Tropical Responses to Altered Climate Experiment (TRACE), the first large-scale forest warming experiment in the tropics (Kimball et al. 2018). We then compared the results of our field experiment with results from an Earth System Model +4°C (7.0 W/m2) to assess implications on global carbon cycle dynamics. Our study was designed to answer three main questions: (1) How does sustained warming affect mass and nutrient loss of surface litter? (2) Does the effect of warming differ across litter substrates? (3) Are our field results captured in Earth System models, and what impact does it have to tropical forest carbon pools and fluxes?

Methods

Study site

The study site is in a subtropical wet forest near the Sabana Field Research Station, part of the Luquillo Experimental Forest (LEF; 18°18′N, 65°50′W) in El Yunque National Forest in northeastern Puerto Rico. Mean annual rainfall is 3,500 mm, and although there is no pronounced dry season, January through April is drier on average (García-Martinó et al. 1996; Heartsill-Scalley et al. 2007) (**Figure 4.1**). The mean monthly temperature is 24°C, with little interseasonal variation (average of 4°C between months) (García-Martinó et al. 1996) (**Figure 4.1**). Elevation is 100 m, with slopes that range from 15 to 26 degrees and average 21° (Kimball et al. 2018). Soils are classified as Ultisols, and are clay-rich and acidic with high aluminum and iron content (Scatena 1989). The site is a secondary forest that has regenerated from pasture for the past 70 years (Kimball et al. 2018).

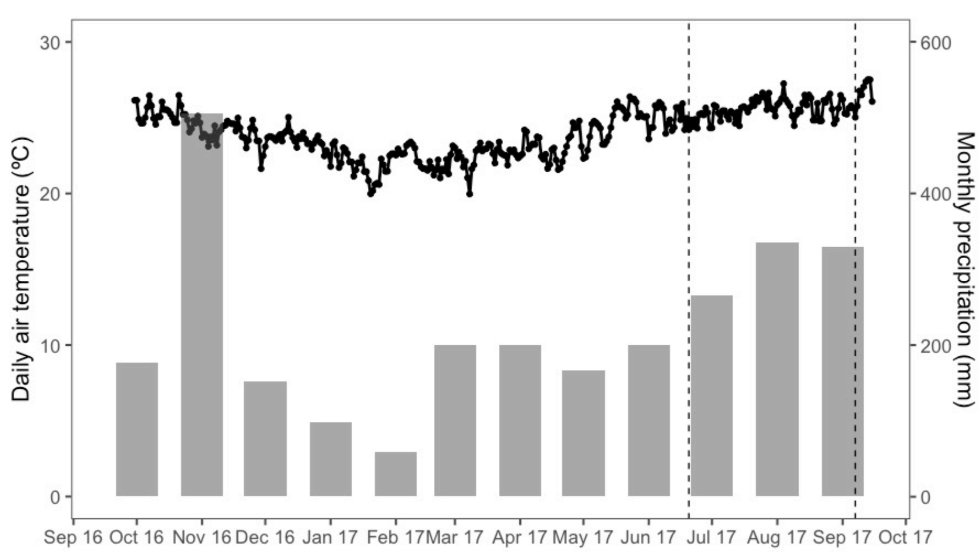


Figure 4.1. Mean daily air temperature (black line) and monthly precipitation (grey bars) at Sabana Field Research Station in 2016-2017.
Period between the dashed black lines represent the decomposition experiment.

Forest warming experiment

This study was conducted as part of the Tropical Responses to Altered Climate Experiment (TRACE). TRACE has three warmed and three control (ambient temperature) hexagonal plots, 4m across (**Figure 4.2b**). In the warmed plots, temperatures are maintained at 4°C warmer than the ambient plots by infrared heaters (Model Raymax 1010, Watlow Electric Manufacturing Co., St. Louis, MO) attached to crossbars at a height of 2.6 m above the ground (Kimball et al. 2018). The heated plots warm understory vegetation and soils. Control plots had identical infrastructure without the electrical wiring to limit any effects of treatment installation. The experimental warming treatments began on September 28, 2016, and the litter decomposition experiment ran almost a year later, from June to September 2017. The TRACE project collects hourly plot-level data on surface air temperature at 2m, surface relative humidity at 2m, soil temperature (0-10cm, 20-30cm, and 40-50 cm), and volumetric soil moisture (same depths as temperature); and quarterly data on soil nutrients (Kimball et al. 2018; Reed et al. 2020).

Figure 4.2. Pictures of the study site and litter experiment.
a) TRACE field site at the Sabana Field Research Station in El Yunque National Forest in NE Puerto Rico, b) Infrared experimental warming per plot, c) Litter samples in the plot. Photo a from Google Earth and photos b and c from Stephanie Roe.

Litter experiment and sample processing

We evaluated litter mass loss and decomposition rates using the litter bag method (Berg et al. 1993; Kurz-Besson et al. 2005) for four litter substrates: native litter and three standardized substrates (green tea, black tea and popsicle stick birch wood). For the native litter, we collected freshly senesced leaves (fallen within the last 24 hours, identified by the white coloration on the petiole scar) from *Inga laurina* and *Guarea guidonia* near the TRACE site. The two tree species are among the six most abundant native trees over 3cm diameter and were selected for leaf size (under 25 cm) and likely decomposition rates (slow and medium). The leaves were air-dried in mesh nets in the air-conditioned laboratory until a constant weight was achieved (4 days).

We placed 5g (± 0.1g) of air-dried, uncut leaves into 10cm x 20cm polyethylene mesh bags with a 2mm mesh to allow access by all decomposers including arthropods. An approximate equal ratio of 1:1 was used for the mass (g) of leaves from *Inga laurina* and *Guarea guidonia* to reflect their abundance in litter fall at the field site. All bags and tags were weighed prior to litter addition, then weighed again after litter addition to determine initial litterbag weights. Subsamples of litter bags were taken to determine oven-dry (65°C) mass and initial nutrient concentrations of the litter. Then, three litter bag replicates were randomly placed in the three warmed forest plots and three ambient plots for six time periods (3 replicates x 6 time periods x 6 plots = 108 total bags). The litterbags were arranged so that none were overlapping, and each had direct contact with the soil surface (**Figure 4.2c**). Litter collections were planned for 2 weeks, 4 weeks, 8 weeks, 16 weeks, and 52 weeks. However, Hurricane Irma and Hurricane Maria severely disturbed the study site in September 2017, disrupting the heaters and dropping heavy debris. Thus, collections were only achieved for the first three time periods (2 weeks, 4 weeks, and 8 weeks), conducted between June and September 2017. In these eight weeks, we capture the initial very rapid mass loss phase, a phase which makes up a large part of the total decomposition in wet tropical forests.

At each collection period, we retrieved 3 replicates from each of the six plots. Litter samples were cleaned of soil particles and visible roots, measured for fresh weight, oven-dried at 65°C until constant weight (3 days), then subsequently weighed to determine oven-dried weight. All fresh and oven-dried weights exclude the litterbag and tag weight. The litter was then finely ground using a ball-mill. The initial soil chemistry (total carbon (C %), total nitrogen (N %), total carbon to total nitrogen ratio (C:N), extractable soil ammonium (NH_4^+ μg/g), extractable soil nitrate (NO_3^- μg/g), and extractable soil phosphorus (PO_4^{3-} μg/g) and litter chemistry (C, N, and C:N) and subsequent sampled litter chemistry were measured at the US Geological Survey laboratory, Utah (**Table 4.1 and 4.2**) according to the laboratory methods for determining soil and litter chemistry described in (Reed, Cleveland, and Townsend 2013; Reed et al. 2020). Soil nutrients were not significantly different between the warmed and control plots (all $p>0.1$, **Table 4.1**).

In addition to the native litter, we also tested the effect of warming on decomposition rates in standardized substrates (**Table 4.2**): green tea, black tea and popsicle sticks. We used high quality (low C:N) Lipton green tea (EAN no.: 8 722700 055525), and lower quality (higher C:N) Lipton rooibos tea (EAN no.: 8 722700 188438) bags with 2g of dried and shredded material in 0.25mm mesh bags, following the Tea Bag Index approach (Keuskamp et al. 2013; Didion et al. 2016). The popsicle sticks were of birch wood, measuring 18mm x 150mm. We placed three replicates per substrate per time period in each of the six plots (108 for each substrate, as above); we collected and processed the samples using the same protocol as the native litter bags.

Table 4.1. Soil nutrient quality 0-10 cm, per plot, and averaged by treatment.
Values (mean ± SD) are given for total carbon (C %), total nitrogen (N %), total carbon to total nitrogen ratio (C:N), extractable soil ammonium (NH_4^+ µg/g), extractable soil nitrate (NO_3^- µg/g), and extractable soil phosphorus (PO_4^{3-} µg/g). Data is from three analyzed soil cores per plot. No significant differences were observed between the control and warmed plots in t-tests (all p>0.05).

Plot	Treatment	C (%)	N (%)	C:N	NH_4^+ (µg/g)	NO_3^- (µg/g)	PO_4^{3-} (µg/g)
1	Control	5.37 ± 0.65	0.50 ± 0.04	10.65 ± 0.57	1.97 ± 0.64	5.95 ± 1.82	0.59 ± 0.09
3	Control	4.51 ± 0.69	0.42 ± 0.05	10.75 ± 0.31	3.61 ± 1.33	6.09 ± 2.55	0.68 ± 0.34
5	Control	5.48 ± 0.70	0.49 ± 0.04	11.26 ± 0.68	5.74 ± 1.76	6.66 ± 3.31	1.14 ± 0.38
2	Warmed	4.40 ± 0.49	0.40 ± 0.02	10.85 ± 0.58	1.48 ± 0.33	5.26 ± 0.91	0.67 ± 0.20
4	Warmed	5.24 ± 0.18	0.45 ± 0.00	11.59 ± 0.37	5.17 ± 2.86	7.35 ± 3.46	0.76 ± 0.41
6	Warmed	5.74 ± 1.35	0.50 ± 0.06	11.48 ± 1.24	2.54 ± 1.05	6.81 ± 2.38	0.51 ± 0.06
Mean	Control	5.12 ± 0.75	0.47 ± 0.05	10.89 ± 0.55	3.77 ± 2.00	6.23 ± 2.30	0.81 ± 0.36
Mean	Warmed	5.12 ± 0.80	0.45 ± 0.06	11.31 ± 0.58	3.06 ± 2.16	6.47 ± 2.31	0.64 ± 0.38

Table 4.2. Initial nutrient content and condition of litter substrates.
Values (mean ± SD) are given for total carbon (C %), total nitrogen (N %), and total carbon to total nitrogen ratio (C:N). Litter type is ordered from lowest to highest C:N (highest to lowest litter quality). Green tea and black tea values are from (Keuskamp et al. 2013). Popsicle stick values are from (Middleton 2019). Native litter from this study.

Litter type	Litter condition	C (%)	N (%)	C:N
Green tea	2g shredded material	49.06 ± 0.11	4.02 ± 0.05	12.23 ± 0.13
Native litter	5g uncut leaves	45.92 ± 0.86	1.66 ± 0.09	27.75 ± 1.59
Black tea	2g shredded material	50.51 ± 0.29	1·19 ± 0.05	42.87 ± 1.84
Wood (popsicle stick)	18x150mm stick	46.33 ± 0.13	0.09 ± 0.01	508.96 ± 47.54

Data analyses

We performed all data analyses in R version 4.0.3 (R Core Team, 2020). For all 54 collected samples and 6 samples at T0 for each of the four litter substrate types (24 T0 samples + 216 collected samples = 240 total samples), we calculated the mass remaining (dry weight at collection period), mass loss (initial dry weight – mass remaining), proportion of litter decomposed ((mass loss/initial dry weight)*100), and mass loss rate (mass loss/time (# of weeks)). We also calculated the percent litter moisture content ((litter moisture content/ fresh litter weight)*100), C loss ((initial C% * initial dry weight) – (C% * mass remaining)), and N loss ((initial N% * initial dry weight) – (N% * mass remaining)).

To test the effects of warming and litter substrate and their interactions on litter decomposition, we used a linear mixed effects (LME) model using the ‘lme4’ R package (Bates et al. 2014). Using proportion of litter decomposed as the dependent variable, our fixed effects included treatment (control/warming), substrate type, time, and all two-way interactions. We controlled for plot-level variation as a random effect. Our experimental design is equivalent to a split plot with repeated measures. We examined the statistical significance of the fixed effects using Satterthwaite’s method of analysis of variance in the ‘lmerTest’ R package (Kuznetsova, Brockhoff, and Christensen 2017). Post hoc pairwise comparisons using the Tukey method were carried out using the R package ‘emmeans’(Lenth et al. 2020). To examine whether litter moisture content contributed to decomposition, we included it as a fixed effect variable in the model, and re-ran Satterthwaite’s method of analysis of variance in the ‘lmerTest’ R package. We tested the significance of two-way interactions and their impact on the model using ANOVA. None of the two-way interactions were significant and did not improve the model, so were left out of the final model (**Table 4.3**). We did not include soil nutrients in the model as the warmed and control plots were not significantly different in any of the soil nutrient variables (**Table 4.1**), and we only had data for the initial time period. To understand the overall model fit, we derived the model R^2 from the ‘MuMIn’ R package (Nakagawa, Johnson, and Schielzeth 2017). To assess differences in soil nutrients and in climatic variables (air temperature, relative humidity, soil temperature and soil moisture) between the warmed and control plots, we used Student’s t-test, Welch’s t-test and Wilcox test as appropriate.

Finally, to test the effects of warming on litter nutrient loss in the native litter, we used an LME model separately for C loss (g), N loss (g) and C:N remaining using the same process and tests as the LME model on mass loss. Ultimately, the fixed effects for C loss were treatment, time, and litter moisture content, and those for N loss and C:N were treatment and time. We also ran two linear regression models to assess the relationships between mass loss and carbon loss + treatment, and mass loss and nitrogen loss + treatment.

Earth System Model comparison

To assess the relevance and potential implications of our experiment to carbon dynamics across tropical forests globally, we compare our field results with projected results in a 4°C (7.0 W/m^2) scenario using an Earth System Model. We adapted data on future forests from (Roe et al., n.d.) which used the Community Land Model (CLM5) of the Community Earth System Model (CESM2) (Lawrence et al. 2019), to examine the impact of climate change on terrestrial carbon pools and fluxes from 2015-2100. CLM was run uncoupled from the rest of the earth system model (CESM) with climate anomaly forcing imposed on 20 years of standard CLM meteorology from the Global Soil Wetness Project (GSWP3). We assess the effects of a 4°C future climate on precipitation, relative humidity and soil moisture in the tropics to see where the conditions predicted by our experiment are likely to occur. We also examined changes in litter turnover rate, net primary production (NPP) and related litter inputs, litter heterotrophic respiration, soil heterotrophic respiration, and total litter and total soil carbon pools. To isolate climate effects from effects due to land-use change, we used a scenario with no land-use change from 2015 (NoLUC 4ºC from Table 3.1 in Chapter 3). We assessed the climate effect across all variables by subtracting the mean values of 2015-2020 from those of 2095-2100.

Results

Effects of experimental warming on soil temperature, soil moisture and relative humidity

During the litter decomposition experiment (June to September 2017), surface air temperature at 2m was 4°C higher ($p < 0.0001$) and mean soil temperature at 10cm was 2.7°C higher in warmed plots compared to controls (p <0.0001, **Figure 4.3**). Average relative humidity at 2m was 4% lower in warmed plots (93.1% ± 2.6) compared to control (97.1% ± 2.3) (p <0.0001). Warming also reduced mean soil moisture (volumetric water content, VWC) at 0-10cm by 1.2% (p =0.02, **Figure 4.3**). During the full year of warming (Oct 2016-Sept 2017), the difference in mean soil temperatures was slightly higher (3.2°C, p<0.0001) and the difference in mean soil moisture VWC was slightly lower (1.5%, p = 0.0008) compared to the experimental period.

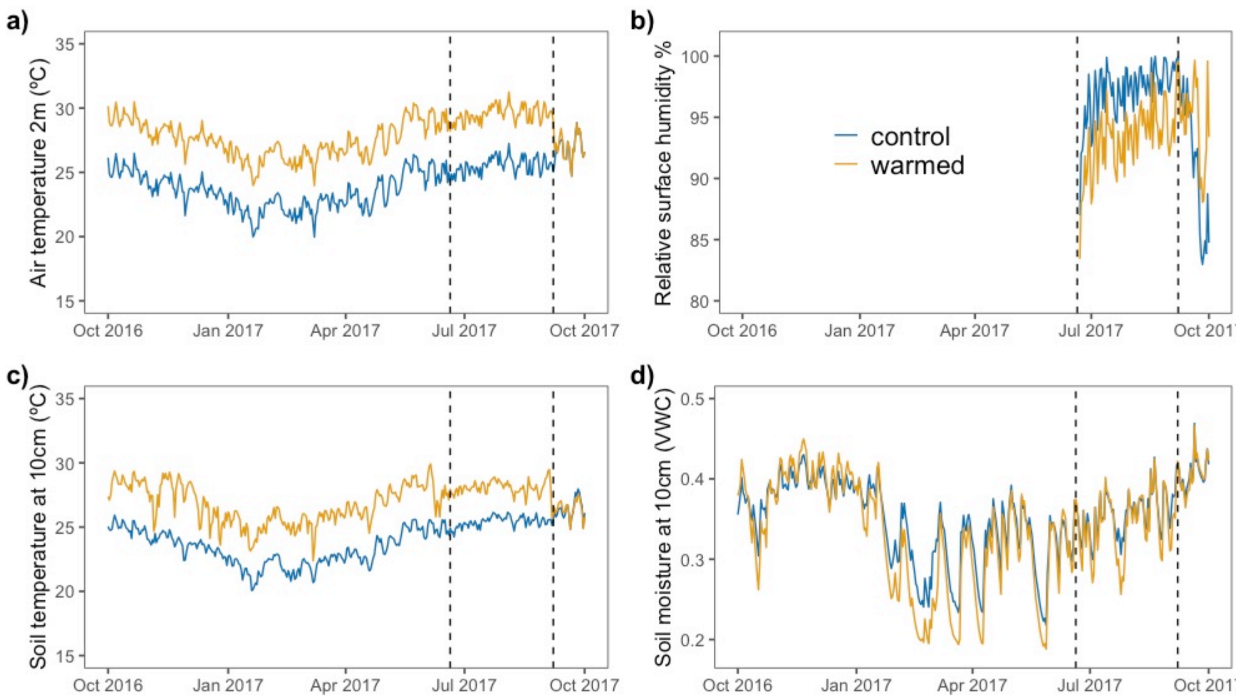
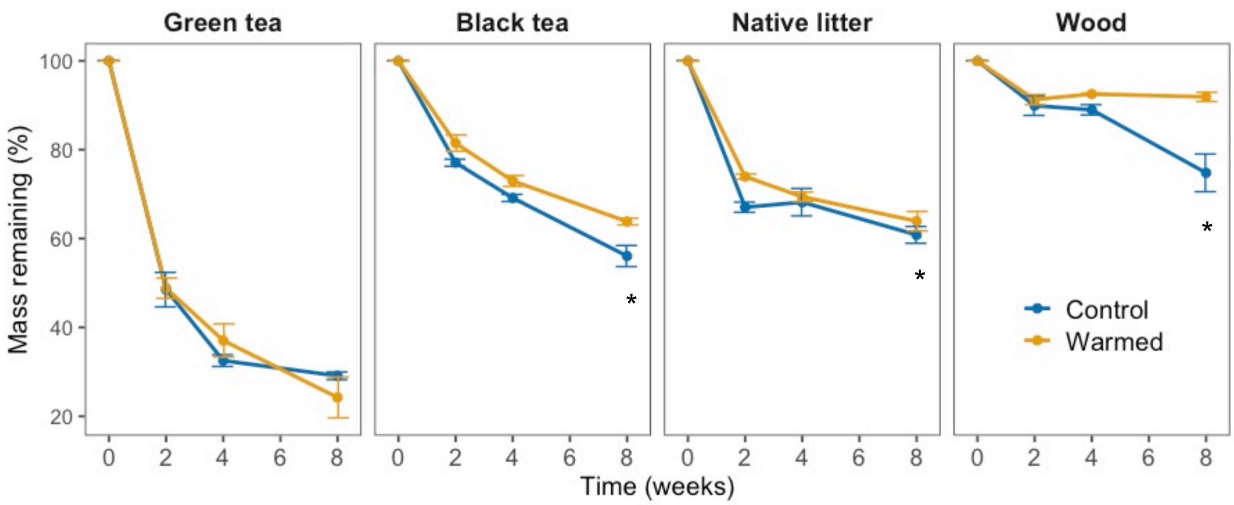


Figure 4.3. Experimental warming effects on surface air temperature, surface relative humidity, soil temperature, and soil moisture from 2016 to 2017.
(a) Surface air temperature at 2m (ºC) (b) Relative humidity in understory at 2m (%), (c) Soil temperature at 10cm (ºC), (d) Soil moisture at 10cm (volumetric water content, unitless). Period between the dashed black lines represent the decomposition experiment. Hurricane Irma and Hurricane Maria occurred in September 2017, after the second dashed line. The relative humidity sensors were only added in June 2017, therefore panel (b) has a shorter timeframe. The difference between warmed and control plots was significant for all parameters during the litter decomposition experiment.

Effects of warming on litter mass loss in four substrates

Warming significantly slowed decomposition in our experimental plots (p = 0.009, **Figure 4.4**). After 8 weeks, mass loss was 7% higher on average in control plots across the four substrates. Warming lowered mass loss by 3% (p = 0.05) in the native litter, 8% (p = 0.04) in black tea and 17% (p = 0.02) in the popsicle stick wood but did not significantly slow decomposition in the highest quality litter (green tea, p =0.43) (**Figure 4.4**). Decomposition was generally faster in substrates with higher nutrient quality. However, black tea decomposed slightly faster than the more nutrient rich native litter in the control plots, likely due to higher edge ratio (shredded black tea compared to uncut native leaves). The green tea litter decomposed by 69-71% after 8 weeks, black tea by 36-44%, native litter by 36-40%, and the popsicle stick wood by 8-25% (range represents mean values from warmed to control).



* Effect of warming significant at the α = 0.05 level

Figure 4.4. Litter decomposition curves showing mass remaining (mean ± SE) in control and warmed plots for each of the four litter substrates over time.
Tukey pairwise comparisons indicate all substrates are different from each other (p<0.0001), except for black tea and native litter (p = 0.8).

Effects of warming on litter moisture

Although our study site received high levels of precipitation (652 mm over 8 weeks), warming reduced litter moisture across all substrates by an average of 36% (p<0.0001) (**Figure 4.5**). The largest differences in litter moisture were in green tea (42% reduction) and native litter (40% reduction). Moisture content of the litter was a significant driver of mass loss (p<0.0001, **Table 4.3**), with wetter litter experiencing significantly higher mass loss than drier litter. In our mixed effects model, litter substrate had the greatest effect on mass loss, followed by litter moisture and warming treatment (**Table 4.3, Figure 4.5**). We found no interaction effects between treatment and substrate, treatment and litter moisture, or substrate and litter moisture. Warming had a significant effect (p = 0.009) on mass loss when litter moisture was excluded from the model. However, when litter moisture was included in the model, the warming treatment was no longer significant (p = 0.21), suggesting moisture explains much of the treatment effect (**Table 4.3**).

Table 4.3. Results of linear mixed effects model on effects of warming, litter substrate, time, and moisture on mass loss. There were no significant interaction effects between the variables, and were not included in the final model. Model $R^2 = 0.9$

Variable	Sum sq	Mean sq	Df (num)	Df (den)	F value	p
Litter substrate	58775	19592	3	205	463.9	<0.0001 ***
Warming treatment	186	69	1	45	1.64	0.21
(w/o litter moisture in model)	*1342*	*1342*	1	*4*	*15.86*	*0.009 ** *
Time	5955	5955	1	205	141.1	<0.0001 ***
Litter moisture	900	900	1	207	21.3	<0.0001 ***

* Significant at the α = 0.05 level
** Significant at the α = 0.01 level
*** Significant at the α = 0.001 level

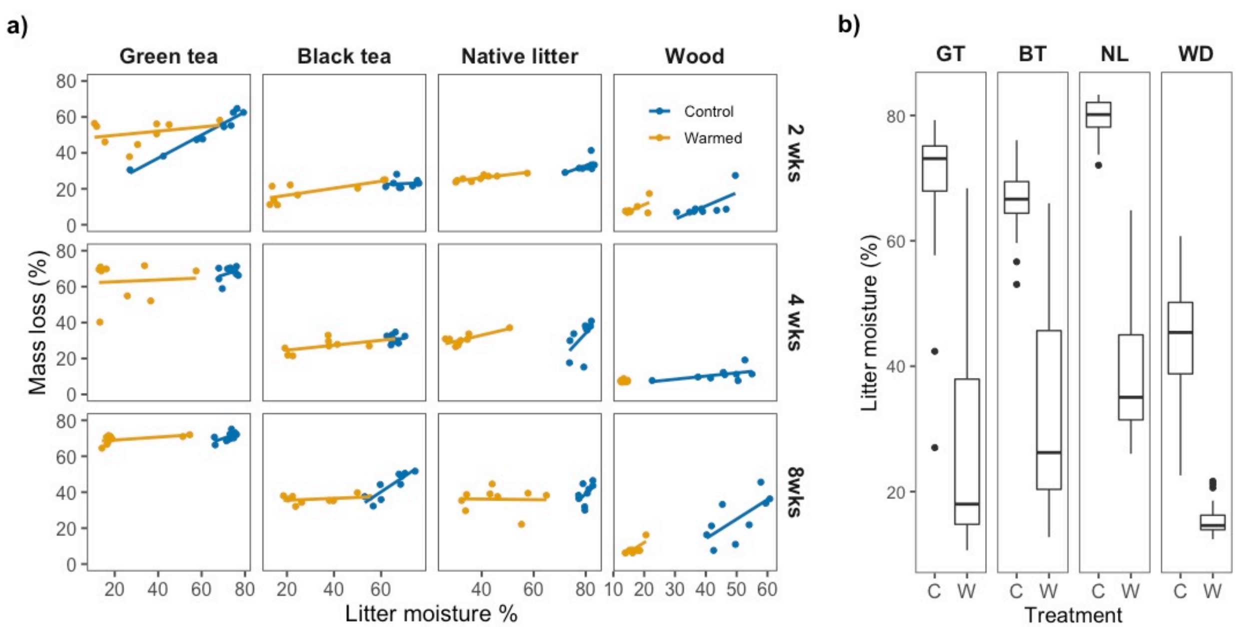


Figure 4.5. Effect of warming on litter moisture and decomposition.
(a) Relationship of mass loss (%) and moisture content (%) by litter type and time period. Solid lines represent line of best fit for each plot treatment (control and warmed). Lines do not indicate a significant relationship per substrate per time point, but are included to help visualize the data. (b) Box plot of litter moisture (%) across all collection time periods for four substrate types

(GT = Green tea, BT = Black tea, NL = Native litter, Wood = WD) in control (C) and warmed (W) plots. The difference in moisture between warmed and control plots is significant ($p<0.0001$) for all four substrates.

Effects of warming on nutrient loss

Warming also significantly reduced nutrient release in the native litter ($p=0.006$ for C:N and $p = 0.04$ for N). Remaining C:N was higher in warmed plots where decomposition was slower **(Figure 4.6a)**. As expected, native litter mass loss correlated directly with carbon loss ($R^2 = 0.69$, $p<0.0001$), with no difference between the treatments ($p=0.2$, **Figure 4.6b**). Similar to mass loss, litter moisture explained much of the treatment effect for carbon loss. Nitrogen loss was also significantly correlated with mass loss ($R^2 = 0.54$, $p<0.0001$), with 5.7% less mass loss per unit of nitrogen loss and a stronger relationship in the warmed treatment ($R^2 = 0.72$, $p<0.0001$, **Figure 4.6c**). Unlike mass loss and carbon loss, litter moisture did not explain the warming effect for nitrogen loss, and was not a significant predictor ($p = 0.8$). In the native litter, the difference in C:N ratios between the treatments at the end of the experiment (14%) was higher than the difference in mass loss (3%, **Figure 4.6a**), suggesting that warming had a larger effect on nitrogen loss than on mass loss.

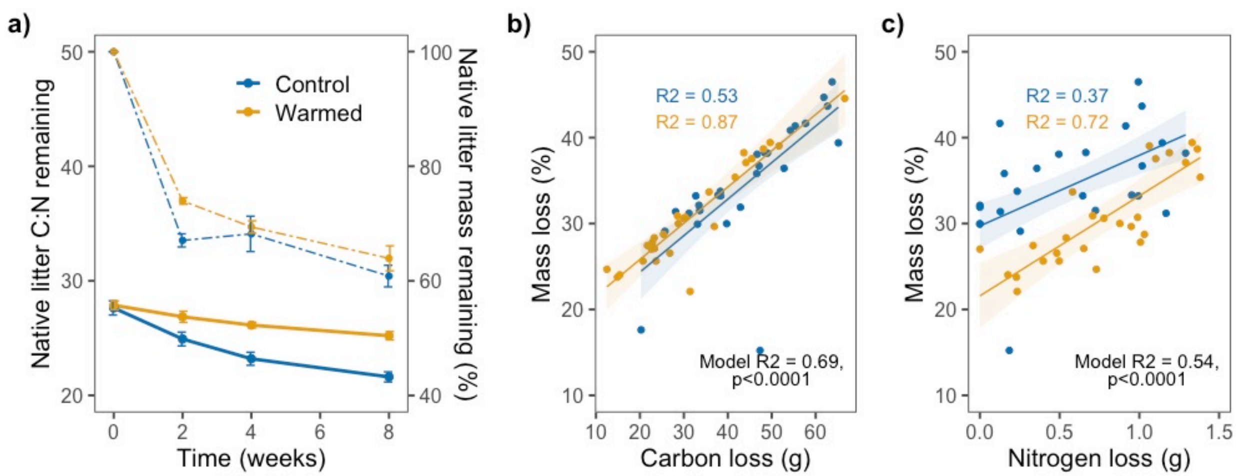


Figure 4.6. Effect of warming on native litter nutrient content.
a) Native litter C:N remaining (solid lines, left y axis) and mass remaining (dashed lines, right y axis) in warmed and control plots over time. b) Linear regression and 95% confidence interval of mass loss explained by carbon loss and warming treatment. Warmed effect = -1.4, p = 0.2. c) Linear regression and 95% confidence interval of mass loss explained by nitrogen loss and warming treatment. Warmed effect = -5.7, p<0.0001. The slope is not significantly different in the two treatments.

Comparing field experimental results to model results

With climate forcing of 7.0 W/m^2 (representing a business as usual emissions scenario), mean surface air temperature at 2m increased by about 4 ºC by the end of the century (2100) and precipitation, relative humidity and soil moisture regimes changed substantially by region (**Figure 4.7a – 4.7c**). Tropical moist and dry forests in Central America, Caribbean and northern South America (including large parts of the Amazon), parts of Western and Southern Africa, as well as the Mekong region countries and western Indonesia (Sumatra and Borneo) saw a reduction in mean annual precipitation and soil moisture by the end of the century. Reduced relative humidity spanned larger areas, across most tropical forest types except in Eastern Africa.

Based on our field experiment, we would expect the decomposition rate to decline in these tropical forest areas that experienced drying. In the model results, the litter carbon turnover rate (decomposition) indeed decreased in parts of Central America and Caribbean, northern South America (small patches in the Amazon) and small areas in the Western and Southern Africa, and Mekong region countries (**Figure 4.7d**). Among forested biomes, litter carbon turnover decreased across dry forests where precipitation and soil moisture decreased, and relative humidity decreased by more than 1.5% (**Figure 4.7a – 4.7c**). Substantial areas of moist and wet forests experienced a reduction in litter C turnover rates in Central America and northern South America, including Puerto Rico (**Figure 4.8**). These forests experienced the highest reduction in precipitation (≥ -2.5mm/day or ≥ 912 mm/yr), soil moisture (≥ -5mm/m^2, -5% VWC) and relative humidity (≥ -5%) compared to other moist and wet forests. In the model, the level of drying related to reduced turnover rates in wet tropical forests is higher than in our field experiment (decrease of ≥ 4% relative humidity and ≥ 1.2% of soil moisture VWC). Discrepancies in the severe drying effect were also evident in the model. For instance, the Amazon region in northeastern Peru saw a large reduction in precipitation (≥ -2.5mm/day) and yet litter C turnover rate increased (**Figure 4.8**). This example is likely due to the very high background levels of precipitation in that region.

The litter carbon pool increased in the areas with reduced litter turnover rates, however, total litter carbon pools increased across all tropical forests, including those areas that became wetter and experienced higher litter turnover rates (**Figure 4.7e**). In a 4ºC future, net primary production was enhanced across most of the tropics (NPP), which increased total litter carbon inputs (**Figure 4.7f**). Lower litter turnover therefore had an effect on the litter carbon pool and related CO_2 efflux in tropical forests, however, increased NPP and litter inputs had a larger global effect. Across a majority of the tropics that experienced increased NPP, litter carbon that was transferred to the soil also increased (**Figure 4.7g)**. Some drier tropical forests and savannas saw decreased NPP in a 4ºC future, which translated to decreased litter C to soil. The soil carbon pool generally increased across the tropics, however, these increases do not appear related to litter turnover rates or total litter C to soil (**Figure 4.7g, Figure 4.7h)**. Overall, the model results show that in a warmer world with 7.0 W/m^2 radiative forcing, all carbon pools (vegetation, litter and soil) accumulate carbon throughout the century across most tropical forests largely in line with increased NPP. Reduced precipitation increased the effect in litter carbon accumulation, particularly in drier forests.

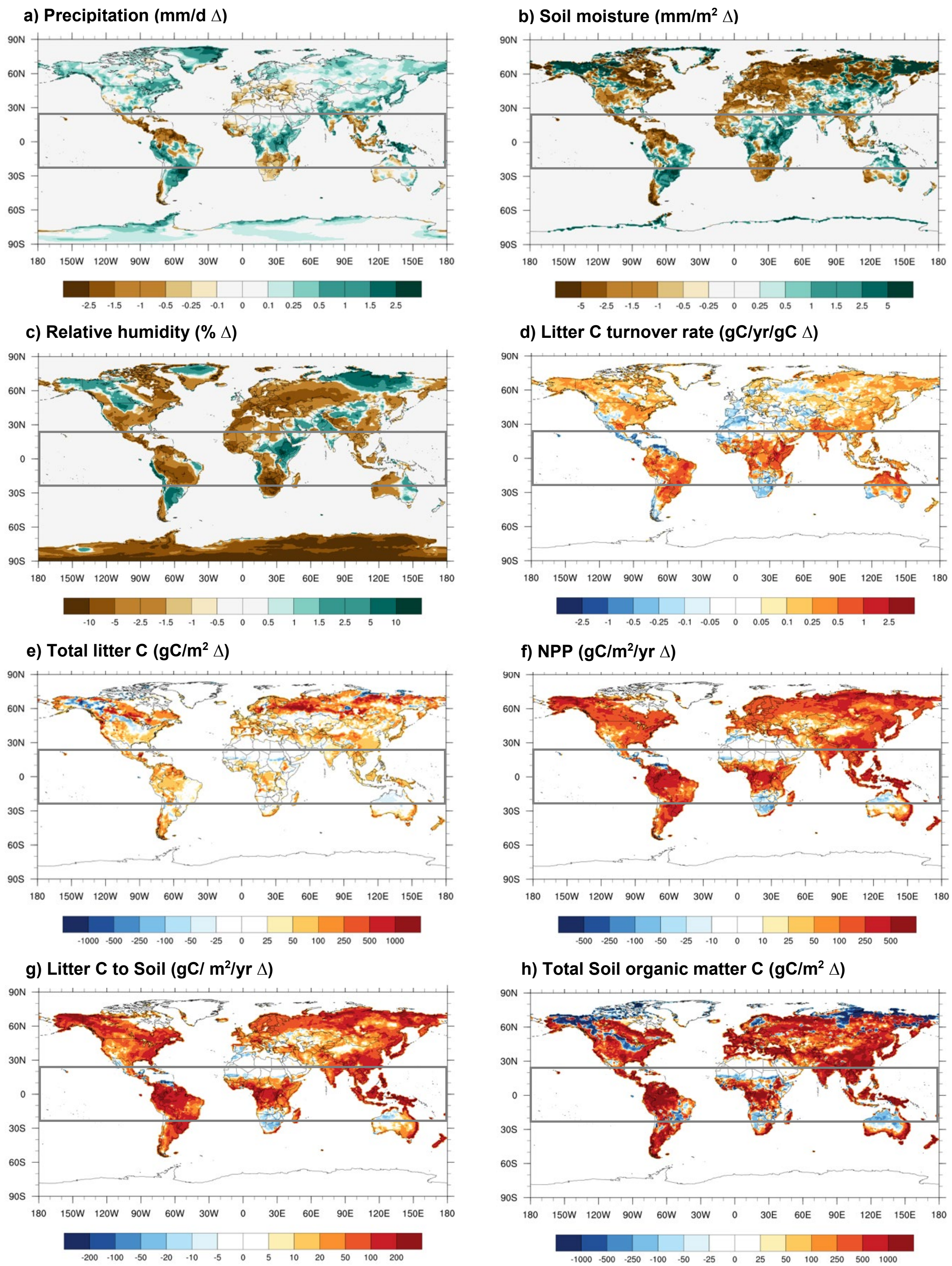


Figure 4.7. CLM model results illustrating the change in a 4ºC world (7.0 W/m^2 forcing).
Values represent mean 2095-2100 minus mean 2015-2020. a) Daily precipitation (mm/d), b) Soil water (mm/m^2) in the top 10cm c) Relative humidity at 2m (%), d) Litter C turnover rate (gC/yr/gC), e) Total litter C pool (gC/m2), f) Net primary production (gC/m2/yr), g) Litter C to Soil (gC/m2/yr), h) Total soil organic matter C pool (gC/m2). Grey box represents the tropics between 23.5º N and 23.5ºS.

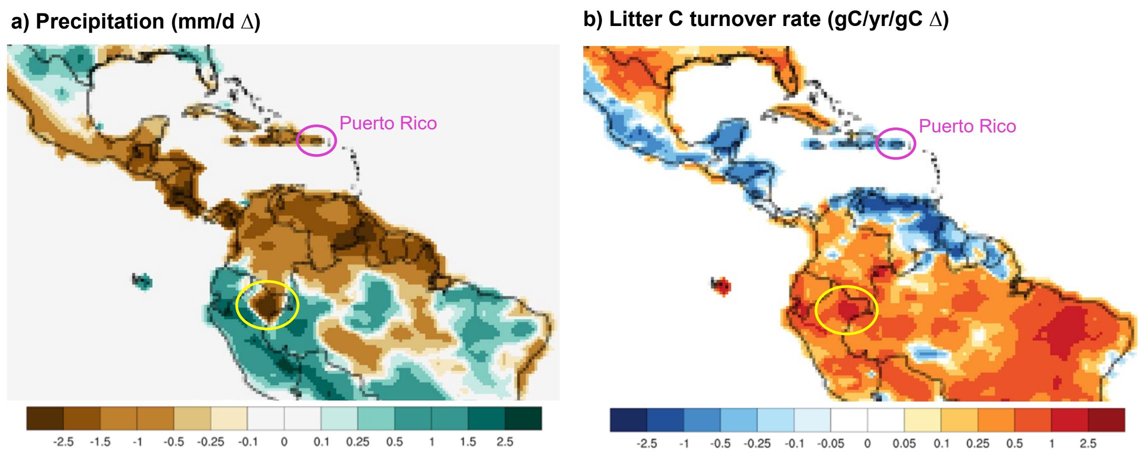


Figure 4.8. CLM model results in Central America and northern South America of change in a 4ºC world (7.0 W/m^2 forcing).
Values represent mean 2095-2100 minus mean 2015-2020. a) Precipitation (mm/d), b) Litter turnover rate (gC/yr/gC). Pink demarcation is of Puerto Rico, and yellow demarcation is an example of very high drying (≥ -2.5mm/day) accompanied by increased litter C turnover rate.

Discussion

Sustained, in-situ warming in a wet tropical forest significantly slowed mass loss (7% lower on average, 3-17% lower across substrates, **Figure 4.4**) and nutrient release (14% higher C:N, 44% higher N in native litter, **Figure 4.6**) in the initial rapid decomposition phase. The effects of our experimental warming on surface and soil moisture explained much of the response (**Table 4.3, Figure 4.5**), suggesting that moisture regimes will be an important determinant of tropical forest litter decomposition with future climate change. Although no particular forest can be a proxy for all tropical forests, the results captured in our field study have interesting and potentially important global implications. Our model experiment captured the litter decomposition response from our field experiment, showing reduced litter carbon turnover rates in tropical forests that experienced drying including Puerto Rico, but with lower sensitivity. Although litter carbon turnover decreased across most dry tropical forests with reduced precipitation, it only decreased in wet tropical forests that experienced higher levels of drying than occurred in our field experiment.

Effect of warming on decomposition and nutrient release

We found that in-situ warming decreased litter decomposition and nutrient release. Reduced mass loss was due to the drying effect in warmed plots. Warming likely increased evaporation, as the experiment reduced soil moisture, litter moisture, and relative humidity. Our results run contrary to most in-situ warming studies. Studies using diverse methods (greenhouse, open-top chambers, infrared air heaters, soil heating cables) show that on average, decomposition rates and nutrient release increase with warming (Lu et al. 2013). A meta-analysis including 34 studies across biomes and ecosystems found experimental warming increased litter mass loss by an average of 6.8% (Lu et al. 2013). However, most experiments that used open top chambers demonstrated a negative effect of warming on decomposition rates (Lu et al. 2013). Similarly, another meta-analysis in cold biomes reported higher decomposition rates with warming, however, the response was strongly dependent on the experimental warming method used (Aerts 2006). Although soil warming with cables and lamps stimulated decomposition, open top chambers reduced decomposition due to moisture limitation (Aerts 2006). More recent studies in arctic tundra using open top chambers (Christiansen et al. 2017; Blok, Elberling, and Michelsen 2016) and in temperate grasslands using infrared heaters (Yoshitake et al. 2020) also found reduced mass loss from warming due to drying. Drying litter substrates below a certain moisture level decreases microbial enzyme activity and slows biogeochemical processes (Schimel, Balser, and Wallenstein 2007). Our study provides another example of warming induced moisture limitation from infrared heating, adding needed data from tropical forests. The evidence suggests experimental warming may enhance litter decomposition, but not when it leads to significant drying, and different kinds of experimental warming methods have a large effect on surface and soil moisture regimes.

In forest ecosystems, most studies measuring temperature effects on litter decomposition use elevational gradients in tropical (He et al. 2009; Salinas et al. 2011; Nottingham et al. 2015; Bothwell et al. 2014), sub-tropical (Liu et al. 2017), and temperate systems (M. M. Coûteaux et al. 2002; Y. Zhou et al. 2014; Qualls 2016; Fujii et al. 2018; Bohara et al. 2020). The few forest litter decomposition studies that employ *in-situ* warming (4 from Lu et al. (2013) meta-analysis and additional literature review) are in temperate and boreal forests where temperature is likely to be limiting in the first place; and all use soil heat-resistance cables (Van Cleve, Oechel, and Hom 1990; McHale et al. 1996; Rustad and Fernandez 1998; Verburg, Van Loon, and Lükewille 1999). Heat-resistance cables heat the soil and thus decouple above and below-ground ecosystem components, whereas infrared heaters heat all ecosystem components up to where they are installed, usually 1-3m above the ground (Aronson and McNulty 2009; Kimball et al. 2018). The existing *in situ* forest studies found increased or no significant difference in litter decomposition after one year of warming at 3 – 8 ºC of warming, and one study found decreased mass loss in the first 6 months with warming at 3 – 5 ºC (**Table 4.4**). No studies reported changes in litter moisture or relative humidity, and one study reported a reduction in soil moisture of 13%. To better understand the interacting effects of experimental warming and moisture regimes on litter decomposition in forest ecosystems, more research and *in situ* experiments are needed that explicitly include temperature and moisture (litter moisture, soil moisture, relative humidity, evapotranspiration) as treatments and explanatory variables (Aerts 2006).

To our knowledge, this is the first in-situ warming study of litter decomposition in a wet tropical forest. Despite very high levels of daily precipitation, a temperature increase of 4ºC and related moisture loss slowed the mean mass loss by 6%. In a litter decomposition study across 23 tropical forests, Powers et al. (2009) found that precipitation rather than temperature best predicted mass loss, explaining 60% of the variation in average decomposition rates among the sites. Similarly, precipitation explained 93% of the variation in initial leaf litter decomposition (up to 50% mass remaining) in five neotropical forests (Cusack et al. 2009). Throughfall (precipitation) reduction of 25% in a Costa Rican rainforest reduced rates of annual litter decomposition by ~20% (Wieder, Cleveland, and Townsend 2009). The study concluded that any reduction in mean annual precipitation would likely slow decomposition rates in the wettest tropical forests, unless litter quality increased concurrently. In our *in situ* warming experiment, soil moisture changes were relatively minor (1% difference between the warmed and control plots, **Figure 4.3**), however, litter moisture decreased by an average of 36% across the substrates (**Figure 4.5**). Relative humidity was therefore a stronger determinant ($R^2 = 0.4$, $p<0.0001$) of litter moisture and mass loss than soil moisture ($R^2 = 0.02$, $p=0.02$). High precipitation during the summer months in our field site seem to have offset much of the drying effect in soils, but not in the surface litter. The minor changes in soil moisture suggest that the litter layer likely acted as a buffer in reducing moisture loss from the soil.

Table 4.4. Results from in situ forest warming experiments on litter decomposition.
References from (Lu et al. 2013) and additional literature review. N.d. = no data.

Ref	Site	Warming method	Species	ΔT	ΔMass loss	ΔSoil moisture	ΔLitter moisture	ΔRH
Rustad et al. 1998	Maine (temperate forest)	Cables, 1-2 cm depth	Red maple Red spruce	4-5ºC	Red maple: ↑ 27% after 6 months of warming, no significant effect after 30 months. Red spruce: No significant difference in 18 mos, ↑ 19% after 30 mos	↓ 13%, from mean of 2050 g/kg to 1770 g/kg	n.d.	n.d.
Van Cleave et al. 1990	Alaska (boreal forest)	Cables	Black spruce	8-10 ºC	↑ 20% of entire forest floor after 2 years	n.d.	n.d.	n.d.
McHale et al. 1996	Adirondack mountains, New York (temperate forest)	Cables, 5cm depth	American beech Maple	2.5ºC, 5ºC, 7.5 ºC	American beech: ↑ ~10% with 5ºC warming and ↑ ~20% with 7.5ºC warming over 2 years, no difference in 2.5ºC Maple: no significant difference	n.d.	n.d.	n.d.
Verberg et al. 1999	Southern Norway (boreal forest)	Cables, 1 cm depth	Birch	3ºC-5ºC	↓ mass loss in first 6 months, no significant difference after 1 year of warming	n.d.	no measurement, stated "litter from warmed plot was significantly drier, most likely caused by the heat treatment"	n.d.

Effect of warming across litter substrates

Like previous studies that found strong control by litter quality on decomposition (Aerts 1997; Cornwell et al. 2008), litter substrate and litter quality had a larger effect on mass loss than the warming treatment in our study. We observed a 3-fold difference in mass loss among the four litter substrates, and a 2.4-fold difference in the three foliar substrates (native litter, green tea and black tea) (**Figure 4.4**). The different litter substrates represent chemical differences in litter quality as well as physical differences in the amount of edge of the substrate. In our two standardized foliar substrates, green tea decomposed about twice as fast as black tea (which has about 3.5 times higher C:N).

Experimental warming had a greater impact on litter substrates with lower nutrient quality and had no effect on decomposition rates in the highest quality substrate (green tea). This finding supports previous studies that find less decomposable substrates have higher temperature sensitivity than readily decomposable substrates (Conant et al. 2008, 2011). Given lower quality litter decomposes the slowest, our findings suggest warming could amplify this effect, further slowing its decomposition. Forest litterfall consists of about 70% leaf tissues and 30% woody debris, with increasing woody litter in old-growth forests (Schlesinger and Bernhardt 2013; Chakravarty et al. 2019). Older tropical forests with lower litter quality and higher proportions of woody debris may therefore experience a larger effect from warming.

At longer time-scales, climate change can affect litter substrate quality through phenotypic responses and changes in species abundance, composition, and diversity, affecting decomposition (Cornelissen et al. 2007; Suseela and Tharayil 2018; Panetta, Stanton, and Harte 2018). Recent studies show increasing CO_2 concentration decreases nutrient quality in litter and lowers decomposition rates (Ball 2003; Cha et al. 2017; Zuo and Knops 2018; Rai et al. 2020). Given that litter quality is positively correlated with the abundance, diversity, and activity of decomposer microorganisms, reductions in litter quality could produce a positive feedback on decomposition rate where lower litter quality slows decomposition, providing fewer nutrients to soil and vegetation, and further limiting litter nutrient quality and decomposition (Fierer and Jackson 2006; Yang and Chen 2009; Nemergut et al. 2010; Handa et al. 2014).

Model results and implications for global carbon cycle

Extrapolating from our field experiment, warming with concomitant drying in tropical forests should slow carbon and nutrient turnover, leading to lower soil and plant nutrient availability, and potentially a decline in soil respiration, gross primary production and litter quality. Our Earth System model provides a way to examine this hypothesis with additional complexity. The model illustrated that while litter turnover rates did slow in some tropical forests with substantial drying, decomposition rate was less sensitive than in the field. Furthermore, slower decomposition did not lead to lower nutrient availability, soil respiration or productivity. Reduced precipitation slowed litter carbon turnover across most dry tropical forests, however turnover only declined in wet tropical forests of Central and northern South America including the Caribbean, and very small pockets in the Congo Basin and Sumatra – areas that experienced among the largest reductions in precipitation, relative humidity and soil moisture globally and at higher levels of drying than our field experiment (**Figure 4.7**). Litter carbon turnover increased with warming in the remaining tropical forest areas. Most tropical forest areas with reduced litter turnover rates also saw increased NPP and litter inputs, which increased total litter carbon and nutrient transfer to soil. The few patches of dry tropical forests and savannas in Central and northern South America that experienced reduced turnover rates and reduced NPP saw reduced litter carbon to soil, but no effect on soil carbon accumulation.

Across most of the tropics, future climate change of 7.0 W/m^2 (4ºC) increased litter carbon turnover but the higher CO_2 efflux was offset by increased NPP (carbon sequestration in vegetation) and greater litter and soil carbon accumulation. The increased vegetation, litter and soil carbon pools suggests an increasing terrestrial sink and a slight negative feedback on warming. A meta-analysis on the observed effects of field experimental warming on global ecosystem carbon cycling (Lu et al. 2013) shows a similar result. On average, warming increases NPP by 4% and plant carbon pools by 7%, offsetting increased carbon fluxes from litter mass loss (+7%) and soil respiration (+9%) (Lu et al. 2013). In contrast, Duffy et al. (2020) conclude that global photosynthesis and global land carbon uptake will decline with additional future warming, and Terrer et al. (2021) show that plant biomass increased with future climate and CO_2 fertilization, but soil organic carbon storage declined in forests.

The effect of temperature and precipitation changes on tropical forest carbon balance, especially for very wet tropical forests, is poorly understood and poorly represented in models (Wieder, Cleveland, and Townsend 2009; Carvalhais et al. 2014), making soil-atmosphere carbon feedback predictions uncertain (Bradford et al. 2016; Wood et al. 2019). The response of litter decomposition and mineralization of soil organic matter to climate change, and the consequences for soil carbon pools and fluxes remain unresolved, with varying methodologies applied in Earth System Models (Huntingford et al. 2009; Conant et al. 2011). A review of CMIP5 models (Fifth Coupled Model Intercomparison Project) found that models underestimate turnover times compared to observations by about 36% globally, and have insufficient sensitivity of decomposition to soil moisture and drought (Carvalhais et al. 2014). In the study, observed carbon turnover times were highly correlated with precipitation, suggesting that future carbon feedbacks could depend more strongly on hydrological changes than are currently captured by models (Carvalhais et al. 2014). Although the CESM model captures reduced turnover rates in the tropical forests that experienced the highest drying, our study along with others (Wieder, Cleveland, and Townsend 2009; Powers et al. 2009) suggest even moderate effects on moisture regimes in a warmer world could have significant impacts on carbon cycling in wet tropical forests.

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Chapter 5: Synthesis and Conclusions

In my dissertation, I investigated terrestrial systems' potential contribution to deliver on the Paris Agreement temperature targets of 1.5ºC and 2ºC (Chapter 2), the impact of climate change on forest sequestration potential (Chapter 3), and the effect of climate on tropical forest litter carbon turnover and consequent impacts on the tropical forest sink (Chapter 4).

The meta-analysis of land-based mitigation and roadmap to 2050 developed in Chapter 2 showed that deploying measures in agriculture, forestry, wetlands, and bioenergy could feasibly and sustainably contribute ~30% (14-15 $GtCO_2e$ yr^{-1}) of the global mitigation needed in 2050 to deliver on the 1.5°C target. The 14-15 $GtCO_2e$ yr^{-1} of mitigation potential is in addition to the 12.5 $GtCO_2e$ yr^{-1} of anthropogenic carbon emissions that unmanaged land already sequesters without intervention (Friedlingstein et al. 2020). Integrated assessment models (IAMs) differ from sectoral studies ("bottom-up" literature) in the types of mitigation measures included and their relative mitigation contributions. Since land-based mitigation in IAMs is relatively new (Popp et al. 2017), IAMs have a much more limited portfolio of land-based activities (8) compared to sectoral studies (24), and thus have a lower range of mitigation potential (0.9 – 36.6 (median 13.8) $GtCO_2e$ yr^{-1} mitigation potential in IAMs, and 2.4 – 48.1 (median 14.6) $GtCO_2e$ yr^{-1} in bottom-up literature).

The largest land-based mitigation potentials come from forest sequestration measures including afforestation and reforestation (A/R) and BECCS (bioenergy with carbon capture and storage). However, additional considerations are needed to account for feasibility and sustainability. The land-sector roadmap illustrates how the 14-15 $GtCO_2e$ yr^{-1} mitigation target for a 1.5ºC pathway can be allocated across eight main land-based measures that consider feasibility, minimize negative trade-offs and optimize co-benefits (biodiversity, water, air, soil, resilience, food security and livelihoods). The roadmap charts a pathway from 2020 to 2050, with approximately 50% from reducing gross emissions and 50% from enhancing carbon uptake by land. The eight measures include actions in forests: 1) reduce deforestation, peatland burning and mangrove conversion in tropical countries (4.6 $GtCO_2e\ yr^{-1}$); 2) restore forests, drained peatlands, and coastal mangroves, particularly in tropical countries (3.6 $GtCO_2e\ yr^{-1}$); 3) improve forest management and agroforestry in the US, Russia, Canada, EU, Australia, Brazil, Indonesia, and other tropical countries (1.6 $GtCO_2e\ yr^{-1}$); in agriculture: 4) enhance soil carbon sequestration in agriculture across all agricultural countries, particularly China, the US, EU, Australia, India, Brazil, Argentina, Mexico, Indonesia and Sub-Saharan Africa (1.3 $GtCO_2\ yr^{-1}$); 5) reduce direct emissions in agriculture in developed and emerging economies (1 $GtCO_2e\ yr^{-1}$); in consumer behaviour: 6) reduce consumer food waste in developed and emerging countries and food loss from production in Southeast Asia and Sub-Saharan Africa (0.9 $GtCO_2e\ yr^{-1}$); 7) converge to 50% adoption of plant-based diets (less than 60g of meat per day) in developed and emerging countries (0.9 $GtCO_2e\ yr^{-1}$); and in bioenergy: 8) pilot and moderately deploy BECCS on degraded land after 2030 (1.1 $GtCO_2\ yr^{-1}$). The roadmap trajectory translates to a needed reduction of land-based emissions by about 50% per decade (85% total decrease by 2050), and about a ten-fold increase in carbon removals over two decades between 2030-2050 (cumulative 184 $GtCO_2e$ by 2050) to make the land sector net zero emissions by 2040 and a net carbon sink of approximately 3 $GtCO_2e\ yr^{-1}$ by 2050. Both 2°C and 1.5ºC temperature targets require steep emission reductions from tropical deforestation, yet the 1.5ºC goal will require earlier and deeper reductions in agricultural and demand-side emissions, and enhanced carbon removals from reforestation, soil carbon sequestration, agroforestry and forest management. The Chapter 2 findings strengthen the evidence for large mitigation potential from land-based measures (Smith et al. 2013; Griscom et al. 2017; Jia et al. 2019), and provide additional granularity on specific land-based measures by region, and trajectories to 2050.

Land-based measures that enhance carbon removals are likely to be affected by future climate change. However, very few studies that estimate land-based sequestration potential consider climate impacts. My study on biophysical sequestration potential for afforestation, reforestation and forest enhancement (A/R/E) under two climate futures in Chapter 3 is one of the first to do so. In line with previous studies (Roe et al. 2019), I found large potentials to sequester additional carbon from A/R/E, 3.8-7.3 $GtCO_2$ yr^{-1} in 2050 depending on future agricultural expansion, with ~45% from afforestation, ~33% from reforestation, and ~21% from forest enhancement. High levels of future agricultural expansion (+650 Mha) not only reduces the A/R/E sequestration potential by 41% (lower end of the ranges), it also substantially reduces (by 62%) the natural capacity of land to act as a carbon sink. Tropical regions provide a majority of mitigation potential (80%), with 65% of afforestation, 90% of reforestation and 92% of forest enhancement. Reforestation and forest enhancement in the tropics and sub-tropics have higher mitigation densities than afforestation, higher potential to deliver multiple benefits including enhanced biodiversity, and are most aligned with countries' restoration pledges, indicating where efforts should be prioritized. In a 4°C climate future (7.0 W/m^2 forcing), sequestration potential is ~20% greater, with 15-30% higher gains in the tropics compared to temperate and boreal regions. Productivity increases outweighed carbon losses from ecosystem respiration and fire, largely due to CO_2 fertilization. Other earth system modelling studies of land futures also find that the positive effect from CO_2 fertilization with higher radiative forcing outweighs the negative effect from warming and other climate-induced disturbances like droughts and fires (Sonntag et al. 2016; Doelman et al. 2020; Arora et al. 2020). However, the strength of carbon–concentration and carbon–climate feedbacks over land varies substantially among models (Arora et al. 2013; Friedlingstein et al. 2014; Friedlingstein 2015; Walker et al. 2020), and represent one of the largest sources of uncertainty in climate change projections (Ciais et al. 2013). Responses in tropical forest soils in particular, including impacts on decomposition and carbon turnover, are poorly represented in models and are a critical source of uncertainty (Cavaleri et al. 2015; Bradford et al. 2016; Wood et al. 2019).

In Chapter 4, I evaluated the effects of sustained 4°C warming on *in-situ* litter decomposition in a tropical forest and then compared the experimental field results to the earth system model results from Chapter 3. I found that warming reduced mass loss by an average of 7% across the four substrates. Warming decreased litter moisture by an average of 36%, relative humidity by 4%, and soil moisture by 1.2%, which appear to have limited microbial activity and decomposition. However, the effect of warming on reduced mass loss varied among the substrates, with a stronger response in lower quality substrates. In the highest quality substrate, warming did not significantly affect decomposition. These results suggest that temperature increases with concomitant drying could significantly slow carbon and nutrient turnover from lower quality litter to soil. In the model experiment, we also found reduced litter carbon turnover rates in tropical forests that experienced drying including Puerto Rico, but with lower sensitivity. Although litter carbon turnover decreased across most dry tropical forests with reduced precipitation, it only decreased in wet tropical forests that experienced higher levels of drying than occurred in our field experiment. Similar to other field and remote sensing studies (Wieder, Cleveland, and Townsend 2009; Powers et al. 2009; Carvalhais et al. 2014), the Chapter 4 findings suggest carbon turnover with future climate change could depend more strongly on moisture regimes in wet tropical forests than currently captured in models.

Overall, the mitigation potential from land-based management measures and the natural role of land as a large carbon sink highlights the critical importance of terrestrial systems in achieving the Paris agreement goal of balancing sources and sinks, and achieving the 1.5ºC target. However, the 30% mitigation potential from terrestrial systems cannot compensate for emissions reductions in other sectors, and this potential is vulnerable to future impacts from unmitigated climate change. Although ESMs project land carbon uptake to increase through the end of the century with future climate change (Arora et al. 2020; Ciais et al. 2013), there is high uncertainty, and regional field and spatial studies show that warming from climate change is already turning or could turn existing global terrestrial carbon sinks into sources by mid- to late century, particularly in the tropics (Duffy et al. 2020; Hubau et al. 2020; Maia et al. 2020; Brienen et al. 2015; Zhou et al. 2014). The work in this dissertation contributes to improving land-based mitigation potential estimates, reconciling observations with model results to improve future predictions of climate change, and informing climate mitigation policies.

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Appendix 1. Follow up study to Chapter 2: "Land-based measures to mitigate climate change: potential and feasibility by country"

In review in *Global Change Biology*

Abstract

Land-based climate mitigation measures have gained significant attention and importance in public and private sector climate policies. This study estimates mitigation potentials for 20 land-based measures in 250 countries and five IPCC regions, comparing sectoral estimates to integrated assessment models (IAMs). We also assess implementation feasibility at the country-level. In our sectoral estimates, land-based measures provide global cost-effective potential (<\$100/tCO_2eq) of 11.9 ± 3.1 GtCO_2eq yr^{-1} between 2020-2050, in line with previous estimates of 11-15 GtCO_2eq yr^{-1}, and about 40% of available technical potential. Cost-effective potential in IAMs is 65% lower than the sectoral estimate, 4.1 median (-0.1 - 9.5 range) GtCO_2eq yr^{-1}, largely due to a more limited portfolio of land-based measures, higher baseline conditions, and the use of overshoot scenarios which delays mitigation to later in the century. The sectoral, cost-effective potential is approximately 50% from forests and other ecosystems, 30% from agriculture and 20% from demand-side measures. The potential varies five-fold across regions (0.7 - 3.9 GtCO_2eq yr^{-1}) and the top 15 countries account for 60% of the global potential. In general, land-based mitigation potential correlates with a country's land area, but many smaller countries have disproportionately high levels of mitigation potential density. The feasibility assessment also suggests that governance, economic development, and socio-cultural conditions create barriers for implementing land-based mitigation. A substantial portion of potential (80%) is in developing countries and LDCs, where feasibility issues are of greatest concern. Assisting countries to overcome these constraints may result in significant quantities of near-term, low-cost mitigation, while achieving important climate adaptation and development benefits locally.

Opportunities among countries are quite heterogeneous, in terms of mitigation potential, types of land-based measures available, their potential co-benefits and risks, and their feasibility. Strategies that determine what, where, when, and how mitigation measures are implemented will therefore vary significantly by country context.

Introduction

Land-based climate mitigation measures, also known as mitigation in Agriculture, Forestry and other Land Uses (AFOLU) or natural climate solutions (Griscom et al., 2017) - which are a subset of nature-based solutions, have gained significant attention and importance in public and private sector climate strategies and policies (Seddon et al. 2020). Land-based measures reduce emissions and/or enhance carbon removals. They include supply-side interventions in forests and other ecosystems (to protect, manage and restore), agriculture (to reduce emissions and enhance carbon sequestration), and bioenergy (to reduce emissions and sequester carbon), as well as demand-side interventions on food waste, diets, and resource use. As of March 2019, 186 countries had included AFOLU measures in their Nationally Determined Contributions (NDCs) under the Paris Agreement, either by specifically listing actions or by including the land sector in their broader greenhouse gas (GHG) reduction targets (Crumpler et al. 2019). Collectively, AFOLU-related NDC actions make up about 25% of planned GHG reductions in 2030 (Grassi et al. 2017), with most focused on reducing deforestation. Land-based mitigation measures are also embedded in other international agreements and initiatives, including the Sustainable Development Goals (SDGs), Land Degradation Neutrality (LDN), Aichi Biodiversity Targets, New York Declaration on Forests (NYDF), the Bonn Challenge, and the UN Decade on Ecosystem Restoration.

Recent studies estimate that land-based measures have the potential to mitigate approximately 11-15 $GtCO_2eq\ yr^{-1}$ by 2050, corresponding to about 25-30% of the mitigation needed to achieve the 1.5°C temperature target (Griscom et al., 2017; IPCC, 2019a, 2018; Roe et al., 2019). Not only can land-based measures help close the mitigation gap, if actions are well designed and implemented, mitigation can be delivered in a way that is also cost-effective, enhances resilience and adaptation to climate change, food security, biodiversity and other ecosystem services, and contributes to international sustainable development goals (Frischmann et al., 2020; Griscom et al., 2017; Roe et al., 2019; Smith et al., 2019a). Poorly planned and implemented AFOLU mitigation activities, however, entail potential risks and tradeoffs, particularly concerning food security, biodiversity and water quality and quantity (Humpenöder et al. 2018; Smith et al. 2020).

Meanwhile, global progress on achieving climate targets and addressing other land-related challenges is lacking. Greenhouse gas (GHG) emissions in AFOLU have been increasing since 2000 (Jia et al. 2019). Over the last 30 years, policies have only delivered a total mitigation of 7.8 Gt CO_2 from AFOLU, or ~0.5% of total emissions during that period (author's calculations based on (Roopsind, Sohngen, and Brandt 2019; UNFCCC 2020a). Current commitments under the Paris Agreement are more in line with 2.5°C to 3°C of warming by the end of the century than the 1.5°C and 2°C committed to in the Paris Agreement (Rogelj et al. 2019). Although some progress has been made, the Aichi biodiversity targets for 2020 and the NYDF, which aimed to halve deforestation and restore 150 million hectares (Mha) by 2020, have not been met, with reversals occurring in some instances since the targets were set (NYDF Assessment Partners 2020; Secretariat of the Convention on Biological Diversity 2020). Substantially more resources and effort will therefore be needed to scale up land-based mitigation to fulfill its potential, maximize benefits, and limit trade-offs.

The efficacy and extent of benefits or risks of land-based measures largely depends on the type of activity undertaken, deployment strategy (e.g. scale, method, complementarity with other measures and sectors), and geographic context (e.g. biome, climate, food system, land ownership) (Smith et al. 2019a). As such, successful and sustainable adoption and appropriate prioritization of land-based mitigation measures would benefit from more regional and country-level information on drivers of emissions, mitigation potentials, co-benefits and risks (Crumpler et al. 2019). Additionally, realizing AFOLU mitigation and co-benefit potential will require policies and measures for land and food system management that are location- and context-specific, and adaptable over time (Hurlbert et al. 2019). The success of different policies and implementation of land-based measures is dependent on enabling conditions and barriers that vary greatly by country. Available funding and economic incentives, governance and institutional capacity, technological capacity, geophysical capacity, socio-cultural context, and environmental-ecological conditions all play a role in making implementation more or less likely (de Coninck et al. 2018). Accordingly, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have requested that the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) provide more focused assessments of regional mitigation potential and their feasibility. Such information could allow national and international actors to better target investment and effort to areas of promise and need.

This study aims to address the outlined data needs by providing: 1) updated and/or new, country-level technical (available with existing technology) and cost-effective (available up to \$100/tCO_2eq) mitigation potentials, using a sectoral approach for 20 land-based measures in the 250 countries in the IPCC country list; 2) new, regional land-based mitigation potential estimates generated from the most recent database on integrated assessment models (IAM); 3) a national feasibility assessment and index as a proxy for gauging the barriers and enabling conditions of implementing land-based mitigation measures by country and 4) an analysis of countries by drivers of emissions, mitigation potentials and feasibility. We compare the available mitigation potentials in the sectoral and IAM approaches, and their feasibility, globally, and across the five high-level IPCC regions: Africa and Middle East, Asia and Developing Pacific, Developed Countries, Eastern Europe and West-Central Asia, and Latin America and Caribbean. Based on the mitigation potential and feasibility data, in combination with information on emissions drivers, we then provide a framing of countries to highlight different contexts, challenges, opportunities, and priorities for land-based mitigation.

Methods

Mitigation potential

Sectoral estimates

To assess national and regional mitigation potentials across a wide suite of land-based measures, we compiled and developed both technical (possible at any carbon price with available technology) and cost effective (possible up to \$100/tCO_2eq) mitigation potentials, implemented between 2020-2050, for 20 land-based measures using the IPCC AR6 Working Group III (WGIII) country and region list. Mitigation up to \$100/tCO_2eq is considered cost-effective as it is in the middle of the range for carbon prices in 2030 for a 1.5°C pathway, and at the low end of the range in 2050 (Rogelj et al. 2018). The 20 land-based measures represent the best available data of land-based mitigation with country-level resolution. The mitigation potential quantified in the 20 measures include reductions and removals of CO_2 and reductions of N_2O and CH_4. Indirect impacts such as the substitution effects of bioenergy, biochar and wood products on fossil fuel emissions are excluded due to a lack of country-level data. The mitigation potentials are derived from individual and/or sectoral approaches (sometimes referred to as bottom-up approaches) which use a range of methods, including sectoral economic modeling, optimization modeling, and spatial analysis (the definitions and methods for each of the 20 mitigation measures are outlined in **Table A1.1**).

Our work builds on and updates previous global studies (Smith et al. 2013; 2014; B. W. Griscom et al. 2017; Fuss et al. 2018; Roe et al. 2019; Jia et al. 2019; UNEP 2017) and regional studies (Griscom et al., 2020; Roe et al., 2019) on land-based mitigation potentials. The new data and advances in analysis presented in this study are the following: 1) We developed new country-level data on two demand-side measures (reduced food waste and shifts to healthy diets), as well as two soil carbon management measures (soil organic carbon enhancement in croplands and grasslands); 2) we created country-level cost-effective mitigation potentials from existing global data on: reduced deforestation, afforestation/reforestation (A/R), forest management, agroforestry, enteric fermentation, manure management, crop nutrient management, rice cultivation, biochar, and bioenergy with carbon capture and storage (BECCS); 3) we expanded the country-level data published by Griscom et al. (2020) to provide global coverage where relevant; 4) we developed data on land area associated with mitigation potentials; and 5) we calculated 'mitigation density' potentials (mitigation available per hectare of land per year between 2020-2050) for each mitigation measure by country. For measures with more than one dataset, we provided a range and calculated average mitigation potentials for the aggregate estimates.

As much as possible, elements of the analysis were designed to avoid potential double-counting of mitigation opportunities. When aggregating total sectoral potentials, we excluded measures that may overlap on the same land. To avoid double counting with reduced deforestation, we excluded reduced peatland conversion and increased clean cookstoves as both may also reduce emissions from avoided forest loss and degradation. We included demand-side measures, shifting to healthy diets and reduced food waste in the aggregate estimate, however, only account for the GHG reductions from diverted agricultural production, and exclude emissions reductions associated with land-use change. To avoid double counting with A/R and biochar, we also excluded BECCS. We did not exclude peatland restoration as the mitigation potential in our estimate comes from rewetting peatlands and avoiding further degradation rather than reforesting. We selected reduced deforestation and A/R over the excluded activities given their scale and geographic scope.

IAM estimates

In addition to the sectoral mitigation potentials in **Table A1.1**, we assess the cost-effective land-based mitigation potentials from integrated assessment models (IAMs) with available data, calculated as the emission reduction and/or carbon enhancement available at a carbon price of up to \$100/tCO_2eq in comparison to the baseline scenario. Similar to the sectoral estimates, the IAMs considered in this assessment only account for direct GHG emissions reductions or removals and do not include indirect substitution effects on fossil fuel emissions. We used available data from the most recent IAM database, IAMC (Huppmann et al. 2018) +ENGAGE, and assessed the global and regional median and range values across 176 scenarios and 6 models. There are currently only six land-based mitigation measures available to extract across all IAMs (enteric fermentation, manure management, rice cultivation, crop nutrient management, BECCS, and land-use change). The impacts of reduced deforestation, A/R and forest management on CO_2 emissions are difficult to disentangle in the IAM database used, and are therefore treated together as a net value of land-use change.

IAMs assess the mitigation potential of multiple and interlinked practices across sectors and regions and can therefore account for interactions and trade-offs (including land competition, use of other resources and international trade) between them. IAMs can also optimize across mitigation measures based on market effects and costs. A few sectoral models also consider some level of inter- and cross-sector interactions and land allocation, however, when aggregating across sectoral estimates with different methods, it is difficult to completely account for land competition and double counting. Since land-based mitigation is relatively new in IAMs (Popp et al. 2017), only a limited portfolio of land-based mitigation measures is included. IAM data also generally have coarser resolution compared to some sectoral estimates, and as such, sectoral estimates may provide more robust mitigation estimates for individual measures. It is therefore helpful to assess and compare both types of approaches and datasets.

Table A1.1. Definitions and methods for estimating the technical and cost-effective (possible up to $100/t$CO_2$eq) mitigation potentials for 20 land-based mitigation measures using a sectoral approach. The definition includes whether the estimate accounts for emission reductions, carbon sequestration or both.

	Mitigation measure	Definition	Method
Forests and other ecosystems - conserve	Reduce deforestation	Avoided emissions from deforestation (forests are defined as 30% or greater tree cover)	**Data from** (Busch et al. 2019), which used a spatially explicit pantropical marginal abatement cost curve model and estimated the mitigation potential of avoided emissions from deforestation between 2020 and 2050 in the tropics. Technical potential was calculated as avoiding all business-as-usual (BAU) deforestation and cost-effective potential was calculated as the difference between BAU and $100/t$CO_2$eq. Carbon price values are in constant USD 2014. Area estimates were extracted from the spatial maps.
		Avoided emissions from deforestation (forests as defined in (FAO 2020b)	**Adapting data from** (Austin et al. 2020), which used the Global Timber Model (GTM), a dynamic economic forest model to estimate global forest sector mitigation potential (mean of avoided annual emissions between 2015 and 2050). Technical potential was calculated as avoiding all BAU deforestation, and cost-effective potential was calculated at a carbon price below$100/t$CO_2$eq compared to baseline levels. Carbon price values are in constant USD 2017. Initial forest area estimates for tropical countries were obtained from FAO, 2020 and country level inventories in temperate countries from Tian et al. (2018)
	Reduce mangrove conversion	Avoided emissions from degradation and/or anthropogenic loss of carbon stocks in mangrove ecosystems	**Data from Griscom et al. (2020),** which calculates the extent of baseline degradation and/or conversion based on an estimate of current forest extent, and recently reported loss rate from 1996 to 2016. Mangrove carbon stocks are calculated by combining the mean of seven above and below-ground vegetation biomass estimates from the literature with the most recent and comprehensive global estimate of SOC density in the top meter. Cost-effective potential was estimated following Griscom et al. (2017). The area data was extracted from Global Mangrove Watch for 1996, 2007, 2010, and 2016 timesteps to calculate rates of mangrove loss (Bunting et al. 2018).
	Reduce peatland conversion	Avoided emissions from the conversion, degradation and burning of peatlands	**Data from Griscom et al. (2017),** which estimated country-level technical potentials using Wetlands International data on recent conversion rates and average carbon stocks. All biomass and soil carbon up to 1m depth were assumed to be released in the BAU scenario over 20 years. Cost-effectiveness thresholds were estimated following Griscom et al. (2017). The area data (2008) was extracted from Joosten (2010).
Forests and other ecosystems - manage	Sustainable forest management	Avoided emissions and enhanced sequestration from improved natural forest management, including reduced-impact logging, extended harvest rotations, increased post-harvest sequestration rates, and designation of set-aside areas for protection from logging activity	**Data from Griscom et al. (2020),** which estimated country-level biophysical (technical) potential based on avoidable selective logging emissions in natural forests reported by Ellis et al. (2019). Ellis et al. (2019) estimate country-level baseline pantropical selective logging emissions and calculate the portion of these emissions that could be avoided through implementing reduced-impact logging for climate practices (RIL-C). Cost-effective potential was estimated following Griscom et al. (2017). The data on forest area with a long-term management plan (ForestMgmt (ha), 2018) is derived from FAO, (2020b).
		Enhanced carbon sequestration from improved forest management activities	**Adapting data from** Austin **et al. (2020),** which used the Global Timber Model (GTM), a dynamic economic forest model to estimate global forest sector mitigation potential (mean of avoided emissions between 2015 and 2050). Technical potential was calculated at a constant carbon price of $2,000/t$CO_2$eq to stimulate the maximum available carbon in the model. Cost-effective potential was the carbon sequestration potential given for scenarios with a carbon price below of $100/t$CO_2$eq in 2050 compared to baseline levels. Carbon price values are in constant USD 2017. Initial forest area estimates for tropical countries were obtained from FAO (2020) and country level inventories in temperate countries from Tian et al. (2018)

	Grassland fire mgmt	Avoided emissions from grasslands fires	**Data from Griscom et al. (2020),** which takes country-level biophysical (technical) potential from Lipsett-Moore, Wolff, & Game (2018), and applies a uniform global cost constraint from Griscom et al. (2017). Estimates primarily reflect N2O and CH4 emissions, since most CO_2 emissions from grassland fires are re-sequestered by re-growth within a few years. Cost-effective potential was estimated following Griscom et al. (2017). Area estimates were determined as savanna habitat within the Global Fire Emissions Database pixels with >600mm annual precipitation and positive emissions abatement potential, as defined by Lipsett-Moore et al. (2018).
Forests and other ecosystems - restore	Afforestation and Reforestation	Carbon sequestration by shifting from non-forest cover to forest cover at 30 percent tree cover threshold with a region-specific mix of plantation forestry and natural forest regrowth	**Data from Busch et al. (2019),** which used a spatially explicit pantropical marginal abatement cost curve model and estimated the mitigation potential of mean annual additional sequestration over the time period 2020-2050. Technical potential was calculated as the enhanced removals at <\$500/tCO_2eq relative to BAU, and cost-effective potential was calculated as at \$100/tCO_2eq relative to BAU. Carbon price values are in constant USD 2014. Area estimates were extracted from the spatial maps.
		Carbon sequestration from afforestation and reforestation (forests as defined in (FAO 2020b)	**Adapting data from Austin et al. (2020),** which used the Global Timber Model (GTM), a dynamic economic forest model to estimate global forest sector mitigation potential (mean of avoided emissions between 2015 and 2050). Technical potential was calculated at a constant carbon price of \$2,000/tCO_2eq to stimulate the maximum available carbon in the model. Cost-effective potential was the carbon sequestration potential given for scenarios with a carbon price below of \$100/tCO_2eq in 2050 compared to baseline levels. Carbon price values are in constant USD 2017. Initial forest area estimates for tropical countries were obtained from FAO (2020) and country level inventories in temperate countries from Tian et al. (2018)
	Mangrove restoration	Carbon sequestration from restoring mangroves lost since 1996, after excluding those converted to urban land or lost to erosion.	**Data from Griscom et al. (2020),** where the potential restorable mangrove area was calculated as the area of mangrove cover lost since 1996, after subtracting the area converted to urban land, or eroded, as these two categories of loss were assumed to not be feasible for restoration.. Carbon sequestration potential from restoration was calculated by multiplying the country-level area of restorable mangroves by a global carbon sequestration value of 6.4 and converting to CO_2 equivalent using a conversion factor of 3.67. Cost-effective potential was estimated using the method in Griscom et al. (2017).
	Peatland restoration	Avoided loss of soil carbon due to soil re-wetting in freshwater wetlands (tropical, temperate, and boreal peatlands).	**Data from Griscom et al. (2020),** which derived the extent of degraded peatlands per country from (Joosten 2010) and assumed that on average degraded peatlands have lost 50% of their original stocks. The calculation omits a sequestration benefit from peatland restoration and assumes that they are offset by methane emissions. Cost-effective potential was estimated using method in Griscom et al. (2017).
Agriculture - reduce emissions	Enteric fermentation	Avoided CH4 emissions from ruminant livestock enteric fermentation through improved feed conversion, antibiotics, bovine somatotropin (bST), propionate precursors, antimethanogens, and intensive grazing	**Adapting data from Beach et al. (2015b) as extended through 2050 in USEPA (2019),** values of technical potential represent net changes in CH4 emissions from global adoption of six mitigation options (listed in definition). Global livestock populations were allocated across livestock production systems in each country based on data from the Food and Agriculture Organization (FAO) and mitigation options were applied where it was technically feasible (applied only to the portion of each livestock type assessed - beef cattle, dairy cattle, goats, and sheep - that are intensively managed). Cost-effective mitigation potential was calculated based on the quantity of mitigation available from options with break-even prices at or below \$100/tCO_2eq (using USD 2017 constant carbon price values). GWP100 values from AR4 (CH4=25) were used to convert CH4 into CO_2eq.
	Manure management	Avoided CH4 and N2O emissions from livestock manure management in anaerobic systems through incorporation of small-scale or large-scale anaerobic digesters.	**Adapting data from Beach et al. (2015b) as extended through 2050 in USEPA (2019),** values of technical potential represent net changes in CH4 and N2O emissions associated with global adoption of different types of anaerobic digesters to manage manure from hogs and dairy cattle. Large-scale anaerobic digester systems were assumed to be technically feasible only in intensively managed dairy cattle and hog production systems. Small-scale digesters suitable for managing waste from only a few head of livestock were assumed to be available only in extensively managed dairy cattle and hog production systems in lower-income countries. Cost-effective mitigation potential was calculated based on the quantity of mitigation available from options with break-even prices at or below \$100/tCO_2eq (using USD 2017 constant carbon price values). GWP100 values from AR4 (CH4=25, N2O=298) were used to convert non-CO_2 gases into CO_2eq.
	Nutrient management	Avoided N2O and CH4 and changes in carbon sequestration in cropland soils associated with nitrogen application through changes in fertilizer application and management practices: split fertilization, 100 percent crop residue incorporation, nitrification inhibitors, and reducing nitrogen fertilizer applications by 20 percent.	**Adapting data from Beach et al. (2015b) as extended through 2050 in USEPA (2019),** values of technical potential represent net changes in GHG emissions associated with global adoption of mitigation options (listed in definition) to reduce emissions from nutrient management on croplands. The DAYCENT crop process model was used to calculate biophysical values including changes in crop yields, N2O and CH4 emissions, and soil organic carbon (SOC) sequestration for barley, maize, sorghum, soybeans, and wheat on a 25-km global grid basis. Cost-effective mitigation potential was calculated based on the quantity of mitigation available from options with break-even prices at or below \$100/tCO_2eq (using USD 2017 constant carbon price values). GWP100 values from AR4 (CH4=25, N2O=298) were used to convert non-CO_2 gases into CO_2eq. It was assumed that cropland areas can adopt only one mitigation measure, though in practice it may be feasible to adopt multiple options simultaneously. The set of technically feasible options that resulted in a net reduction in GHG emissions for a given crop/country combination were each applied to an equal share of land area for that crop/country. Thus, these estimates of mitigation potential may be conservative.
		Avoided N2O emissions (direct and indirect) and production-linked CO_2 emissions from reducing total fertilizer application through the use of best practices and/or improved technologies	**Data from Griscom et al. (2020),** which estimated country-level mitigation potential for improved cropland nutrient management practices based on optimizing the efficiency of nitrogen inputs relative to nitrogen harvested in products. Savings in nitrogen fertilizer consumption per country were estimated from projections of BAU and optimized consumption in 2030, assuming fertilizer efficiency can be raised to regional targets identified in Zhang et al. (2015). Estimates include direct and indirect reductions in N2O emissions as well as upstream CO_2 emissions from fertilizer manufacture. GWP100 values from AR4 (CH4=25, N2O=298) were used to convert non-CO_2 gases into CO_2-eq. Cost-effective potential was estimated as in Griscom et al. (2017). The applicable area in each country is assumed to be the total cropland area in 2018 as reported by FAO, (2020a).

	Rice cultivation	Avoided CH4 and N2O emissions and enhanced soil organic carbon sequestration from rice cultivation through: nutrient management (reduced or optimized nitrogen fertilizer application, use of slow release fertilizer, application of nitrification inhibitors, switching from urea to ammonium sulfate), residue management (100 percent crop residue incorporation), water management (midseason drainage, alternate wetting and drying, switching from irrigated to dryland rice), dry seeding, and tillage strategies, and combinations of these activities	**Adapting data from Beach et al. (2015b) as extended through 2050 in USEPA (2019),** values of technical potential represent net changes in GHG emissions associated with global adoption of mitigation options to reduce emissions from rice cultivation (listed in definition). The DeNitrification-DeComposition (DNDC) crop process model was utilized to estimate changes in rice yields, N2O and CH4 emissions, and soil organic carbon sequestration. The DNDC model includes data on global rice production that enabled characterization of the baseline distribution of water management and seeding practices. Thus, mitigation was estimated relative to baseline practices in each rice-producing country. Cost-effective mitigation potential was calculated based on the quantity of mitigation available from options with break-even prices at or below \$100/tCO_2eq (using USD 2017 constant carbon price values). GWP100 values from AR4 (CH4=25, N2O=298) were used to convert non-CO_2 gases into CO_2eq.
		Avoided CH4 and N2O emissions associated with anaerobic decomposition by employing the periodic draining of rice soils and the removal of rice residues in flooded and upland rice production lands	**Data from Griscom et al. (2017),** which assumed an average 35% reduction in combined CO_2-equivalent emissions from using improved rice management practices. GWP100 values from AR4 (CH4=25, N2O=298) were used to convert non-CO_2 gases into CO_2-eq. Country level estimates were then derived by applying the reduction to rice-derived CO_2-equivalent emissions per country in 2030 as projected by USEPA (2013). Cost-effective mitigation targets are based on averages of Golub, Hertel, Lee, Rose, & Sohngen (2009), Beach et al. (2015a), and USEPA (2013), and are aligned with the values reported by the IPCC.
Agriculture - sequester carbon	Agroforestry	Carbon sequestration from adding aboveground woody carbon storage in agriculture systems (crop and pasture pixels with <25% tree cover)	**Adapting data from from Chapman et al. (2020)**, which estimated the potential above ground carbon contributions of trees integrated into agricultural lands (defined as crop and pasture pixels with <25% tree cover to avoid potential overlap with A/R) by calculating the median above ground carbon density in crop and pasture land pixels with >5 MgC ha^{-1}in each country-biome combination and applying that value across a range of area percentages of the agricultural area in that country-biome region with little to no standing trees (<5 MgC ha^{-1}). Soil organic carbon changes were not considered. We estimated the technical sequestration potential using a 50% adoption scenario (based on Chapman et al. (2020)) and developed (**new estimates**) of cost-effective sequestration potential using a 10% adoption scenario which is a proxy for mitigation at \$100/tCO_2eq (based on Griscom et al. (2017)). Sequestration rates were calculated assuming a 30-year horizon to meet the area-based 50% and 10% potential scenario of CO_2 sequestration. Area values were extracted from the spatial map outputs.
	Biochar from crop residues	Enhanced carbon sequestration by amending agricultural soils with biochar, which increases the agricultural soil carbon pool by converting rapid-mineralizing carbon (crop residue biomass) to persistent carbon (charcoal) through pyrolysis.	**Data from Griscom et al. (2017),** which estimated country-level mitigation potentials including biochar production from crop residues, whereas the full potential of biochar could also include other biomass sources such as biomass crops and forestry residues. It was assumed that 79.6% of biochar carbon persists on a timescale of >100 years. The estimate does not consider indirect effects on methane or nitrous oxide emission, soil organic matter, plant growth increases, or use of pyrolysis energy to offset fossil fuel use that is typically generated during biochar production (Woolf et al. 2014), collectively accounting for about half of life-cycle emission reductions (Woolf et al. 2010). The global total was allocated across countries in proportion to estimated residue availability from the ten most important global crops, based on FAO crop production data for 2018 (FAO 2020a) and recoverable residue fractions from Searle & Malins (2015). The cost-effective mitigation potential (\$100/tCO_2) was derived using the method in Griscom et al. (2017).
	Soil organic carbon in croplands	Enhanced soil organic carbon sequestration by shifting from current management to no-till management with an input scenario consistent with cover cropping.	**Adapting data from Soils Revealed (2020)**, which calculates the annual rate of change in soil organic carbon (SOC) stocks based on IPCC (2019b) Tier 1 stock difference approach, we develop **(new estimates)** for technical potential and cost effective potential (\$100/tCO_2eq) for croplands and grasslands. Maps of climate zones and SOC reference stocks were developed following IPCC guidance. For the technical potential, SOC is defined relative to the reference SOC stock (SOCref) for a given location by a combination of linear SOC-modifying factors for land use (FLU), management (FMG) and input levels (FI): SOCt = SOCref × FLU,t × FMG,t × FI,t. Thus, ΔSOC will be non-zero only if at least one of land-use, management or inputs differs between the start and end of the 20-year accounting period, at which time most of the SOC accrual has occurred. Current land use (FLU) was defined by reclassifying the ESA's Climate Change Initiative Land Classification (CCI LC) map for the year 2018 using an overlay of rice production and ley forage production from Monfreda, Ramankutty, & Foley (2008), forest, wetland, urban/built up, grassland, cropland (non-paddy rice), paddy rice and managed pasture. Wetland and urban areas are not considered in this analysis. Current cropland FMG was assumed to represent conventional tillage everywhere. Current grassland FMG was defined based on soil degradation level from The Global Assessment of Soil Degradation (GLASOD) map (Oldeman, Hakkeling, and Sombroek 1991). For croplands, FI was defined as low where >50% of crop residues are used as animal forage based on Wirsenius (2003) or where >50% of area harvested is allocated to vegetable or fiber crops according to Monfreda et al. (2008). Remaining cropland FI was set to medium. These conditions then defined the 2018 SOC stock levels at each pixel. Future SOC stocks for the year 2038 were then calculated at each pixel using the SOC-modifying factors associated with the assumptions listed in each scenario. Then, for each pixel, ΔSOC was calculated as the difference between 2038 and 2018 stocks divided by 20 years. This unconstrained technical potential was then reduced using a climatic constraint on cropping interventions - for tillage, tropical montane, tropical wet and polar climates were masked out; for cover crops, tropical dry, warm/cool temperate dry, boreal and polar climates were masked out. Area available was further constrained by current regional adoption rates of no till based conservation agriculture adoption (Prestele et al., 2018) and winter crops (Siebert, Portmann, and Döll 2010). In this constrained cropping area, we assumed 90% adoption for the cost-effective potential at \$100/tCO_2eq (based on Griscom et al. (2017)). For grasslands, the technical potential was constrained to degraded grasslands - non-degraded grasslands (defined by GLASOD) were masked out due to lack of opportunity - and we assumed 60% adoption based on cost-effective potential at \$100/tCO_2eq (Griscom et al., 2017).
	Soil organic carbon in grasslands	Enhanced soil organic carbon sequestration in managed pastures, by shifting from current practices to improved sustainable management with light to moderate grazing pressure and at least one improvement. For rangelands, a shift from current management defined by land degradation to nominally managed.	

Bioenergy	BECCS	Carbon sequestration from electricity generation derived by combusting lignocellulosic crop-based biomass (Miscanthus, switchgrass, short-rotation coppiced trees like poplar and Eucalyptus) and combined with carbon capture and storage.	**Adapting data from Hanssen et al. (2020)**, values of technical potential represent the amount of net negative CO_2 emissions that can biophysically be achieved over a 30 year evaluation period, while considering all relevant flows of GHGs, including land-use change emissions, the lost carbon sequestration capacity of natural vegetation ('foregone sequestration'), bioenergy supply chain emissions including fertilizers, CO_2 capture efficiency, and CO_2 that is sequestered through carbon capture and storage (CCS). Alternative uses of biomass crops such as for pyrolysis or direct biomass burial were not considered. Further, we exclude the mitigation potential from the substitution of fossil fuels that occurs from producing the bioenergy. We develop **(new estimates)** of cost-effective mitigation potential at \$100/tCO_2eq by adding costs for biomass production, and conversion to electricity combined with CCS. These costs are based on the IMAGE integrated assessment model on an SSP2 baseline, with biomass costs calculated on a 0.5°×0.5° grid, and conversion and capture costs for 26 global regions. Carbon stock changes and biomass yields are based on the LPJml global vegetation model and are supplemented with literature-derived yield calibration factors and supply chain emissions. Land availability assumed in determining biophysical potential is constrained by excluding projected urban and agricultural land (cropland and pastures according to an SSP2 land use projection of the IMAGE model as presented in Doelman et al. (2018)), as well as areas with low bioenergy crop yields (<5% of global maximum) or no potential to deliver net negative emissions through BECCS.
Demand-side	Increase clean cookstoves	Avoided emissions due to the introduction of improved cookstoves which leads to reduced harvest of woodfuel used for cooking and heating	**Data from Griscom et al. (2020)** which developed country-level technical potentials based on Bailis, Drigo, Ghilardi, & Masera (2015), applying a 49% potential reduction to the national emissions from unsustainable woodfuel estimated by the latter, and excluding potential woodfuel that could have arisen as a by-product of other land use change. Cost-effective mitigation (\$100/tCO_2eq) was estimated following Griscom et al. (2017).
	Reduce food waste	Emissions reductions from diverted agricultural production (excluding land-use change) from reduced food loss and wastage from all stages of production, distribution, retail, and consumption through the implementation of measures such as improved storage and transport systems, generation of public awareness and changing consumer behaviors.	**Adapting data from Project Drawdown (2020), we provide (new country-level estimates for)** technical potential and cost-effective potential for reduced food waste at a country level. Total food loss and wastage is calculated according to regional estimates of waste generated at each supply chain stage projected to 2050 (FAO, 2011), applied to aggregated country-level food demand by commodity type. The technical potential was estimated as emissions reductions from the incremental reduction of food waste until 75% reduction is achieved in 2050, applied across all stages of the supply chain. The cost-effective potential assumes a 50% reduction in food waste by 2050. The resulting reductions represent the total global reduction from avoided agricultural production and does not include emissions reductions from avoided land conversion and ecosystem protection to avoid double counting. GWP100 values from AR4 (CH4=25, N2O=298) were used to convert into CO_2eq.
	Shift to sustainable healthy diets	Emissions reductions from diverted agricultural production (excluding land-use change) from the adoption of sustainable healthy diets: (a) maintain a 2250 calorie per day nutritional regime; (b) meet daily protein requirements while decreasing meat consumption in favor of plant-based food items; and (c) purchase locally produced food when available.	**Adapting data from Project Drawdown (2020), we provide (new country-level estimates for)** technical potential and cost effective potential for shifting to healthy diets at a country level. Technical potential is estimated as the difference between the emissions from projected baseline country-level dietary trends (FAO, 2013; Alexandratos & Bruinsma, 2012) and emissions with a 75% global adoption of a sustainable and healthy diet (components listed in definition), averaged over the years 2020-2050. The cost-effective potential assumes a 50% adoption of a healthy diet. Adoption scenarios in this model grow linearly over time starting from the base year of 2014 and are considered "complete" in 2050. The resulting reductions represent the total global reduction from avoided agricultural production and does not include emissions reductions from avoided land conversion and ecosystem protection to avoid double counting. GWP100 values from AR4 (CH4=25, N2O=298) were used to convert into CO_2eq.

Feasibility assessment

The global shift needed to limit warming to 1.5°C or 2°C will require a range of enabling conditions to catalyze action and adequately address the synergies and trade-offs between mitigation and sustainable development (IPCC 2018). The enabling conditions, or feasibility of effectively implementing mitigation measures, are highly contextual and vary according to each country's circumstances. We developed a quantitative index as a proxy for country-level feasibility to implement actions and realize mitigation potentials. Our framework is based on the IPCC's definition of feasibility, defined as the capacity of a system to attain a specific outcome (de Coninck et al. 2018), and includes six dimensions of feasibility: economic, institutional, geophysical, technological, socio-cultural, and environmental-ecological feasibility. Given the broad scope of "feasibility," we considered a range of enabling conditions across the six dimensions, including both state capacity and private sector/ land-owner enabling conditions across all land-use management types. Our feasibility index represents a first attempt to quantify country-level feasibility using the IPCC's qualitative feasibility assessment framework. The resulting feasibility index is intended to illustrate where mitigation potential and feasibility are correlated, and identify gaps that can be addressed to increase likelihood of implementation. Where more detailed regional data exist, the approach can be refined. The feasibility assessment consisted of a two-part literature review followed by expert review of the datasets found, harmonization and scaling, and finally, calculation of a feasibility score for each country.

Literature review

A preliminary literature review identified the most important enabling conditions and barriers for land-based mitigation actions. A list of feasibility factors was drawn from this literature review, which included a broad range of empirical and theoretical studies across activities in the AFOLU sector (more detail provided in the Supplementary Information). Factors were categorized under one of the six abovementioned IPCC dimensions of feasibility. A second literature review identified quantitative datasets describing the enabling conditions and barriers previously documented as relevant.

Expert review and indicator selection

We evaluated the quality of the datasets to determine the country coverage and to highlight potential correlations among potential feasibility factors. For the final selection of indicators (**Table A1.2**), feasibility factor candidates were required to meet a minimum of two specific criteria. First, indicator data should be available from the last five years for a sufficient number of countries (>100) in order to make a meaningful assessment. Second, a clear logic should exist in the direction of the relationship between the variable in question and the feasibility of implementation of a mitigation measure. For instance, increased tenure insecurity is clearly associated with greater difficulty in implementing land use activities in the AFOLU sector (Djenontin, Foli, and Zulu 2018; Robinson, Holland, and Naughton-Treves 2014). To incorporate more detailed enabling factors, we included some indicators that apply to the feasibility of implementing mitigation activities in either agriculture or forests and other ecosystems (agricultural value added, agriculture total factor productivity and forest rents), recognizing that they may not necessarily apply to the other. Variables that exerted either an unclear or mixed effect (e.g., subsidies in the agriculture sector) were excluded. These two criteria resulted in the selection of 19 feasibility indicators (**Table A1.2**).

Harmonization and scaling

Processing of the selected feasibility indicators and associated data was done following a two-step approach. First, all raw data was scaled from 0 to 100 using the formula: $(x_i - min(x))/(max(x)-min(x))*100$ where *i* indicates the value of indicator x for a given country. When the raw data was already scaled 0-1, it was then multiplied by 100. The data was also harmonized for direction by applying *1-x*, to ensure that higher feasibility was represented by a higher indicator value as well as to ensure consistency between indicators.

Feasibility score

The final step involved the calculation of feasibility scores by averaging all indicators per category, then averaging each of the six categories. We calculated scores including and excluding autocorrelated indicators (*Score 1 and 2*), then we calculated scores with complete and incomplete country observations (*Score 1a and 1b*). *Score 1 and 2* resulted in very similar feasibility rankings, therefore we chose to include all indicators. Using all indicators (*Score 1*), we then calculated *Score 1a* by including only countries with complete observations (N=113); and *Score 1b* by including countries with five NAs out of six (N=169). Score 1a and 1b resulted in very similar feasibility scores, although the latter allowed for a larger coverage of countries. As such, Score 1a was chosen as the final country-specific feasibility score.

Table A1.2. Indicators (19) used in the feasibility assessment, based on the six IPCC feasibility dimensions (de Coninck et al. 2018)

IPCC Feasibility dimensions	Indicators and justification	Sources	Year	Number of countries	References
Economic	**Gross domestic product (GDP) per capita, converted by purchasing power parity (PPP) conversion factor (constant 2017 international $).** The implementation costs of mitigation measures will be easier to bear for countries with stronger economic capacity.	World Bank ICP, 2020	2018	188	Jewell & Cherp, 2019
	Forest rents ($/ha of forest area) calculated as forest rents multiplied by GDP, PPP (constant 2017 international $)) divided by forest area (hectares). Countries with a strong forest sector will face fewer barriers implementing AFOLU implementations and will have a stronger strategic interest to invest in the forest sector.	World Bank, 2011, 2020; FAO	2016	182	Bustamante et al., 2019
	Agricultural value-added (constant 2010 USD/ha of agricultural land). A higher value-added indicates a larger more profitable agricultural sector, with widespread use of technology and intensive use of non-land inputs; thus, suggestive of intensification rather than extensification as key approach to increasing output. .	World Bank; OECD; FAO	2017/2016	209	Beach et al., 2015b
	Ease of doing business (ranked out of 190). Measures business regulation, regulatory outcomes, the extent of the legal protection of property, the flexibility of employment regulation, and the tax burden on businesses. Countries that establish a regulatory environment that is conducive to business operations are more likely to mobilize resources from the private sector.	World Bank Doing Business, 2019	2019	178	Ahenkan, 2019; Patel, 2011; Stewart, Kingsbury, & Rudyk, 2009
	Ease of obtaining a bank loan (indexed 1-7) with only a good business plan and no collateral. Local actors' access to credit is key to enable the implementation of new practices across sectors.	World Economic Forum, 2017	2017	136	Bustamante et al., 2014; Madlener, Robledo, Muys, & Freja, 2006
Institutional	Good governance, political stability, and institutional capacity are critical for land-use actors to implement new practices (z-scores). **Voice and accountability**	Kaufmann & Kraay, 2019	2019	198	Bustamante et al., 2019; da Conceição, Börner, & Wunder, 2015; Demenois et al., 2020; Djenontin et al., 2018; Doshi & Garschagen, 2020; Regina et al., 2016; Wollenberg et al., 2016
	Political stability and absence of violence			204	
	Government effectiveness			202	
	Regulatory quality			202	
	Rule of law			202	
	Control of corruption			203	
	Tenure insecurity. Proportion of people who believe it is somewhat or very likely that they could lose the right to use their property or part of it against their will in the next five years. Insecure land tenure is a key barrier to investment and the implementation of new practices across sectors.	Global Property Rights Index (Prindex), 2020	2020	135	Descheemaeker et al., 2016; Djenontin et al., 2018; Minang, Duguma, Bernard, Mertz, & van Noordwijk, 2014; Robinson et al., 2014; Saito-Jensen et al., 2015
Geophysical	**Total land-based technical (biophysical) mitigation potential, by total land area, measured in tCO2/ha**	Our data	2020	212	
Technological	**Access to information and communications** includes access to online governance, media censorship, internet users, mobile telephone subscriptions. Scored from 0 to 100, limited access to information and communications hinders the ability of local actors to implement updated technological knowledge across sectors.	Social Progress Imperative, 2020	2020	174	Descheemaeker et al., 2016; Grunfeld & Houghton, 2013
	Market access and infrastructure measures the quality of the infrastructure that enables trade, and distortions in the market for goods and services. Scored from 0 to 100, lower market access and infrastructure reduces the likelihood of local actors to implement new changes in practice.	(Legatum Institute 2019)	2019	166	(Descheemaeker et al. 2016; Minang et al. 2014)
	Agricultural TFP (Total Factor Productivity). The output is gross agricultural output (GAO) while input growth is the weighted-average growth in quality-adjusted land, labor, machinery power, livestock capital, synthetic NPK fertilizers, and animal feed, where weights are input (factor) cost shares. Countries with a higher TFP on the 66.2 to 222.8 index, indicating more efficient use of land and non-land inputs, are more likely to prevent further land expansion and effectively implement new practices across sectors.	(USDA 2019)	Avg. 2014-2016	179	(Villoria 2019)

Socio-cultural	Countries with higher social progress levels are more likely to absorb the costs and/or trade-offs of implementation	**Personal rights (scored 0-100)**, include political rights, freedom of expression, freedom of religion, access to justice, and property rights for women.	(Social Progress Imperative 2020)	2020	170	(Jewell and Cherp 2019; Riahi et al. 2017)
		Nutrition and basic medical care (scored 0-100), includes undernourishment, deaths from infectious diseases, child stunting, maternal mortality, child mortality.			177	
Environmental	**EPI (Environmental Performance Index)** assesses environmental health and ecosystem vitality, as well as performance towards environmental targets, using eleven criteria (air quality, sanitation & drinking water, heavy metals, waste management, biodiversity & habitat, ecosystem services, fisheries, climate change, pollution emissions, water resources, and agriculture). Countries with higher scores from 0 to 100 will have higher feasibility of implementing land-based mitigation measures.		(Wendling et al. 2020)	2020	175	(Djenontin, Foli, and Zulu 2018; Dumbrell, Kragt, and Gibson 2016; Mbow et al. 2014a; 2014b; 2014c; Tvinnereim et al. 2017)

Emissions and drivers

To contextualize regional and country-level circumstances for adopting and implementing land-based measures in our results, we assessed total country-level GHG emissions, land-based emissions in agriculture and land-use change, as well as the various drivers of agricultural emissions and forest cover loss. For total emissions, we summed the most recent available data on fossil CO_2 emissions (averaged 2015-2019) (IPCC 2019a), agriculture GHG emissions (averaged 2013-2017) (FAO 2020a), as well as land-use, land-use change, and forestry (LULUCF) emissions (2013-2017) (Grassi 2020). We analyzed the drivers of agricultural emissions using data from FAOSTAT, 2020 (averaged 2013-2017), and tree cover loss using data from Global Forest Watch (averaged 2013-2017).

Results

Global

<u>Mitigation potential across land-based measures</u>

Between 2020-2050, the total technical mitigation potential of land-based measures using a sectoral approach (**Table A1.1**, 20 measures minus BECCS, reduced peatland conversion and increased clean cookstoves, to avoid double counting with reduced deforestation and A/R) is 30.5 ± 7.2 $GtCO_2eq\ yr^{-1}$, while cost-effective potential (up to \$100 per tCO_2eq) is 11.9 ± 3.1

$GtCO_2eq\ yr^{-1}$, about 40% of the technical potential (**Figure A1.1**). The cost-effective mitigation potential, which represents a more realistic level of deployment, is about the same as the average annual AFOLU emissions in 2007-2016 of 12 ± 2.9 $GtCO_2eq\ yr^{-1}$ (IPCC 2019a), and is about 25% of global emissions. The IAM cost-effective potential (up to $100 per tCO_2eq) for AFOLU (agriculture + land-use change) averaged between 2020-2050 is 4.1 median (-0.1 - 9.5 range) $GtCO_2eq\ yr^{-1}$ and 6.8 (-0.2 - 10.5) $GtCO_2eq\ yr^{-1}$ in 2050. The IAM potential up to $100 per tCO_2eq is about half of the potential of the sectoral potentials up to $100 per tCO_2eq. The difference is largely due to three main reasons: 1) the IAMs in the most recent IAM database (IAMC+ENGAGE) incorporate a limited selection of land-based mitigation measures compared to our list in the sectoral approach (**Figure A1.1**); 2) there are already carbon prices and substantial land-based mitigation in some baseline scenarios in IAMs, particularly from reduced deforestation, which dampens the mitigation potential available in the $100 per tCO_2eq carbon price scenario 3) the IAM estimates also include overshoot scenarios which places most of the mitigation after 2050, especially terrestrial carbon dioxide removal (CDR) options. Total CDR potential in IAMs, combining A/R and BECCS is 0.8 (0 – 5.9) $GtCO_2eq\ yr^{-1}$ at $100/tCO2eq in 2020-2050 and 1.3 (0 – 6.9) $GtCO_2eq\ yr^{-1}$ in 2050. In the sectoral estimates, CDR potential, which makes up "restore" measures in forests and other ecosystems, "sequester carbon" measures in agriculture, and BECCS (although there is a risk of double counting with A/R and BECCS) is 20.9 ± 3.0 $GtCO_2eq\ yr^{-1}$ for technical and 5.4 ± 0.3 $GtCO_2eq\ yr^{-1}$ for cost-effective.

In the sectoral estimates, forests and other ecosystems (excluding reduced peatland conversion to avoid double counting with reduced deforestation) provide the largest share, 17.4 ± 6.9 $GtCO_2eq\ yr^{-1}$ technical potential and 6.1 ± 2.9 $GtCO_2eq\ yr^{-1}$ cost-effective potential, or 57% and 52% of the total land-based potential respectively (**Figure A1.1**). In IAMs, cost-effective potential in land-use change averaged between 2020-2050 is 2.4 median (-0.6 - 8.6 range)

$GtCO_2eq\ yr^{-1}$, less than half of the cost-effective sectoral estimate. Within forests and other ecosystems in the sectoral estimates, measures that protect (reduce deforestation and conversion of coastal wetlands (mangroves)) make up 20% and 30% of the total technical and cost-effective potential respectively, measures that manage (sustainable forest management and grassland fire management) make up 6% and 8% respectively, while measures that restore (A/R, peatland restoration and coastal wetland restoration (mangroves)) make up 30% and 14% (**Figure A1.2a**). "Protect" measures make up an increased share of the cost-effective land-based mitigation compared to the technical, while "restore" measures decrease by about half due to its higher cost of implementation. Across all land-based measures, "protect" measures also have the highest mitigation density per year between 2020 and 2050, at an average of about 280 $tCO_2eq\ ha^{-1}$, followed by "restore" measures at 160 $tCO_2eq\ ha^{-1}$, and manage measures at 70 $tCO_2eq\ ha^{-1}$. Mitigation measures in forests and other ecosystems have significant potential for delivering co-benefits, particularly from reducing deforestation and conversion of primary ecosystems as these ecosystems can continue to sequester carbon and provide vital ecosystem services (Figure 1, Supplementary Information). However, the potential co-benefits, and possible trade-offs depend on how and where the measure is implemented. The co-benefits from reforestation, for example, will depend on the type of species used, method of deployment (natural regeneration vs mixed species planting vs monoculture), and location (which type of biome, climate, water availability). Trade-offs include competition with producing food crops, potentially resulting in indirect land use change.

Agriculture provides the second largest share of mitigation, with 10 ± 0.3 $GtCO_2eq\ yr^{-1}$ technical potential and 3.9 ± 0.2 $GtCO_2eq\ yr^{-1}$ cost-effective potential, or 33% and 32% of the total land-based potential respectively (**Figure A1.2a**). In IAMs, cost-effective potential in agriculture (non-CO_2) averaged between 2020-2050 is 1.6 median (0.3 - 3.3 range) $GtCO_2eq\ yr^{-1}$.

In 2050, the potential increases to 2.3 (-0.07 - 4.9) $GtCO_2eq\ yr^{-1}$, more in line with the sectoral estimates. Within agriculture, "emissions reductions" measures account for 3% and 5% of the total technical and cost-effective potential respectively, and "carbon sequestration" measures make up 30% and 28%. Agroforestry stands out as the agriculture measure with the highest mitigation density, at an average of about 70 $tCO_2eq\ ha^{-1}$ annually between 2020-2050. The remaining measures have more modest mitigation densities ranging from 0.3 to 2 $tCO_2eq\ ha^{-1}$ as many agriculture measures can be applied across more land (i.e., nutrient management and soil carbon management across a majority of croplands and pasturelands). Agriculture measures that enhance soil quality, water efficiency and yields and reduce pollution - such as soil organic carbon sequestration, agroforestry, biochar and nutrient management - can provide a relatively wide array of potential co-benefits (**Figure A1.1**). Unlike measures in forests and other ecosystems (aside from forest management), multiple agriculture measures can often be applied on the same parcel of land.

Demand-side measures provide 3.1 $GtCO_2eq\ yr^{-1}$ technical and 1.9 $GtCO_2eq\ yr^{-1}$ cost-effective potential, or 10% and 16% of the total land-based potential respectively (**Figure A1.2a**). This total excludes land-use change benefits from reduced food waste and shifts to healthy diets, and also excludes clean cookstoves to avoid double counting with reduced deforestation. Shifting to sustainable healthy diets makes up 7% and 12% of the total land-based technical and cost-effective potential respectively, with reducing food waste accounting for 3% and 4%. Demand-side measures are included in IAMs as scenario elements and/or as an endogenous response to food prices typically increased in response to carbon prices. Generally, the more sustainable the socioeconomic scenario used, the more diet shifts and food system efficiencies are deployed. Decreasing consumption of high greenhouse gas-intensive foods like animal-based proteins, particularly beef, and reducing food loss and waste, reduces land used for feed, water use and soil degradation, thereby increasing resources for improved food security, reducing land competition and enabling supply-side measures such as reduced deforestation and reforestation (**Figure A1.1**).

Bioenergy potential from BECCS is the most modest, with technical and cost-effective potential in our sectoral estimate of 2.5 $GtCO_2eq\ yr^{-1}$ and 0.5 $GtCO_2eq\ yr^{-1}$, respectively (a percentage of AFOLU mitigation is not provided as BECCS is not added to the total potentials to avoid overlaps and double counting with A/R). BECCS provides CDR as well as energy and/or materials which may be used to substitute for fossil fuels and further reduce emissions in the energy system. Our study only includes the CDR potential, which accounts for the net mitigation, considering the full life-cycle emissions. This potential is constrained by the 30-year payback-period used here, with potentials increasing at longer evaluation periods (Hanssen et al., 2020). In IAMs, the cost-effective potential of BECCS is 0.6 (0 - 2.8) $GtCO_2eq\ yr^{-1}$ in 2020-2050 and 0.9 (0.01 - 6.3) $GtCO_2eq\ yr^{-1}$ in 2050, slightly higher than the sectoral estimates. In our sectoral estimates, the land area required for BECCS to realize its technical potential is 740 Mha and 160 Mha for cost-effective potential. BECCS, from our assessment, has a significantly lower mitigation potential density (3 $tCO_2eq\ ha^{-1}$) compared to A/R (160 $tCO_2eq\ ha^{-1}$), however, this is because BECCS uses the land cyclically to grow and harvest the biomass annually, whereas A/R is the total sequestration capacity over multiple decades. Similar to A/R, when deployed at a large scale, BECCS poses trade-offs and risks for resource use, land competition and food security. However, if well implemented (for example, at lower scales and deployed in tandem with forest management, A/R and biochar strategies on marginal or degraded lands), BECCS also has the potential to deliver co-benefits.

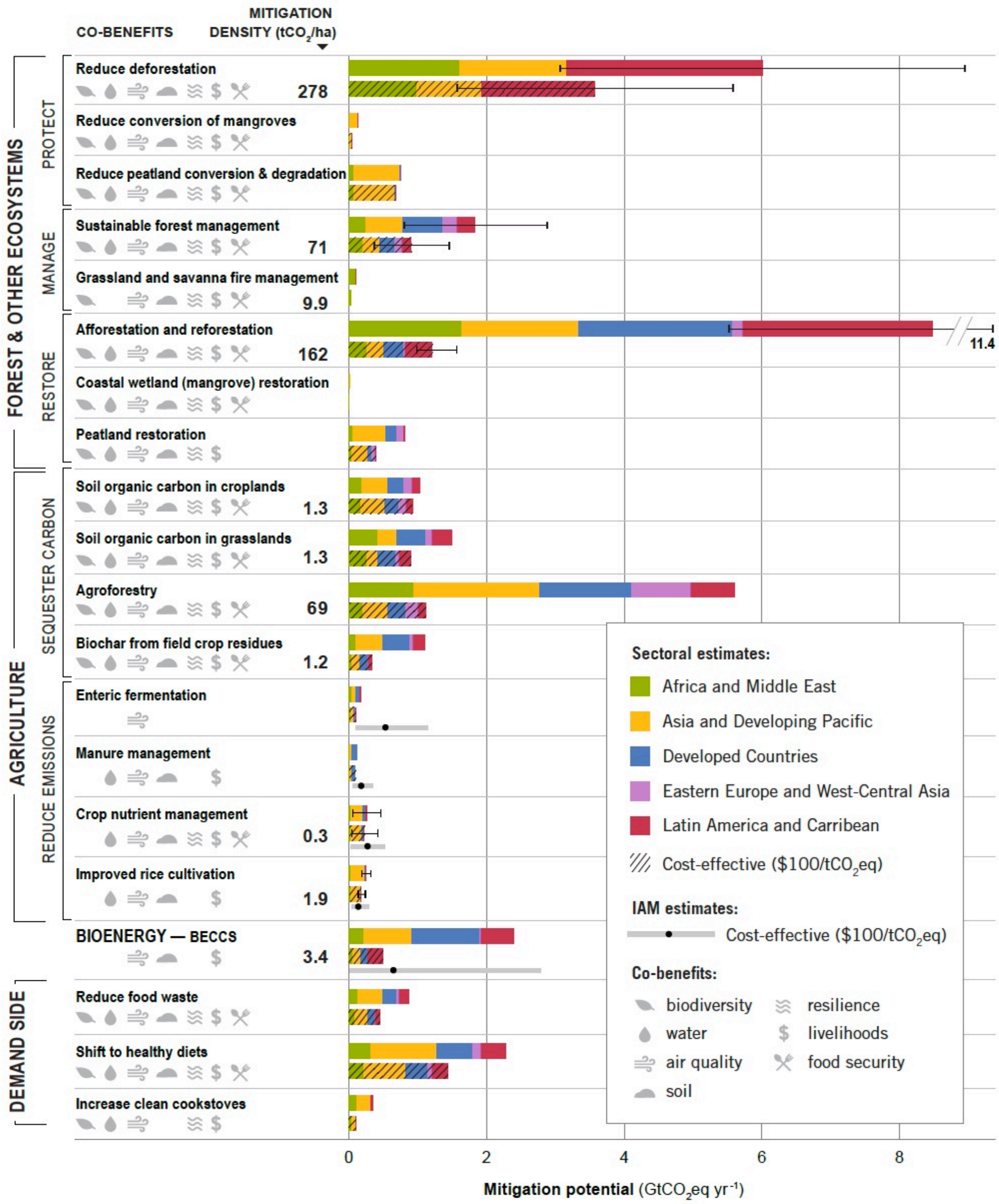


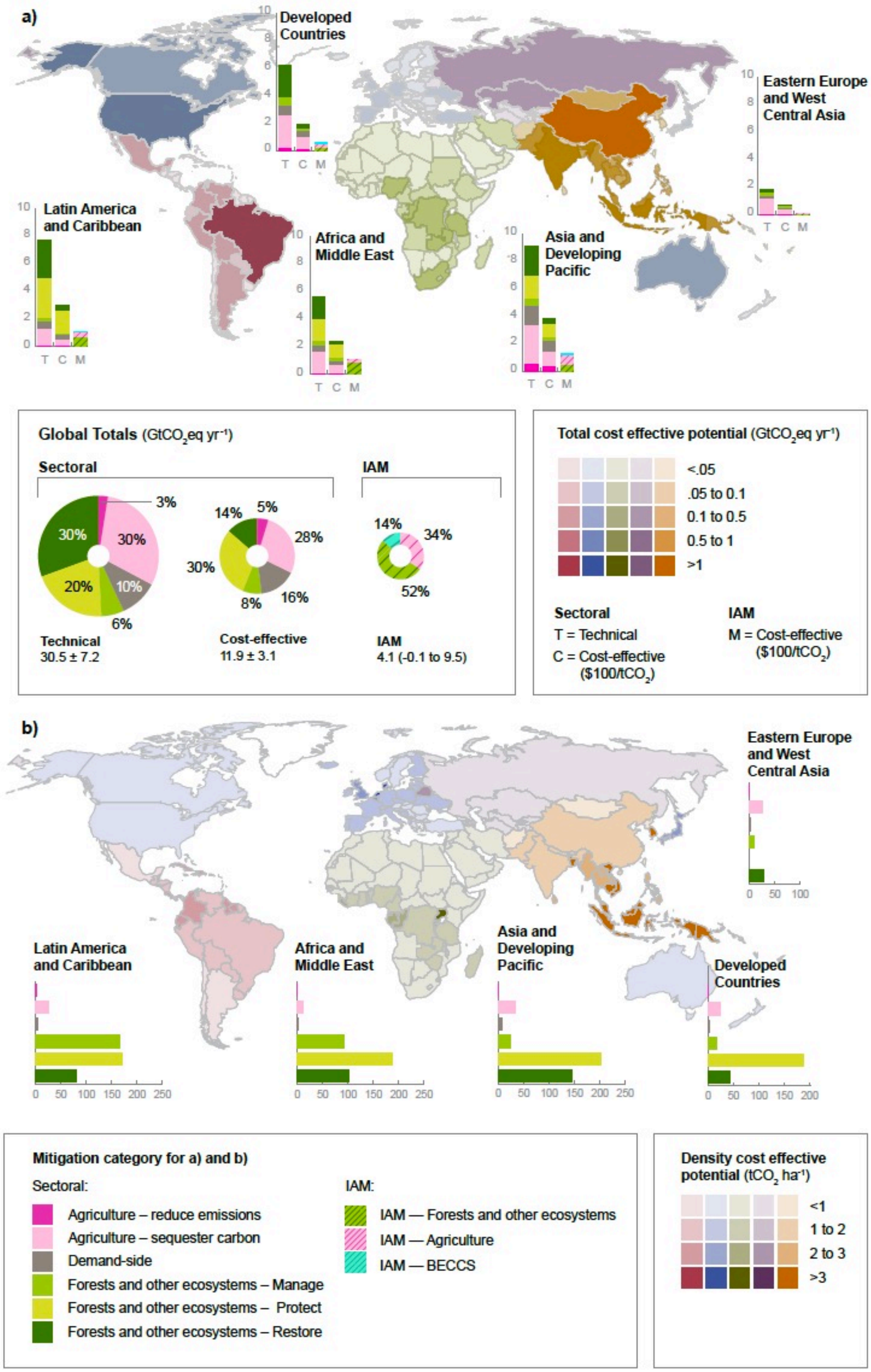
Figure A1.1. Climate mitigation potentials for 20 land-based measures in 2020-2050, by region. Technical and cost-effective ($100/$tCO_2eq$) mitigation potentials are provided for each measure using a sectoral approach according to Table 1. The 20 measures are grouped into four systems-level mitigation categories, and seven management-level categories. For measures with more than one dataset, the bar graph represents the mean estimate, and the error bars represent the min and max potential range. IAM estimates (range and median, up to $100/$tCO_2eq$) are provided for the five measures where data is available in the IAMC+ENGAGE database. Potential co-benefits are indicated with icons, and the average global mitigation 'density' (mitigation potential per hectare per year) is noted for measures with available data.

<u>Comparing mitigation potential across countries and regions</u>

The top 15 countries with the highest total cost-effective mitigation potential from land-based measures are (in descending order): Brazil, China, Indonesia, United States, India, Russian

Federation, the Democratic Republic of the Congo (DRC), Colombia, Canada, Bolivia, Peru, Australia, Mexico, Myanmar and Argentina (**Figure A1.2a**). Together they account for 60% of the global mitigation potential. The countries with highest mitigation potential are generally those with the highest AFOLU emissions. Countries such as Ethiopia and Sudan are an exception, with high AFOLU emissions and relatively lower cost-effective potential because their emissions are predominantly from livestock, which are costlier to mitigate. Total potential is generally highest in countries with large land areas. However, when the density of mitigation potential (total potential per hectare of land) is considered, some small island states move to the top, largely due to high mitigation potential in protecting or restoring wetlands and forests. The top 15 countries with the highest density potential are (in descending order): Maldives, Brunei, Trinidad and Tobago, Indonesia, Bangladesh, Malta, Rwanda, Vietnam, Netherlands, Malaysia, South Korea, Cambodia, Denmark, Uganda, and Papua New Guinea (**Figure A1.2b**).

Across the IPCC regions, the highest cost-effective potentials are found in Asia and developing Pacific with 3.9 ± 1 $GtCO_2eq\ yr^{-1}$ (33%), followed by Latin American and Caribbean (3.0 ± 1.2 $GtCO_2eq\ yr^{-1}$; 25%), then Africa and Middle East (2.4 ± 0.7 $GtCO_2eq\ yr^{-1}$; 20%), Developed countries (2 ± 0.1 $GtCO_2eq\ yr^{-1}$; 17%), and Eastern Europe and West-Central Asia (0.7 ± 0.1 $GtCO_2eq\ yr^{-1)}$ (**Figure A1.2a**). The cost-effective mitigation potential (up to $100/$tCO_2eq$) is about 40% of the global technical potential, but with considerable regional variation: 43% is cost-effective in Asia and developing Pacific, 39% in Latin American and Caribbean, 32% in Developed countries, 42% in Africa and Middle East, and 36% in Eastern Europe and West-Central Asia. Tropical countries in Asia, Africa and Latin America have the largest proportions of cost-effective potential; proportions are low in developed countries largely due to higher costs of implementation. Additional detail on the five IPCC regions is outlined in the next section 3.2 "Five Regions."



a)
Developed Countries
Eastern Europe and West Central Asia
Latin America and Caribbean
Africa and Middle East
Asia and Developing Pacific
T C M
Global Totals ($GtCO_2eq\ yr^{-1}$)
Sectoral
IAM
Technical
30.5 ± 7.2
Cost-effective
11.9 ± 3.1
IAM
4.1 (-0.1 to 9.5)
Total cost effective potential ($GtCO_2eq\ yr^{-1}$)
<.05
.05 to 0.1
0.1 to 0.5
0.5 to 1
>1
Sectoral
T = Technical
C = Cost-effective ($100/tCO_2$)
IAM
M = Cost-effective ($100/tCO_2$)
b)
Eastern Europe and West Central Asia
Latin America and Caribbean
Africa and Middle East
Asia and Developing Pacific
Developed Countries
Mitigation category for a) and b)
Sectoral:
Agriculture – reduce emissions
Agriculture – sequester carbon
Demand-side
Forests and other ecosystems – Manage
Forests and other ecosystems – Protect
Forests and other ecosystems – Restore
IAM:
IAM — Forests and other ecosystems
IAM — Agriculture
IAM — BECCS
Density cost effective potential ($tCO_2\ ha^{-1}$)
<1
1 to 2
2 to 3
>3

Figure A1.2. Country-level land-based mitigation potentials. a) Country-level map of total cost-effective ($100/t$CO_2$eq) mitigation potential (taking the average potentials for measures with more than one dataset). The five colors on the map correspond to the five IPCC regions assessed in our study. Bar charts show the share of mean technical, cost effective, and IAM mitigation by mitigation category, aggregated into the five IPCC regions. Aggregate potentials exclude reduced peatland conversion, BECCS and clean cookstoves to avoid double counting. Pie charts provide the share of mitigation potential by mitigation category.; b) Country-level map of cost-effective mitigation potential density (total potential per hectare). Bar charts show the mean mitigation density per year, by type of measure, by region between 2020-2050.

Feasibility across regions and categorization of countries

Globally, the median feasibility score was 48 (40 – 56 IQR), which corresponds approximately to the median scores for developing countries (**Figure A1.3**). The highest feasibility scores were for Denmark (74), the Netherlands (73) and Luxembourg (72), while the lowest feasibility scores were for Eritrea (20), Chad (24) and Central African Republic (27). Developed countries had the highest median feasibility scores (64), followed by developing countries (48) and then least developed countries (LDCs) (36). Developed countries had higher scores in five of the six feasibility categories assessed: economic, institutional, technological, social and environmental, while developing countries and LDCs scored higher in the geophysical category. Among developed countries, Denmark (74) was highest overall, among developing countries, Brunei (68) was highest, and among LDCs, Bhutan was highest (51). The Russian Federation was lowest among developed countries, Republic of the Congo among developing countries, and Eritrea, lowest in feasibility among LDCs. Comparisons between regions show that Developed Countries (Europe, North America, Developed Pacific) had a median feasibility score of 64, followed by Latin American and Caribbean countries with 50, Asian and developing Pacific countries with 48, Eastern European and West-Central Asian countries with 47, and African and Middle Eastern countries with 39.

When feasibility scores are compared to the share of cost-effective land-based mitigation potential relative to national emissions, countries can be broadly categorized into nine categories (numbered in **Figure A1.3**) of either high, medium or low across the two variables. Countries in the top tier (#1-3) are those with land-based mitigation potential greater than 100% of total country emissions, or “Surplus potential” countries. Tropical forest countries with relatively low fossil fuel emissions in Africa, Southeast Asia and Latin America are found in the “Surplus potential” tier, with Iceland as the exception. Countries in the middle tier (#4-6), or “High relative potential” countries, have land mitigation potentials between 30% and 100% of economy-wide emission levels, higher than the global average to meet the 1.5°C pathway. “High relative potential” includes tropical forest countries and large agriculture countries with average fossil fuel emissions. Countries in the lower tier (#7-9) have lower than 30% of mitigation potential relative to total emissions, largely due to their high levels of fossil fuel emissions and/or low land-based potential (e.g., desert biomes), thus labelled “Limited relative potential” countries. The feasibility score categories of “low” (<25th percentile), “medium” (25-75 percentile), and “high” (>75th percentile) largely reflect countries’ development level, with LDCs predominantly aggregated in “low”, developing countries in “medium” and developed countries in “high”, with some exceptions including Bhutan (an LDC) with a feasibility score above the 50th percentile and Russia (a developed country) scoring below the 50th percentile. Our characterizations of low, medium, and high zones for each variable are conceptual and should not be interpreted as sharp distinctions, even though they use numerical thresholds to define different zones.

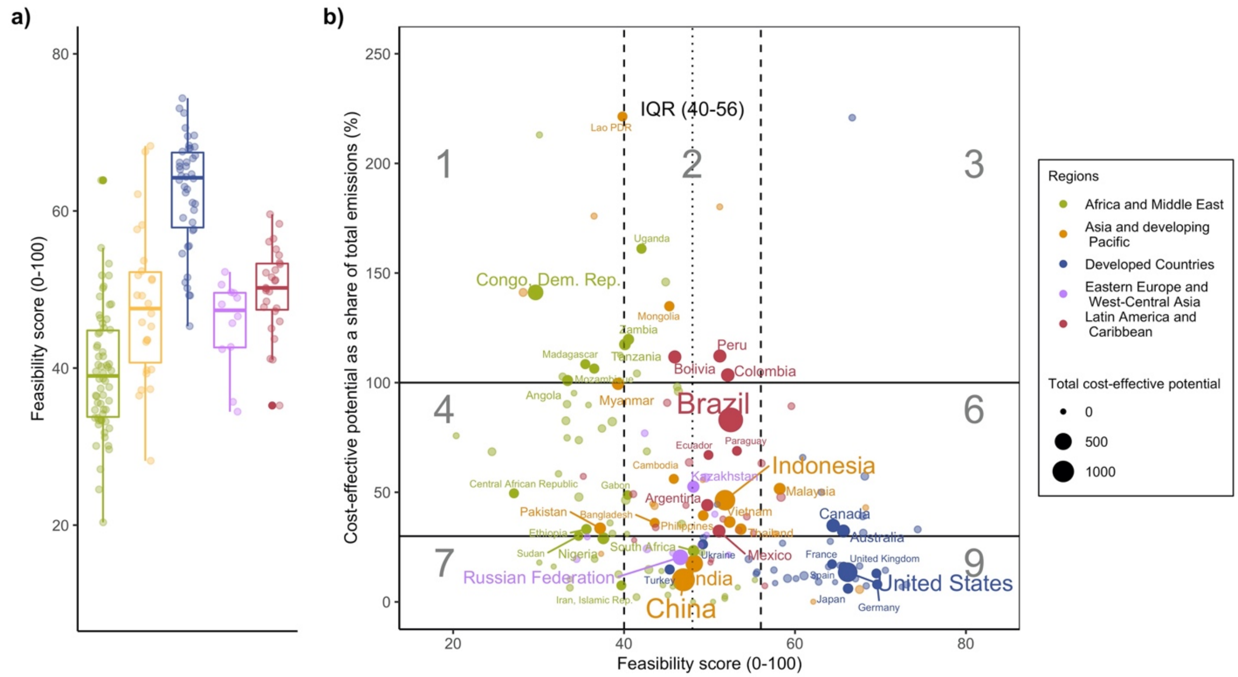


Figure A1.3. Country Feasibility. a) Boxplot of feasibility scores by region b) Feasibility score by total cost-effective mitigation potential as percent of emissions. The vertical dashed lines represent the interquartile range and median, and the horizontal lines represent the share of cost-effective mitigation potential land-based measures can deliver over 30% (in line with global 1.5°C trajectory) and over 100% (can achieve net zero emissions or negative emissions with land-based measures only). Countries are grouped and numbered into nine categories, according to their relative mitigation potential as a share of total emissions and feasibility score. In six countries, the proportion of cost-effective potential relative to total emissions is higher than the y-axis of 250%: Papua New Guinea, Republic of Congo, Cameroon, Guyana, Suriname, and Rwanda; these can be seen in Figures A1.4-8.

Five regions

Africa & Middle East

Africa and the Middle East (AME) comprises approximately 35 million km^2, of which 19% is forest (20.6% primary, 2% planted) and 39% is agricultural land. Total AFOLU emissions were 2.7 GtCO$_2$eq yr^{-1} (averaged between 2013-2017), 0.9 GtCO$_2$eq yr^{-1} (35%) from agriculture and 1.7 GtCO$_2$eq yr^{-1} (65%) from land-use change. The main drivers of agriculture emissions are enteric fermentation (42%), manure left on pastures (30%) and the burning of grasslands and savannahs (17%), whereas the main driver of tree cover loss (proxy for land-use change) is shifting agriculture (90%), far ahead of commodity production (4%).

The total technical mitigation potential in AME is 5.6 ±2.3 $GtCO_2eq\ yr^{-1}$, and the cost-effective mitigation potential ($100/$tCO_2eq$) is 2.4 ±0.7 $GtCO_2eq\ yr^{-1}$ (43%). The highest cost-effective mitigation potential comes from reducing deforestation (0.97±0.4 $GtCO_2eq\ yr^{-1}$; 40%), then afforestation and reforestation (0.25±0.2 $GtCO_2eq\ yr^{-1}$; 10%), sequestering soil organic carbon in grasslands (0.24 $GtCO_2eq\ yr^{-1}$; 10%) and shifting diets (0.2 $GtCO_2eq\ yr^{-1}$; 8%) (Figure A1.4b). The IAM cost-effective potential (up to $100 per tCO_2eq) for AFOLU (agriculture + land-use change) averaged between 2020-2050 is 1.2 median (-0.1 – 3.8 range) $GtCO_2eq\ yr^{-1}$ and 1.7 (-0.4 – 3.4) $GtCO_2eq\ yr^{-1}$ in 2050.

Across the countries, the DRC has the most cost-effective mitigation potential at 0.4 ±0.2 $GtCO_2eq\ yr^{-1}$, or about 17% in AME (**Figure A1.4a**). The DRC is followed by Nigeria, Tanzania, South Africa, Zambia and the Republic of Congo. In the DRC, the Republic of the Congo, Tanzania, and Zambia, where land-based emissions are largely driven by deforestation from shifting agriculture, "forest protection" measures present the highest cost-effective mitigation potential. Almost half (43%) of AME countries have cost-effective potentials that are over 30% of their total emissions, or "High relative potential." Seven countries (Cameroon, Rwanda, the Republic of Congo, Uganda, Burundi, Namibia and the Gambia) have cost-effective potentials exceeding their total emissions, or "Surplus potential" (**Figure A1.4c**). Rwanda and Uganda have the highest mitigation densities at over 3 $tCO_2eq\ ha^{-1}$ (**Figure A1.4a**). At the regional scale, average mitigation density is at 1 $tCO_2eq\ ha^{-1}$, with the protection of forests and other ecosystems offering the highest mitigation density at 188 $tCO_2eq\ ha^{-1}$, followed by the restoration of forests and other ecosystems at 102 $tCO_2eq\ ha^{-1}$ and improved and sustainable forest management at 91 $tCO_2eq\ ha^{-1}$ (**Figure A1.4b**)

The median feasibility score in AME (39) is nine points below the global median, with more than half of AME countries being below the 25th percentile "low" and Israel being the only country above the 75th percentile "high" (**Figure A1.4c**). AME countries scored below-average feasibility compared to global scores in all six feasibility dimensions (economic, political, geophysical, technological, social, environmental).

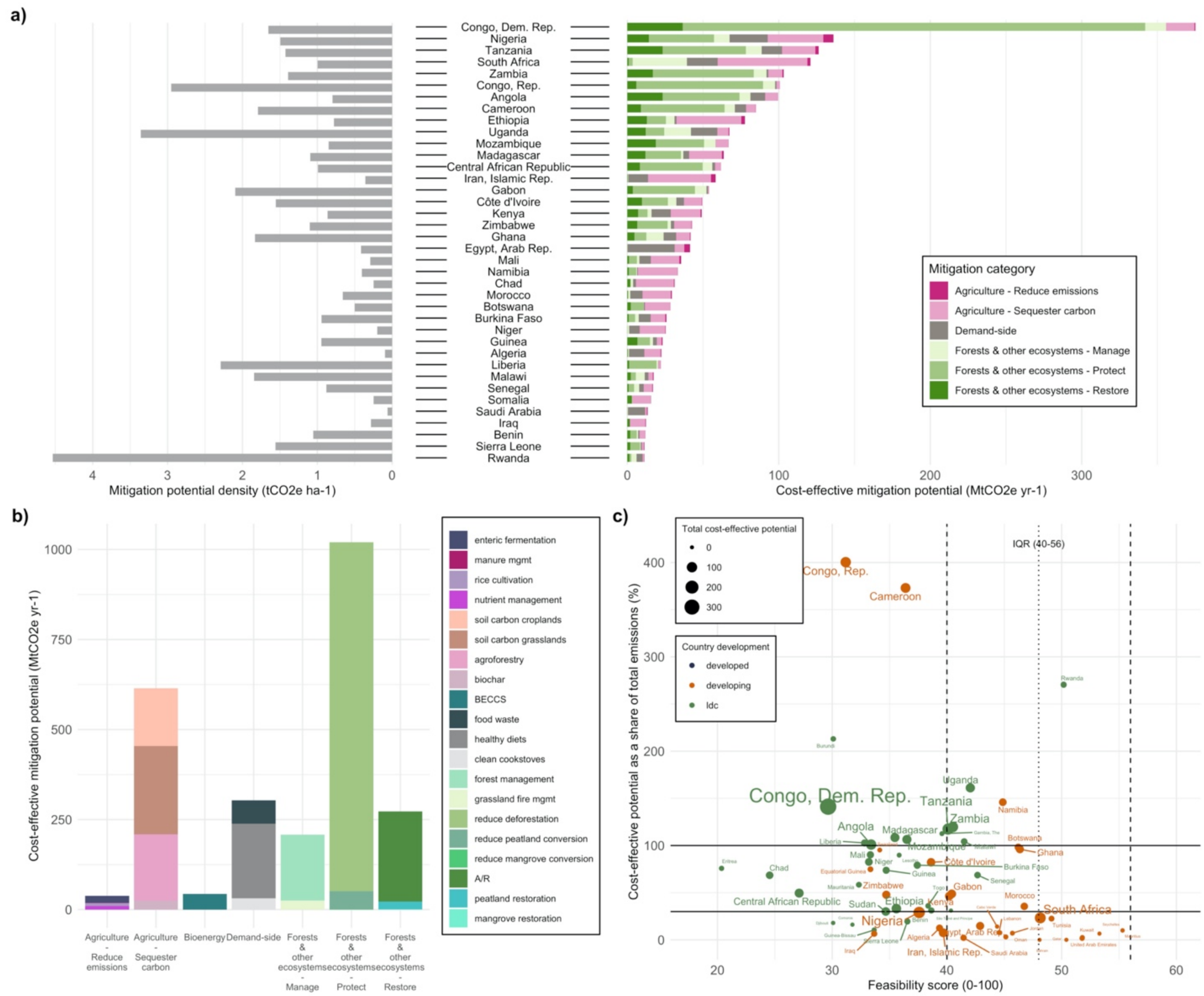


Figure A1.4. Africa and Middle East (AME) land-based mitigation potentials and feasibility. a) Total cost-effective mitigation potential by mitigation category (colored bars) and mitigation density of cost-effective potentials (grey bars), by country; b) Total cost-effective mitigation potential by mitigation category and measure in AME; c) Feasibility score by cost-effective mitigation potential as a share of total country GHG emissions (%) in AME.

<u>Asia & Developing Pacific</u>

Asia and the developing Pacific (ADP) is approximately 21 million km^2, of which 28% is forest (22% primary, 20% planted), and 51% is agricultural land. Total AFOLU emissions were 3.6 $GtCO_2eq$ yr^{-1} (averaged between 2013-2017), 2.1 $GtCO_2eq$ yr^{-1} (58%) from agriculture and

1.5 $GtCO_2eq\ yr^{-1}$ (42%) from land-use change. The main drivers of agriculture emissions are enteric fermentation (32%), rice cultivation (21.5%) and synthetic fertilizers (18%), whereas the main drivers of tree cover loss (proxy for land-use change) are agricultural commodities (57%) and forestry (27%).

The total technical mitigation potential in ADP is 9.1 ±1.0 $GtCO_2eq\ yr^{-1}$, and the cost-effective mitigation potential ($100/$tCO_2eq$) is 3.9 ±1.0 $GtCO_2eq\ yr^{-1}$ (43%). The highest cost-effective mitigation potential comes from reducing deforestation (0.95 ±0.6 $GtCO_2eq\ yr^{-1}$; 24%), then shifting diets (0.61 $GtCO_2eq\ yr^{-1}$; 16%), reducing peatland conversion (0.59 $GtCO_2eq\ yr^{-1}$; 15%), forest management (0.43 ±0.2) $GtCO_2eq\ yr^{-1}$; 11%) and agroforestry (0.37 $GtCO_2eq\ yr^{-1}$; 10%) (**Figure A1.5b**). The IAM cost-effective potential (up to $100/$tCO_2eq$) for AFOLU (agriculture + land-use change) averaged between 2020-2050 is 1.1 median (0.15 – 2.2 range) $GtCO_2eq\ yr^{-1}$ and 1.8 (0.02 - 2.9 range) $GtCO_2eq\ yr^{-1}$ in 2050.

Across the countries, China has the highest cost-effective mitigation potential at 1.2 ±0.2 $GtCO_2eq\ yr^{-1}$, or about 31% in ADP, largely due to its size which is 45% of the land area in ADP (**Figure A1.5a**). China's AFOLU emissions are concentrated in agriculture (97%), accordingly, its largest mitigation potential is from demand-side measures (40%), then "sequester carbon" measures in agriculture (37%), and "reduce emissions" measures in agriculture (13%). China is followed by tropical forest countries, Indonesia, Malaysia and Vietnam (28% of potential in ADP), where land-based emissions are driven by commodity production, then Myanmar and Papua New Guinea, where land-based emissions are driven by forestry and shifting agriculture, and thus have the largest mitigation potential in the protection of forest and other ecosystems. India, where land-based emissions are primarily driven by synthetic fertilizer use, has the third highest cost-effective mitigation potential in the region at 0.5 ±0.3 $GtCO_2eq\ yr^{-1}$; as such agriculture measures, particularly "carbon sequestration" offer the highest mitigation potential.

About one third (35%) of ADP countries have cost-effective potentials that are over 30% of their total emissions “High relative potential” tier. Papua New Guinea, Mongolia, Lao PDR, Afghanistan, Bhutan and Kiribati all have “Surplus potential,” or cost-effective potentials that are over 100% of their total emissions (**Figure A1.5c**). The Maldives and Brunei Darussalam have the highest mitigation densities at over 5 $tCO_2eq\ ha^{-1}$ (**Figure A1.5a**), although they have relatively modest total potentials due to their small size. At the regional scale, mitigation density is 1.6 $tCO_2eq\ ha^{-1}$, with the protection (202 $tCO_2eq\ ha^{-1}$) and restoration (145 $tCO_2eq\ ha^{-1}$) of forests and other ecosystems offering the highest mitigation density, followed by “sequester carbon” measures in agriculture (34 $tCO_2eq\ ha^{-1}$) (**Figure A1.2b**).

Countries in ADP are evenly distributed on either side of the global median with regards to their feasibility scores, most countries being located in the 50-75th percentile, “medium”. Brunei, the Republic of Korea, Malaysia, the Maldives and Singapore are above the 75% percentile, “high”, while Afghanistan, Lao PDR, Myanmar, Pakistan, Papua New Guinea, the Solomon Islands and Vanuatu are below the 25% percentile “low” (**Figure A1.5c**). Relative to global scores, ADP countries scored below-average in five feasibility dimensions (economic, political, technological, social and environmental) and above-average scores in the geophysical dimension.

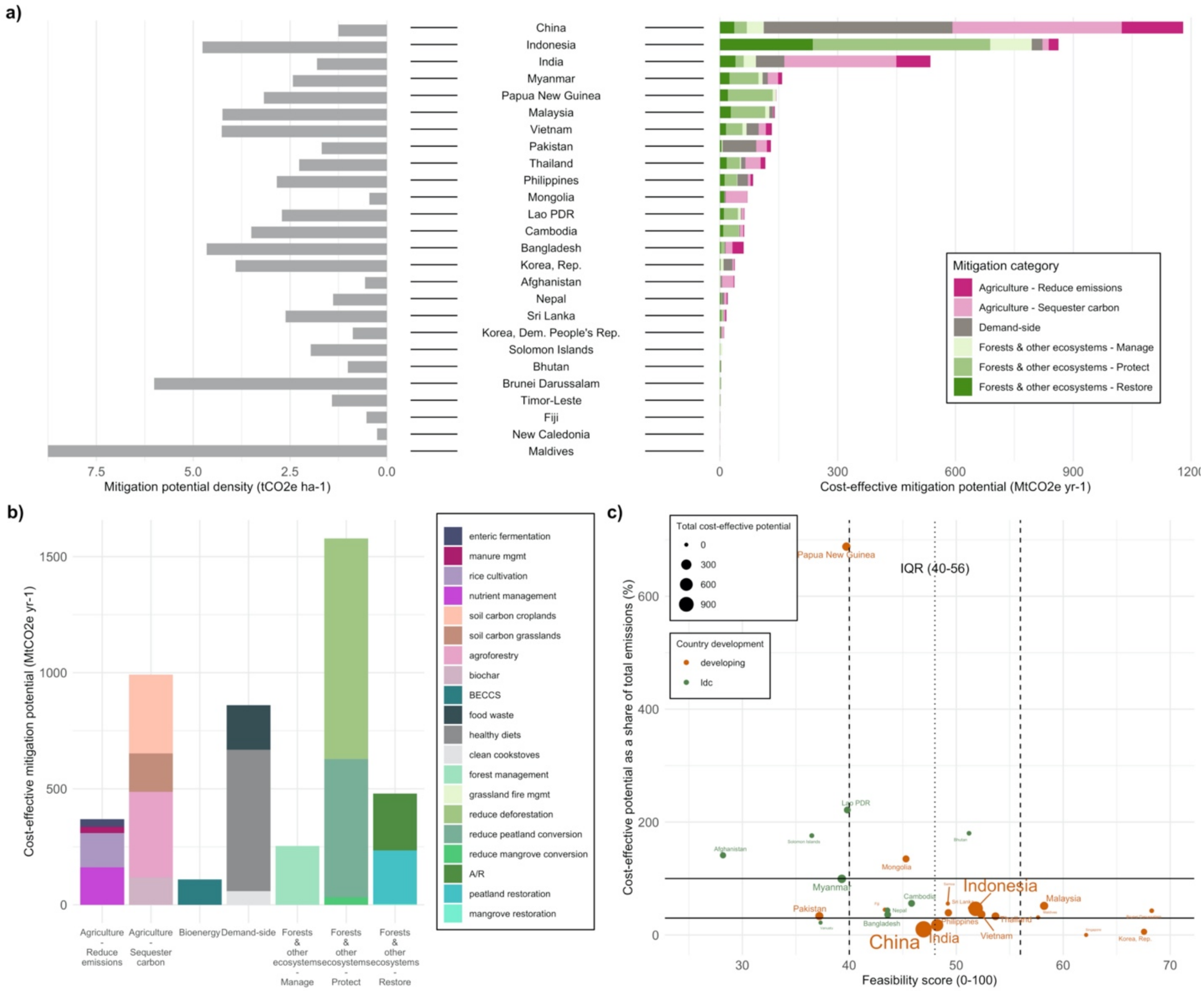


Figure A1.5. Asia & Developing Pacific (ADP) land-based mitigation potentials and feasibility. a) Total cost-effective mitigation potential by mitigation category (colored bars) and mitigation density of cost-effective potentials (grey bars), by country; b) Total cost-effective mitigation potential by mitigation category and measure in ADP; c) Feasibility score by cost-effective mitigation potential as a share of total country GHG emissions (%) in ADP.

Developed countries

Developed countries (DC) cover approximately 33 million km^2, of which 31% is forest (32% primary, 12% planted), and 37% is agricultural land. Total AFOLU emissions were 1.25 GtCO$_2$eq yr^{-1} (averaged between 2013-2017), 1.1 GtCO$_2$eq yr^{-1} (86.6%) from agriculture and 0.2 GtCO$_2$eq yr^{-1} (13.4%) from land-use change. The main drivers of agriculture emissions are enteric fermentation (37%), synthetic fertilizer use (18%) and manure deposition on pasture (12%), whereas the main driver of tree-cover loss is forestry (76%).

The total technical mitigation potential in DC is 6.3 ±0.3 $GtCO_2eq\ yr^{-1}$, and the cost-effective mitigation potential ($100/$tCO_2eq$) is 2 ±0.1 $GtCO_2eq\ yr^{-1}$ (32%). The IAM cost-effective potential (up to $100 per tCO_2eq) for AFOLU (agriculture + land-use change) averaged between 2020-2050 is 0.4 median (-0.1 – 1 range) $GtCO_2eq\ yr^{-1}$ and 0.7 (-0.1 – 1.6) $GtCO_2eq\ yr^{-1}$ in 2050. The highest cost-effective mitigation potential comes from shifting to healthy diets (0.3 $GtCO_2eq\ yr^{-1}$; 15%), then afforestation and reforestation (0.29 ±0.04 $GtCO_2eq\ yr^{-1}$; 14.5%), agroforestry (0.26 $GtCO_2eq\ yr^{-1}$; 13%) and soil organic carbon sequestration in grasslands (0.25 $GtCO_2eq\ yr^{-1}$; 12.5%) (**Figure A1.6b**).

Across the countries in DC, the United States (US) has by far the largest cost-effective mitigation potential at 0.75 ±0.04 $GtCO_2eq\ yr^{-1}$, 38% of the potential (**Figure A1.6a**), followed by Canada (0.22 ±0.02 $GtCO_2eq\ yr^{-1}$), Australia (0.19 ±0.02 $GtCO_2eq\ yr^{-1}$, 11%) and Japan (0.07 ±0.02 $GtCO_2eq\ yr^{-1}$, 4%). The land-based emissions from these countries are primarily driven by agriculture, as such, the highest cost-effective mitigation potentials are in "sequester carbon" measures (highest proportion of the US' and Australia's total cost-effective potentials), followed by demand-side measures. Reforestation and forest management also provide significant potentials across these countries, representing the highest opportunities for Canada and Japan, respectively. Only seven DC countries have cost-effective potentials that are over 30% of their total emissions, "High relative potential," while Iceland is the only country to have cost-effective potential exceeding its total emissions "Surplus potential" (**Figure A1.6c**). Bermuda, Malta and the Netherlands have the highest mitigation densities, more than 4 $tCO_2eq\ ha^{-1}$ (**Figure A1.6a**). At the regional scale, average mitigation density is 2.8 $tCO_2eq\ ha^{-1}$, with the protection of forests and other ecosystems offering the highest mitigation density at 188 $tCO_2eq\ ha^{-1}$, followed by the restoration of forests and other ecosystems at 42 $tCO_2eq\ ha^{-1}$ and "sequester carbon" measures in agriculture at 24 $tCO_2eq\ ha^{-1}$ (**Figure A1.2**).

The median feasibility score in DC (62.3) is well above the global median, a vast majority of DC countries being above the 75th percentile, or "high" feasibility (**Figure A1.6c**). For the remaining countries, eight are in the 50-75th percentile, Turkey is the only country in the 25-50% percentile, and no DC country scored under the 25th percentile. DC countries obtained above-average scores compared to global scores in five out of the six feasibility dimensions (all but the geophysical dimension).

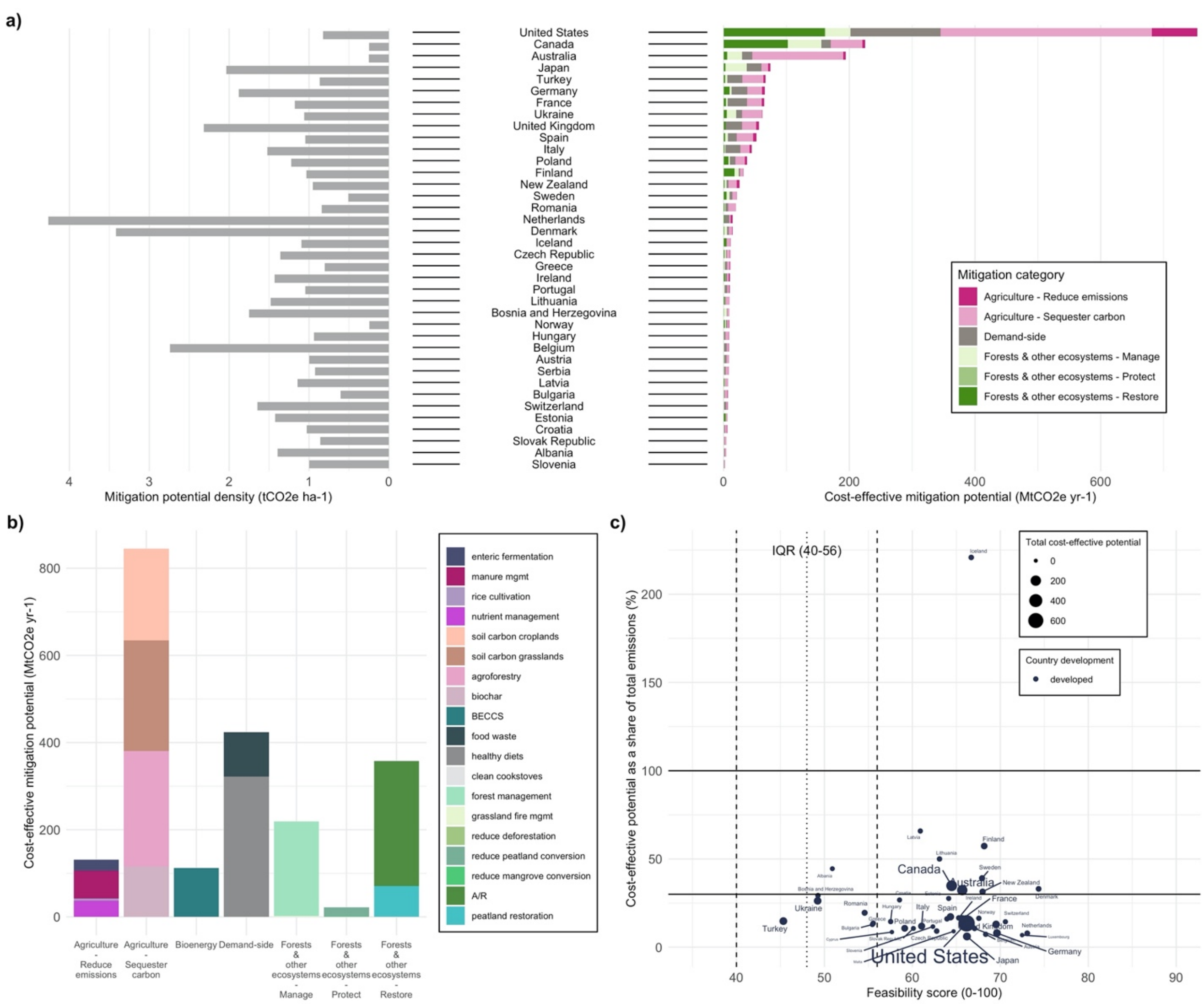


Figure A1.6. Developed countries (DC) land-based mitigation potentials and feasibility. a) Total cost-effective mitigation potential by mitigation category (colored bars) and mitigation density of cost-effective potentials (grey bars), by country; b) Total cost-effective mitigation potential by mitigation category and measure in DC; c) Feasibility score by cost-effective mitigation potential as a share of total country GHG emissions (%) in DC.

Eastern Europe and West-Central Asia

Eastern Europe and West-Central Asia (EEWA) is approximately 21 million km2, of which 41% is forest (33% primary, 3% planted) and 25% is dedicated to agriculture. Total AFOLU emissions were 0.19 $GtCO_2eq\ yr^{-1}$ (averaged between 2013-2017), 0.18 $GtCO_2eq\ yr^{-1}$ (95%) from Agriculture and 0.01 $GtCO_2eq\ yr^{-1}$ (5%) from land-use change. The main drivers of agriculture emissions are enteric fermentation (46%), manure management (11%) and synthetic fertilizers (10%), whereas the main drivers of tree cover loss are wildfires (59%) and forestry (35%).

The total technical mitigation potential in EEWA is 1.8 ±0.1 $GtCO_2eq\ yr^{-1}$, and the cost-effective mitigation potential (\$100/tCO_2eq) is 0.66 ±0.1 $GtCO_2eq\ yr^{-1}$ (37%). The highest cost-effective mitigation potential comes from agroforestry (0.18 $GtCO_2eq\ yr^{-1}$; 27%), then forest management (0.12 ±0.08 $GtCO_2eq\ yr^{-1}$; 17.6%), soil organic carbon in croplands (0.1 $GtCO_2eq\ yr^{-1}$; 16%) and shifting diets (0.07 $GtCO_2eq\ yr^{-1}$; 10.6%) (**Figure A1.7b**). The IAM cost-effective potential (up to \$100/tCO_2eq) for AFOLU (agriculture + land-use change) averaged between 2020-2050 is 0.07 median (-0.1 – 1.8 range) $GtCO_2eq\ yr^{-1}$ and 0.1 (-0.09 – 0.5) $GtCO_2eq\ yr^{-1}$ in 2050.

Across the countries, Russia has the largest cost-effective mitigation potential at 0.4 ±0.05 $GtCO_2eq\ yr^{-1}$, or about 61% in EEWA, largely due to its size which is 78% of the land area in EEWA (**Figure A1.7a**). The Russian Federation is followed by Kazakhstan, Belarus, Uzbekistan, Turkmenistan, the Kyrgyz Republic and Azerbaijan. The land-based emissions in these countries are attributed to agriculture, and the highest cost-effective mitigation potentials are in "sequester carbon" measures (except for Belarus, where improved forest management measures have the highest potentials due to the importance of their forestry sector on emissions). Five EEWA countries have cost-effective potentials that are over 30% of their total emissions, “High relative potential,” however, unlike in other regions, none have cost-effective potential exceeding their total emissions (**Figure A1.7c**). Belarus has the highest mitigation density, greater than 2 $tCO_2eq\ ha^{-1}$. At the regional scale, average mitigation density is fairly low, 0.8 $tCO_2eq\ ha^{-1}$, with carbon sequestration from agriculture offering the most mitigation density at 26 $tCO_2eq\ ha^{-1}$, followed by the restoration of forests and other ecosystems at 28 $tCO_2eq\ ha^{-1}$ (**Figure A1.2b**).

The median feasibility score in EEWA (47) is slightly below the global median, with half of EEWA countries in the 50-75th percentile and one third in the 25-50th percentile (all “medium” feasibility). No EEWA country lies in the 75-100% percentile, while Tajikistan and Turkmenistan are below the 25% percentile, or “low” feasibility (**Figure A1.7c**). EEWA countries have below-average scores in five feasibility dimensions (political, geophysical, technological, environmental, social), and above-average scores in the economic dimension.

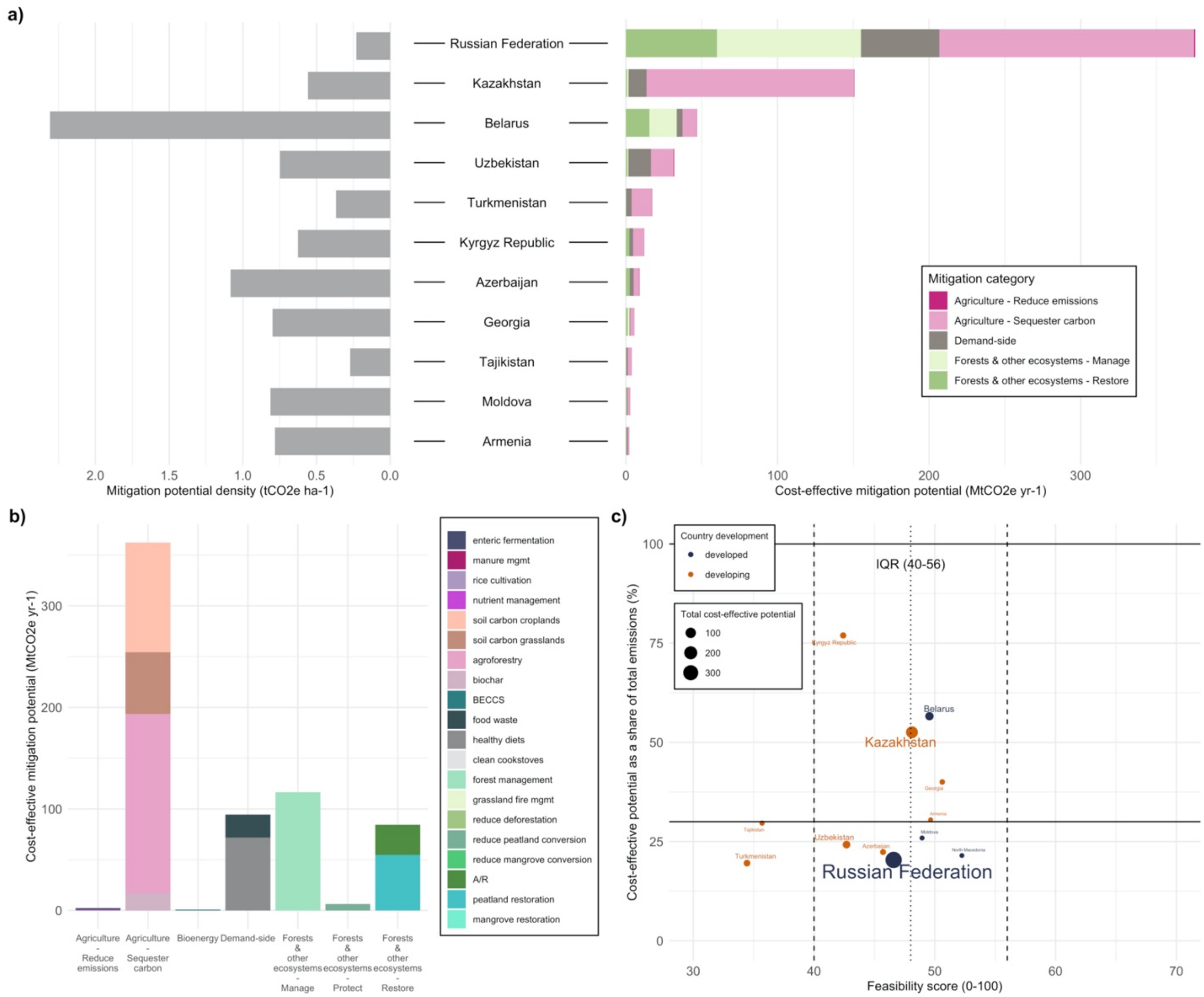


Figure A1.7. Eastern Europe and West-Central Asia (EEWA) land-based mitigation potentials and feasibility. a) Total cost-effective mitigation potential by mitigation category (colored bars) and mitigation density of cost-effective potentials (grey bars), by country; b) Total cost-effective mitigation potential by mitigation category and measure in EEWA; c) Feasibility score by cost-effective mitigation potential as a share of total country GHG emissions (%) in EEWA.

Latin America & Caribbean

Latin America and the Caribbean (LAC) is approximately 20 million km2, of which 47% is forest (46% primary, 3% planted) and 36% is dedicated to agriculture. Total AFOLU emissions were 2.3 $GtCO_2eq\ yr^{-1}$ (averaged between 2013-2017), 0.9 $GtCO_2eq\ yr^{-1}$ (39%) from agriculture and 1.4 $GtCO_2eq\ yr^{-1}$ (61%) from land-use change. The main drivers of agriculture emissions are from livestock production, enteric fermentation (58%) and manure left on pasture

(23%), whereas the main drivers of tree cover loss (proxy for land-use change) are commodity agriculture (51%) and shifting agriculture (38%).

The total technical mitigation potential in LAC is 7.7 ±2.3 $GtCO_2eq\ yr^{-1}$, and the cost-effective mitigation potential ($100/tCO2eq) is 3.0 ±1.2 $GtCO_2eq\ yr^{-1}$ (42%). The highest cost-effective mitigation potential comes from reducing deforestation (1.6 ±0.96 $GtCO_2eq\ yr^{-1}$; 50%), then A/R (0.4 ±0.1$GtCO_2eq\ yr^{-1}$; 13%), BECCS (0.23 $GtCO_2eq\ yr^{-1}$; 7%), shifting diets (0.22 $GtCO_2eq\ yr^{-1}$; 7%), soil organic carbon in grasslands (0.17 $GtCO_2eq\ yr^{-1}$; 5%) and agroforestry (0.13 $GtCO_2eq\ yr^{-1}$; 4%) (**Figure A1.8b**). The IAM cost-effective potential (up to $100 per tCO_2eq) for AFOLU (agriculture + land-use change) averaged between 2020-2050 is 1.0 median (-0.2 – 3.2 range) $GtCO_2eq\ yr^{-1}$ and 1.9 (-0.3 – 2.7) $GtCO_2eq\ yr^{-1}$ in 2050. The highest mitigation potential measures in LAC also have among the highest potential co-benefits, with the exception of BECCS (**Figure A1.1**).

Across the countries, Brazil has the highest cost-effective mitigation potential by several orders of magnitude at 1.4 ±0.5 $GtCO_2eq\ yr^{-1}$, or about 45% in LAC, largely due to its size which is 42% of the land area in LAC (**Figure A1.8a**). Brazil is followed by Colombia, Bolivia, Peru, Mexico, Argentina and Venezuela which are predominantly high forest and/or high meat producing and consuming countries and thus have protecting forests, restoring forests and shifting to healthy diets among the highest potentials (**Figure A1.8b**). A large majority of LAC countries have cost-effective potentials that are over 30% of their total emissions, higher than the global median to achieve a 1.5°C trajectory, or "High relative potential". High forest and lower fossil fuel emissions countries, Suriname, Guyana, Peru, Bolivia and Colombia all have cost-effective potentials that are over 100% of their total emissions, or "Surplus potential" (**Figure A1.8c**). When looking at the density of cost-effective mitigation potentials (total potential by total area), the average across all the regions is about 2 $tCO_2eq\ ha^{-1}$ (**Figure A1.8a**). Trinidad and

Tobago, Barbados, El Salvador, Costa Rica and Cuba have the highest mitigation densities, even though they have relatively modest total potentials compared to the other countries in the region (**Figure A1.8a**).

Most countries in LAC have higher feasibility scores than the global median and are in the 50-75% percentile (“medium” feasibility). Costa Rica, Chile, Trinidad and Tobago, and Uruguay are above the 75% percentile (“high” feasibility), while Haiti is below the 25% percentile (“low feasibility”) (**Figure A1.8c**). Relative to global scores, LAC countries scored below-average in four feasibility dimensions (economic, institutional, geophysical and environmental) and above-average scores in the technological and social dimensions.

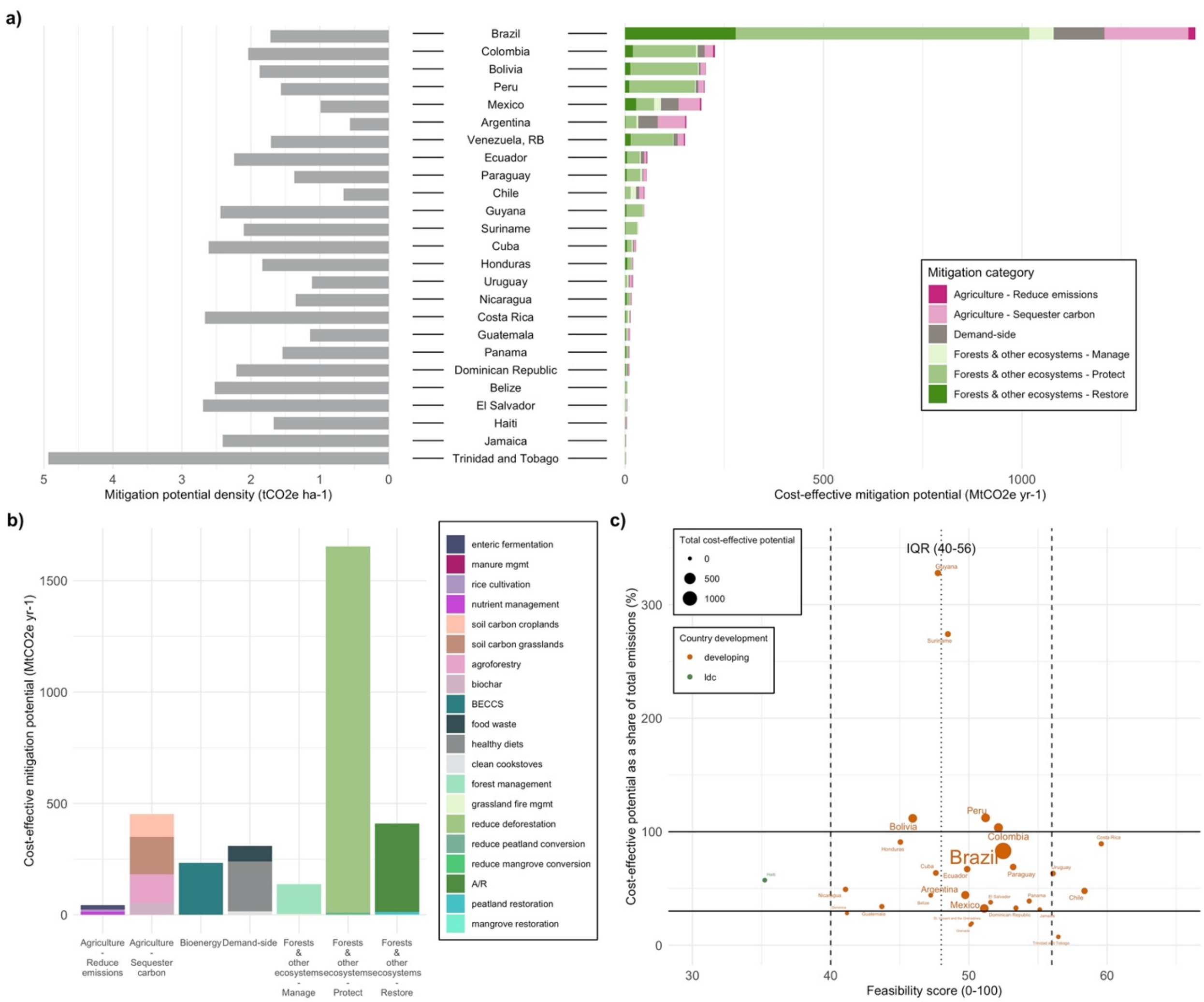


Figure A1.8. Latin America & Caribbean (LAC) land-based mitigation potentials and feasibility. a) Total cost-effective mitigation potential by mitigation category (colored bars) and mitigation density of cost-effective potentials (grey bars), by country; b) Total cost-effective mitigation potential by mitigation category and measure in LAC; c) Feasibility score by cost-effective mitigation potential as a share of total country GHG emissions (%) in LAC.

Discussion

Data advances made, but gaps remain

In this study, we show that within the cost-effective range (up to \$100/tCO_2eq), our sectoral portfolio of 20 land-based mitigation activities have the potential to deliver 11.9 ± 3.1 GtCO_2eq yr^{-1}, about even with current AFOLU emissions and about 25% of current levels of global GHG emissions (~50 Gt CO_2eq yr^{-1}). Our estimate of mitigation potentials available under \$100/tCO_2eq represent a more realistic near-term range of public willingness to pay for climate mitigation than do technical potentials. The cost-effective potential is roughly allocated as 50% from forests and other ecosystems, 30% from agriculture and 20% from demand-side measures. Each of the 20 land-based measures incorporated in our study have potential co-benefits and risks, depending on how and where it is implemented. Feasibility conditions, however, could limit countries, particularly developing and LDC countries, which make up 80% of the global cost-effective potential, from realizing their climate mitigation potentials and the associated co-benefits.

Our work builds on and includes several advances (detailed in Methods 2.1) beyond previous studies on land-based mitigation potential (Smith et al. 2013; 2014; Griscom et al. 2017; UNEP 2017; Roe et al. 2019; Jia et al. 2019; Griscom et al. 2020). Our global estimate of 11.9 ± 3.1 GtCO_2eq yr^{-1} cost-effective potential between 2020-2050 is slightly higher than the IPCC-AR5 AFOLU economic mitigation potential of 7.18– 10.60 GtCO_2eq yr^{-1} in 2030, in line with the UNEP Emissions Gap economic potential of 12 GtCO_2eq yr^{-1} in 2050 (6.7 and 5.3

$GtCO_2eq\ yr^{-1}$ for agriculture and forests respectively), in line with the global cost-effective potential of 11 $GtCO_2eq\ yr^{-1}$ in Griscom et al. (2017), and slightly higher than the median estimate of supply-side measures in AFOLU of 10.6 $GtCO_2eq\ yr^{-1}$ between 2030-2050 in Roe et al. (2019). Our estimate is set apart from these studies in that it is the only one that includes cost-effective potential for demand-side and soil organic carbon sequestration in croplands and grasslands. Without the demand-side measures, our total cost-effective potential would be reduced to 8.7 ± 3.1 $GtCO_2eq\ yr^{-1}$. Our estimate without demand-side measures is more conservative compared to Griscom et al. (2017), Roe et al. (2019) and UNEP (2017), and could be due to additional data sources that generated average potentials that resulted in lower estimates for A/R and reduced deforestation, even though we covered a larger set of countries and scope of land-based mitigation activities.

Even with the advances made in this study, certain limitations and gaps remain. As highlighted in the Methods, completely accounting for land competition and double counting is difficult when aggregating sectoral estimates from different activities and methodologies. Separate studies may allocate the same land for divergent abatement activities. We attempt to limit double counting by excluding certain measures that could overlap (Methods). However, while we can limit overlapping activities, we are not able to adequately account for land competition and sub-optimal allocation of land and feedstocks when combining all activities from our sectoral approach assessed in **Table A1.1**. Due to these limitations, we also provide a comparison with IAM estimates that account for land allocation and optimization across all economic sectors, and thus avoid double counting. IAMs (in inter-model comparisons), however, only include about one quarter of the land-based measures we include in the sectoral estimates, and thus may be underestimating mitigation potential in the land sector. The cost-effective mitigation potential for AFOLU averaged between 2020-2050 in IAMs is 4.1 median (-0.1 - 9.5

range), less than half the estimate from the sectoral approach. In addition to a more limited portfolio of land-based measures, the large difference between the sectoral and IAM estimates are also likely due to IAM baselines and overshoot scenarios. Some IAM baseline scenarios include carbon prices and significant amounts of land-based mitigation, thus reducing the mitigation potential estimate in the \$100/tCO_2eq mitigation scenario. A majority of IAMs also include overshoot scenarios which places most of the mitigation after 2050, especially terrestrial CDR, which is beyond the time horizon considered in our estimates.

Our estimates (both sectoral and IAMs), similar to most current land-based mitigation estimates, do not yet account for: 1) the substitution effects for avoiding fossil fuel emissions, 2) the foregone sequestration potential from avoided land-use change and 3) the potential impacts from future climate change. These issues could have a substantial impact on land-based mitigation globally and regionally. Substitution effects of land-based measures, particularly of BECCS, biochar and wood products have the potential to reduce significant fossil fuel emissions. Accounting for the continued carbon sequestration potential of protecting forests and other ecosystems, rather than just avoided emissions, would also increase mitigation potential. On the other hand, inadequate action to reduce atmospheric GHG concentrations enhances the risk that climate impacts will reduce future potential for land-based mitigation and turn residual land sinks into sources (Jia et al. 2019). Additional research is therefore needed on the impact of substitution effects, foregone sequestration and global warming on individual land-based mitigation activities at a regional or country level. More data on country-level trade-offs (e.g., biodiversity, resource-use) from land-based measures could also aid country-level planning. Finally, expanding the portfolio of land-based mitigation measures in IAMs and country-level sectoral approaches would broaden the range of AFOLU potential considered.

Global and temporal implications of land-based mitigation

To stay on a 1.5°C pathway, total emissions will need to fall by about 50% each decade, until net zero emissions are reached about mid-century (Rockström et al. 2017; Roe et al. 2019; Rogelj et al. 2018). This process will require the transformation of every economic sector (Rogelj et al. 2018). The vast majority of land-based mitigation potentials could be mobilized quickly, and most are relatively lower cost compared to mitigation in other sectors. Near-term opportunities in the land sector would reduce the risk of overshooting a 1.5°C pathway (Roe et al. 2019), even as efforts to reduce emissions in other sectors take effect. Because of their economic characteristics, their substantial co-benefits, their ability to work in tandem with the decarbonization of other sectors, and their potential for rapid implementation, land-based mitigation activities could provide a larger share of the near-term, low-cost mitigation necessary to meet such ambitious decadal milestones. Longer-term opportunities which require more time to see mitigation gains, like carbon sequestration measures (A/R, soil carbon management) and/or additional research, technology and development, like the deployment of BECCS, will need up-front investment and long-term land-use planning including risk mitigation.

Our analysis adds new dimensions relevant to strategic planning and successful implementation of land-based measures, which can be used to plan and prioritize policies and measures, target co-benefits and help achieve other international goals and targets, such as the SDGs, NYDF, and the UN Decade on Ecosystem Restoration. In general, land-based mitigation potential correlates with countries' land area, but our analysis of mitigation densities reveals that many smaller countries have disproportionately high levels of mitigation potential for their size, suggesting fertile ground for investment there. Our feasibility assessment also suggests that governance, economic development, technology, socio-cultural conditions and acceptance of policies could create barriers for implementing land-based mitigation. A substantial portion of land-based mitigation potential is in developing countries and LDCs, where feasibility issues are of greatest concern. Collaborative efforts to unblock these constraints at the country or regional level may release globally significant quantities of near-term mitigation at relatively low costs. The timing, quantity and cost are key considerations for external actors who seek to help these countries mobilize their mitigation potential. Our research raises the possibility that investments to increase feasibility may, in fact, prove to be more cost-effective than investments aimed at the land-based mitigation activities themselves (i.e., by helping shift countries from left to right in **Figure A1.3**, mobilizing mitigation that might otherwise be infeasible).

Country context for implementing and scaling-up action

Our results show that the opportunities among countries are quite heterogeneous, in terms of the relative scale of mitigation potential, the types of land-based measures available, their potential co-benefits and risks, and the feasibility of realizing them. Strategies that determine what, where, when, and how mitigation measures are implemented will therefore vary significantly by country. Implementing mitigation measures that maximize co-benefits and limit risks will require strategies that consider mitigation costs and opportunities in other sectors, environmental and socio-economic consequences across stakeholders, trade-offs with other policy goals, and budgetary implications. To aid the development of such strategies, it is helpful to look at individual country plans and glean lessons learned from experiences in implementing land-based mitigation measures and policies. We highlight three countries below according to three mitigation potential tiers “Limited relative potential,” “High relative potential,” and “Surplus potential” (**Figure A1.3**) to outline some lessons and considerations in scaling-up action.

China, a "Limited relative potential, medium feasibility" country, recently announced a long-term climate mitigation plan to peak emissions before 2030 and achieve net zero emissions, or carbon neutrality, by 2060. To achieve its goals, China has to restructure its economy (Mallapaty 2020), including a 90% reduction of all GHG emissions by 2050 compared to 2005 levels and carbon removals using natural carbon sinks such as A/R and other CDR technologies (Tianjie 2020). China has significant experience with large-scale A/R programs, including the Grain for Green initiative to mitigate soil erosion, that resulted in a 25% net increase in global canopy area on 6.6% of global vegetated area between 2000-17 (Chen et al. 2019). However, China's A/R programs experienced significant localized trade-offs like water depletion and reduced biodiversity, which led to criticisms of, and adjustments to government programs (Hua et al. 2016). China's long-term climate mitigation plan highlights the need to harmonize climate with sustainable development goals. However, China has not yet included policy targets or measures for shifting diets or reducing food waste, which make up about 40% of its cost-effective land-based mitigation potential and can deliver significant co-benefits. China is an example of an industrialized country which, as a matter of priority, has to decarbonize its energy and industrial sectors (>90% of its emissions), but can use AFOLU mitigation to tap into near-term mitigation potentials that can deliver social and environmental co-benefits. Furthermore, any efforts to shift diets and reduce food waste could alter the long-term trajectory of agriculture emissions in China and beyond, especially considering its role as a major importer of agricultural commodities, including those that cause deforestation.

In contrast, the Democratic Republic of Congo, a "Surplus potential, low feasibility country", is characterized by relatively low fossil fuel emissions and high AFOLU emissions. DRC has the potential to generate surplus AFOLU mitigation, largely through the protection of forests and other ecosystems (95%), that can enable the country to achieve net negative emissions by mid-century. However, according to their NDC, the DRC faces a series of feasibility challenges that undermine the deployment and scaling up of mitigation action: limited national financial resources, external financial support, and technical, jurisdictional and institutional capacity; as well as the absence of policy and incentives that adequately addresses competing sectoral interests (mining, agriculture, forestry) (Government of the Democratic Republic of the Congo 2015). Activating DRC's mitigation potential will require addressing drivers of deforestation (commercial agriculture (40%), subsistence farming (20%) or wood fuel harvesting (20%)) and development challenges at the nexus of food security, rural development, energy supply, and forest conservation. Various programs and initiatives to reduce deforestation in the DRC have been in place since 2015 (Central African Forest Initiative created, FCPF Readiness Package approved); however, funding has been slow to materialize and feasibility constraints make it difficult for DRC to access result-based finance. DRC is an example of a forest LDC country that needs to deploy an integrated development strategy that leapfrogs carbon-intensive development in favor of clean and sustainable development choices and could significantly benefit from international partnership and assistance.

Another example, Ecuador, is a "High relative potential, medium feasibility country" with large potentials for protecting forests and other ecosystems (~60%). Reducing deforestation is identified as one of the main mitigation options in the country's NDC, which proposes to reduce deforestation by 4% (unconditional) or 20% (conditional on support) compared to a 2000-2008 reference level (Government of the Republic of Ecuador 2015). The country's existing payment-for-ecosystem services program, established in 2008 (Acuerdo Ministerial 161, Plan Nacional del Buen Vivir), proves the ability to successfully realize AFOLU mitigation potentials while delivering substantial co-benefits including ecosystem services and income to forest communities. Landowner contracts are for 20 years and commit to the preservation of tree cover.

As of December 2018, almost 175,000 people participated in the program, resulting in estimated avoided deforestation of 1.6 Mha, spanning about 15% of Ecuador's territory (Ecuadorian Ministry of Environment 2018). The program also led to a decrease in land conflicts in areas with ambiguous land titles (Jones et al. 2020) and generated both socioeconomic and ecological benefits. However, the program depends on continued government funding to incentivize persistent conservation behavior (Etchart et al. 2020). Ecuador expanded its funding sources for conservation programs by receiving results-based finance from the REDD+ Early Movers program (Germany/Norway, signed 2018) and the Green Climate Fund (2019). The country's experience with payment-for-ecosystem services shows how conservation payments can strengthen land governance, but also that continued funding and support is essential for its success.

These country examples within to our country categories (**Figure A1.3**), highlight various important considerations in implementing and scaling-up land-based mitigation. 1) AFOLU mitigation strategies are more successful when part of long-term strategies and policies that have a holistic view of emissions and decarbonization options from other sectors, of various land-use needs and challenges, and of sustainable economic development (Hurlbert et al. 2019). 2) Allowing for adaptive adjustments over time could enable needed corrections and enhance program sustainability and effectiveness (Smith et al. 2020; Hurlbert et al. 2019). 3) The integration of global commodity markets means that demand-side measures have to complement local supply-side measures. Embedded emissions and carbon leakage, particularly for large agricultural importers, make it difficult for medium- or low-feasibility countries to collectively address AFOLU emissions, particularly where agricultural demand and economic opportunity act as drivers of deforestation (Pendrill et al. 2019). While demand-side measures are largely lacking in country NDCs, they are essential to achieve AFOLU potentials. 4) Developing and

LDC countries will need to continue to develop, and could benefit from leap-frogging fossil-fuel intensive infrastructure and moving directly to sustainable energy infrastructure (Levin and Thomas 2016). 5) Global cooperation and assistance could help address feasibility barriers in developing countries, particularly to increase economic and institutional capacity.

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Appendix 2. Supplemental information to Chapter 2

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To provide a comprehensive assessment of the entire land sector (agriculture, LULUCF, and bioenergy), and its potential contributions to the Paris Agreement temperature target of 1.5°C, we conducted four separate, yet complementary analyses: 1) Review and synthesis of published, economy-wide 1.5°C pathways, 2) top-down comparative analysis of integrated assessment modelling of 1.5°C pathways in the land sector, 3) review and bottom-up assessment of land sector mitigation potential, updating the IPCC AR5 Ch11 findings, and 4) a geographically explicit roadmap of priority mitigation measures or "wedges" and regions to fulfil the 1.5°C land sector transformation pathway, informed by a triangulation of the first three analyses. The detailed methods and some resulting data are outlined below, structured in four sub-sections according to the four analyses.

1 Review of 1.5°C modelled pathways

We assess the pathways to 1.5°C and 2°C by compiling and analysing published, publicly available modelled data for emissions reductions to 2100. We chose studies that modelled emissions pathways for 1.5°C and 2°C scenarios, including scenarios that exceeded one or both of the temperature targets but met the target by the end of the 21st century. The studies were examined on a decade by decade basis, and we explored the assumptions regarding reductions in land versus non- land sectors, negative emissions deployment, total carbon budgets until 2100, and forecast trajectories of emissions reductions.

We examined both 2.6 w/m^2 (2°C forcing target) and 1.9 w/m^2 (1.5°C forcing target) Integrated Assessment Model (IAM) runs from the Shared Socioeconomic Pathways (SSP) Database (Version 2.0)[1,2] published in Rogelj et al. (2018)[2], the Integrated Assessment Modeling Consortium (IAMC) Database[3] (Version 1.0) that accompanied the IPCC special report on 1.5C, as well as individual estimates from Rockstrom et al. (2017)[4], Millar et al. (2017)[5], Walsh et al. (2017)[6], Goodwin et al. (2018)[7], and Tokarska and Gillett (2018)[8]. Rogelj et al. (2015)[9] was also reviewed but excluded in the analysis given its overlap with the new Rogelj et al. (2018) which assessed the same underlying IAMs with small version differences. The 2.6 w/m^2 model runs suggest that emissions reductions of between 70% and 90% are needed between 2020 and 2060, with net-negative emissions in most models starting between 2060 and 2080 in order to meet a 66% probability threshold keeping emissions below 2°C by 2100. 1.9 w/m^2 models require still steeper reductions, with emissions dropping to zero in all models between 2040 and 2060 and net-negative thereafter for the same probability threshold of 66%.

The total carbon budget available in the SSP Database 2.6 w/m^2 models between 2018 and 2100 ranges from 436 $GtCO_2$ to 1159 $GtCO_2$, with a median estimate of 964 $GtCO_2$. Models limiting 2100 radiative forcing to 1.9 w/m^2 (and 2100 temperatures to below 1.5°C) show correspondingly smaller carbon budgets from 2018-2100, ranging from requiring net-negative emissions of -174 $GtCO_2$ to allowing up to 402 $GtCO_2$, with a median estimate of 237 $GtCO_2$. Much of the difference in the budgets results from the treatment of non-CO_2 GHGs and aerosols in different IAMs[2,9], though the duration of net-negative emissions can also affect the results as it tends to deviate from the linear relationship between cumulative CO_2 and warming during periods of positive emissions[10].

The IAMC Database[3] models also include a wide range of 2018-2100 carbon budgets. Excluding those model runs also found in the SSP Database, the IAMC 2C runs have a budget ranging from 135 $GtCO_2$ to 1887 $GtCO_2$ with a median estimate of 951 $GtCO_2$. IAM 1.5C runs have a correspondingly lower cumulative carbon budget, ranging from -182 $GtCO_2$ to 745 $GtCO_2$ with a median of 144 $GtCO_2$.

Individual studies (Rockstrom et al. (2017), Walsh et al. (2017), and our own estimates) of the available carbon budget to limit 2100 warming to below 1.5°C provide results comparable to the range of SSP and IAMC Database IAMs for both 2°C and 1.5°C targets. Rockstrom et al. combined published model findings with expert judgment to prescribe a 50% reduction in CO_2 emissions per decade (88% total) between 2020 and 2050 until net zero emissions are reached in order to meet a 66% probability threshold for 2°C and a 50% probability threshold for 1.5°C, with an available 2018-2100 carbon budget of 132 $GtCO_2$. Walsh et al. derive emissions and temperature change from the FeliX integrated assessment model to find CO_2 emissions must peak in or slightly before 2020 and achieve net zero by about 2040 for 1.5°C, equating to 5% annual emissions reductions, and net zero by 2050 for 2°C, equating to 3% annual emissions reductions – or 100% and 97% by 2050, respectively. Their available 2018-2100 carbon budget is 371 $GtCO_2$ for 2°C and -489 $GtCO_2$ for 1.5°C, respectively, and is a bit below the range of values for IAM models. Our own model suggests 2018-2100 budgets of 979 $GtCO_2$ for 2°C and 268 $GtCO_2$ for 1.5°C, close to the median of SSP Database models.

The SSP and individual IAM studies represent avoidance budgets that target limiting warming in 2100 below 1.5°C by limiting end-of-century forcings to around 1.9 w/m^2. Millar et al. (2017), Goodwin et al. (2018), and Tokarska and Gillett (2018) use observational warming and cumulative emissions to-date to observationally constrain CMIP5 Earth System Model (ESM) results, and suggest significantly higher remaining 1.5°C carbon budgets than IAM-based approaches. Remaining 2018-2100 carbon budgets in Millar et al. are 625 $GtCO_2$ to 695 $GtCO_2$ for a 66% to 50% chance of preventing warming from exceeding 1.5°C, respectively. Goodwin et al. find a similar range from 693 $GtCO_2$ to 766 $GtCO_2$, while Tokarska and Gillett find somewhat lower values (395 $GtCO_2$ and 681 $GtCO_2$) for a 66% and 50% chance. These papers calculate exceedance rather than avoidance budgets, looking at how long emissions can continue increasing by 1% per year until temperatures exceed 1.5°C.

As Rogelj et al. (2018) point out, observation and ESM-based exceedance budgets that increase CO2 by 1% per year until temperatures exceed 1.5°C and IAM-based avoidance budgets that limit radiative forcing to 1.9 w/m^2 (and temperatures to below 1.5°C) in 2100 are not easily comparable. ESM-based approaches use the 50th and 66th percentiles of CMIP5 models, while IAMs use a prescribed climate sensitivity probability density function. This leads to somewhat more conservative outcomes among IAM-based approaches. While exceedance budgets using ESMs that have a 66% chance of avoiding 1.5°C still show maximum warming of around 1.45°C, IAMs with a 66% chance of avoiding 1.5°C have much lower 2100 warming, reaching only 1.3°C to 1.4°C above pre-industrial levels (though most IAMs exceed 1.5°C mid-century before reducing temperatures through the large-scale application of negative emissions).

Because the maximum warming lags emissions of carbon by about a decade, exceedance budgets do not fully account for emissions over the final decade before the 1.5°C threshold is exceeded. IAMs, on the other hand, are somewhat penalised because the cooling from negative emissions in the last decade before 2100 is not fully accounted for[2]. Additionally, many observationally-constrained ESM budgets use global surface temperature records that are not globally complete and use slower-warming ocean surface temperatures rather than the surface air temperatures over oceans[11,12].

These combine to make IAM-based avoidance carbon budgets relatively low compared to combined observation/ESM exceedance budgets. Rogelj et al. (2018) recalculated the Millar et al. carbon budget and found that a comparable globally-representative 2018-2100 avoidance budget would be somewhere between 25 $GtCO_2$ and 375 $GtCO_2$, overlapping with the majority of SSP Database IAM 1.9 w/m^2 budgets. Thus, we suggest that these recent exceedance budget studies are not necessarily at odds with the 1.5°C budgets used in this paper. Similarly, while the IPCC SR15 provides a best-estimate remaining 1.5C carbon budget of 420 $GtCO_2$, this value is not inconsistent with IAM-derived 2018-2100 cumulative budgets due to the differences in exceedance and avoidance calculations.

The IAM studies show a dramatic transformation of the energy and land sectors. Energy system transformation is generally characterized by a fossil fuel phase out, energy efficiency improvement, more rapid decarbonization of electricity compared to industry, buildings and transport, and extensive use of CO_2 capture and storage (CCS)[9]. The land sector transformation includes a dramatic decline in deforestation, a significant increase in afforestation and reforestation (A/R) and forest management, and reduced agricultural emissions after 2030-2040, facilitated by improved crop production efficiencies and yields[13,14]. These broad transformations are in line with those observed in the main IPCC AR5 RCP 2.6 scenario.

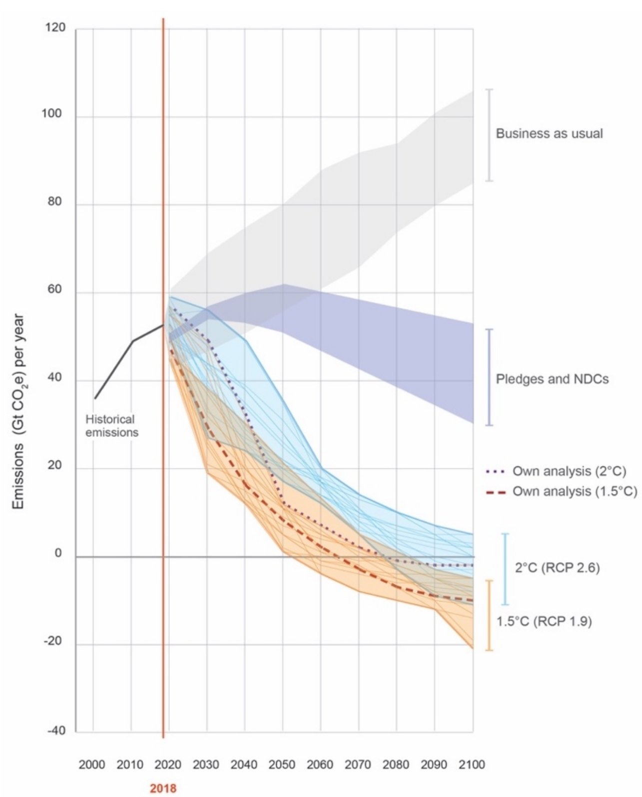

Figure A2.1 Greenhouse gas emission trajectories of 2°C and 1.5°C scenarios.

This figure includes major anthropogenic greenhouse gas emissions (CO_2, CH_4, N_2O, and various halocarbons, represented as $GtCO_2e$ per year using 100-year global warming potential values) and is a variant of the main text Figure 2.1 (which only includes CO_2). The 2°C (18 model runs in blue lines) and 1.5°C (13 model runs in orange lines) scenarios, from the recently updated SSP Database of Integrated Assessment Model runs, present values at a >66% probability threshold[1,2]. NDC numbers are adapted from Climate Action Tracker, 2018. Business as usual numbers represent the range of SSP2 baseline scenarios. Historical emissions data is from EDGAR 4.3.2.

2 Review of 1.5°C modelled pathways in the land sector

To gauge the contribution of the land sector in 1.5°C and 2°C pathways, we conducted a comparative assessment of model outputs from the Integrated Assessment Modeling Consortium (IAMC) Database[3] and Shared Socioeconomic Pathways (SSP) Database[1,2]. We reviewed emission pathways and land cover balances of the various pathways. We also conducted a sensitivity analysis to test the effect of reducing BECCS.

Emission pathways

We used the IAMC Database[3] (Version 1.0) to assess net CO_2, CH_4, and N_2O emissions trajectories to 2100 in 1.5°C (1.9 w/m^2), 2°C (2.6 w/m^2), and Reference (BAU) scenarios in LULUCF, Agriculture and BECCS (**Figure 2.2a**). We combined the LULUCF and Agriculture categories to derive trajectories for AFOLU. We calculated the mitigation potential for the land sector in the 1.5°C scenarios by summing mitigation potentials from AFOLU and BECCS (**Figure 2.2c**). Mitigation potential for all other sectors represents global mitigation minus land sector mitigation. Mitigation potential is the difference between the reference scenario and the 1.5°C scenario for each model and scenario, summed for AFOLU, BECCS and Other sectors. The Database represents 19 models and 90 model scenarios. More detailed information is provided in the IPCC Special Report on 1.5°C Chapter 2[15] and the IAMC Database website[3].

The IAMC Database does not have data for specific activities in agriculture, therefore, we used the updated SSP Database (Version 2.0)[1,2] to assess the N2O emission pathways for Cropland Soils, Manure, and Pastures, the CH4 emission pathways from Enteric Fermentation, Manure, and Rice, and CO2 emission pathways for Land-use change, A/R and Forest

Management, and BECCS in a 1.5°C scenario (1.9 W/m^2) (**Figure 2.2b**). We also calculated the mitigation potentials for the mentioned activities (Difference between BAU and 1.5°C for each model scenario) to compare with the bottom-up assessment of literature (**Figure 2.4**). The SSP Database represents five Shared Socio-economic Pathways (SSPs – described in Box S1) and includes six integrated assessment models (AIM, GCAM, IMAGE, MESSAGE-GLOBIOM, REMIND-MAgPIE, and WITCH-GLOBIOM). Popp et al. (2017)[13] provide a comparative assessment of emission pathways, land use changes, prices and consequences for the agricultural system across the SSPs in the BAU, 2°C (2.6 w/m^2), and 4°C (4.6 w/m^2) scenarios – but not for 1.5°C (1.9 W/m^2). More detailed information on the SSPs and the six models in the SSP Database, including their underlying assumptions for the energy sector (energy demand, supply and conversion technologies) and the land sector is provided in Riahi et al. (2017)[1] and the Supplementary Information of the same study.

Box 1. Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSP)

Developed by the scientific community for the IPCC, four RCPs have been developed to provide climate modelers a consistent framework of possible development trajectories for the main forcing agents of climate change (van Vuuren et al., 2011). RCPs can be used in General Circulation Models (more complex, full Earth System Models) and in Integrated Assessment Models (simpler models that use socio-economic development pathways) to project temperature increases and related impacts. Other concentration pathways have since been developed, including one with radiative forcing of 1.9 W/m^2 which is consistent with 1.5°C of warming. The four RCPs include:

- RCP 2.6: Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2e) and then decline to 2.6 W/m^2 by 2100
- RCP 4.5: Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2e) at stabilization after 2100
- RCP 6: Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2e) at stabilization after 2100
- RCP 8.5: Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2e) by 2100

Five Shared Socioeconomic Pathways (SSP1-SSP5) have been developed by the climate modelling community to facilitate comparable integrated assessments of future climates. The SSPs are based on different socio-economic development narratives, including:

- SSP1: Sustainable Development;
- SSP2: Middle-of-the-road development (business as usual);
- SSP3: Regional rivalry;
- SSP4: Inequality;
- SSP5: Fossil-fueled development.

References: [1,13]

Land cover balance

To assess projected land cover changes, we used the updated SSP Database (Version 2.0)[1,2] to compare land cover (Mha) trajectories in 1.5°C (1.9 w/m^2), 2°C (2.6 w/m^2), and BAU scenarios until 2100. We used the SSP Database instead of the IAMC Database as there are more land cover categories (e.g. managed vs unmanaged forests). Two land cover change calculations were assessed: the change in 2050 and 2100 compared to 2020, and compared to BAU for each model and scenario (**Table A2.1**).

Natural forests (unmanaged forests) are primary, secondary, and protected forests with no planned timber production and tree felling either for wood extraction or for silvicultural purposes such as pre-commercial thinnings. Managed forests are forests which are managed either for timber production and/or carbon sequestration which could include BECCS. Energy Crops are short rotation plantations and other feedstocks for bioenergy including BECCS. The definitions for natural and managed forests are not fully harmonized across models. Two models account for A/R (e.g. newer forests) in natural forests – making it possible for natural forests to increase over time, another three models have a separate A/R forest category, and one model did not include A/R (**Table A2.2**). The different methodologies makes the distinction between natural and managed forests difficult to disentangle and natural forest loss difficult to evaluate. However, instead of including all forests under one category, we think it is helpful to distinguish in our study to shed a light on these issues.

As mentioned in our paper, BECCS deployment (and hence land dedicated to energy crops) is one of the main reasons for land-use change. The scale of BECCS deployment is influenced by the SSP and radiative forcing scenario, and differing model assumptions. To elucidate some of these assumptions, we compare model methodologies on biomass feedstock, current and future agricultural yields, and conversion efficiencies (**Table A2.3**).

Table A2.1. Land cover changes in Mha in 1.5°C scenarios across all SSPs, compared to 2020 and BAU levels.
The change in land cover balance is calculated as the difference in Mha between the two scenarios being compared for each model scenario, then aggregated into quartiles (positive numbers indicate increase in land cover, negative numbers indicate decrease).

Energy crops	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	647	1051	Min	649	757
	Q1	554	705	Q1	494	589
	Median	287	594	Median	204	299
	Q3	168	371	Q3	113	175
	Max	91	152	Max	48	-24
Food (and feed and fibre) crops	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	50	66	Min	-40	41
	Q1	-69	-206	Q1	-205	-284
	Median	-159	-334	Median	-294	-393
	Q3	-254	-517	Q3	-327	-423
	Max	-470	-775	Max	-423	-616
Pasture	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	-40	-107	Min	-11	-14
	Q1	-123	-242	Q1	-49	-49
	Median	-386	-583	Median	-359	-520
	Q3	-456	-730	Q3	-496	-709
	Max	-632	-1155	Max	-625	-1474
Managed forest	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	313	1348	Min	545	1431
	Q1	127	165	Q1	58	72
	Median	43	42	Median	22	27
	Q3	-66	-134	Q3	-12	-3
	Max	-116	-225	Max	-48	-36
Natural (unmanaged) Forests	**Compared to 2020**	**2050**	**2100**	**Compared to BAU**	**2050**	**2100**
	Min	1014	1809	Min	972	1534
	Q1	734	932	Q1	846	801
	Median	182	364	Median	303	446
	Q3	-9	4	Q3	76	60
	Max	-294	-929	Max	-313	-1070

TableA2.2. Treatment of A/R across the six models in the SSP Database.

AIM/CGE 2.0	A/R is included in natural forests
GCAM4 4.2	A/R is included in natural forests
IMAGE 3.0.1	A/R (forests afforested or reforested after 2020) is reported in a separate A/R category, the vegetation type is natural, secondary forest after natural regrowth and succession dynamics
MESSAGE-GLOBIOM 1.0	A/R (forests afforested or reforested after 2000) is accounted for in a separate A/R category, there is also an increase in managed forests which come from a decrease in natural forests
REMIND-MAgPIE 1.5	There is no A/R in the SSP runs. All forest area increases are related to regrowth of natural vegetation on abandoned agricultural land
WITCH-GLOBIOM	Relies on GLOBIOM assumptions

Table A2.3 Assumptions and methodologies relevant for bioenergy and BECCS deployment in the six models in the SSP Database

	AIM/CGE 2.0	GCAM 4.2	IMAGE 3.0.1	MESSAGE-GLOBIOM 1.0	REMIND-MAgPIE 1.5	WITCH-GLOBIOM
Feedstocks used for BECCS	Dedicated 2nd generation bioenergy crops such as miscanthus and switchgrass, as well as residues	A variety of BECCS feedstocks, including grassy crops (e.g., switchgrass), woody crops (e.g., willow), and residues are used. In practice, most of the bioenergy pool comes from grassy crops and residues – not a lot of woody bioenergy	Dedicated bioenergy crops (sugar cane, miscanthus, short-rotation forestry) and crop residues	Short rotation tree plantations such as poplar, willow or eucalyptus as biomass feedstock, and forest biomass feedstocks. Grassy crops such as Miscanthus or switchgrass are not represented in GLOBIOM due to a lack of information on spatially explicit productivities and costs at global scale	Residues as well as dedicated 2nd generation bioenergy crops such as Miscanthus and Poplar	Energy crops and residues for BECCS
Average yield of bioenergy feedstock	Average yields varies across scenarios and time. Energy-crop yield is estimated using a process-based biogeochemical model, VISIT (Ito et al. 2012)[16] and data from the H08 model (Hanasaki et al. 2018)[17].	Average yields vary depending on feedstock, region, year, and scenario.	Yields differ through time - described in detail in Daioglou et al. (2019)[18]	Yields change over time and across SSP scenario following the GLOBIOM assumptions on different SSPs – described in detail in in Fricko et al. (2017)[19]	Average yields vary across time, scenario and region - described in detail in Kriegler et al (2017)[20] and Popp et al (2014)[21] (compares bioenergy yields for IMAGE, MAgPIE and GCAM)	Same as GLOBIOM

Conversion efficiency of BECCS EJ/yr to CO2/yr captured	The conversion efficiency is 75 MtCO2/EJ. As CO2 emissions associated with life cycle is considered in an input-output table structure in the CGE model, this number represents direct emissions only, but the emissions associated with life cycle is considered in our calculation. Energy loss rate is 30%.	Two different types of BECCS power plants and four different types of BECCS refineries are included. These differ in their energy conversion efficiency (EJ of bioenergy input divided by EJ of electricity/liquids output) and their capture rates (what % of the CO2 is captured post-combustion/conversion). We calculate the potential emissions from combustion (for electricity) or conversion (for liquids). For BECCS plants, we then remove some fraction (~90% for electricity, 25-90% for liquids) of the CO2 and put it underground instead of in the atmosphere.	Varies significantly according to scenario - described in Daioglou et al. (2018)[18]	MESSAGE includes four BECCS technology types: Hydrogen production via biomass gasification; Fischer-Tropsch biomass-to-liquids; Ethanol synthesis via biomass gasification; and biomass IGCC power plant. Capture rates for non-liquefaction processes with BECCS vary from around 86%-90%. Ethanol production from biomass with BECCS have a capture rate of around 65-67%. Detailed are described online and in Chapter 13 of the GEA[22].	Differ according to scenario - described in Kriegler et al. (2017)[20]	In WITCH, conversion efficiency of BECCS plant is 90% - described in Vinca et al. (2018)[23]
Main land cover changes in 1.5C scenario and rationale	Bioenergy crops are allocated on abandoned cropland and natural grasslands	Where bioenergy is actually grown depends on the relative profitability, which in turn depends on the yield & price of bioenergy and the yield & price of alternative land uses. The exact distribution of bioenergy is very scenario dependent, with assumptions about trade and land policy strongly influencing where it is grown.	Bioenergy crops are preferably allocated on abandoned cropland and natural grasslands - with large variations based on location.	Bioenergy crops largely replace pasture lands, and managed forests replace natural forests. In the 1.5°C scenario, intensity of forest resource use (share of total harvest volumes in total forest increment) increased significantly by 2100.	Bioenergy crops primarily replace pastures. Land cover changes detailed in Popp et al. (2017)[13] and Rogelj et al. (2018)[2]	Same reference as REMIND

Sensitivity analysis using GLOBIOM

We explored the effect of limiting bioenergy demand on land cover balance, and the impact on natural ecosystems and food security using one of the models in the SSP Database, MESSAGE-GLOBIOM[24]. In the 1.5°C scenario for MESSAGE-GLOBIOM, a significant amount of unmanaged (natural) forests were converted into managed forests (~400 Mha in 2050) to meet additional demand for bioenergy for BECCS. By optimizing for cost-efficiency, the model increased the intensity of forest resource use (share of total harvest volumes in total forest increment) and harvested large areas instead of enhancing harvest in smaller areas. To test the effect of carbon price and bioenergy demand on natural ecosystems and food security we conducted a sensitivity analysis for the 1.5˚C scenario using GLOBIOM. In the sensitivity analysis, we used SSP 2, "middle of the road", and disentangled bioenergy demand from the carbon price by setting a bioenergy threshold at baseline levels (53 EJ/yr and 59 EJ/yr in 2050 and 2100 respectively compared to 109 EJ/yr and 220EJ/yr in the 1.5°C scenario) while still applying the same carbon price trajectories from the 1.5°C and 2°C scenarios. Energy crops were reduced by 75% in 2050, and the conversion of ~500 Mha of natural forests, ~100 Mha of grassland, and 20 Mha food and feed crops was avoided (**Figure A2.2**). The results of the analysis show that bioenergy deployment had a large impact on natural ecosystems, yet a high carbon price for agricultural emissions was the main driver of food price increases (and food security concerns). While the sensitivity scenario is a departure from the most cost-effective pathway, it demonstrates that alternative paths to 1.5˚C can lower pressure on land. This pathway with reduced bioenergy and CDR from BECCS, however, would need to be counterbalanced by more rapid emission reductions in the short run and additional efforts in potentially more costly sectors such as transportation, industry, agriculture and non-BECCS CDR such as A/R or DAC [15,25,26]. The carbon price would need to increase in the shorter and mid-term to drive these efforts. If agriculture emissions will need to be reduced further, food prices may likely increase in this scenario, and thus potentially affect food security. However, the sensitivity analysis does not represent a fully consistent 1.5˚C scenario across all sectors, hence it was not possible to show this effect.

GLOBIOM is a partial equilibrium model of the global agricultural and forestry sectors. The model is spatially explicit at a high resolution of 5x5 minutes of arc, and depict different production and management systems, differences in natural resource and climatic conditions as well as differences in cost structures and input use. The model explicitly represents technical mitigation options for the agricultural and forestry sectors. For the agriculture sector, mitigation is based on the EPA database on mitigation options[27], structural adjustments in the crop- and livestock sector i.e. through transition in management systems or reallocation of production within and across regions[24], and consumers' response to model endogenous price signals[28]. For the forestry sector the model considers the reduction of deforestation area, increase of afforestation area, and change in forest management activities such as rotation length, thinnings, harvest intensity etc. The carbon price is implemented in the objective function of the model as a tax on GHG emissions, consequently mitigation options get adopted if the carbon price exceeds the marginal cost of a mitigation practice. More information on the mitigation options in the model is provided in Frank et al. (2018)[29] and Gusti and Kindermann (2011)[30]. More detailed information on GLOBIOM is available in Havlík et al. (2014)[24].

GLOBIOM is coupled with the MESSAGE[31] energy model which calculates carbon prices, as well as biomass demand for energy use, compatible with the respective climate stabilization scenarios. Biomass demand in GLOBIOM can be satisfied from multiple sources: managed forests, short rotation tree plantations and forest industry residues. Bioenergy plantations are accounted for in the land sector (under forest management) until harvest, then bioenergy, processing, use and carbon removal through CCS is accounted for in the energy sector. In the event of conversion of natural forests into managed forests for BECCS, the deforested biomass is used for BECCS. The MESSAGE energy model and its methodologies and assumptions on future energy demand and use of fossil fuels, nuclear, renewables, and biomass for energy are outlined in Fricko et al. (2017)[19].

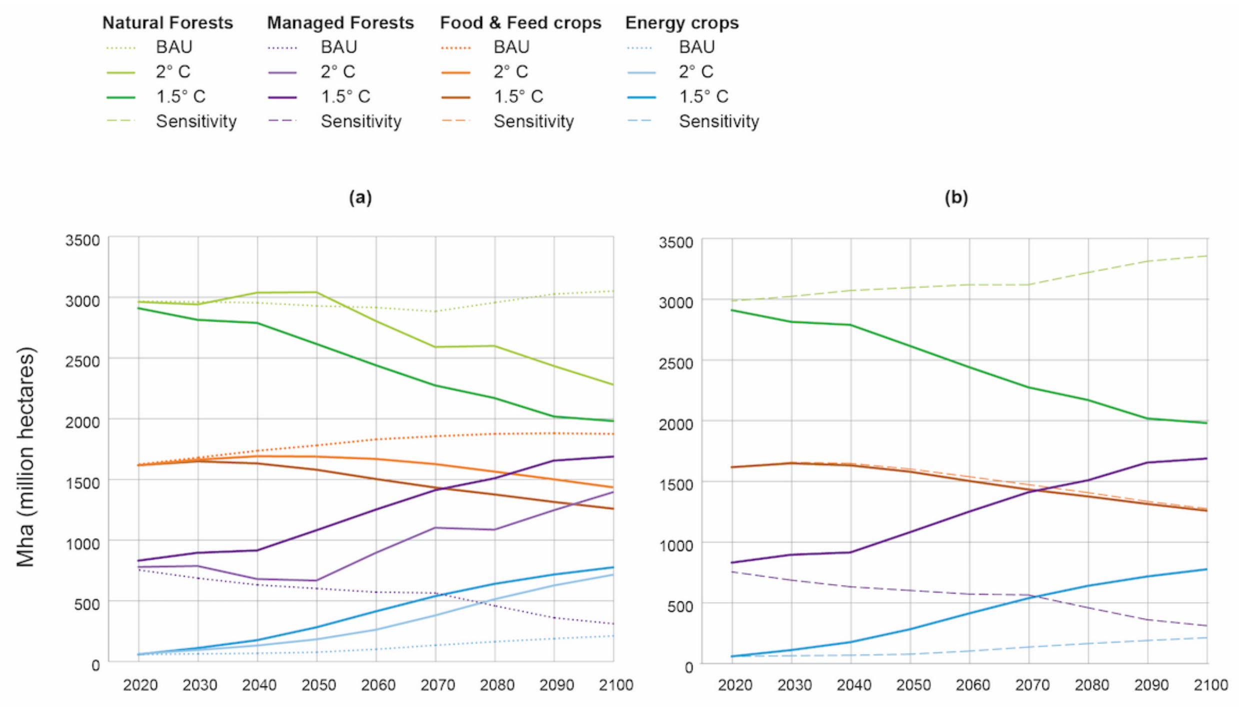

Figure A2.2. Sensitivity analysis of land cover balance trajectory in GLOBIOM.
(a) Land cover balance (Mha) in BAU, 2°C and 1.5°C scenarios, (b) Land cover balance (Mha) in the 1.5°C and sensitivity (bioenergy threshold) scenarios. Unmanaged forests (natural forests) are defined as primary, secondary, and protected forests with no planned timber production and tree felling either for wood extraction or for silvicultural purposes such as pre-commercial thinnings. Managed forests are forests which are managed either for timber production and/or carbon sequestration, including BECCS. Energy Crops are short rotation plantations for bioenergy including BECCS, and consist of willow, poplar, eucalyptus or other fast-growing species.

3 Bottom-up assessment of mitigation potential in the land sector

To gauge what activities will be the most effective in meeting the 1.5°C temperature target, we assessed the full range of technical and economic mitigation potential by synthesizing published literature and data for the following main categories: land-use change, carbon sequestration, and agriculture on the supply-side, and food waste and losses, diets, wood fuel, and wood products on the demand side. Technical mitigation potential is the amount of additional emissions reductions and carbon sequestration possible with current technologies without economic and political constraints. Economic mitigation potential is the amount of emissions reductions and carbon sequestration possible given cost constraints, usually a carbon price at $/tCO_2$. We also identified “Sustainable mitigation potential” when it was explicitly specified by studies, defined as technical or economic mitigation potential constrained by food security and environmental considerations. We adopted the framework and data from the IPCC AR5 AFOLU Chapter 11[32] and updated with more categories and newer data from recently published literature. We include all mitigation potential estimates that provide a CO2e/yr (or similar derivative) figure by 2050, from studies published on or after 2010 (after IPCC AR5). Given that we combine estimates from multiple studies and sources, there are a range of methodologies reflected that may not be directly comparable or additive. Some of the studies use biophysical estimates, and others combine biophysical and economic mitigation potential. Insofar as it was possible, elements of the analysis were designed to avoid potential double-counting of mitigation opportunities (each of the categories and what was considered and calculated is detailed below). Some of the estimates are imprecise due to limited data, uncertainties in emissions, and variable mitigation interventions, and some do not include time-bound pathways.

For the regional estimates, we used the country-level mitigation potential estimates of Reduced deforestation, Afforestation/Reforestation, Forest Management (Natural Forest Management + Improved Plantations + Forest Fire Management), Rice cultivation, Pasture management (Optimal intensity of grazing + Legumes), Peatland Restoration, Reduced peatland conversion, and Reduced coastal conversion from Griscom et al. (2017)[33]. We disaggregated the global mitigation potential of avoided forest conversion as reported in Griscom et al. (2017), to country level using proportional historic forest loss emissions as derived through Global Forest Watch using datasets from Hansen et al. (2015)[34] and Zarin et al. (2016)[35]. We also produced country mitigation potential estimates of enteric fermentation, manure management and synthetic fertilizer by using percentages of FAOSTAT emissions averaged between 2010-2015 (40% reduction of enteric fermentation in countries with extensive cattle production and 10% reduction in countries with intensive cattle production, 70% reduction of manure emissions, and 30% reduction of synthetic fertilizer emissions). The percentages are based on technical feasibility ranges presented in literature ([36–40]) to generate a rough technical mitigation potential by country. EU emissions were derived by summing the mitigation potential of all EU countries by category. Categories and numbers are presented in **Table A2.4**.

Supply-side Measures

Reduce land cover and land-use change: *The overall mitigation potential for the land use change category include deforestation + coastal wetlands + savannas and natural grasslands. We do not include the estimates for degradation and reduced conversion and burning of peatlands as some deforestation estimates include degradation and peatlands.*

Land conversion is the single largest source of land sector emissions, with estimates ranging between 2.3 – 5.8 Gt CO_2/yr for deforestation and 2.1 – 3.67 $GtCO_2$/yr for degradation[34,35,41–46]. Agriculture drives 50-80% of tropical deforestation, primarily from commodity-driven agribusiness[47]. Peatland conversion (fires and peat decomposition from drainage) account for 0.6 – 1.2 $GtCO_2e$/yr[48,49]. Globally, the drainage of peatlands generates 32% of cropland emissions yet only produce 1.1% of total crop calories[49]. While only 10% of peatlands are located in the tropics, they account for more than 80% of peatland soil emissions, primarily in Indonesia (~60%) and Malaysia (~10%)[48,50]. Wetlands (mangroves, tidal marshes, and seagrasses) have also been converted, with over 25-50% of wetlands lost in the last 50-100 years due to aquaculture, agriculture, industrial use, upstream dams, dredging, eutrophication of overlying waters, and urban development[51–53]. Limiting warming to 1.5°C will require a near halt of all gross deforestation and conversion by 2040.

Table A2.4 Country- level mitigation potential in $MtCO_2e/yr$ in the top 25 countries.
The categories used for country-level mitigation potential in Figure 2.5 are highlighted in grey. Data is from Griscom et al., 2017 and calculations from FAOSTAT 2017. Estimates of mitigation potential for enteric fermentation, manure management, and synthetic fertilizer were calculated from country-level FAOSTAT emissions data. We derived mitigation potential by multiplying acceptable % emissions reductions from the literature with the emissions data. For enteric fermentation, 40% emissions reductions are for extensive pasture-based systems in developing and emerging countries and 10% are for more intensive systems in developed countries.

	FAOSTAT				Griscom et al., 2017											FAOSTAT croplands + Griscom pasture
	30%	40% /10%	70%	30%												
	Cropland mgmt	Enteric fermentation	Manure mgmt	Synthetic fertilizer	Reduced deforestation	Avoided wood fuel	A/R	Forest mgmt	Grazing-Optimal Intensity	Grazing-Legumes	Pasture mgmt (optimal intensity + legumes)	Rice cultivation	Peatland restoration	Reduced conversion of peatlands	Reduced coastal conversion	Agriculture soil carbon sequestration
Brazil	6.55	105.63	7.66	7.81	990.23	25.12	1549.72	121.39	10.52	0.23	10.75	4.38	8.74	1.75	3.79	17.3
China	12.19	80.46	51.93	46.5	208.05	65.2	1256.71	35.27	25.04	19.4	44.44	51.42	36.32	42.47	0.05	56.63
Indonesia	12.28	7.95	4.88	5.56	570.24	27.42	212.02	80.25	0.24	8.58	8.82	21.56	363.85	514.24	60.2	21.11
EU	25.3	22.07	59.41	4.01	0	0	1140.28	60.75	14.19	15.37	29.56	1.9	104.94	13.86	0	54.86
India	8.8	113.72	19.93	32.66	28.55	53.88	519.47	42.58	0.93	0	0.93	69.66	1.46	0.29	2.18	9.74
Russia	6.77	14.45	7.77	2.32	0	0	351.33	245.05	0.78	0	0.78	0.33	89	2.07	0	7.55
Mexico	1.02	18.01	2.41	2.37	53.25	4.8	516.96	0	5.23	1.46	6.69	0.26	2.91	0.58	2.33	7.72
USA	12.91	12.32	30.07	23.62	0	0	357.98	65.72	13.73	13.79	27.52	2.35	17.58	3.54	3.8	40.43
Australia	17.11	19.84	3.59	2.26	0	0	385.67	60.35	8.95	2.43	11.38	0.28	2.5	0.21	0.77	28.49
Colombia	0.43	12.79	1.02	1.14	80.09	1.8	295.04	0	1.84	0.77	2.61	0.71	0.09	0.1	0.16	3.04
Myanmar	1.66	2.01	4.82	0.23	60.33	6.24	237.27	28.89	0.2	2.51	2.71	13.03	2.91	0.58	18.4	4.37
Malaysia	1.36	0.43	0.62	0.89	182.86	0.9	29.38	19.14	0	0	0	1.1	34.93	57.01	17.94	1.36
Argentina	2.72	25.16	1.32	1.51	65.68	2.13	207.41	3.08	8.27	0.77	9.04	0.34	0.07	0.05	0	11.76
Thailand	1.28	2.99	2.31	3.03	38.57	5.67	186.18	0.8	0	0.05	0.05	19.7	1.57	0.25	3.74	1.33
Venezuela	0.37	1.99	0.75	0.55	30.92	0.67	165.53	52.04	0.94	0.37	1.31	0.48	2.62	1.11	0.97	1.68
Paraguay	0.44	6.31	0.32	0.2	53.96	2.07	150.16	0	1.01	0.03	1.04	0.07	0.06	0.01	0	1.47

Vietnam	1.4	3.67	4.29	2.44	47.66	6.76	128.2	5.4	0.21	0.63	0.84	12.16	3.81	0.76	0.65	2.24
Canada	4.23	6.4	4.26	4.95	0	0	54.58	127.86	0	5.32	5.32	0	0.99	0.2	0	9.55
UK	1.14	7.96	3.44	2.03	0	0	153.05	0	1.31	8.53	9.84	0	5.76	1.15	0	10.98
DRC	4.75	0.41	0.15	0.01	130.92	0.9	35.64	0.1	0.1	0	0.1	0.34	0.01	0.01	0.05	4.85
Tanzania	2.97	7.69	0.56	0.12	33.14	8.94	66.73	55.26	0.95	0.01	0.96	1.72	0.26	0.11	0.16	3.93
Philippines	0.65	2.69	2.4	0.97	24.06	3.29	118.84	6.47	0.09	0	0.09	7.08	0.23	0.05	2.03	0.74
Bolivia	0.48	5.46	0.58	0.04	84.32	0.41	64.37	0.03	0.89	0.26	1.15	0.38	0.04	0.01	0	1.63
Cote d'Ivoire	0.46	0.58	0.1	0.06	41.07	2.95	101.23	10.72	0.26	0	0.26	0.8	0.87	0.47	0.05	0.72
Peru	0.18	4.97	0.6	0.5	64.52	1.2	32.88	45.61	0.86	0.5	1.36	0.62	0.29	0.06	0	1.54

Land can be spared and conserved through direct activities (e.g., REDD+, land planning policies, and supply chain interventions), and indirect activities (agricultural intensification to increase yields and reduce conversion pressure, reduce food waste to increase yields, and shift diets to reduce demand for commodities that cause deforestation.

Countries with the highest area of deforested lands include Brazil, Indonesia and the Democratic Republic of Congo (DRC), while countries with the highest deforestation rates include West African and Southeast Asian countries, as well as Paraguay in South America (**Figure A2.3 and A2.4**). Tropical peatland forests have a deforestation rate of 4% per year, significantly higher than the average rate for tropical forests at 0.5%[46,54].

The potential for reducing emissions from reducing and/or halting deforestation range between 0.4 – 5.8 Gt CO_2/yr, with the higher estimate representing a complete halting of land use conversion in forests and peatlands and accounting for biomass and soil carbon[33,35,37,44,55–60]. Reducing annual emissions from peatland conversion, draining and burning would mitigate 0.45 – 1.22Gt CO_2e/yr[33,48,56], while reducing the conversion of coastal wetlands (mangroves, seagrass and marshes) would realize mitigation of 0.11 – 2.25 Gt CO_2e/yr of emissions[33,51,56,61]. These estimates represent biophysical and technical potential (higher ranges) and economic and feasible mitigation potential (lower ranges). The upper estimates reflect the theoretical avoidance of all land-use change emissions. Differences in estimates also stem from varying land cover definitions, time periods assessed, and carbon pools included (most lower estimates only include aboveground biomass, and most higher estimates include all five IPCC carbon pools: aboveground, belowground, dead wood, litter, soil, and peat).

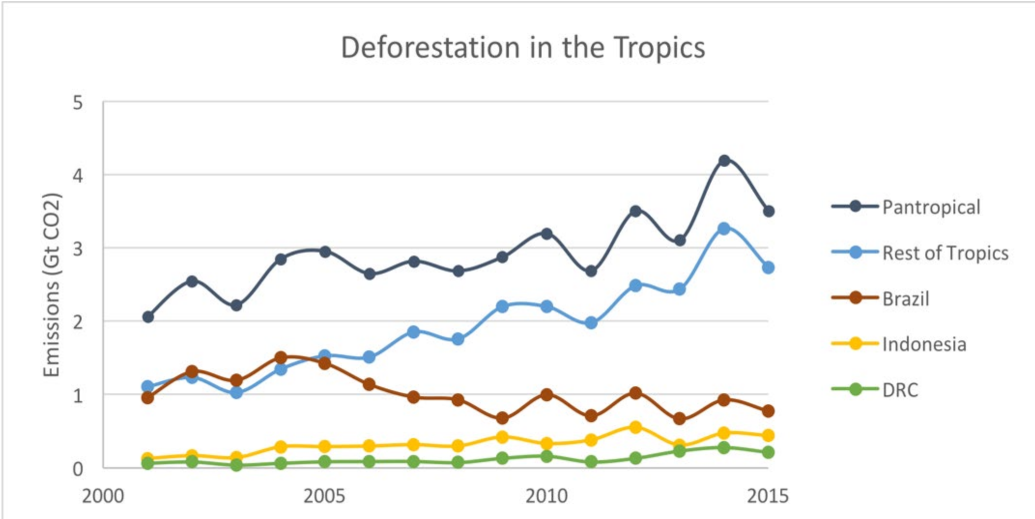

Figure A2.3. Trends in tree cover loss in the tropics from 2000-2015.
Data source: Global Forest Watch, 2017

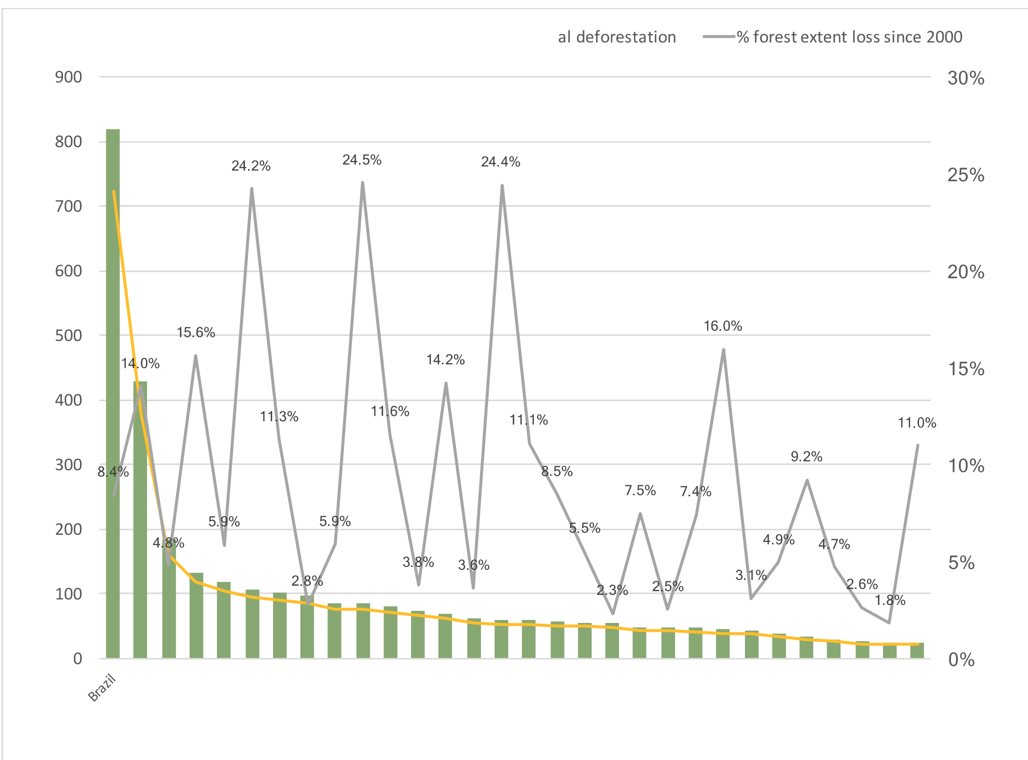

Figure A2.4. Land use change emissions (deforestation) by country.
The green bars represent emissions ($MtCO_2e/yr$) using a five-year average (2011-2015). The yellow line represents the share of total tropical deforestation by each country (it is not continuous data). The grey line represents the percent of forest extent lost in each country since 2000 (it is not continuous data). Data source: Global Forest Watch, 2017

Enhance carbon sequestration

The overall mitigation potential for the carbon sink enhancement category includes afforestation / reforestation (converting non-forest land into forests, and reforesting and restoring forests) + restoration of coastal wetlands (mangroves and marshes) + agricultural soil carbon enhancement (soil carbon sequestration in croplands and grazing lands) + biochar application. We do not include forest management (natural forest management, improved plantations, forest fire management), agroforestry and peatland restoration due to some estimate overlaps with A/R.

Increasing sequestration of vegetation and soil carbon in natural and managed systems can remove a significant amount of carbon emissions in the atmosphere. Currently, the terrestrial carbon sink removes 30% of anthropogenic emissions[62]. Land-based activities that could sequester additional carbon include A/R, forest management, agroforestry, peatland restoration, coastal wetland restoration, agricultural soil carbon enhancement, biochar, harvested wood products and bioenergy with carbon capture and storage (BECCS).

Afforestation, the conversion of non-forested land into forests, and reforestation, restoring and replanting deforested or degraded forests, can increase carbon sequestration in both vegetation and soils by 0.5 – 10.12 Gt CO_2/yr[33,55,56,58,63–70]. The lower estimate represents the lowest range from an earth system model[68] and of sustainable global negative emissions potential[65], and the higher estimate[33] reforests all areas where forests are the native cover type, constrained by food security and biodiversity considerations. Recent mitigation potential estimates for A/R provide "plausible" figures of 3.04 GtCO_2/yr by 2030 with environmental, social and economic constraints (<\$100/tCO_2)[33], and 3.64 GtCO_2/yr between 2020-2050 based on a conservative scenario of restoration commitments and smaller scale afforestation[56]. The annual reforestation in 2015 was reported at 27 Mha, and countries have committed to restore another 161 Mha of forests by 2030 led by China, Brazil, India and the US[71,72].

Improving forest management includes extending rotation cycles between harvests, reducing damage to remaining trees when harvesting, reducing logging waste, implementing soil conservation practices, fertilization, and using wood more efficiently. Forest management could potentially mitigate 0.44 – 2.1 Gt CO_2/yr[33,73,74], where the low estimate is the "low cost" (<$10/t$CO_2$) implementation of natural forest management and improving plantations[33] and the upper estimate represents switching from conventional logging to reduced-impact logging practices[74]. A new study asserts that Climate Smart Forestry, a technique addressing the ecosystem, wood products and the energy supply chain in Europe, could double the forest management climate mitigation potential by 2050[75].

Agroforestry is a land management system that combines woody biomass (e.g., trees or shrubs) with crops and/or livestock, and can include fruit or timber trees for harvest, windbreaks, riparian buffers, and silvopasture. Agroforestry systems have a long tradition in temperate regions around the world and have also been developed as a land management practice in many developing countries, particularly for smallholder systems. The mitigation potential ranges between 0.11 – 5.68 Gt CO_2/yr[33,38,56,76], where the low estimate represents a conservative adoption of agroforestry practices in mixed crop-livestock systems in humid and tropical highland areas of the developing world, and the high estimate represents the "optimum" implementation scenario of "silvopasture" + "tree intercropping" + "multistrata agroforesty" + "tropical staple trees."[56]

Wetland and peatland restoration includes rewetting peat soils and replanting peatland and mangrove vegetation. Approximately 0.6 Gt CO_2/yr can be mitigated if 30% of the 65 Mha of drained peatlands were rewetted to stop continued emissions from carbon oxidation, and about

3.2 Gt CO_2/yr if all ongoing CO_2 emissions from continued peat oxidation were ceased[77,78]. The mitigation potential range is between 0.15 – 0.81 Gt CO_2/yr from studies since 2010[33,77], where the lower estimate represents "low cost" (<\$10/tCO_2) restoration[33] and the higher estimate represents biophysical potential constrained by food security and environmental considerations[33]. Mangrove restoration can mitigate the release of 0.20 Gt CO_2/yr through "cost effective" (<\$100/tCO_2) restoration[33] and 0.84 Gt CO_2/yr from biomass and soil enhancement[33]. Peatland restoration, as well as agroforestry and forest management mitigation potential are included in some of the A/R estimates and are therefore not added to the total terrestrial carbon enhancement mitigation potential.

Sequestering carbon in agricultural systems through regenerative and conservation agriculture practices (including use of perennials or deeper rooted cultivars, reduced tillage, crop residue management, organic amendment and fire management), and grazingland management (including managing stocking rates, timing and rotation of livestock, higher productivity grass species or legumes, and nutrient management) have considerable mitigation potential. Soil carbon sequestration (SCS) in croplands have a potential range of 0.25 – 6.78 Gt CO_2/yr[14,33,38,40,56,79–84], where the low estimate is the "low cost" (<\$10/tCO_2) implementation of conservation agriculture[33], and the high estimate is the increase of soil organic carbon in 0-30 cm of all cropland soils from 0.27% to 0.54%[85]. The SCS potential in grazing lands is 0.13 – 2.56 CO_2/yr[14,33,56,63,79,81,82,84–88], where the low estimate is the "low cost" (<\$10/tCO_2) implementation of "grazing - optimal intensity" + "grazing - legumes in pasture" and "fire management in savannas" [33], and the high estimate is a maximum biophysical potential[81]. Storing carbon by converting biomass into recalcitrant biochar to use for soil amendment also has the potential to mitigate 0.030 – 6.6 Gt CO_2/yr[33,38,56,64,65,70,82,88–92]. The higher end of the estimate assumes bioenergy crops can be used to make biochar and includes syn-gas production as offsetting fossil fuel usage[92], while the lower estimate uses a fraction of available residues only (no purpose grown crops)[56]. While soil carbon and biochar have large mitigation potential, there continues to be a great deal of uncertainty in the science of soil carbon, specifically on issues of storage capacity and permanence[82,88]. Levels of carbon in the soil, as well as biomass, trend towards a new equilibrium level, meaning that sequestration rates steadily drop to negligible levels over the course of several decades for most soils[93]. In the future, that carbon can also be released back into the atmosphere depending on the crop management practice and climatic conditions. Additionally, there is great inconsistency in observed carbon sequestration rates from different management practices (particularly on tillage), primarily due to variety of environmental factors including soil type, moisture, temperature, microbial and fungi composition, nutrient availability[94], and the particulars of how the management is actually applied.

Carbon can also be removed through technologies that use land such as bioenergy with carbon capture and storage (BECCS). Biomass used for BECCS (trees, energy crops and residues) sequester carbon as they grow, the biomass is then processed in plants to produce energy, and finally the CO_2 is stored in geological reservoirs to produce net negative emissions. The mitigation potential is estimated to be approximately 0.4 – 11.3 Gt CO_2/yr in 2050[63–65,70,91,95,96]. The low estimate only uses available residues[95] and the high estimate is the upper range from a modelling study[91]. BECCS is included in our mitigation potential estimate, however, it is important to note that BECCS deployment is still in the development, exploration, and piloting stages.

Reduce direct agricultural emissions

The overall mitigation potential for the agriculture category includes all direct CH_4 and N_2O emissions: CH_4 and N_2O from manure management, N_2O emissions from cropland nutrient management and manure on pasture, CH_4 emissions from rice cultivation and enteric *fermentation, and all emissions from synthetic fertilizer production. We do not include cropland and pastureland management as they are accounted for in the soil carbon enhancement category.*

Sustainable intensification reduces the emissions intensity of agriculture by using inputs more efficiently or adding new inputs that address limiting factors of production. These practices are typically based on changes or increases in the use of direct inputs, such as improved varieties/breeds, nutrient and organic amendments, water and mechanization. In addition, a variety of farming practices can be adopted that optimize density, rotations and precision of inputs.

Reducing emissions intensity from agriculture: cropland nutrient managagement, enteric fermentation, manure management, rice cultivation and fertilizer production has a total mitigation potential of 0.30 – 3.38 Gt CO_2/yr (**Figure A2.4**). The mitigation potential of cropland nutrient management (fertilizer application) 0.03 – 0.71 Gt CO_2/yr[27,33,38,56,82], and manure on pasture is 0.01 Gt CO_2/yr[39].

Enteric fermentation is responsible for over 40% of direct agricultural emissions with beef and dairy cattle accounting for approximately 65%[40]. The three main measures to reduce enteric fermentation include improved diets (higher quality, more digestible livestock feed), supplements and additives (reduce methane by changing the microbiology of the rumen), and animal management and breeding (improve husbandry practices and genetics)[38]. Applying these measures can mitigate 0.12 – 1.18 Gt CO_2/yr[33,36,38,40]. Most livestock production systems in highly developed countries (e.g., the U.S., E.U., Australia, and Canada) have intensified systems and thus have lower mitigation potential per unit compared to developing countries with large livestock herds managed at low productivity levels, suboptimal diets, nutrition and herd structure (e.g., India, Latin America and Sub-Saharan Africa). These developing countries have higher mitigation potential gains from sustainable intensification.

Manure from livestock cause both nitrous oxide and methane emissions, and account for roughly one quarter of direct agricultural GHG emissions[38]. Although stored manure accounts for a relatively small amount of direct agricultural emissions, it is technically possible to mitigate a high percentage of these emissions (as much as 70% for most systems)[36,38]. The mitigation potential ranges from 0.01 – 0.26 Gt CO2/yr[38,40]. The highest manure management emissions come from China, India, the US and the EU (**Figure A2.6**). Measures to manage manure include anaerobic digestion for energy use, composting as a nutrient source, reducing storage time, and changing livestock diets. Improved manure management practices have important co-benefits including reducing water and air pollution, and increased yields and income from nutrient and energy inputs produced.

Rice production contributes about 11% of emissions from agriculture and 90% of this is from Asia[97]. The top rice producing countries—China, India, Indonesia, Thailand, Philippines, Vietnam Bangladesh, and Myanmar—account for more than 85% of global rice emissions (**Figure A2.5**). Reducing emissions from rice production through improved water management (periodic draining of flooded fields to reduce methane emissions from anaerobic decomposition), and straw residue management (apply in dry conditions instead of on flooded fields, avoid burning to reduce methane and nitrous oxide emissions) has the potential to mitigate up to 60% of emissions[98] or 0.08 – 0.87 Gt CO_2/yr[27,33,38,56,82,98]. While well managed rice fields can increase yields and reduce water needs, correct management of water levels requires precise control of irrigated systems and high technical capacity that may present barriers to adoption[38].

Synthetic fertilizer production is a major source of GHG emissions and air pollution as it requires a large amount of energy to produce and uses fossil fuels (natural gas or coal) as feedstocks. China has the largest emissions from synthetic fertilizer production as they have older, less efficient plants and use coal feedstocks[38]. Improvements in industrial efficiency are typically cost effective, would improve the productivity of the sector, reduce pollution, and have the potential to mitigate 0.05 to 0.36 Gt CO_2e/yr in China (there are no global estimates)[38,99].

Efficiency improvements from sustainable intensification generally produce productivity gains and improve farmers' livelihoods, especially smallholders. If managed well, intensification can also spare land/avoid land conversion because greater agricultural production occurs on the same area of land. However, efficiency improvements also carry the risk of environmental and social trade-offs that need to be managed. Intensification will likely produce an increase in fertilizer use and other agrochemicals which may increase emissions and pollution. Further, more efficient production methods can reduce costs and increase yields, and therefore, may encourage farmers to further increase production and expand land use (deforest)[100]. Sustainable intensification will need to go hand in hand with improved land-use planning, environmental safeguards and standards, and law enforcement to avoid these negative impacts.

Demand-side Measures

The overall mitigation potential for the demand-side measures includes diet shifts + food waste + demand for wood products + demand for wood fuel. We provide separate estimates for total supply-side and demand-side measures as these two categories are not additive.

Demand-side measures reduce GHG emissions by cutting down the overall level of production and increasing the efficiency of high emission intensity products, thus sparing land and decreasing direct agriculture emissions. Most of the impacts from demand-side interventions are therefore generally positive as they reduce competition and pressure on land, water and other inputs in contrast to supply-side measures that require more land and/or more inputs[37].

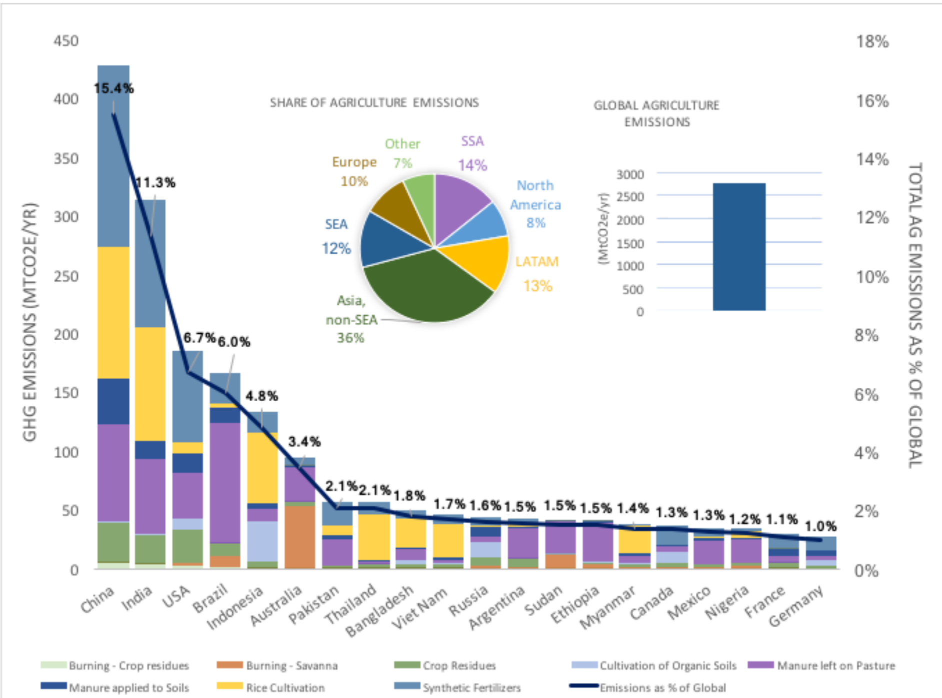

Figure A2.5. Agriculture emissions (crops and soils) by country.
Bars represent emissions (in $MtCO_2e/yr$) using a five-year average (2010-2014). The blue line represents share of global emissions by country (data is not continuous). Data source: FAOSTAT, 2015

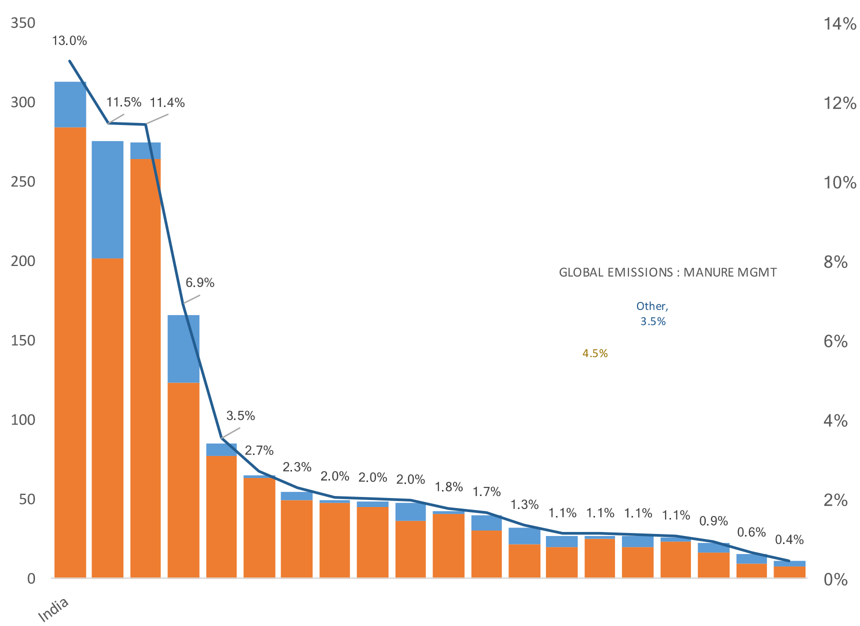

Figure A2.6. Livestock emissions (enteric fermentation and manure management) by country.
Bars represent emissions (in $MtCO_2e/yr$) using a five-year average (2010-2014). The blue line represents share of global emissions by country – data is not continuous. Data source: FAOSTAT, 2015

The discussion on food security and agriculture mitigation over the last two decades has almost exclusively focused on ways to increase productivity and reduce net GHGs emissions from production – i.e., the supply side. However, as the global population grows and incomes rise, the demand-side of the equation will become more important, including which products are consumed, how much is consumed, and how much food is wasted. Demand-side measures have the potential to significantly mitigate emissions of 1.81 – 14.31 Gt CO_2e/yr from reductions in food loss and waste (food wastage), changes in diets, the substitution of wood for cement and steel in construction, and the use of cleaner cookstoves. Approximately 55% of the upper bound of this estimate comes from changes in diet, and another 30% comes from reductions in food wastage.

Shifting away from emissions-intensive foods like beef delivers a substantial mitigation potential of 0.7 – 8 Gt CO_2e/yr[37,38,40,56,101–104], with the high estimate representing a vegan diet[101]. The production of beef produces the highest GHG, water, land, and energy footprint of all proteins – approximately 10 times higher in GHG emissions than any other animal protein (dairy cattle, pigs, chicken)[38,47,102]. Countries with the highest overall and projected beef consumption include predominantly developed and emerging countries: US, EU, China, Brazil, Argentina, Russia (**Figure A2.7**). A recent study finds "plausible" mitigation potential of 2.2 $GtCO_2e$/yr (0.9 $GtCO_2e$/yr without land-use change impacts) if 50% of the global population adopted "plant-based diets" constrained to 2500 kilocalories/ person/day and 57g of meat protein per day[56]. In addition to reduced emissions, shifting diets has the potential to deliver additional environmental, health and economic co-benefits. Decreasing meat consumption, primarily of ruminants, reduces water use, soil degradation, pressure on forests, and manure and pollution into water systems[38]. Reducing the amount of land and grains used for livestock could also increase food supply by 50% by freeing available resources[105]. Given the established links between diet-related diseases and high levels of meat consumption, keeping global average per capita meat consumption at healthy levels will also have important health benefits (reduced risks of cardiovascular diseases, cancer, stoke and diabetes)[101].

Reducing food losses and waste increases the overall efficiency of food value chains, reduces land pressure, and could contribute to reducing 0.76 – 4.5 of CO2e/year[38,56,103]. A recent study finds "plausible" mitigation potential of 2.4 $GtCO_2e$/yr (0.9 $GtCO_2e$/yr without land-use change impacts) if food waste is reduced by 50% in 2050[56]. In the developing world, losses mainly occur postharvest as a result of financial and technical limitations in production techniques, storage and transport[106] (**Figure A2.8**). In contrast, losses in the developed world are mostly incurred by end consumers[106]. The highest overall food waste occurs in China, the US and the EU, while the highest food losses occur primarily in Southeast Asia and Sub-Saharan Africa. When considering per capita waste and losses however, the US is almost double that of the EU and China. Strategies to reduce food loss and waste include improving harvesting, handling and storage techniques for the downstream losses, and consumer awareness campaigns and policies for the upstream food waste. Cutting current food loss and waste levels in half has the potential to close the 70% gap of food needed to meet 2050 demand by roughly 22%, potentially making the reduction of food wastage a leading strategy in achieving global food security[106]. As food wastage is a by-product of inefficiency, the negative trade-offs are limited and there are vast opportunities for savings along the entire supply chain.

Increasing demand of wood products in construction to substitute more GHG intensive materials like cement and steel could also present an opportunity for emissions reductions. Pathways to reduce emissions include increasing carbon storage in harvested wood products (HWP) and avoiding emissions from the production of concrete and steel[107,108]. Various studies have calculated the displacement factor, or the substitution benefit in CO_2, when wood is used instead of another material – with a range of -2.3 to 15 tC of emission reduction per tC in wood product and a mode range of 1.0 to 3.0 tC[107]. Displacement factors, as well as calculations of carbon storage from HWPs have been used to calculate mitigation potential of wood substitution in various countries including Canada[108], the EU[109], Japan[110] and the US[111]. However, there are limited estimates of global mitigation potential from increasing the demand of timber products to replace construction materials, as well as their potential risks and co-benefits. The range of 0.25 – 1.0 $GtCO_2$ of mitigation potential[63,112] is relatively small compared to other demand-side measures. There is concern that increased demand for wood products may reduce forest stocks and have other environmental risks, however studies have shown that increased wood demand led to higher wood prices and investments in forest management in some parts of Europe, China and New Zealand[19,75,113]. Additional studies are needed to better understand the global dynamics (GHG emissions, trade, deforestation impacts) of increasing wood products in construction.

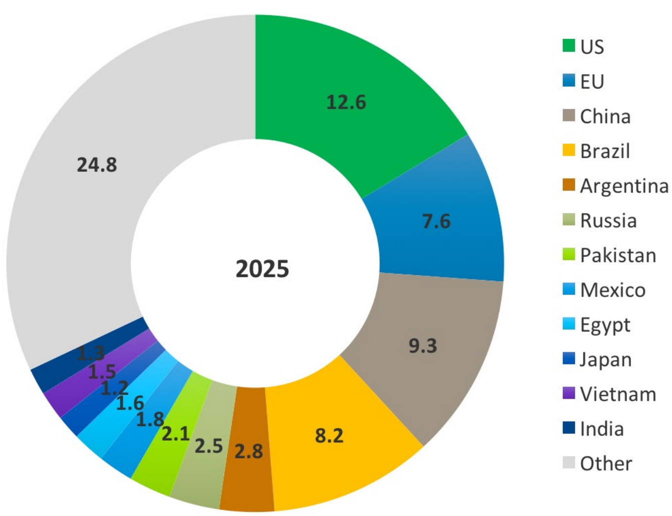

Figure A2.7. Beef consumption projected by 2025 in total tons of kcal by country.
Data source: FAOSTAT, 2015

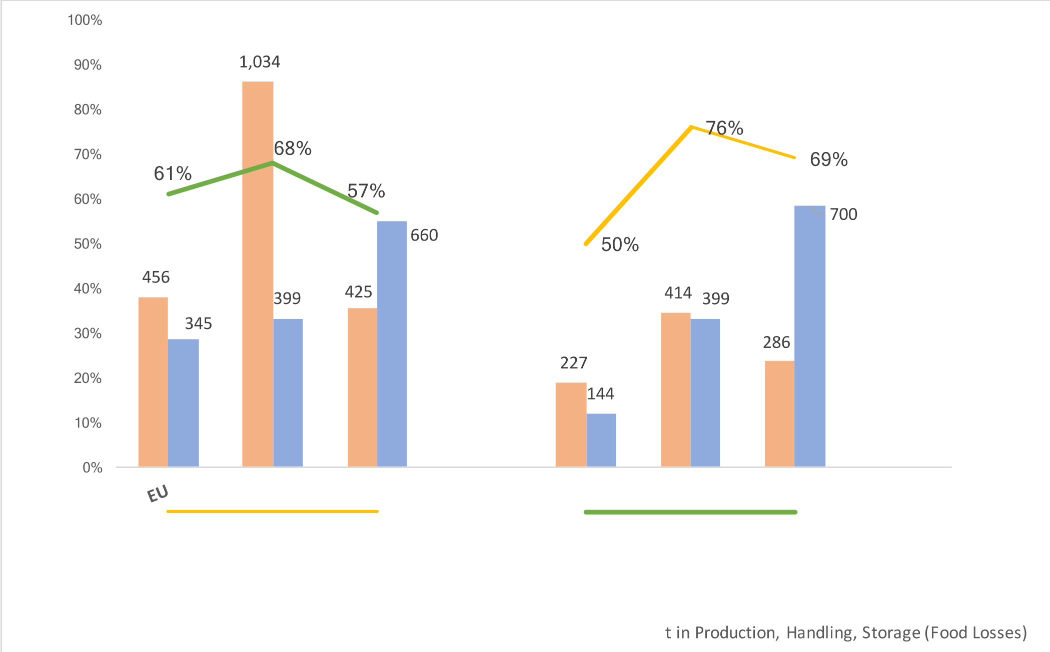

Figure A2.8. Food loss and food waste in by region.
Data source: World Resources Institute, 2014

4 Roadmap of priority mitigation wedges for the land sector to 2050

We developed a roadmap of priority activities and geographies to deliver on the 1.5°C temperature goal, drawing upon our modelled pathways and the bottom-up mitigation potential assessment. Reconciling the median top down modelling (13.8 $GtCO_2e/yr$) and bottom up literature review (14.6 $GtCO_2e/yr$) estimates, we established a viable mitigation target (sum of emission reductions and removals) for the land sector of ~14 $GtCO_2e/yr$ (15 $GtCO_2e/yr$ with BECCS) in 2050. We then divided the mitigation effort into eight priority mitigation measures, or "wedges"[114]. The wedges incorporate the 24 activity types from all four main mitigation categories from the bottom-up literature assessment: reduced land-use change, reduced agricultural emissions, reduced overall production through demand shifts, and carbon removal through enhanced carbon sinks. The amount of mitigation for the individual wedges were determined by first qualitatively weighing associated risks and co-benefits (**Table A2.6**), and then identifying feasible estimates (plausible, cost effective, sustainable, desirable) in the bottom-up assessment of the literature (**Table A2.5**). Given the strong interaction effects of land-based mitigation activities on each other (e.g. land competition, prices, yields), on ecosystem services (e.g. water, air, biodiversity and resilience) and on biophysical impacts (e.g. radiative cooling/warming and albedo), we prioritized measures that minimize risks, maximize co-benefits and overlap with Sustainable Development Goals, the New York Declaration on Forests (NYDF) and United Nations Convention on Biological Diversity (UNCBD), Aichi Targets (**Table A2.6**). The wedges are measures which are individually accounted for with the intent of avoiding double counting of emissions reductions so that the measures are additive (**Table A2.5**, described in activity types and source).

For each wedge, we then disaggregated action into geographies, prioritizing countries/regions according to their mitigation potential (Section 3 above, **Table A2.4, Figures A2.7 and A2.8**), and constrained by our political feasibility assessment as outlined in the next section. We developed implementation trajectories based on the total emission reductions or carbon removals required in 2050 for the literature source used for each wedge (**Table A2.5**). The 2020-2050 trajectories of percent emissions reductions and cumulative carbon removals also relied on carbon budget trajectories from our inter-model assessment, and used political feasibility (next section) and cost considerations (by aligning our priority wedges and mitigation trajectories to our modelled results, e.g on reducing deforestation). Cumulative carbon removal trajectories use 25% of mitigation potential per year for 2020-2030, and full mitigation potential per year after 2030 for biological measures and after 2040 for BECCS. We compared our roadmap emissions reductions to BAU and to 2020 emissions, both of which are similar (~11 $GtCO_2e$/yr).

Table A2.5. Priority mitigation measures ("wedges) in 2050 Land Sector Roadmap by activity types, GHG mitigation potential, and related source and rationale for mitigation estimate.

	Mitigation wedge	Activity types	Mitigation potential	Source
Land-use change	Reduce deforestation and degradation, conversion of coastal wetlands, and peatland burning	Conservation policies, establishment of protected areas, law enforcement, improved land tenure, REDD+, sustainable commodity production, improved supply chain transparency, procurement policies, commodity certification, cleaner cookstoves	4.6 $GtCO_2e$/yr: 3.6 from deforestation 0.7 from conversion of peatlands 0.3 from coastal wetlands	"Maximum additional" mitigation potential by 2030 from Griscom et al. (2017)[33]. Estimate is constrained to be consistent with meeting human needs for food and fiber.
Agriculture	Agriculture	Reduce CH4 and N2O emissions from enteric fermentation, fertilizer management, synthetic fertilizer production, water and residue management of rice fields, and manure management	1.0 $GtCO_2e$/yr	"Needed mitigation" from Wollenberg et al. (2017)[115] and "feasible mitigation at $25/$tCO_2e$" from Frank et al. (2017)[14]
Demand shifts	Shift to plant-based diets	Reduce production of high GHG intensive foods through public health policies, consumer campaigns, development of novel foods	0.9 $GtCO_2e$/yr	"Plausible scenario" from Hawken (2017)[56] where 50% of the global population will adopt a plant-rich diet by 2050 (criteria: 2500 kilocalories/ person/day; Meat protein constrained to 57 grams per day; Purchasing locally produced food when possible) by 2050. Estimate only reflects emissions reductions from diverted agricultural production, and not from avoided land use change.
	Reduce food waste	Reduce food waste: consumer campaigns, private sector policies, supply chain technology, improved food labelling, waste to biogas Reduce food loss: improve handling & storage practices through training, investment and technology	0.9 $GtCO_2e$/yr	"Plausible scenario" from Hawken (2017)[56] where 50% reduction in total global food loss and wastage is achieved by 2050 compared to BAU. Estimate only reflects emissions reductions from diverted agricultural production, and not from avoided land use change.
Carbon enhancement	Restore forests, coastal wetlands and drained peatlands	Investment in restoration, national and local policies, payment for ecosystem services, integration of agroforestry into agricultural and grazing lands	3.6 $GtCO_2$/yr: 3.0 from reforestation 0.4 from peatland restoration 0.2 from coastal wetland restoration	"Cost effective" mitigation at <$100/$tCO_2$ in 2030 from Griscom et al. (2017)[33]. Estimate is constrained to be consistent with meeting human needs for food and fiber, and avoiding negative impacts to biodiversity (no establishment of forests where they are not the native cover type).
	Improve forest management and agroforestry	Optimizing rotation lengths and biomass stocks, reduced-impact logging, improved plantations, forest fire management, certification, integration of agroforestry into agricultural and grazing lands	1.6 $GtCO_2$/yr: 0.9 from natural forest management 0.3 from improved plantations 0.4 from trees in croplands	"Cost effective" mitigation at <$100/$tCO_2$ in 2030 from Griscom et al. (2017)[33]. Estimate is constrained to be consistent with meeting human needs for food and fiber, and avoiding negative impacts to biodiversity.
	Enhance soil carbon sequestration in agriculture and apply biochar	Erosion control, use of larger root plants, reduced tillage, cover cropping, restoration of degraded soils, biochar amendments	1.3 $GtCO_2$/yr: 0.8 from agriculture soil carbon enhancement 0.5 from biochar	"Plausible scenario" from Hawken (2017)[56] adopting regenerative agriculture practices on 407Mha by 2050 to sequester carbon. To be conservative, mitigation potential of other SCS activities from Hawken (2017) is excluded. "Sustainable global NET potential" of biochar from Fuss (2018)[65]. Lowest estimate in the range of 0.5-2 $GtCO_2$/yr
	Deploy BECCS	R&D, investment and deployment	1.1 $GtCO_2$/yr	Mitigation potential of "sustainably harvestable" biomass for BECCS on "marginal land" overlapping CO_2 storage basins, from Turner et al. (2018)[95]

Table A2.6. 2050 Land Sector Roadmap priority mitigation measures ("wedges) and their related risks, co-benefits, and alignment to international policies and commitments.

			Co-benefits[33,38,122,65,66,116–121]							International policies and commitments		
	Mitigation wedge	**Risks** [38,65,116]	Biodiversity	Water (filtration, flood control, reduced pollution)	Soil (fertility, water retention, reduced erosion)	Air (filtration, reduced pollution)	Resilience (enhanced adaptation capacity)	Food security (increased yields, available land)	Livelihoods (incomes, jobs)	Sustainable Development Goals (SDGs)[123]	New York Declaration on Forests (NYDF)	United Nations Convention on Biological Diversity (UNCBD), Aichi Targets
Land-use change	Reduce deforestation and degradation, conversion of coastal wetlands, and peatland burning	Potentially impact farming practices and development	✓	✓	✓	✓	✓	✓	✓	Goal 14.5 By 2020, conserve at least 10 per cent of coastal and marine areas... Goal 15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands... Goal 15.2 By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally	Goal 1: "…halve rate of loss of natural forests globally by 2020…end natural forest loss by 2030"	Target 5: "By 2020, rate of loss of all natural habitats… is at least halved…and degradation and fragmentation is significantly reduced"
Agriculture	Agriculture	Technology and capacity needs for farmers; Potential to reduce yields depending on mgmt; Interventions can be costly		✓	✓	✓	✓	✓	✓	Goal 2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change... and that progressively improve land and soil quality Goal 14.1 By 2025, prevent and significantly reduce marine pollution...in particular from land-based activities, including...nutrient pollution		

Demand shifts	Shift to plant-based diets	Shift to unsustainable fisheries; Potentially reduce farmer incomes	✓	✓	✓	✓	✓	✓		Goal 12. Ensure sustainable consumption and production patterns Goal 12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature Goal 2.4 (see above)		
	Reduce food waste	Short-term profit shortfalls for retailers	✓	✓	✓	✓	✓	✓	✓	Goal 12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses		
Carbon enhancement	Restore forests, coastal wetlands and drained peatlands	Land requirements; Net-positive warming effect from albedo in high latitudes; Permanence; Possible nutrient and water requirements	✓	✓	✓	✓	✓	✓	✓	Goal 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes Goal 15.1 (see above) Goal 15.2 (see above)	Goal 5: "Restore 150 million hectares of degraded landscapes and forestlands by 2020…an additional 200 million hectares by 2030"	Target 15: "By 2020… restoration of at least 15% of degraded ecosystems"
	Improve forest management and agroforestry	Land requirements; Net-positive warming effect from albedo in high latitudes; Permanence; Possible nutrient and water requirements	✓	✓		✓	✓		✓	Goal 15.2 (see above)		
	Enhance soil carbon sequestration in agriculture and apply biochar	Permanence; Competition for biomass resources in biochar	✓	✓	✓	✓	✓	✓	✓	Goal 2.4 (see above)		
	Deploy BECCS	Land competition; Natural ecosystem conversion; Biodiversity losses; Nutrient and water requirements; Reduce mitigation ambition							✓	Goal 15.2 (see above)		

Political feasibility assessment

We conducted a political feasibility assessment based on two main criteria: 1) The political will to realize mitigation potentials and 2) The ability to implement mitigation policies. As a proxy (indicator) for political will, we analysed the land-sector goals included by countries in their NDCs (Nationally Determined Contributions) submitted to the UNFCCC secretariat. We assessed NDCs according to the following categories:

a. Specified activities, policies and measures for the land-use sector (2 points);
b. Specified land-use targets that are quantifiable in terms of emissions reductions (4 points);
c. Specified economy-wide targets that include land use and are quantifiable in terms of emissions reductions (6 points).

Countries were assigned scores according to the category they fall into (**Figure A2.9**). NDCs that achieved the highest score contained quantifiable measures that were economy-wide. Countries with specified and quantifiable targets for the land-use sector scored slightly lower, while lowest scores were assigned to NDCs that communicate non-quantifiable activities or measures. Subtractions were made if emissions reductions targets were made relative to projected business-as-usual scenarios (-2 points) or if made contingent upon the provision of international climate finance (-1 point).

To gauge the ability of countries to implement mitigation policies, we used (a) governance indicators; and (b) access to finance as indicators. For governance, we used six of the World Bank governance indicators (government effectiveness, regulatory quality, rule of law, political stability, control of corruption, and voice and accountability), and averaged the rankings to create a governance score for each country (**Figure A2.10**). For access to finance, we used GDP per capita of a country to serve as proxy (indicator), differentiating countries along four World Bank income categories: low income, lower middle, upper middle, and high income (**Figure A2.11**).

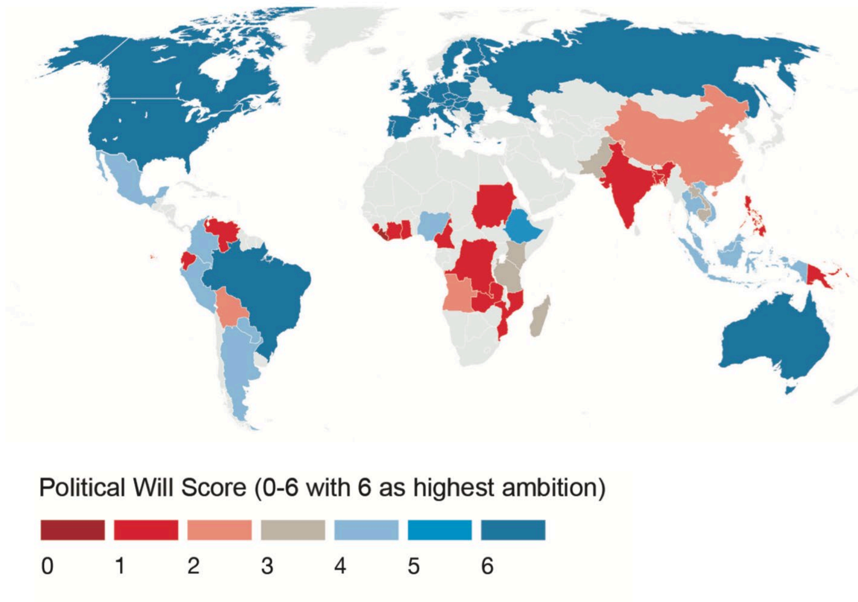

Figure A2.9. Political will of top 40 emitting countries including the European Union which submitted a regional NDC.
Scores are based on current NDCs and not political declarations or elections. Data source: UNFCCC submissions

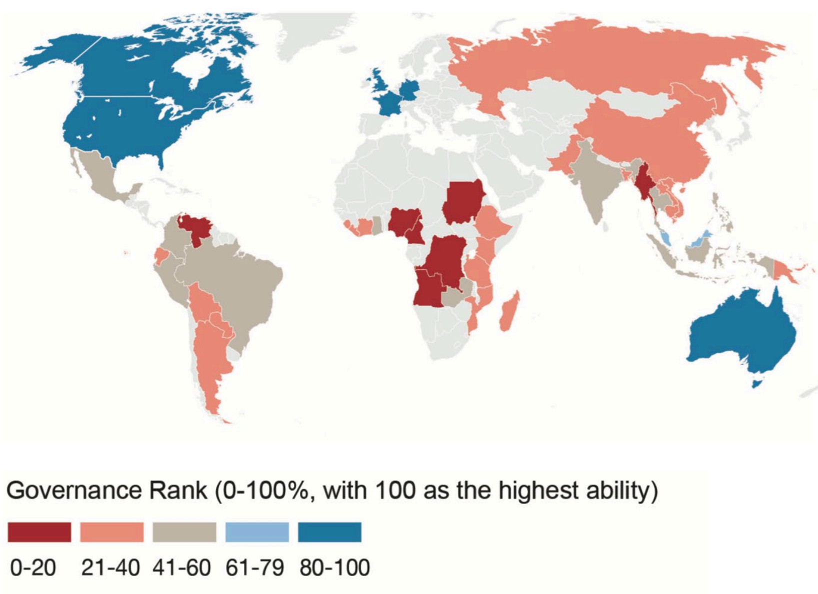

Figure A2.10. Governance rank of top 40 emitting countries.
Data source: World Bank governance indicators, 2014 (government effectiveness, regulatory quality, rule of law, political stability, control of corruption, and voice and accountability)

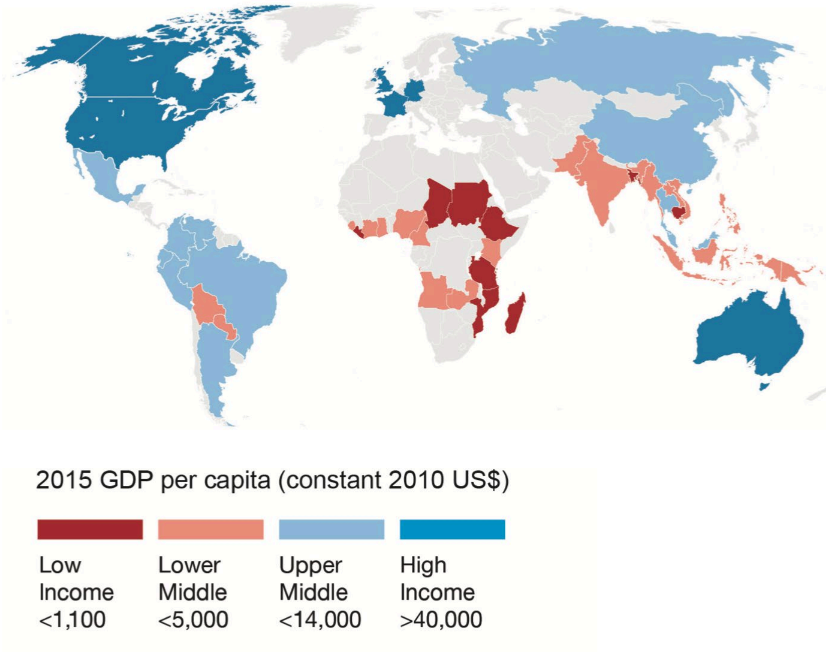

Figure A2.11. GDP per capita of top 40 emitting countries.
Data source: World Bank, 2014

Geographic priorities

Considering the technical mitigation potential as well as feasibility of action, countries can be grouped according to their impact, ability to act, and need for support and assistance. The countries below are listed according to their technical potential.

- High-income and capacity countries with large mitigation potential (210-1500 $MtCO_2e$/yr) that need early aggressive action: the EU, the US, Australia, and Canada. Main areas of action include A/R and restoration, forest management, diet shifts, reduced food waste, reduced enteric fermentation, and improved crop-land management and soil carbon restoration, fertilizer use, and synthetic fertilizer production.
- Upper-middle-income countries that have high mitigation potential (700-1800 $MtCO_2e$/yr) also need early and aggressive action: Brazil, China and Russia. Main areas

of action include A/R, and restoration, forest management, diet shifts, reduced food waste, reduced enteric fermentation, and improved crop-land management and soil carbon restoration, fertilizer use, and synthetic fertilizer production. Deforestation emissions in Brazil, peatland restoration in Russia and rice paddy emissions in China are also of priority.

- Lower-middle income countries with less financial and governance capacity (will require high levels of assistance) and have high mitigation potential (800-1800 $MtCO_2e/yr$) need to act by 2025-2030: Indonesia and India. Reduced deforestation, peatland and coastal wetland conversion, A/R and restoration, forest management, food loss and soil carbon enhancement are important actions in Indonesia, while A/R and restoration, enteric fermentation, food loss, synthetic fertilizer production, manure management and rice paddy emissions are priorities for India.
- Other upper-middle-income countries that have important mitigation potential (150-600 $MtCO_2e/yr$) need to act by 2020-2025: Mexico Colombia, Malaysia, Argentina, Thailand, Venezuela, and Peru. Main areas of action include A/R and restoration, reduced deforestation, peatland and coastal wetland conversion, forest management, food loss and soil carbon enhancement. Enteric fermentation is important in Latin American countries, and rice paddy emissions are important in Asian countries.
- Other low and lower-middle income countries requiring high levels of assistance with important mitigation potential (150-380 $MtCO_2e/yr$) need to act by 2030: Myanmar, Paraguay, Vietnam, the Democratic Republic of Congo, Tanzania, Philippines, Bolivia, Cote d'Ivoire. Main activities are the same as the previous bullet.

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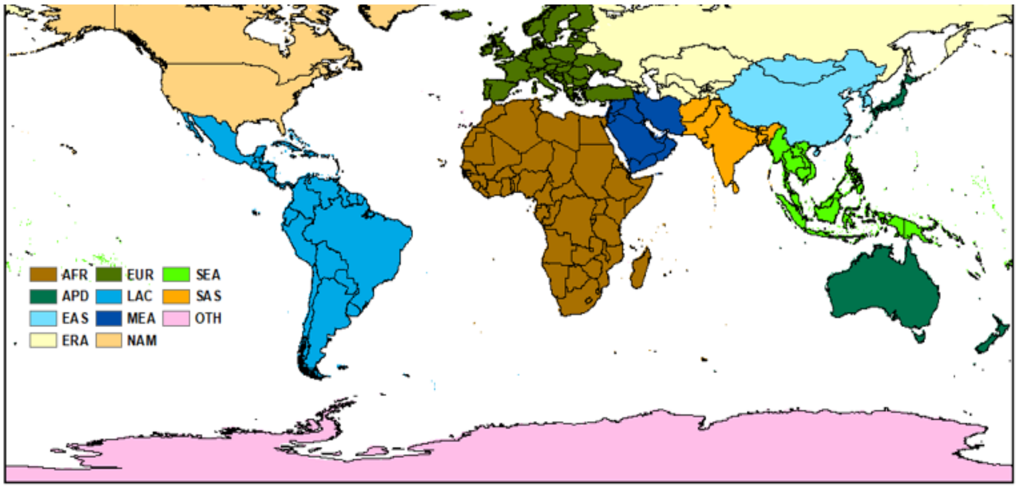
Appendix 3. Supplemental information to Chapter 3



1	AFR	Africa
2	APD	Asia-Pacific Developed
3	EAS	Eastern Asia
4	ERA	Eurasia
5	EUR	Europe
6	LAC	Latin America and Caribbean
7	MEA	Middle East
8	NAM	North America
9	SEA	South-East Asia and developing Pacific
10	SAS	Southern Asia

Figure A3.1. Regions (10) from IPCC AR6 WG3

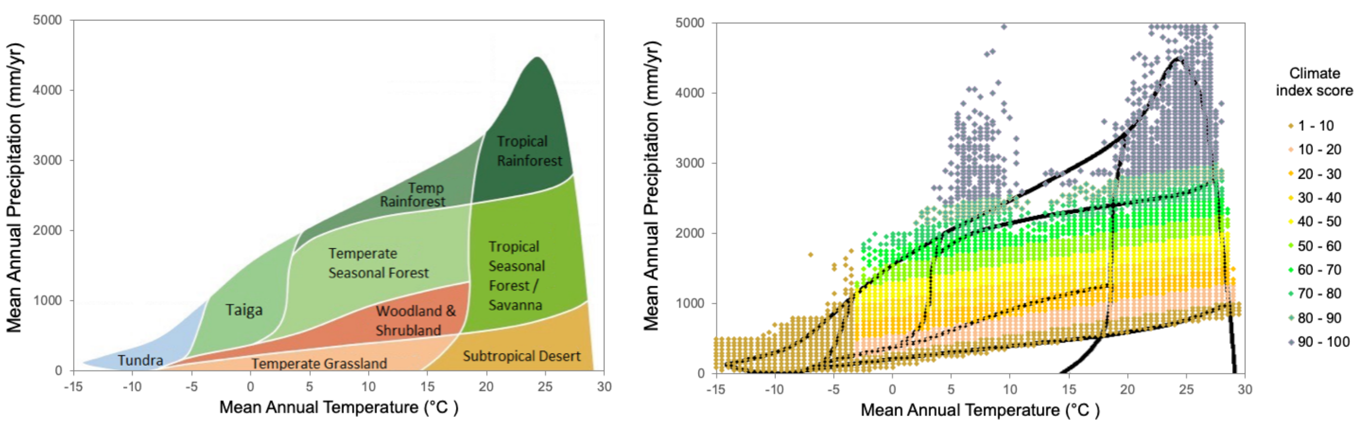


Figure A3.2 Climate index score mapped on to the Whittaker climatic biomes A/R/E is prioritized in areas and biomes with higher climate index score.

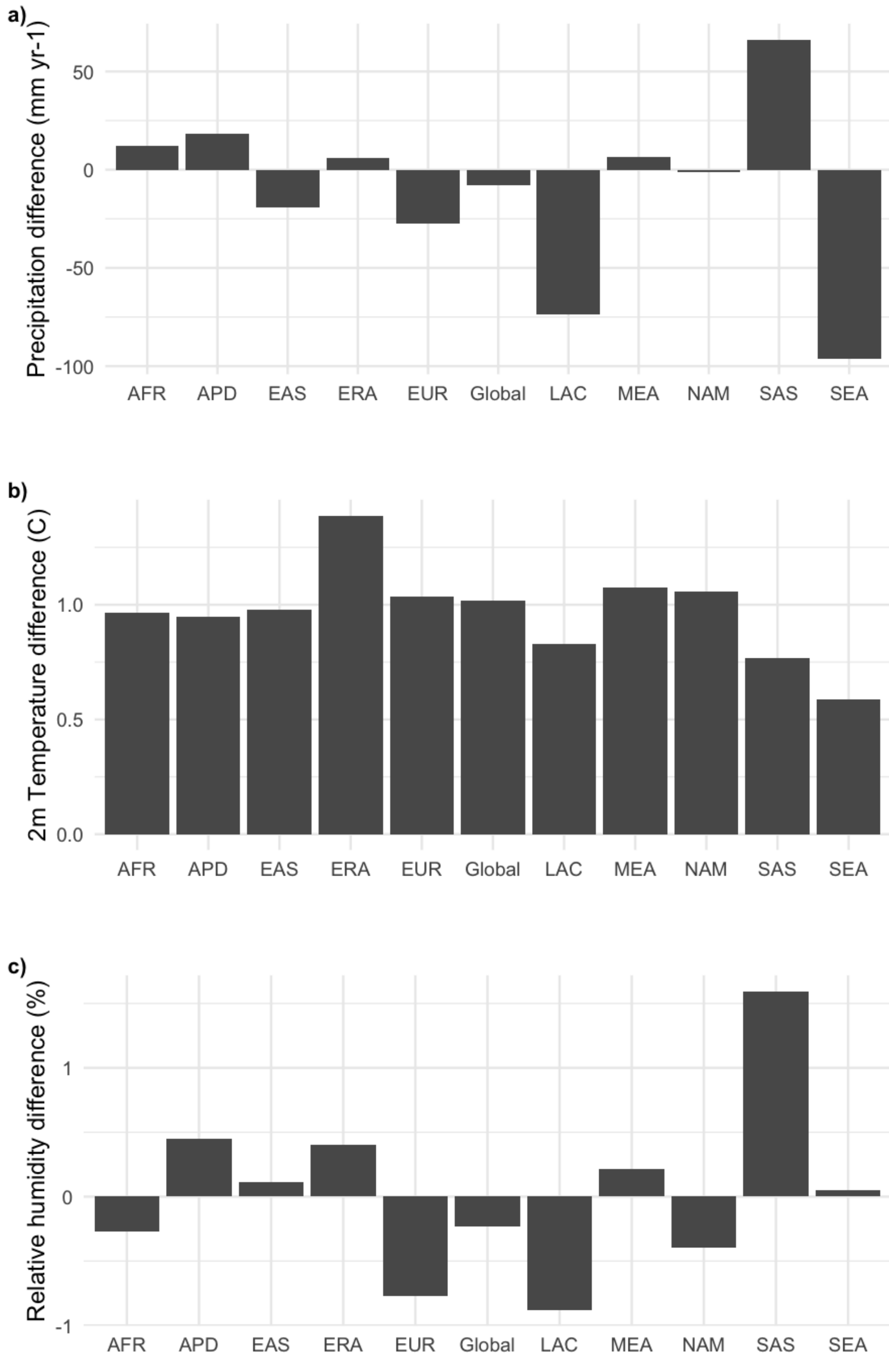


Figure A3.3 Change in (a) Precipitation, (b) Temperature and (c) Relative Humidity, by region between 4°C (7.0 W/m^2) and 2°C (2.6W/m^2). Calculated as the difference in mean values (2015-2100) between 4ºC and 2ºC.

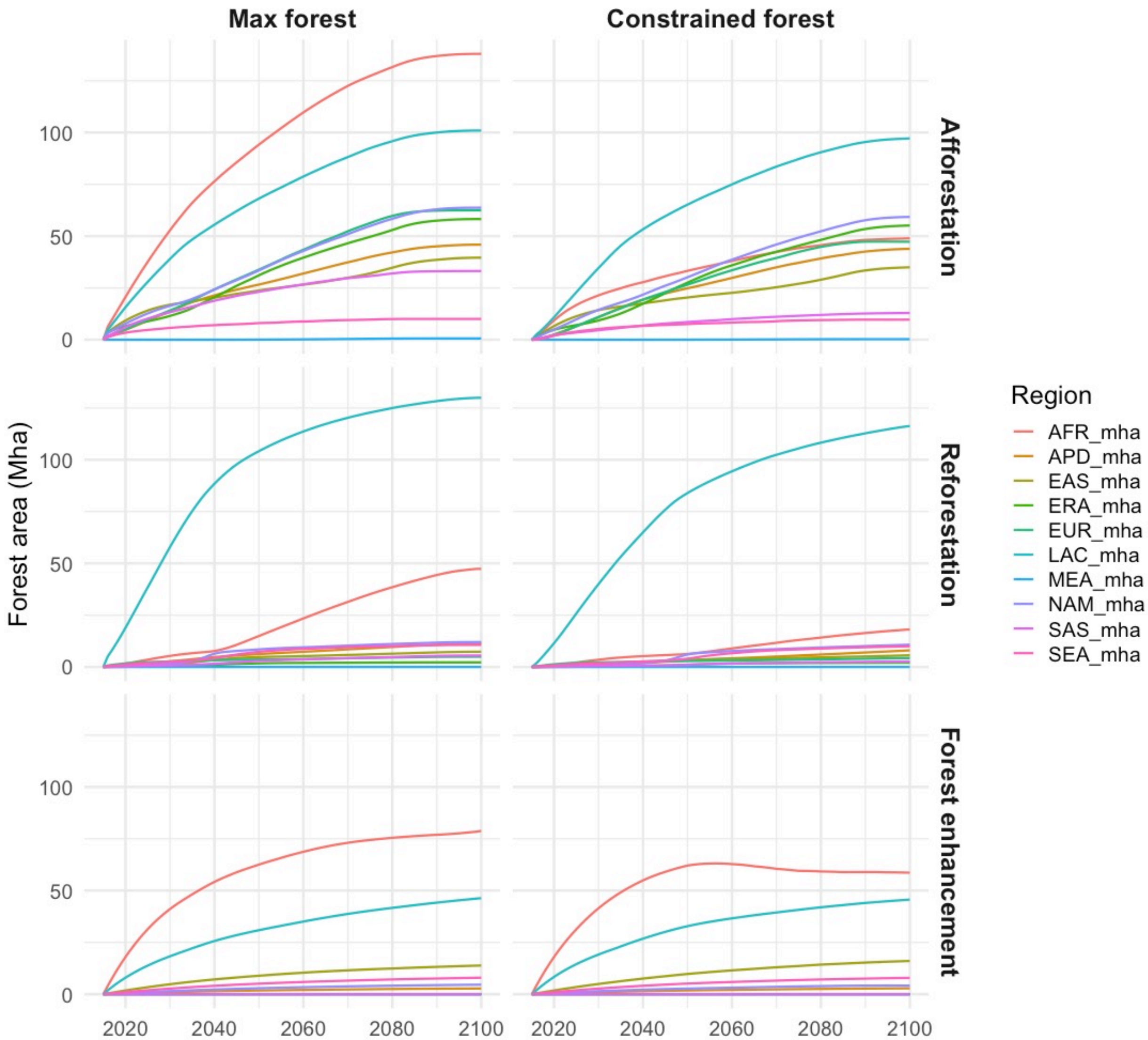


Figure A3.4 Regional forest area for A/R/E in Max Forest and Constrained Forest (Mha)

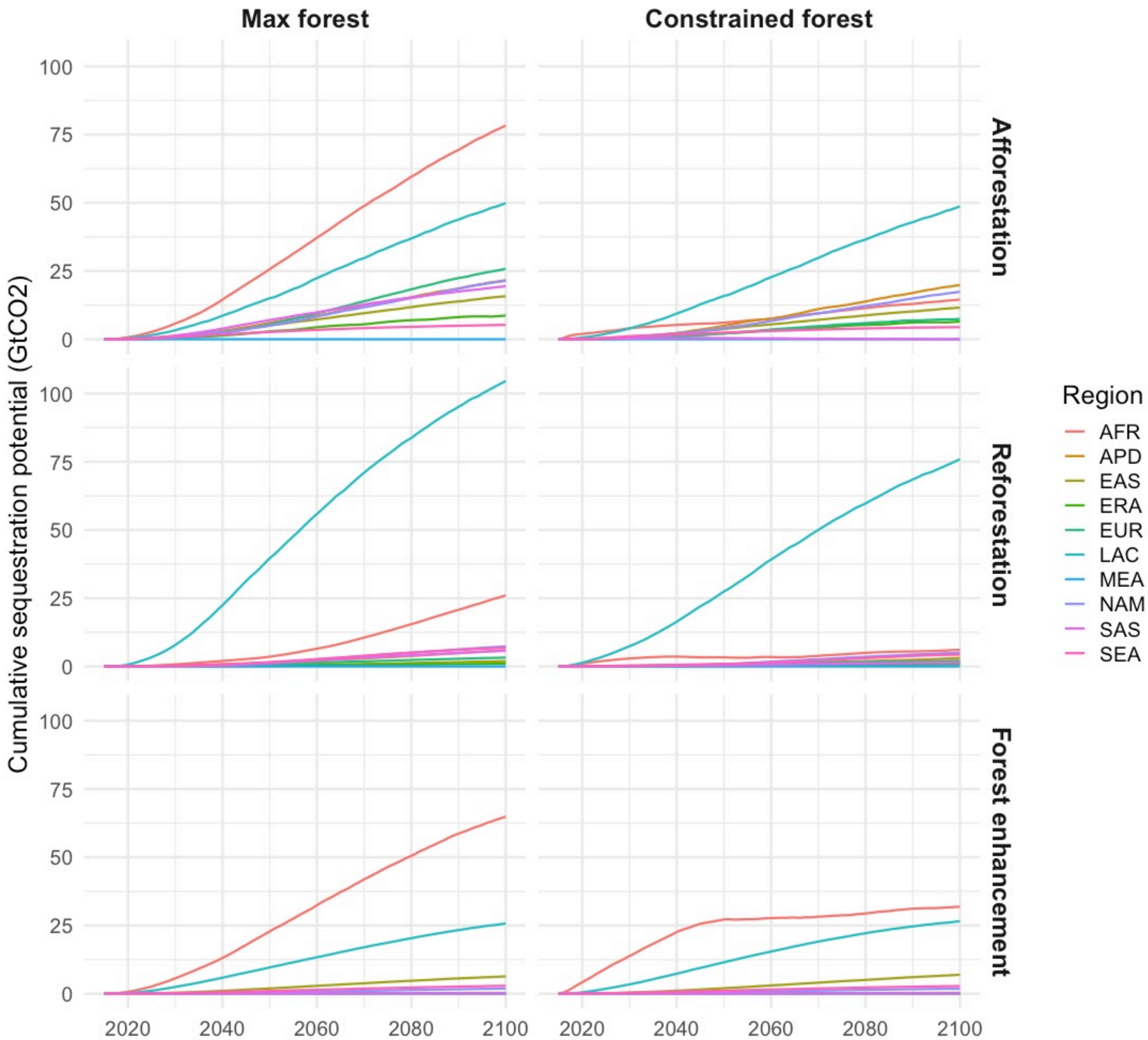


Figure A3.5 Regional sequestration potential for A/R/E in Max Forest and Constrained Forest.
Estimates are cumulative and represent the 2°C (2.6W/m^2) climate.

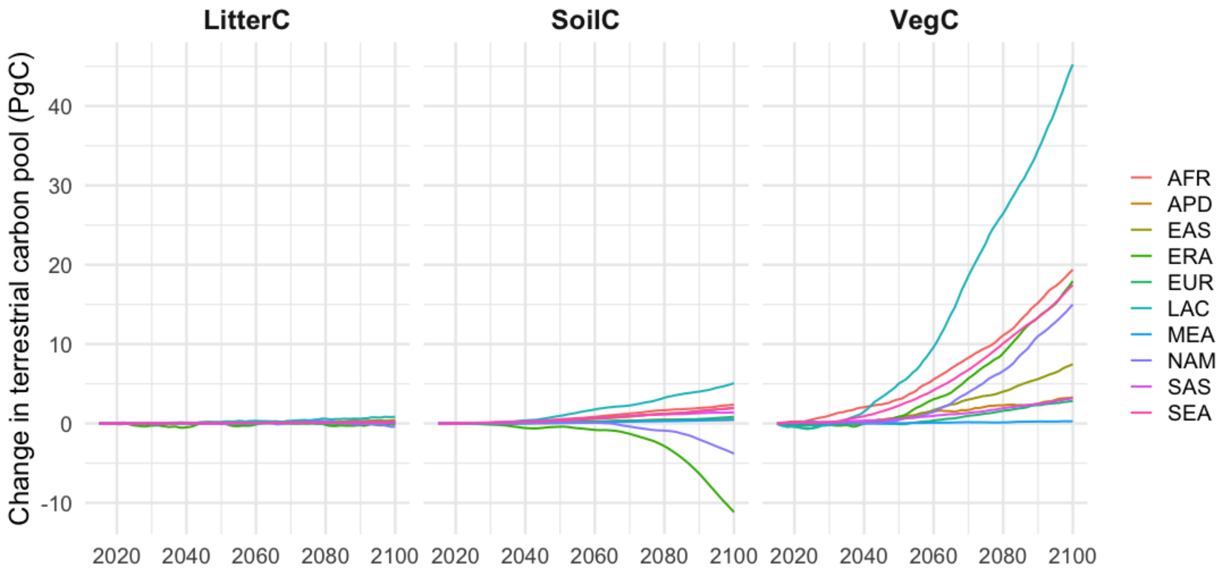


Figure A3.5 Change in the terrestrial carbon pool per region between 4°C (7.0 W/m^2) and 2°C (2.6W/m^2) in the NoLUC scenario

Table A3.1 Total forest area (Mha) for A/R/E by region

Years	Scenario	Type	Global	AFR	APD	EAS	ERA	EUR	LAC	MEA	NAM	SAS	SEA
2030	Max forest	Afforestation	182.4	52.8	13.7	16.9	11.5	14.1	39.0	0.0	16.3	13.3	5.7
2050	Max forest	Afforestation	340.6	94.1	26.6	23.8	31.1	33.8	68.1	0.1	33.4	23.1	8.0
2100	Max forest	Afforestation	549.5	137.9	45.9	39.6	58.2	62.5	101.0	0.6	63.7	33.2	10.0
2030	Max forest	Reforestation	74.8	5.3	2.7	1.1	0.4	2.6	57.9	0.0	1.7	0.8	2.5
2050	Max forest	Reforestation	153.7	14.9	6.2	4.8	1.8	3.6	104.1	0.0	8.5	2.9	7.3
2100	Max forest	Reforestation	230.9	47.3	11.4	7.3	2.2	4.9	129.9	0.0	12.0	5.5	10.6
2030	Max forest	Forest enhancement	69.6	41.1	1.0	4.8	0.0	0.0	18.3	0.0	1.5	0.0	2.7
2050	Max forest	Forest enhancement	112.6	62.5	1.8	8.9	0.0	0.0	30.9	0.0	2.9	0.0	5.1
2100	Max forest	Forest enhancement	155.2	78.8	2.8	13.8	0.0	0.0	46.3	0.0	4.6	0.0	7.9
2030	Max forest	ARE	326.8	99.2	17.4	22.7	11.9	16.7	115.1	0.0	19.5	14.1	10.9
2050	Max forest	ARE	607.0	171.6	34.6	37.4	32.9	37.4	203.1	0.1	44.8	26.0	20.4
2100	Max forest	ARE	935.7	264.1	60.0	60.7	60.5	67.4	277.2	0.6	80.3	38.7	28.6
2030	Constrained forest	Afforestation	124.9	21.4	10.9	14.3	9.3	11.0	34.6	0.0	14.4	4.6	5.2
2050	Constrained forest	Afforestation	242.6	33.2	24.8	20.4	27.5	26.6	65.2	0.0	30.1	8.5	7.5
2100	Constrained forest	Afforestation	406.9	48.9	43.9	35.0	55.1	47.3	97.1	0.3	59.3	12.9	9.7
2030	Constrained forest	Reforestation	50.5	3.5	1.1	0.5	0.3	2.2	40.0	0.0	0.7	0.5	1.8
2050	Constrained forest	Reforestation	111.3	6.3	3.3	3.2	1.0	2.9	83.9	0.0	6.0	1.1	4.0
2100	Constrained forest	Reforestation	177.4	18.1	8.0	5.6	2.1	4.3	116.3	0.0	10.7	2.7	10.0
2030	Constrained forest	Forest enhancement	71.0	41.5	1.0	4.9	0.0	0.0	19.1	0.0	1.5	0.0	2.7
2050	Constrained forest	Forest enhancement	114.8	62.1	1.8	9.7	0.0	0.0	32.8	0.0	2.7	0.0	5.1
2100	Constrained forest	Forest enhancement	136.1	58.6	2.8	16.0	0.0	0.0	45.6	0.0	4.1	0.0	7.8
2030	Constrained forest	ARE	246.4	66.4	12.9	19.7	9.6	13.2	93.7	0.0	16.6	5.1	9.7
2050	Constrained forest	ARE	468.8	101.5	29.9	33.3	28.6	29.4	181.9	0.0	38.8	9.6	16.6
2100	Constrained forest	ARE	720.3	125.7	54.7	56.6	57.2	51.5	259.1	0.3	74.1	15.6	27.5

Table A3.1 Cumulative mitigation potential ($MtCO_2$) for A/R/E and Terrestrial carbon sink by region

Years	Climate	Scenario	Type	Global	AFR	APD	EAS	ERA	EUR	LAC	MEA	NAM	SAS	SEA
2030	2C	Max forest	Afforestation	15057	5777	875	1187	443	487	3298	0	892	1356	802
2050	2C	Max forest	Afforestation	74394	25665	6007	5012	2846	5447	15018	0	5034	7029	2655
2100	2C	Max forest	Afforestation	245381	78350	21624	15732	8679	25827	49880	-14	21498	19431	5257
2030	2C	Max forest	Reforestation	9660	772	286	34	21	218	7850	0	83	129	294
2050	2C	Max forest	Reforestation	50136	3595	1461	310	186	928	39664	0	1337	1235	1573
2100	2C	Max forest	Reforestation	162233	26027	5929	1897	995	3245	104555	0	7356	5766	6865
2030	2C	Max forest	Forest enhancement	8769	5640	13	351	0	0	2475	0	67	0	216
2050	2C	Max forest	Forest enhancement	35940	22801	76	1926	1	0	9616	0	503	0	987
2100	2C	Max forest	Forest enhancement	102085	64873	273	6342	2	0	25741	0	1878	0	2877
2030	2C	Max forest	ARE	33486	12189	1173	1572	464	705	13623	0	1042	1485	1312
2050	2C	Max forest	ARE	160470	52060	7543	7248	3033	6375	64298	0	6874	8264	5215
2100	2C	Max forest	ARE	509699	169251	27827	23971	9676	29072	180176	-14	30732	25197	14998
2030	2C	Max forest	Terrestrial sink	207652	22771	5876	18944	26353	11608	60905	1183	27392	8005	25578
2050	2C	Max forest	Terrestrial sink	472173	53325	13175	41224	60845	24929	135563	2506	66869	18046	57827
2100	2C	Max forest	Terrestrial sink	849696	92330	22433	76305	118829	47833	228193	4440	137735	29433	95878
2030	4C	Max forest	Afforestation	15082	5786	905	1131	482	475	3127	0	959	1465	815
2050	4C	Max forest	Afforestation	78321	27163	6914	5078	2916	5629	14988	0	5277	7901	2787
2100	4C	Max forest	Afforestation	315277	99593	30616	19378	11431	30741	63230	26	27601	27184	6576
2030	4C	Max forest	Reforestation	9929	760	287	46	18	223	8080	0	84	160	302
2050	4C	Max forest	Reforestation	52507	3965	1558	333	170	947	41229	0	1334	1421	1715
2100	4C	Max forest	Reforestation	205935	35975	7764	2358	926	3926	128405	0	10065	7876	9101
2030	4C	Max forest	Forest enhancement	8757	5624	12	333	0	0	2501	0	66	0	214
2050	4C	Max forest	Forest enhancement	37686	23765	76	1929	1	0	10343	0	492	0	1048
2100	4C	Max forest	Forest enhancement	124878	76122	299	7597	2	0	34613	0	2119	0	4004
2030	4C	Max forest	ARE	33768	12170	1205	1510	500	698	13707	0	1110	1624	1331
2050	4C	Max forest	ARE	168514	54892	8549	7341	3087	6576	66560	0	7103	9322	5550
2100	4C	Max forest	ARE	646090	211690	38679	29333	12359	34667	226248	26	39785	35060	19681
2030	4C	Max forest	Terrestrial sink	211755	25527	6356	19368	24511	10810	61365	1159	27763	8915	26913
2050	4C	Max forest	Terrestrial sink	536247	67098	15953	45522	62427	25728	159980	2907	69469	21765	67754
2100	4C	Max forest	Terrestrial sink	1338827	175856	37353	112873	134542	59809	429565	7530	168327	46794	172175
2030	2C	Constrained forest	Afforestation	12156	4000	657	829	310	296	3934	1	704	347	1116
2050	2C	Constrained forest	Afforestation	41518	6059	4921	3742	2099	2140	15858	1	4042	414	2432
2100	2C	Constrained forest	Afforestation	129961	14524	19849	11584	6480	7461	48702	-13	17434	12	4416

2030	2C	Constrained forest	Reforestation	11373	2925	190	75	9	231	7419	0	91	144	324
2050	2C	Constrained forest	Reforestation	34721	3341	745	214	99	802	27472	2	769	465	908
2100	2C	Constrained forest	Reforestation	99536	6055	3102	1013	815	2097	75921	1	4989	1420	4340
2030	2C	Constrained forest	Forest enhancement	18135	13796	15	397	0	0	3420	0	165	0	335
2050	2C	Constrained forest	Forest enhancement	42550	27186	83	2004	6	0	11509	0	635	0	1097
2100	2C	Constrained forest	Forest enhancement	70336	31845	295	6944	1	0	26553	0	1813	0	2789
2030	2C	Constrained forest	ARE	41664	20720	863	1301	319	527	14772	1	960	491	1775
2050	2C	Constrained forest	ARE	118790	36586	5749	5960	2204	2942	54838	3	5445	879	4438
2100	2C	Constrained forest	ARE	299833	52423	23246	19541	7296	9557	151176	-13	24236	1432	11546
2030	2C	Constrained forest	Terrestrial sink	74091	-19014	3367	14258	22098	5676	29706	1192	12931	-1401	5602
2050	2C	Constrained forest	Terrestrial sink	203058	-40922	8294	38528	52213	12140	73633	2704	35075	-598	23231
2100	2C	Constrained forest	Terrestrial sink	322108	-146264	12786	93827	103993	27945	107712	5476	71361	847	47247
2030	4C	Constrained forest	Afforestation	12075	3918	669	800	337	266	3902	0	750	366	1107
2050	4C	Constrained forest	Afforestation	43226	6290	5796	3732	2149	2236	16016	0	4186	479	2539
2100	4C	Constrained forest	Afforestation	167442	18686	28096	13989	8249	8257	61390	-25	22963	799	5598
2030	4C	Constrained forest	Reforestation	11392	2766	192	86	0	229	7580	0	88	159	329
2050	4C	Constrained forest	Reforestation	35796	3340	813	203	91	782	28466	0	757	490	951
2100	4C	Constrained forest	Reforestation	123425	7388	4394	1238	798	2058	94589	3	5774	1767	5653
2030	4C	Constrained forest	Forest enhancement	17642	13188	15	377	0	0	3556	0	163	0	336
2050	4C	Constrained forest	Forest enhancement	43455	27177	83	1983	1	0	12391	0	628	0	1161
2100	4C	Constrained forest	Forest enhancement	88464	38554	325	8335	2	0	35258	0	2028	0	3844
2030	4C	Constrained forest	ARE	41110	19871	875	1263	337	495	15039	0	1002	525	1772
2050	4C	Constrained forest	ARE	122476	36807	6692	5918	2241	3019	56873	-1	5571	968	4650
2100	4C	Constrained forest	ARE	379331	64628	32815	23563	9050	10315	191237	-23	30764	2566	15095
2030	4C	Constrained forest	Terrestrial sink	77620	-14777	3846	14692	20241	4878	28177	1174	13316	-515	6879
2050	4C	Constrained forest	Terrestrial sink	262910	-27605	11041	43129	53699	12883	95385	3133	37607	2296	32743
2100	4C	Constrained forest	Terrestrial sink	751644	-102497	27037	137925	120313	40582	295285	8612	98019	12564	118822