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Contents

Abstract

Managing forests and forest products to help mitigate climate change was quantified in three coordinated studies involving six regions within North America. Each country-specific study examined several mitigation scenarios in a comparative analysis, using harmonized tools with site-specific data and a systems approach that included forest ecosystem, harvested wood products, and substitution benefits relative to a forward-looking baseline. Here we synthesized the North American case studies by comparing normalized annual mitigation potential (net change in emissions and removals relative to the baseline), and examined differences in ecosystems and drivers that affected the ranking of mitigation activities. Considering all six study sites, the highest mitigation potential over the 32-year study period occurred in southern temperate and tropical regions where avoided deforestation, increased afforestation, and accelerated forest recovery after disturbance resulted in the greatest reduction in net emissions. The only effective scenario common to all regions was increased production of longer-lived wood products, where longer product lifetimes delayed emissions to the atmosphere, and increased substitution benefits from using wood in place of more emissions-intensive materials. We conclude that regionally differentiated mitigation scenarios that take into account diverse ecosystems dynamics and drivers offer the highest mitigation potential and a practical way to allocate resources for forestry activities.

Résumé

On a coordonné trois études dans six régions nord-américaines, dans le but de calculer la façon dont la gestion des forêts et des produits forestiers pourrait atténuer les changements climatiques. Dans chaque étude d'un pays particulier, on a réalisé une analyse comparative de divers scénarios d'atténuation à l'aide d'outils harmonisés aux données d'un certain lieu, et selon une approche systémique qui englobait l'écosystème forestier, les produits ligneux récoltés et l'avantage du remplacement par rapport à des données de référence prévisionnelles. Nous avons synthétisé les études nord-américaines, en comparant la potentielle atténuation normalisée annuelle (évolution nette des émissions et de l'élimination par rapport données de référence), et examiné la différence entre les écosystèmes et les éléments moteurs qui influaient sur le classement des activités d'atténuation. Les 32 ans d'étude dans les six régions révèlent que le plus haut potentiel d'atténuation s'est produit dans les régions tropicales et tempérées australes, où on a évité le déboisement, augmenté le reboisement et accéléré la restauration après une perturbation, ce qui a permis de réduire davantage les émissions nettes. Le seul scénario envisageable pour chaque région, était une production croissante de produits de bois à durée de vie plus longue, puisque la plus grande longévité des produits permettait de remettre à plus tard les émissions atmosphériques, et d'accroître les avantages de remplacer les matières générant plus d'émissions par du bois. Nous en venons à la conclusion que les scénarios d'atténuation qui diffèrent selon la région, et qui tiennent compte de la dynamique et des éléments moteurs des écosystèmes, augmentent le potentiel d'atténuation et constituent un moyen pratique d'attribuer les ressources à des activités forestières.

Introduction

Under current Intergovernmental Panel on Climate Change (IPCC) emission scenarios, keeping the global average temperature increase to less than two degrees Celsius above pre-industrial levels requires negative net greenhouse gas (GHG) emissions through to the end of this century (IPCC 2018). The Paris Agreement, adopted in December 2015 (UNFCCC 2015), aims to achieve a balance between anthropogenic GHG emissions and removals in the second half of this century (Article 4), and includes a commitment to the enhancement and conservation of forest-based carbon (C) sinks (Article 5). As part of the agreement, each of the member countries must determine and report on their national contributions to mitigate climate change. Canada, the US and Mexico have identified country-specific forest sector opportunities to achieve these goals.

Canada has committed to a 17% reduction in emissions by 2020, and a 30% reduction in emissions by 2030, relative to 2005 emissions (ECCC 2017; Envionment Canada 2013b). Existing policies at federal and provincial/territorial levels of government have reduced emissions by, for example, C pollution pricing, regional phasing out of coal-fired power plants, support for renewable energy technologies, and improved vehicle standards. Forest sector efforts supported by the Pan-Canadian Framework for Clean Growth and Climate Change include rehabilitation of forests after natural disturbances, construction of innovative wood structures, and the use of wood for heating in remote and rural communities instead of fossil fuel burning (Environment and Climate Change Canada 2018a). Moreover, analyses of future mitigation options and costs in the forest sector have examined increased stand-level and landscape-level C density, increased use of longer-lived products (LLP), as well as avoided emissions when wood is substituted for other products and fossil fuel energy sources that are more emissions-intensive on a life-cycle basis (Dominy et al. 2010; Lemprière et al. 2017; Smyth et al. 2017; Smyth et al. 2014).

The United States (US), which is the second largest GHG emitter in the world, committed to a net GHG emission reduction of 26-28% by 2025 relative to 2005 levels (UNFCCC 2015). Existing policies at federal, state, and local levels of government include emission reductions from power plants, expanded solar and wind energy, additional low C transportation fuels, and improved forest management (e.g. Service 2017; Stokes and Breetz 2018; USDA 2016; USGCRP 2018). However, the US has announced its intention to withdraw from the Paris Agreement, and the country's emissions are expected to have increased in 2018, after having fallen for about a decade (USGCRP 2018). It is estimated that the US forest sector offsets approximately 12% of gross annual GHG emissions (US EPA 2018), and there is considerable potential to reduce forest sector emissions and increase C sinks. The main forest sector mitigation options that have been explored in the US are reducing net forest loss, altering harvest rotations to increase C storage in the forest ecosystem or product sector, improving forest management to enhance productivity or reduce mortality-inducing disturbances, and increasing use of longer-lived wood products and some bioenergy applications (Birdsey et al. 2018; Gunn and Buchholz 2018; Law et al. 2018; Malmsheimer et al. 2008; Nunery and Keeton 2010; Wiedinmyer and Hurteau 2010).

Mexico has pledged to reduce unconditionally its GHG emissions and short-lived climate pollutants by at least 25% with a desired reduction of 40% by 2030 relative to a business as usual scenario (SEMARNAT - INECC 2016). Moreover, Mexico has been a leader among Non-Annex I countries in developing a monitoring, reporting and verification system (MRV) for reducing emissions from deforestation and forest degradation (REDD+) and has pledged a 0% deforestation rate by 2030 (CONAFOR 2017). Policy goals for the forest sector (CONAFOR 2017) call for the protection of biodiversity, the sustainable use of forest resources with increased harvest levels, improved economic return; increased ecosystem goods and services, and the reduction of emissions from deforestation and forest degradation (REDD+). The country's existing policies focus on reducing emissions in the transportation, electricity, energy, agriculture and forestry sectors, and include specific plans for reducing emissions of black C and methane, and growing the renewable energy sector (SEMARNAT - INECC 2016). Additionally, the National Climate Change Strategy includes a series of adaptation strategies in addition to mitigation activities (NCCS 2013). Forest sector mitigation options to date have included increased afforestation, more diverse management strategies including certification, reduced illegal deforestation and forest degradation, and improved technology for charcoal production (SEMARNAT- INECC 2018).

To better quantify the potential contribution of the forest sector towards emissions reductions and enhanced removals, comparative analyses of mitigation activities using consistent methods and toolsets are needed. Understanding the timing of the effects of activities is also important, because some scenarios are associated with high near-term potential, while others may increase emissions or reduce removals initially but have high long-term potential for positive benefits. Forest C dynamics involve long time scales on the order of decades and centuries, and therefore longer-term analyses are needed to capture decreased forest sequestration associated with forest aging and natural disturbances, the impacts of increasing management intensity, and changes in forest area related to afforestation and deforestation. Longer-term analyses are also needed to capture emissions from wood products, and from use to post-consumer release from incineration and/or landfills.

The work presented here synthesizes the results of a Commission for Environmental Cooperation (CEC) project to assess forest sector mitigation options related to improved management of lands and wood products in two strategic landscapes for each country in North America: Mexico (Olguin et al. 2018), the US (Dugan et al. 2018) and Canada (Smyth et al. 2018). A harmonized modelling approach with consistent methodologies based on a systems approach was used in all six landscapes to assess suites of mitigation scenarios to 2050. The systems approach, shown in Figure 1, depicts estimated changes in emissions and removals in forest ecosystems, emissions from harvested wood products, and substitution benefits, all assessed relative to a forward-looking baseline (Nabuurs et al. 2007). Mitigation activities varied by country and by regional circumstances, but all three studies applied harmonized methods and tools that were consistent with IPCC guidelines for national GHG reporting (IPCC 2006), and site-specific datasets that were compliant with international reporting requirements and that reflect ecosystem dynamics. Drivers of the ecosystem GHG balance for the forest sector in the three countries vary because of differences in ecosystem productivity, land-use change (LUC) rates, impacts of natural disturbances, and management regimes.

In this synthesis of studies, we compared and contrasted regional circumstances, and examined the efficiency of regionally differentiated mitigation activities for the six strategic landscapes, after standardizing the results to enable comparisons. The goal was to understand the impacts and timing of alternative management options for forests and harvested wood products, and to synthesize these findings to more broadly support policy and management decisions regarding climate change mitigation at regional scales.

Land management jurisdictions and characteristics of disturbances are important distinguishing factors in each country. In Canada, 90% of the 347 Mha of forest is publically owned and under provincial or territorial jurisdiction (Natural Resources Canada 2018). These extensive, slow growing boreal and temperate forests are impacted by large natural disturbances (e.g. fire and pests) which are beyond control efforts (Environment and Climate Change Canada 2018b; Kurz et al. 2018; Kurz et al. 2008; Kurz et al. 2013). Land-use change drivers are minimal in Canada: since 1990, deforestation has affected an average of 49 kha yr^{1} i.e. 0.014% of the forest area - and there has been even less reported afforestation (Environment and Climate Change Canada 2018b; Natural Resources Canada 2018). In the US, about 75% of the 310 Mha of forest is privately owned, and LUC rates are higher than those in Canada: large areas affected by similar amounts of deforestation (355,000 ha yr^{1} i.e. 0.11% of the forest area), and reforestation plus afforestation (430,000 ha yr^{1}) (Oswalt et al. 2014; US EPA 2018). Natural disturbance rates are much lower in parts of the US than in Canada, but burned areas and insect outbreaks have been increasing since the 1990s particularly in the Western States (Domke et al. 2018). In Mexico, most of the 66 Mha of forest areas are owned or managed by communities (Madrid et al. 2009), and a range of forest types are present, including temperate, tropical humid and dry forests (Challenger and Soberón 2008). Average gross deforestation rates are approximately 232,000 ha yr^{1} i.e. 0.35% of the forest area, while forest recovery rates are 137,387 ha yr^{1} (SEMARNAT- INECC 2018). Compared with Canada and the US, smaller areas are affected by natural disturbances, although hurricanes and fires are common in some areas such as the Yucatan peninsula (Mascorro et al. 2014).

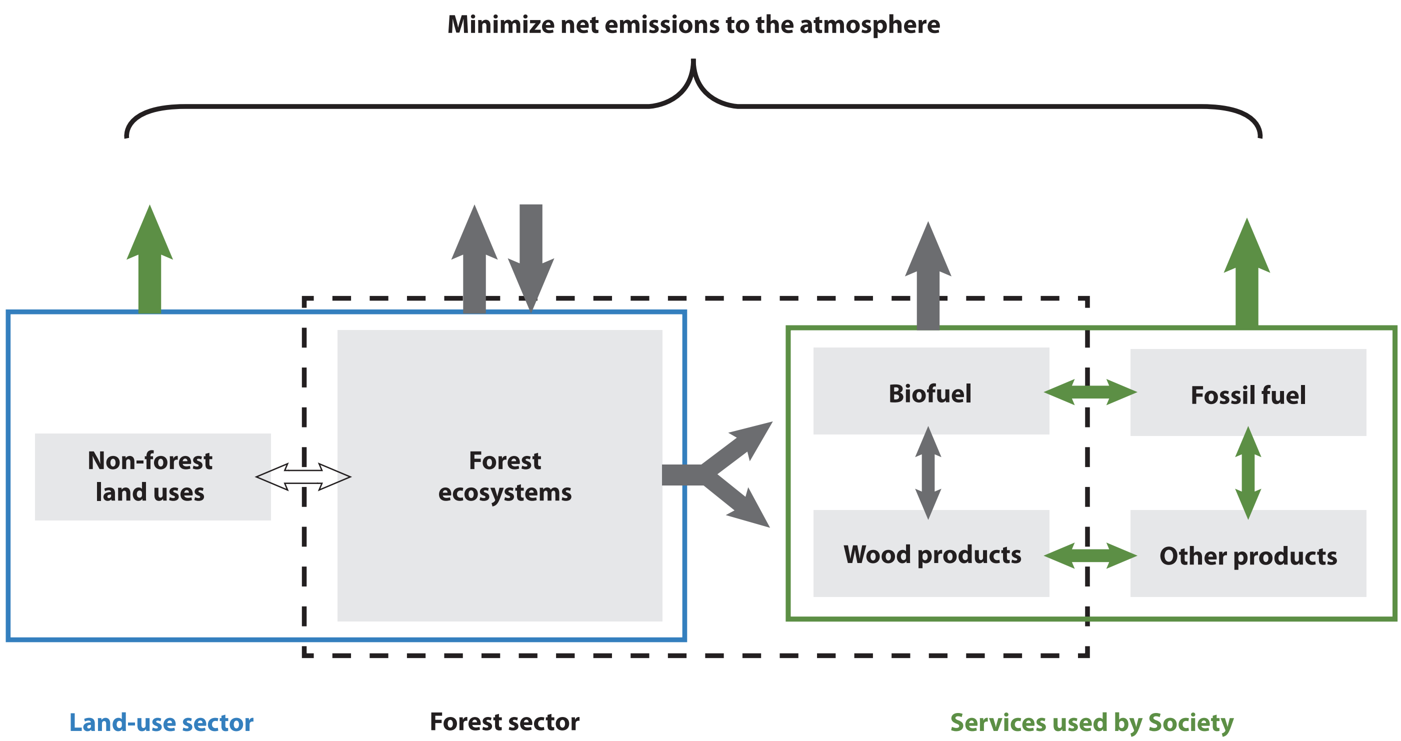

Figure 1. The mitigation potential was estimated using a systems approach which considers changes in emissions and removals in the forest ecosystem, emissions from wood products and biofuels as well as and substitution benefits associated with using bioenergy and wood products in place of fossil fuel energy and more emission-intensive materials. Modified from (Nabuurs et al. 2007) IPCC AR4, WG3.

Methods

The three studies are briefly described here, but details of the country-specific analyses, data sources, models, and assumptions are provided for each country: Mexico (Olguin et al. 2018), the US (Dugan et al. 2018) and Canada (Smyth et al. 2018). The six study sites included 16 Mha of forests ranging from boreal and temperate coniferous and broadleaf forests to tropical humid and dry forests (Figure 2). The western Canada site in Cranbrook, British Columbia, was roughly 1 Mha of pine and fir. Two Great Lakes sites, one in Canada (Ontario) mostly of spruce and poplar, and a nearby site in the US (Wisconsin), consisting of maple and birch, added another 0.8 Mha and 4.1 Mha, respectively. The second US site of 0.6 Mha was predominantly pine and oak forests in the southeastern region (South Carolina). The two sites in Mexico had 6 Mha of mostly coniferous and broadleaf forests in the northern region (Durango) and 3.7 Mha of tropical forests in southeastern Mexico (Quintana Roo).

The models included the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al. 2009) which was used to track ecosystem C, the Carbon Budget Modelling Framework for Harvested Wood Products (CBM-FHWP) which tracked emissions in HWP utilising the production approach (Environment and Climate Change Canada 2018b; Smyth et al. 2017a), and displacement factors for products and energy substitution based on published values (Smyth et al. 2017). The CBM-CFS3 employs the IPCC gain-loss method to estimate emissions and removals, which permits the time series of activity data from 1990 to the present to be extended into the future within the same modeling framework to compare alternative scenarios. We used the country-specific information on forest inventories and

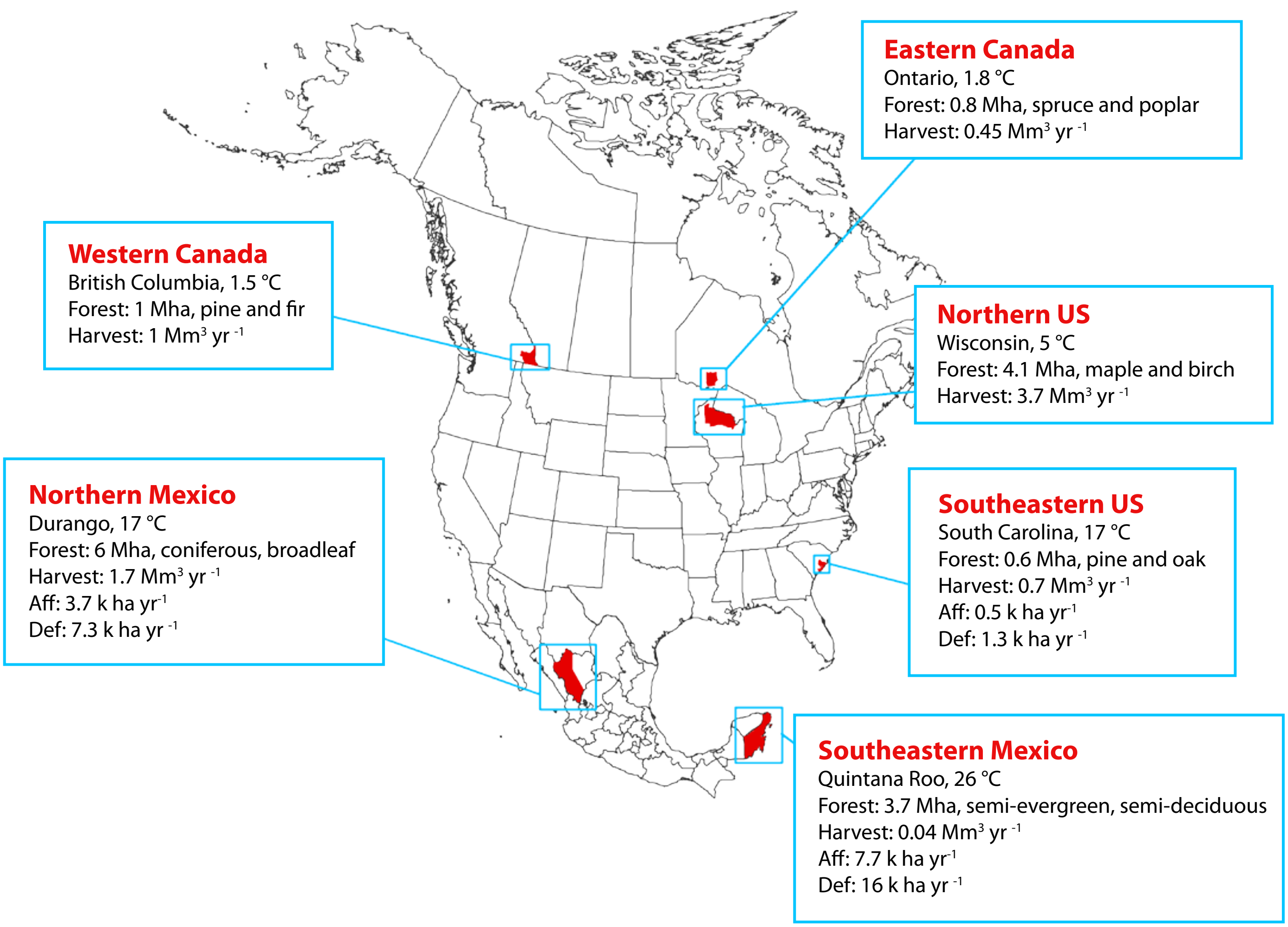

Figure 2. Map of the six regions with basic information on forest type and area, and baseline information on harvest amounts and afforestation in the US or forest recovery in Mexico (Aff) and deforestation rates (Def).

associated yield tables, disturbance and LUC rates, and wood product commodities were applied in the models.

The modeled mitigation scenarios and associated implementation levels differed among the six study sites (Table 1). In consultation with regional stakeholders, scenarios were selected that represented potential or likely activities which could be feasibly implemented in each region. Common among the studies was a scenario which increased LLP, either by shifting wood commodities away from short-lived products, or directing additional harvested wood to products with longer lifetimes. A scenario of using logging residues for bioenergy was modeled in four sites by two countries (US and Canada), and scenarios relating to LUC (afforestation or forest recovery and deforestation) were modeled in three sites by two countries (US and Mexico). The remaining mitigation scenarios were site specific and sometimes modeled in only one of the two study sites within a country. Several scenarios, with additive rather than interactive effects, could also be evaluated without additional modeling by summing scenario results.

The 2050 cumulative reduction in GHG emissions reported in the three studies ranged from less than 1 MtCO2e to over 100 MtCO2e, which reflected differences in baseline drivers, scenario implementation levels, and the difference in forest area (a 10-fold variation) among study sites. To standardize the climate change mitigation potential between the six regions, we estimated the mitigation potential per unit area by dividing emission reductions by the total forest area at each study site.

We also normalized the mitigation potential by the mitigation activity area in each study site, which reflected the scenario implementation level. Activity area was defined as the area of forest harvested for the following scenarios: bioenergy, higher harvested wood recovery, higher productivity and harvest, and long-lived wood products. For the reduced slash pile burning and reduced harvest (extended rotation) scenarios, the activity area was defined as the difference in the area affected by these management activities relative to the baseline. For LUC scenarios, the activity area was defined as the reduction in deforested area, and for afforestation, forest recovery, and increased productivity, the activity area was the affected area. Each of the scenarios listed above is outlined in Table 1.

Table 1. Scenario parameters for the six regions in the three study sites within Canada (CAN), the United States (US) and Mexico (MX) Mexico, labeled by cardinal directions N- North, S- South, W- West, E- East.

ACTIVITY	DESCRIPTION	PARAMETER CHANGED	W-CAN	E-CAN	SE-US	N-US	N-MX	SE-MX
Avoid slashpile burning	Stop slashpile burning after harvest	Slashpile burn area reduction		-25%				
Higher harvest through higher utilization	Increase the percentage of stemwood transferred to products	Harvest utilization rate	5%	5%				
Decrease harvest	Remove scheduled harvest areas	Harvest area	-2%	-5%				
Residues for bioenergy	Collect logging residues for bioenergy	Harvest residue collection rate	25%	25%	+40 to +70%	+29 to +70%		
		Decrease in slash burn area	-25%	-25%	0	0		
		Shift HWP commodities to bioenergy	0	0	+30%	+41%		
Increase Long Lived wood Products (LLP)	LLP (saw logs) are increased, while pulp and paper products are decreased. Total harvest removals are not changed.	Increase solid wood	+4%	+4%	+10%	+10%		
Decrease LLP	Decrease LLP increase bioenergy	Increase bioenergy			+10%	+10%		
Increase harvest for bioenergy	Increase harvests. All additional wood used for bioenergy production	Harvest volume				+10%		
Extended rotation and LLP	Increase average rotation length by reducing harvests and increasing the minimum harvest age. The proportion of harvests used for LLP is increased (assumed larger diameter trees) while pulp and paper products decreased.	Harvested area				-10%		
		Harvest age				+10		
		Increase solid wood				+5%		
Increase productivity	Increase growth rates for half of the pine plantations that are 12 years or younger on private lands	Growth increase			+15%			
Increase afforestation	Increase annual area afforested on private lands so that it equals to annual area deforested (no net loss)	Increase afforested area			+300% private land			
Reduce deforestation	Reduction in deforestation rate	Reduction in deforestation rate			-25% private land			
Reduced deforestation plus recovery	Reduce deforestation and increase recovery rate	Reduction in deforestation rate					-49%	-53%
		Increase in forest recovery rate					+10%	+10%
Reduced deforestation plus recovery, increase growth and harvest with LLP	Reduce deforestation and increase recovery rate, increased productivity and harvest with incremental harvest to LLP	Reduction in deforestation rate					-49%	-53%
		Increase in forest recovery rate					+10%	+10%
		Additional growth (m^3/ha/yr)					2.7	2.7
		Additional harvest					50%	50%
		Increase solid wood					+9%	+7%

Results

Normalizing the mitigation potential by the forest area of each study site (Figure 3, Table 2), shows the scenarios for Mexico were ranked highest (reduced deforestation, reduced deforestation plus recovery) with much larger impacts for southeastern Mexico. There was much greater mitigation potential in the southeastern region because of relatively higher gross deforestation rates in the base scenario and higher initial forest C densities and growth rates for that region. Additional mitigation activities that increased growth and harvest to produce long-lived products and substituted energy-intensive materials in northern Mexico, contributed net GHG mitigation benefits towards the end of the simulation period in this region. In the US study sites, scenarios that reduced the net forest cover loss, either by increasing afforestation or reducing deforestation, ranked highest for the southeastern study site. Overall, these two scenarios targeting LUC on private lands resulted in greater reduction in net emissions compared to all other US scenarios. In the northern US site, increasing the proportion of LLP from shorter-lived pulp and paper, and extending harvest rotation were both highly ranked scenarios. In Canada, two highly ranked scenarios included the use of harvest residues for bioenergy and thus avoiding fossil fuel burning, as well as increasing the proportion of LLP to substitute for emissions-intensive materials.

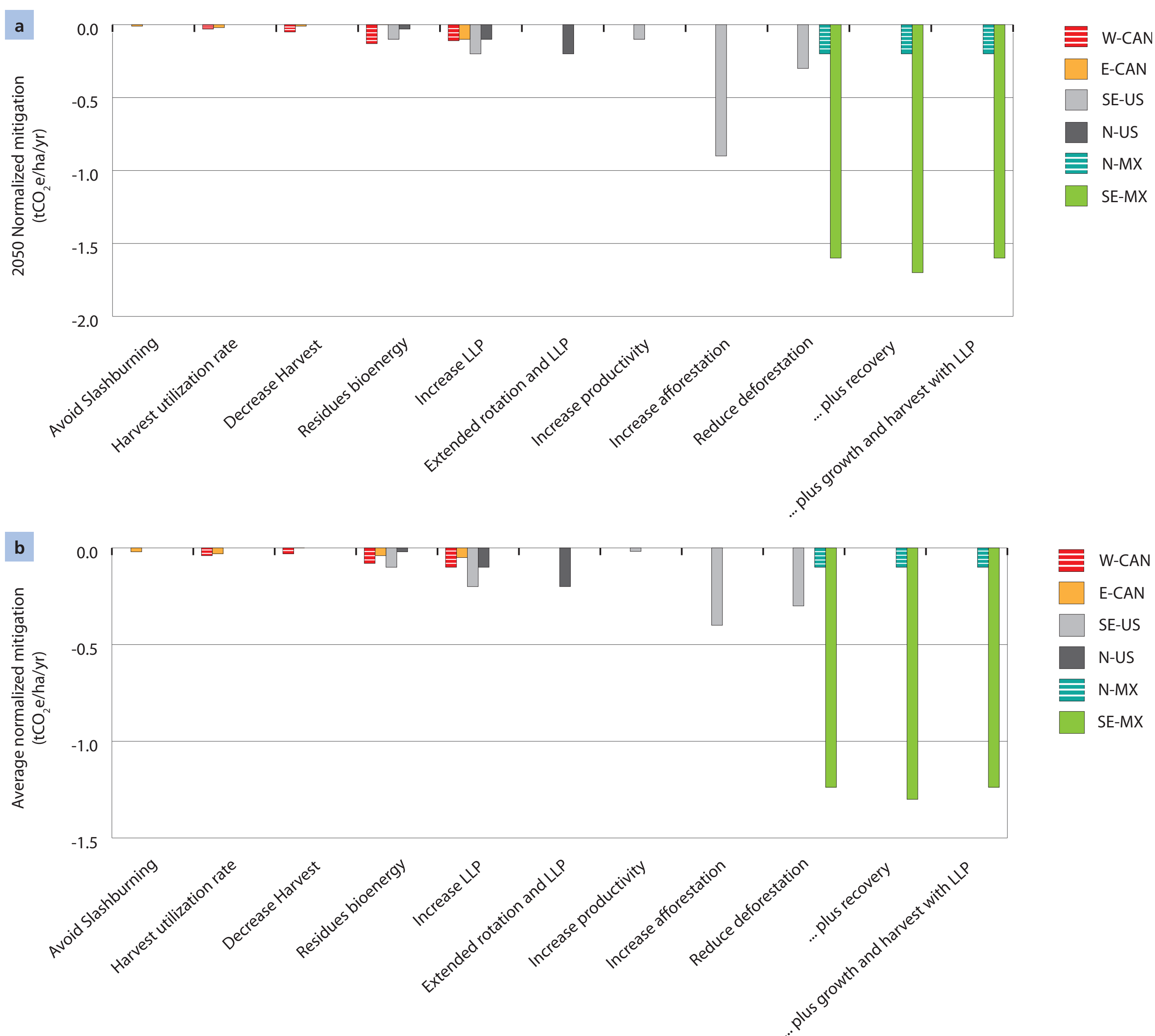

Figure 3. a) Annual mitigation potential in 2050 and **b)** average annual mitigation potential (2018 to 2050); both normalized by the forest area.

Table 2. Ranking of normalized mitigation potential scenarios for forest management and wood use; 2018-2050 average, normalized by forest area.

LARGE REDUCTION	Reduce deforestation – tropical forest
MODERATE REDUCTION	Increase afforestation – temperate forest
	Reduce deforestation – temperate forest
SMALL REDUCTION	Extend rotation length and LLP – temperate forest
	Increase proportion of HWP for LLP – all locations
	Increase use of harvest residues for bioenergy – boreal and temperate
	Reduce harvest volume – boreal and temperate
	Increase productivity – temperate plantations
	Reduced deforestation, increased productivity and harvest with incremental harvest to LLP – tropical forest – temperate forest
	Stop slash burning – boreal forest

Several scenarios which increased emissions (relative to a forward-looking baseline) involved significantly increasing harvest without any enhancement of forest sinks, or expanding harvest for bioenergy. Consequently, these scenarios were not compared with others in Figure 3 because we only included scenarios that resulted in a reduction in net emissions by 2050. Mitigation benefits may eventually be achieved for these scenarios if they were evaluated over a longer timeframe whereby forests could recover the C removed from intensified harvesting and/or bioenergy burning (e.g. Birdsey et al. 2018; Ter-Mikaelian et al. 2015). However, mitigation activities that increase emissions in the next decades are ineffective because they contribute to climate warming (IPCC 2018).

Annual mitigation potential normalized by the activity area is shown in Figure 4. The highest-ranking scenarios again included reducing deforestation, and increasing afforestation or forest recovery. In the southeastern US site, increased afforestation to achieve no net forest area loss surpassed the reduced deforestation scenario to become the top ranked US scenario in 2050. In Mexico, reducing deforestation and increasing forest recovery had the greatest normalized emission reductions, with the southeastern site having the highest overall ranking, along with a contribution from the northern site. Normalizing the mitigation potential by activity area, instead of forest area, increased the relative ranking for scenarios where activities were focused on small areas, Table S1. Scenarios related to enhanced productivity in the US and decreased harvest in Canada had small activity areas and resulted in large normalized mitigation potentials (per unit activity area).

The scenarios selected for analysis in the six sites varied by region, with some activities focused on wood products, while others focused on forest management and LUC. We examined the three components of the mitigation potential: the forest ecosystem, HWP, and the avoided emissions (which we further subdivided into product and energy substitution) to understand the scenario impacts and how they differed by region. For the best-performing scenarios, or combinations of scenarios, we compared the proportional contribution of the three components (Figure 5). The forest ecosystem was favoured in the reduced deforestation, increased afforestation and increased forest recovery scenarios analysed in the southeastern US site and southeastern Mexico, because landscape C was maintained or increased. Extending harvest rotation in the northern US study site also resulted in an increase of landscape C, and diminished harvests led to smaller emissions from wood products, relative to the forward-looking baseline. However, the reduced availability of wood products increased fossil fuel burning instead of using bioenergy. In Canada, the combined strategy of using harvest residues for bioenergy and managing harvest residues to create more wood products resulted

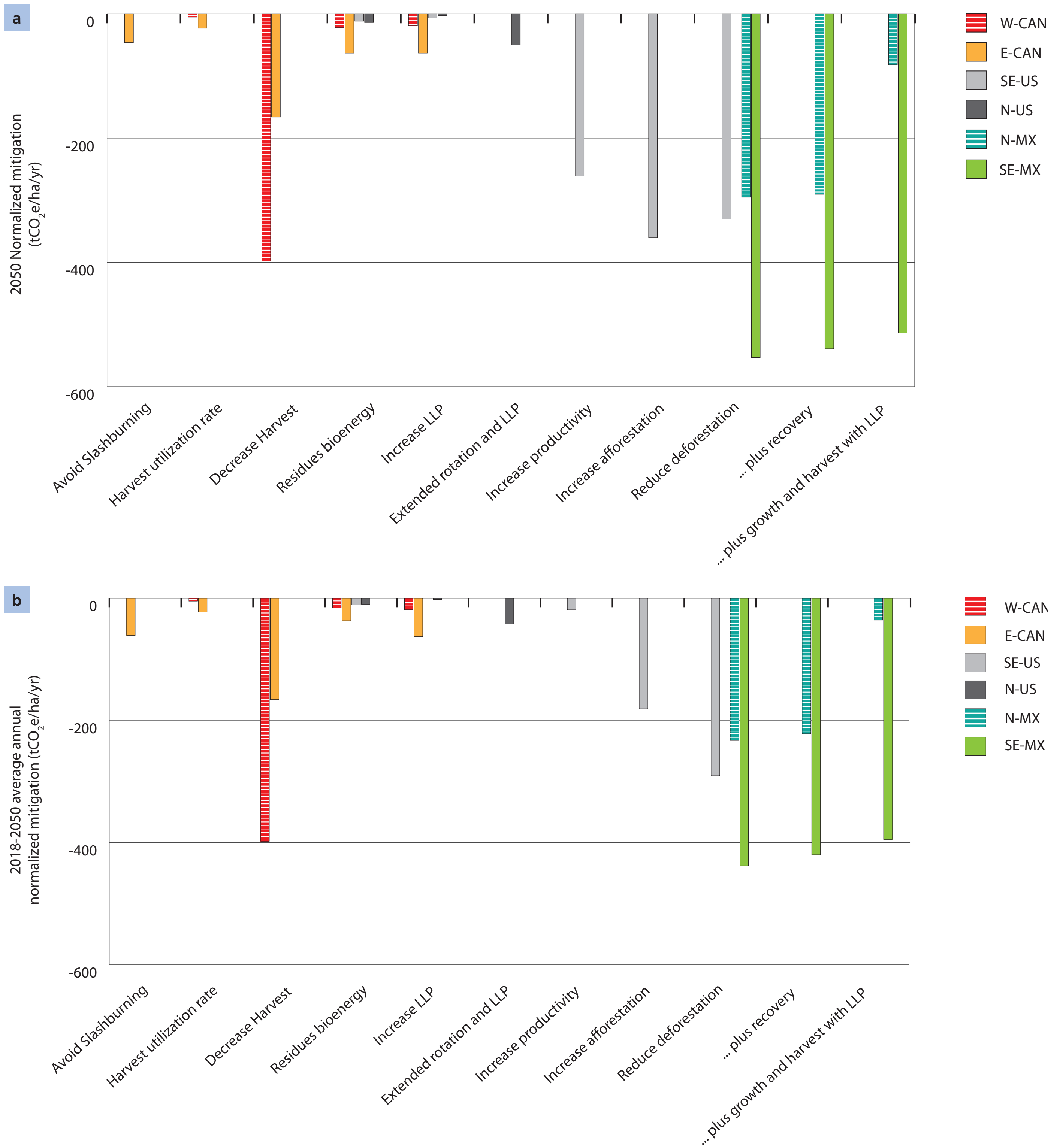

Figure 4. a) Annual mitigation potential in 2050 and **b)** average annual mitigation potential (2018 to 2050); both normalized by the activity area.

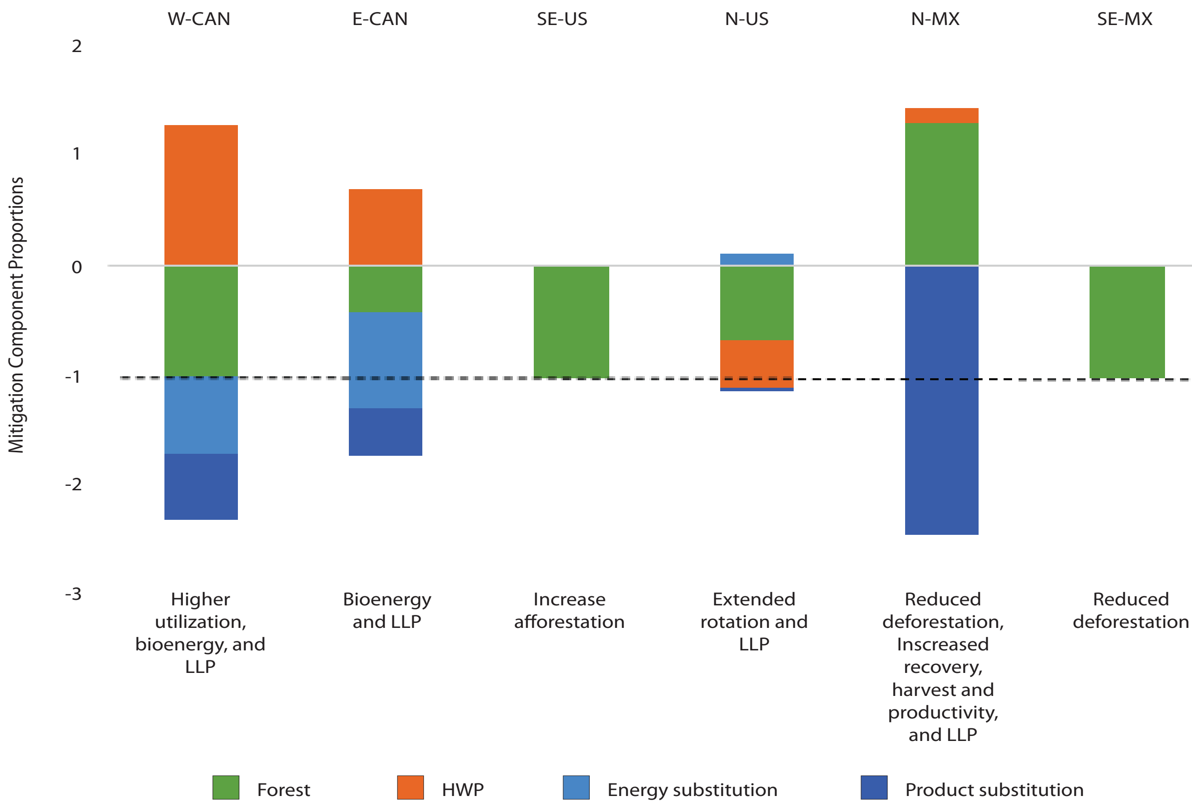

Figure 5. Mitigation component proportions for some of the best mitigation scenarios for the six study regions. Proportions were estimated by dividing the cumulative mitigation components by the total cumulative mitigation in 2050. The normalized total cumulative mitigation, equal to minus one, is indicated by the horizontal dashed line.

in smaller emissions from the forest ecosystem component, because C that would have been emitted from slash pile burning or decay was instead burned to produce energy and create wood products. The increase in HWP emissions associated with incremental bioenergy and products was partially offset by delaying emissions through longer product lifetimes, and by additional substitution benefits. In northern Mexico, reduced deforestation and increased forest recovery was combined with increased growth and increased harvest. The mitigation profile showed a net increase in emissions from the forest ecosystem, indicating that forest gains were more than offset by the losses due to increased harvest. Overall, there was a mitigation benefit because the forest ecosystem losses and increased emissions from wood products were more than offset by substitution benefits.

The timing of the forest ecosystem mitigation varied by activity, both in sign and magnitude, and reflected changes in mitigation activities (changes in disturbance rates) and their impacts on subsequent growth and decay. Net Ecosystem Productivity (NEP) describes the net impact of growth and decay. The baseline time series showed a declining forest ecosystem sink for most of the study sites (Figure S1). NEP has been found to be relatively insensitive to historical climate, and is more likely impacted by successional stage, management, site history, and site disturbance (Luyssaert et al. 2007). Mitigation activities increased the NEP per hectare for five of six scenarios by 2050, enhancing the sink through time and slowing the declining trends in the baseline (Figure 6). For the Canadian sites, the scenario that used harvest residues for bioenergy and/or products reduced emissions from decay and/or slashpile burning in the forest ecosystem. The decrease in forest ecosystem emissions, relative to the baseline, was reflected in a modest increase in NEP. The northern US scenario of extending harvest rotation also had a modest increase in NEP relative to the baseline, with a maximum increase achieved in 2040, as the longer rotation permitted more mature forests to continue to grow. The southeastern US scenario of increasing afforestation and the southeastern Mexico scenario of reducing deforestation both showed a large increase in NEP relative to the baseline. In all cases, the gains in NEP for the mitigation activities were able to lessen, but not eliminate, the downward trend in the NEP time series. In northern Mexico, the combination strategy (reduced deforestation, increased forest recovery, increased productivity and increased harvest) resulted in a lower NEP per hectare relative to the baseline.

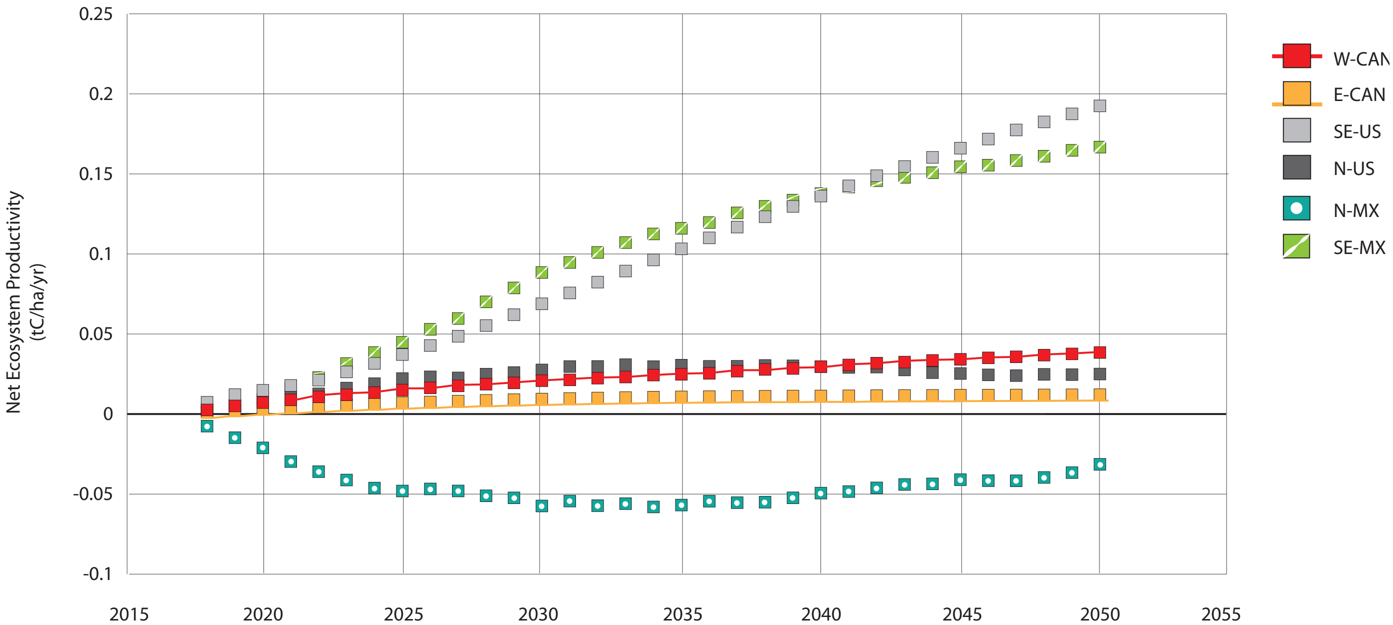

Figure 6. Change in net ecosystem productivity (relative to the baseline Figure S1) normalized by forest area, for selected mitigation scenarios. W-Can Higher harvested wood utilization + harvest residues for bioenergy + shift to Longer Lived wood Products (LLP); E-Can Harvest residues for bioenergy + shift to LLP; SE-US Increase afforestation; N-US Extended harvest rotation and LLP; N-MX Reduced deforestation + increased forest recovery + increased harvest + increased forest productivity + LLP; E-MX Reduced deforestation.

Discussion

Estimation of the mitigation potential based on harmonized methods and tools permitted comparisons of the impacts of changes in behaviour or technology on net GHG emissions for the six regions in North America. The use of a systems approach encompassed all relevant sectors and allowed full consideration of primary and secondary impacts on the forest ecosystem, harvested wood products and substitution. This approach is consistent with the few other comprehensive mitigation studies from countries outside North America (e.g. Klein et al. 2013; Lundmark et al. 2014; Pilli et al. 2017; Werner et al. 2010). The design of mitigation scenarios needs to be regionally differentiated to capture relevant differences in forest ecosystems, disturbance risks, climate change impacts, current age-class structures, forest management activities and wood use, and fossil fuel alternatives. Mitigation scenarios for the six regions showed a range of possible outcomes with some similarities but notable differences among regions.

The only scenario common among all three countries was increasing the proportion of HWPs with longer lifetimes relative to the proportions assumed for the forward-looking baseline. This scenario reduced emissions immediately at all sites by shifting wood commodities to structural wood products which delayed end-of-life emissions from HWPs, enhanced C storage in HWPs, and provided increased substitution benefits. Reductions in GHG emissions from changes in HWP lifetimes would be reported in the national inventory reports for Annex I countries, and for the non-Annex I countries that include HWP pools and emissions in their reports. Extended product lifetime (LLP) results from our study were similar to findings from other findings (e.g. Malmsheimer et al. 2011; Nunery and Keeton 2010), showing the mitigation benefit of enhancing C storage in HWP.

The scenario of increasing productivity was examined in northern Mexico and the southeast US where more intensive forest management is commonly practiced. The potential of increasing productivity was limited by the small area or young forests that can be effectively treated to enhance productivity, by biological limitations to achieving increases if stands are already growing close to their maximum productivity, as well as by the timing and duration of the forest ecosystem growth response.

Reducing harvest levels in the Canadian sites or the extended rotation scenario in the US sites enhanced CO_2 removals by the forest and reduced HWP emissions relative to the baseline. However, the reduction in harvest levels resulted in fewer substitution benefits because the use of fossil-based products and/or fossil fuel burning increased to compensate for the reduction of HWPs; this partially or fully offset forest sector gains when displacement factors were high. The range of displacement factors selected in the studies (0.45 tC/tC to 2.1 tC/tC) was based on values selected from the literature, and encompassed the average displacement factors estimated in a recent review (Leskinen et al. 2018). It can be argued that leaving trees unharvested in forests with long lifespans and low disturbance rates could be an effective mitigation strategy because C may be stored for centuries in forest ecosystems compared to only decades in wood products (Law et al. 2018). However, it is important to consider that ecosystems with historically low disturbance rates and long lifespans are uncommon, especially in boreal forests. Moreover, natural disturbance risk, although not considered to impact mitigation activities in the three studies, can reverse mitigation benefits and add more C to the atmosphere. Rising global temperatures have increased the area of forests burned in recent decades (Domke et al. 2018; Flannigan et al. 2009), and elevated fire risks are projected for the future (Boucher et al. 2018; Hurteau et al. 2014; Peterson et al. 2014). Moreover, drought-induced mortality rates have grown significantly in recent years throughout North America (Allen et al. 2010; Hember et al. 2017) and with increasing climate change impacts and resulting disturbances, conservation-based mitigation strategies need to be assessed against risk of future losses.

The use of harvest residues for bioenergy reduced emissions when high-emissions fossil fuels were avoided. This was particularly evident if the harvest residues were used by efficient bioheating systems, and if some of the residues were piled and burned rather than left to decay slowly. These findings from Canada and US sites confirm that the use of wood residues for bioenergy is an effective GHG mitigation scenario when high-emissions fossil fuels are avoided and the wood residues would otherwise be burned or decompose rapidly (Birdsey et al. 2018; Domke et al. 2012; Guest et al. 2013; Smyth et al. 2017a). Allowing residues to decay, rather than being burned in slash burning piles also reduced emissions, but forest management regulations for harvest residues may require abatement treatments. We assumed no increase in wildfire burned area or severity as a result of increased fuel loads and these risk factors should be considered (e.g. Hurteau and North 2009).

Two methods were selected to standardize the mitigation potential for individual and combinations of activities for the six sites. We normalized the mitigation potential to evaluate results among study sites (which had large difference in forest area as well as percent of national forest covered, and large differences in activity implementation levels) and to compare results to estimates from North America and other countries.

The first normalization method used the forest area to enable comparison between the mitigation potentials for the six regions which had an order of magnitude difference in forest size. The forest regions were based on current administrative boundaries: forest management units in the US and Canada, and state-level forestry in Mexico, and reflected feasible landscape-level opportunities within those regions. The other method—normalizing by the activity area—provided a second comparison of the mitigation potential for the various activities and regions. Typically, mitigation activities are applied to a small proportion of the landscape, and normalizing by activity area can provide a 'per unit activity' comparison. Activity area was difficult to apply to some scenarios, such as long-lived wood products, and normalizing by small areas resulted in large normalized values (e.g. reduced harvest scenario in Canada and increased productivity for plantations in the US). However, despite these challenges, standardizing by activity area could help inform activity-level analysis of mitigation benefits and associated costs.

The mitigation potential in 2050 was small in northern US and Canadian sites, at most 0.2 tCO_2 yr^{1} ha^{-1} of forest. These results are similar to Alam et al. (2017) who found an emission reduction of 0.28 tCO_2 yr^{1} ha^{-1} of boreal forest in Finland, and Nunery and Keaton (2010) who found that annual emission differences between silvicultural systems ranged from 0 to -0.23 tCO_2 yr^{1} ha^{-1} of northern temperate forest.

The highest-ranked mitigation activity for the six regions was reduced deforestation at 1.6 tCO_2 yr^{1} ha^{-1} of forest, followed by increased afforestation at -0.9 tCO_2 yr^{1} ha^{-1} of forest. Reducing deforestation immediately avoids significant emissions from the loss of previously accumulated C in forests (even if the HWP C stocks are considered), and delayed but increasing mitigation benefits from afforestation as forests accumulate higher levels of C stocks compared with non-forest land uses. These findings are consistent with other studies that have compared mitigation scenarios by the forest sector (Fargione 2018; Fuss et al. 2018; Griscom et al. 2017; Nabuurs et al. 2007; Nunery and Keeton 2010). By order of magnitude, our results are similar to a global synthesis that gave roughly equal potential to reducing deforestation and increasing afforestation when economic and practical limits to afforestation were considered (Kindermann et al. 2008). Mitigation benefits from both afforestation and avoided deforestation are subject to reversals from natural disturbances, which is in contrast to mitigation benefits from using wood product to avoid fossil fuels because these benefits are not reversible. Risks to afforestation and avoided deforestation also involve the changing climate which is modifying growth rates, growth potential, and partly increasing mortality events (Hember et al. 2017; Turner 2010).

Every scenario we examined had hard-to-assess induced secondary effects, risks, and uncertainties. Key uncertainties in the landscape-level scenarios related to the use of historical LUC trends to project 'business as usual' activities in the forward-looking baseline and scenario implementation levels. Improvements to the LUC activity data with attribution for all of North America would greatly improve the ability to estimate the projected ecosystem C balances for 'business as usual' activities. Scenarios were selected in consultation with stakeholders to represent likely or potential activities that would be regionally feasible to implement, but the same activities at different activity levels or other activities are also possible. Additional research on impacts of climate change on growth, mortality and impacts of natural disturbances would reduce uncertainty in these long-term modeling studies, as well as additional research on substitution benefits with future decarbonization.

There are significant economic challenges and other barriers to deploying forest sector mitigation scenarios on a large scale that we did not consider. Forest sector connections to other economic sectors may change in response to additional forest sector activities, thus impacting economy-wide emissions or removals (Abt et al. 2012; Bustamante et al. 2014; Murray et al. 2004). Induced effects involve potential for leakage or activity shifting that result in offsetting emissions elsewhere. Likewise, scenarios that seek to increase the supply of wood-based building materials or bioenergy would require a matching demand for these commodities to make such approaches economically viable (e.g. Daigneault et al. 2012; Nepal et al. 2015; Nepal et al. 2012). Large scale afforestation could be limited by competition for land for food production, subsistence living, and availability or alternate needs for water (Fuss et al. 2018; Humpenöder et al. 2018; Smith et al. 2016).

The social acceptance of implementing forest management mitigation activities must also be considered by factoring in socioeconomic concerns, encouraging adaptation initiatives, and engaging the forestry sector (Peterson St-Laurent et al. 2018). Community-based forest management and ecosystem services payments programs are among the most effective policy options for improving forest cover in Mexico (Min-Venditti et al. 2017). Moreover, increasing the area under forest management would help to reduce the overall rate of deforestation and avoid forest degradation through illegal logging practices (Ellis et al. 2017). Forest landowners could receive C credits for avoided conversions, afforestation and reforestation activities, and improved forest management (ARB 2011; Galik et al. 2012), all of which were found to be effective emissions reductions scenarios in the forest ecosystem component.

Effective mitigation strategies take into account baseline forest ecology, including growth and disturbance drivers, and consider activities to reduce emissions within the forest ecosystem, in harvesting operations and manufacturing, wood use and post-consumer treatment. Ecosystem drivers for the six regions were different, and net ecosystem productivity showed a decline into the future for most regions even with mitigation activities, and without assumed increases in natural disturbance rates (Figure 6, Figure S1). The declining sink in forests is indicative of a potential global challenge: to keep average global temperature increases to well below 2 degrees Celsius, net negative emissions are required by the second half of this century, which, in turn, requires increasing land sector C sinks and greatly reducing emissions from fossil fuel use. It is important to note that diminishing C sinks, as projected in the baseline scenarios in this study and in others (Nabuurs et al. 2013; Wear and Coulston 2015), will make it even more difficult to achieve future net negative emissions. Thus, forest management strategies that sustain and increase future forest C sinks will have to be developed, while anticipating the impacts of climate change.

Conclusions

We identified regionally diverse mitigation opportunities for the forest sector using a harmonized and consistent methodological approach that was applied to 16 Mha of forests within six regions of North America. A sound analytical framework for assessing mitigation strategies examined the forest ecosystem, C use and storage in HWPs and landfills as well as substitution benefits from using wood in place of emissions-intensive products or fossil fuel-based energy. Mitigation scenarios can target one or more of these three components, and decreasing fluxes in one component often increases fluxes in one or both of the others, highlighting potential trade-offs. Each of the components had different risks associated with GHG reductions, with C storage in forests subject to reversal from disturbances such as wildfires, and saturation of HWP or use of products from another region. Substitution benefits are non-reversible, but have higher uncertainty because benefits depend on the wood products from a harvested tree and the alternative non-wood products that are not selected. Combinations of scenarios that target more than one component can offer the highest mitigation potential while at the same time minimizing future risks. In addition, combinations of activities can balance immediate GHG reductions from scenarios that avoid disturbances, with longer-term GHG reductions related to future forest growth. Long-term mitigation benefits related to future forest growth can be increased by starting early, ensuring sustained actions in the future, and selecting regions with low risk of natural disturbances.

There were regional differences in ecosystems and drivers in the six study sites within North America. Mitigation scenarios in southeastern Mexico and southeastern US focused on avoided deforestation or increased afforestation (or forest recovery), because deforestation rates are high in these regions. For the other regions, land-use change drivers were less important, and scenarios instead concentrated on changes to forest management to reduce emissions associated with harvesting, managing residues for bioenergy, and shifting commodities to longer-lived wood products. Overall, the highest mitigation potential, normalized by either forest area or mitigation activity area, was avoided deforestation and increased afforestation in tropical and southern temperate regions where growth rates and undisturbed C stocks were high. Opportunities for greater mitigation benefits may be realized through collaboration with HWP trade between countries (Magnan et al. 2017) by generating longer-lived wood products for construction of buildings and substitution of high-emissions materials and fossil energy. Overall, the findings from these six regions support the conclusion of the IPCC, that sustainable forest management strategy aimed at maintaining or increasing forest C, while producing products and energy, will generate the largest sustained mitigation benefit (Nabuurs et al. 2007).

The demand for climate change mitigation analyses in the forest sector has never been higher. Signatory countries to the Paris Agreement aim to keep the global temperature increase to well below two degrees Celsius, and to enhance and conserve forest-based C sinks. Over 100 member counties have included the land sector in their nationally determined contribution. Moreover, each member country must determine and report on the national contributions to mitigate climate change, with updated mid-century projections required every five years. In addition, each country has domestic forest sector efforts under national initiatives such as the Pan-Canadian Framework for Clean Growth and Climate Change, the US Climate Alliance, regional carbon trading markets, and Emission Reduction and Forest Management Conservation Initiatives (REDD+, Forest Carbon Partnership Facility, BioCarbon Fund). We have shown that the tools are maturing to perform these analyses for all of

North America, but access to forest inventory data and associated growth, as well as a lack of coordinated funding present challenges to such analyses. Many data holders and stakeholder communities in the three countries were needed to provide information for the model simulations and scenario parameters. The support provided by the Commission for Environmental Cooperation and the resulting cooperation among the three national forest services allowed for a previously unprecedented tri-national scientific collaboration on the climate change mitigation potential for the forest sector in North America.

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Supplementary information

The SE-US coastal South Carolina study site remained a C sink until 2045 and then switched to a C source through to 2050. Recovery from disturbance caused the sink, and the switch to source resulted primarily from age-induced declines in productivity and a decrease in forested area. Forest ecosystems of the N-US Wisconsin study site showed a shift from a sink to a source in 2022. This shift to a C source was largely a result of forest aging causing productivity to decline, combined with net emissions from disturbances including deforestation.

The SE-MX Quintana Roo site was a sink throughout the time series, with a trend of decreasing sink strength over time due to forest ageing and continuous reduction in forest area. The sink strength was generally stronger in this region than at the northern site due to fast growing young stands and high stand capacity. The N-MX Durango site showed a gradually declining sink to 2050. The forest age-class structure in Durango was more evenly distributed, with lower growth rates than in southeastern Mexico.

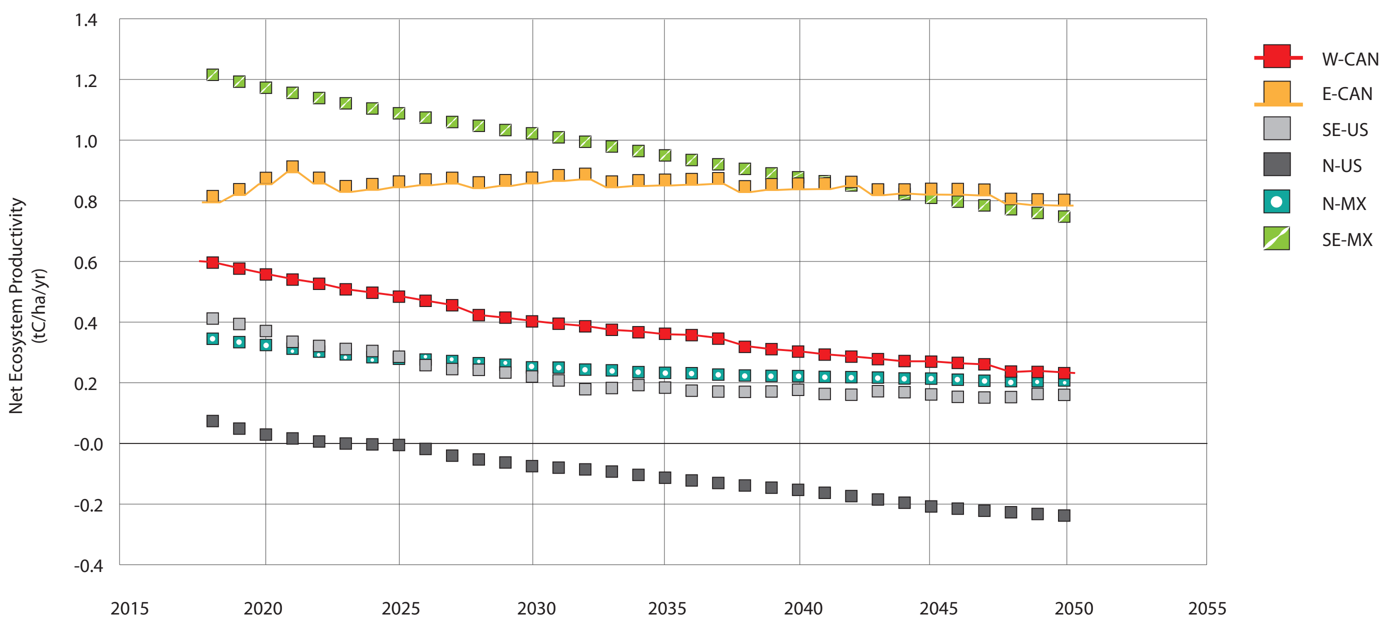

Figure S1. Ecosystem Productivity (NEP) time series for the baseline scenarios at each of the six study sites.

Table S1 Cumulative, 2050, and average annual mitigation potential by scenario and areas for normalization. Average values were estimated from 2018 to 2050.

Activity	Region	Cumulative mitigation potential in 2050 ($MtCO_2e$)	Annual mitigation potential in 2050 ($MtCO_2e\ yr^{-1}$)	Average mitigation potential ($MtCO_2e\ yr^{-1}$)	Annual activity area in 2050 (kha)	Average activity area (kha)	Average activity area (kha)
Higher harvest through higher utilization	W-CAN	-1.3	-0.03	-0.04	5.6	4.8	946
Decrease harvest	W-CAN	-0.8	-0.04	-0.02	0.1	0.1	946
Residues bioenergy	W-CAN	-2.5	-0.12	-0.08	5.6	4.8	946
Increase LLP	W-CAN	-3.1	-0.11	-0.09	5.6	4.8	946
Avoid slash burning	E-CAN	-0.39	0.01	-0.01	0.2	0.2	739
Higher harvest through higher utilization	E-CAN	-0.65	-0.02	-0.02	0.67	0.75	739
Decrease harvest	E-CAN	-0.02	-0.01	-0.001	0.03	0.04	739
Residues for bioenergy	E-CAN	-0.91	0.00	-0.03	0.67	0.75	739
Increase LLP	E-CAN	-1.29	-0.04	-0.04	0.67	0.75	739
Residues for bioenergy	SE-US	-0.78	-0.03	-0.02	2.47	2.16	337
Increase LLP	SE-US	-1.73	-0.07	-0.05	9.95	7.11	337
Increase productivity	SE-US	-0.44	-0.02	-0.01	0.08	0.70	337
Increase afforestation	SE-US	-5.21	-0.31	-0.16	0.87	0.87	351
Reduce deforestation	SE-US	-3.13	-0.11	-0.09	0.33	0.33	342
Residues bioenergy	N-US	-2.15	-0.09	-0.07	6.7	6.5	3062
Increase LLP	N-US	-8.50	-0.32	-0.26	122.9	109.9	3062
Extended rotation and LLP	N-US	-17.69	-0.68	-0.54	13.6	12.7	3062
Reduce deforestation	N-MX	-23.2	-1.1	-0.7	3.6	2.9	5398
Reduced deforestation plus recovery	N-MX	-24.3	-1.1	-0.7	3.9	3.2	5399
Increase growth and harvest with LLP	N-MX	-15.1	-1.0	-0.5	12.5	10.0	5398
Reduce deforestation	SE-MX	-106.6	-4.7	-3.2	8.5	7.0	2975
Reduce deforestation plus recovery	SE-MX	-111.4	-5.0	-3.4	9.3	7.6	2977
Reduce deforestation plus recovery plus increase growth and harvest with LLP	SE-MX	-107.5	-4.9	-3.3	9.4	7.7	2976