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YSSP Report

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Including biodiversity conservation in forest management decisions

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ABSTRACT

Forests play a major role in two of the biggest challenges humans face today, climate change and biodiversity loss. Increased interest in nature-based solutions, the expectation of increased dependence on negative emission technologies such as Bioenergy with Carbon Capture and Storage (BECCS), and biodiversity conservation goals, puts forest management and land use change decisions in the spotlight. Forest and land management decisions respond to economic incentives of landowners or forest managers, but frequently ignore the related biodiversity impacts. So, what happens if we include biodiversity in the decision making? Which are the trade-offs? Could we find solutions that favor both biodiversity conservation and forestry economic outputs? Here, we tackled this issue and included biodiversity impacts in forest management decision making, in a spatially explicit manner, by incorporating the countryside species area relationship (cSAR) model into the partial equilibrium model GLOBIOM-forest. We tested three forest management intensities (low, medium and high) and limited biodiversity loss via an additional constraint on total species loss. We present the results for 6 scenarios that correspond to the combinations between 2 climate change scenarios and 3 different constraints on biodiversity loss. Our results indicate that (1) omitting biodiversity loss in forest management decisions imply significantly more species loss, however the magnitude varies by taxa, (2) there are combinations of ecoregions and taxon that have more species loss when biodiversity constraint is introduced because the model allows for reallocation between species loss between taxa and ecoregions, (3) RCP1.9, the higher mitigation scenario, has more biodiversity loss than the reference RCP7.0 due to increase areas of intensively managed forests and (4) there are no significant changes on a global basis of harvest volumes for roundwood, but there are differences in the boreal and temperate zones.

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List of Abbreviations and Acronyms

Below is the list description of all abbreviations or acronyms used in the following text.

Abbreviations/Acronym	Description
IIASA	International Institute for Applied Systems Analysis
CBD	Convention on Biological Diversity
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
cSAR	Countryside Species-Area Relationship model
GLOBIOM	Global Biosphere Management model
LP	Linear Programming
NLP	Non-Linear Programming
MIP	Mixed Integer Programming
SRP	Short Rotation Plantations
FRA	Global Forest Resource Assessment
WDPA	World Database on Protected Areas
SSP	Shared Socioeconomic Pathway
RCP	Representative Concentration Pathway
LCA	Life Cycle Assessment
LPI	Living Planet Index
MSA	Mean Species Abundance
BII	Biodiversity Intactness Index
AEZ	Agro-Ecological Zones
IAM	Integrated Assessment Model

1 Introduction

Forest management decision making has always responded to how humans view, define, assess and value forests. According to Chazdon et al. [2016] when forests are seen as a source of timber, forest management decisions focus on obtaining higher yields and in being able to produce timber sustainably through time. When forests are seen as ecosystems, forest management decisions change towards protecting and conserving biodiversity and functions in forest ecosystems. Then, if forests are seen as carbon stocks and sources of carbon sequestration, forest management decisions must follow and consider the sources and sinks of carbon associated with forest management.

Today we see forests as providers of several ecosystem services, including (1) provision of timber and other forest products, (2) cultural services as spiritual and religious values, inspiration and recreation, (3)supporting services as nutrient cycling and habitat provision and (4) regulating services as carbon sequestration. Therefore, forest management decisions should now reflect all these objectives which, we as humans, have with forests. However, current models used to assess and evaluate forest management decisions still do not reflect current definitions and objectives of forest management. Partial equilibrium models, such as the Global Timber Model (GTM) [Austin et al., 2020, Sohngen and Mendelsohn, 2003, Sohngen et al., 1999] and GLOBIOM forest [Lauri et al., 2021, Lauri, 2021] are used today to assess forest management decisions. These models are used in isolation to understand the effects of several scenarios on forests and forest markets, but also are used in combination with other land use models or even integrated assessment models (IAMs) to represent forestry sector decisions within a bigger interconnected system.

These partial equilibrium models incorporate forest products' markets where consumers and producers interact with prices and as a result of these interactions, the quantities being produced of each forest product are determined. Usually, on the production side these models incorporate transportation costs, harvesting costs, transformation costs and depending on the model land use change costs. Similarly on the demand side, these models incorporate how consumers demanded quantities may respond to changes in prices of the produced goods. Since these partial equilibrium models reflect only market goods, they ignore non-market goods, such as biodiversity and ecosystem services, and also several more externalities associated with forest industry. This gap implies that the forest management decisions made using these models are only reflecting the definition of forests as providers of timber products.

It must be highlighted however, that in the effort to understand and find mitigation alternatives for climate change, some models as [Johnston and Withey, 2017] have incorporated carbon stocks and potential for carbon sequestration. When this is done, these models also reflect a definition of forests as carbon stocks. But still other ecosystem services provided by forests remain excluded.

Biodiversity loss is one of the main challenges that humans face today. As mentioned by the Convention of Biological Diversity (CBD) and the IPBES, we are facing an era of extreme biodiversity loss. Considering biodiversity an its relation with the maintenance of ecosystems function and therefore the provision of several ecosystem services, this paper is going to focus on biodiversity conservation.

Responding to the new definitions of forests, several researchers have started assessing the impacts of forest management decisions in what is called an ex-Post analysis. This approach consists in deplyoing models as partial equilibrium models to represent forest management and land use change decisions under several scenarios, including different climate change scenarios and then the impacts on, for example biodiversity, are estimated after the model solution is found. Examples of this approach for biodiversity impacts of different land use change scenarios include Leclere et al. [2020], Di Marco et al. [2019], Duden et al. [2018], Di Fulvio et al. [2019], Hill et al. [2018], Chaudhary and Mooers [2018].

This step has been very important since it has given information about the feasibility and impact of current trends, has allow us to evaluate scenarios and pathways for potential improvement and in summary has indicated us that we humans cannot continue with current trends if we want to avoid massive extinctions and surpassing the planetary boundaries. However, this approach has two important conceptual limitations. First, with it, it is not possible to identify solutions that could have similar economic benefits, but less biodiversity loss associated. Second, it is an approach where forest management decisions are being made, then if an environmental problem is generated, a solution is attempted to be found for it. Meanwhile, if biodiversity loss is endogeneized in the decision making models, a solution that avoids generating the environmental problem since the beginning could be identified.

Therefore the next step, the one consistent with our current definition of forests is to incorporate biodiversity loss into forest management decision making, which is the objective of this paper. The first section starts describing the economic (GLOBIOM forest) and ecologic (Countryside Species Area Relationship Model- cSAR) models used. It details on how biodiversity loss will be measured and represented, including three different methodologies to incorporate the cSAR model, 2 linear versions, via characterization factors and linear approximations and a nonlinear version. The second section explains how the cSAR model was integrated in GLOBIOM forest. Finally, in the third section the results are shown for 6 scenarios that correspond to the combinations between 2 climate change scenarios and 3 different constraints on biodiversity loss. These compare the baseline model (without biodiversity loss) with the extended model (with biodiversity loss) for year 2100.

2 Methodology

2.1 GLOBIOM forest

The GLObal BIOsphere Management model (GLOBIOM)[Havlík et al., 2011, Havlik et al., 2014] is a land use change model that represent the interactions between the agricultural (including livestock), the forestry, the bioenergy and fisheries & Aquaculture sectors to understand and estimate land allocations and future land cover under different scenarios. It is a partial equilibrium model that follows a bottom up approach, where supply is represented on a spatial explicit basis (using the simulation units (SimU) that correspond to the intersection of countries, grid cells, altitude, slope and soil class), the demand is represented on a regional basis and bilateral trade between regions is included. Since it maximizes total surplus, land allocation decisions are based on the profitability of the activities by land use type. It incorporates information from the EPIC agricultural model and its coupled with G4M forest management model. The model is run recursively dynamic with 10 year time steps, from 2000 to 2100. It corresponds to the land module of two integrated assessment models, WITCH (from the RFF-CMCC European Institute on Economics and the Environment) and MESSAGEix (from the International Institute of Applied System Analysis (IIASA)).

GLOBIOM-Forest is a version of GLOBIOM that focuses on a more detailed representation of the forest sector, while simplifying the representation of the agricultural and bioenergy sectors. It is a bottom up partial equilibrium model in which total economic surplus is maximized. In it, supply related decisions are made on a spatial explicit scale with spatial units that correspond to the intersection of a grid, that can be $200km \times 200km$ or $50km \times 50km$ resolution, with countries boundaries. On the other hand, demand is represented on a regional basis (up to 58 regions[1]). The model includes: (a) transportation costs of woody biomass from forest to mill gate within each region,(b) harvest costs, (c) process cost, (d) investment costs, (e) trade costs, and (f) land use change costs. a,b,f are spatially explicit and c,d,e are on a regional basis. It includes a representation of both forestry and the forest industry. The *biomass production* via the primary harvested products (Pulplogs, sawlogs, other industrial roundwood, fuelwood, logging residues) and one non-harvested product (deadwood), and the *forest industry* via the by-products (Sawdust, woodchips, bark, black liquor, recycled wood), the intermediate products (chemical pulp, mechanical pulp, recycled pulp) and the final products (Sawnwood, plywood, fiberboard, other industrial roundwood, fuelwood, energy wood).

Regarding the production of biomass, it decides on (1) the *area* of forest to be harvested during the rotation period for each spatial unit and forest management type and (2) the harvested *quantities* of a particular primary product in each spatial unit and under each forest management type. In comparison to GLOBIOM, GLOBIOM-Forest includes more than one forest management intensity (Low, Medium and High), have detail on tree species (distinguishing between coniferous (softwood) and non-coniferous (hardwood)) and includes details on age-class dynamics [2]. Management intensities are defined as a combination of assumptions on (1) the percentage of the increment that is harvested, (2) the limit on logging

[1]For the results presented here, the model was run with 58 regions that include 180 countries.

[2]However, the results presented here exclude the age-class and carbon dynamics of forests. This means that all forest area is assumed to be "normal forests" with constant carbon stocks and increments.

residues that can be obtained and (3) a minimum amount of the increment that has to be left as deadwood.

Regarding the production of intermediate and final demand products, it decides on (1) the quantity of final products to produce by processing primary product and (2) the processing capacity of the main final products. It also decides on the level of investment in each region and each product, which will increase the production capacity.

GLOBIOM-Forest also includes bilateral trade of forest products between regions, where it decides the quantities of each product that are exported or imported from region to region.

Finally, it incorporates energy crops through short rotation plantations (SRP). This is represented separately from the previous forest management types because by a sustainability assumption energy crops are not allowed to be located in forestland [3]. Instead, the model decides the amount area devoted to these industrial plantations by transforming from natural land, grasslands or cropland. The representation of these land use changes is simplified in this version compared to GLOBIOM. The biodiversity impact of these SRPs is not included in the scope of this paper.

GLOBIOM-forest is a recursive optimization model that is calibrated from years 2000 to 2020, and runs in ten years intervals up to 2100. Data sources for calibration include the Global Forest Resource Assessment (FRA) that provides regional data on forest types and harvest potential between coniferous and not coniferous tree species; the World Database on Protected Areas (WDPA) for grid level data on forest managements and Nature Map Explorer. These three databases were used to improve the allocation of forest and forest management areas during the calibration period. Additionally, FAOSTAT database was used for reference volumes for demand functions, forest industry production capacities, the separation between coniferous and non coniferous final products, harvest volumes and net trade quantities. Finally, BACI trade data was used for the bilateral trade quantities. Other sources of data, beyond calibration purposes, include increments, harvest costs and total forest area (as a result of deforestation and afforestation decisions) from the G4M model .

The model is run under Shared Socioeconomic Pathway 2 (SSP2)- the middle of the road and includes various Representative Concentration Pathways (RCPs): RCP1.9, RCP2.6, RCP4.5 and RCP8.5 (the business as usual, here called RCPref) . In the model, the SSP affect the GDP and population data which then affects the demand functions and the RCPs affect the bioenergy demand.

2.2 Biodiversity model assessment

In this paper, biodiversity impacts will be estimated as a response to habitat loss driven by changes in forest management. It includes changes from Primary and Secondary forest to each of the three levels of intensity of managed forests, changes in intensity in already managed forests and changes from managed forests to secondary forests. Only the species level dimension of biodiversity is included and the model chosen is the Countryside Species Area Relationship model (cSAR)[Pereira and Daily, 2006, PEREIRA et al., 2014]. The indicator estimated by the model is the potential regional species loss. The cSAR model

[3] If forests are converted to SRP, it will usually decrease the biomass stock per ha, whereas when cropland or managed grassland are converted to SRP, biomass stock per ha is usually increased.

belongs to the family of SAR models, derived from ecology, and widely used in Life Cycle Assessment (LCA) to evaluate the impacts of products and services on biodiversity due to land use change. In the family of SAR models, the cSAR model distinguishes because it assumes that when transforming natural habitat, some species may adapt to human-modified habitat and therefore not all species will be lost. The model used and presented here 1 is based on [Chaudhary and Brooks, 2018, Chaudhary et al., 2015, 2016].

$$Slost_{g,j} = Sorg_{g,j} \left[1 - \left(\frac{\sum_{i \in ForMngTypes} h_{g,i,j} A_{i,j}}{Aorg_j} \right)^{z_j} \right] \forall g \in G, j \in L \tag{1}$$

where G is the set of taxonomic groups and L is the set of ecoregions. An ecoregion is a biogeographical characterization made by the World Wildlife Fund (WWF) that groups land that shares a large majority of species, dynamics and environmental conditions. Forest management types in GLOBIOM-forest are the set {Primary forest, Secondary forest, Low intensity management, Medium intensity management, High intensity management}.

The model is based on the proportion between the areas available for species in a reference scenario versus the area available for species in the new scenario. The former will correspond to the denominator of the fraction inside the parenthesis and the latter will correspond to the numerator. $Aorg_j$ and $Sorg_{g,j}$ are the amount of natural habitat and number of species of taxon g in the "original" period in ecoregion j, respectively. $A_{i,j}$ is the amount of area devoted to each forest management type i on each ecoregion j in the future scenario; $h_{g,i,j}$ represents the affinity of the taxonomic group g for forest management type i on ecoregion j and z_j a constant from classic SAR model for region j, that reflects the slope that describes how rapidly species are lost due to habitat loss.

A typical assumption when assessing biodiversity changes is to use this reference scenario as a pristine scenario without human intervention [Curran et al., 2016], which implies to assume that $Aorg_{g,j} = TotalArea_j$. Also, the affinity h can be interpreted as the proportion of the area under each management type i that can be used by the taxon g in each ecoregion j [PEREIRA et al., 2014, Pereira and Daily, 2006]. Therefore $0 \leq h_{g,i,j} \leq 1$. In this way, $S_{lost,g,j}$ correspond to the potential species loss in each ecoregion due to the decrease of habitat from $Aorg_j$ to $\sum_{i \in ForMngTypes} h_{g,i,j} A_{i,j}$. Note that the disappearance of a species in an ecoregion does not imply the disappearance of the species in a global basis, therefore this indicator does not correspond to global extinctions.

There are some important limitations of the cSAR model that should be accounted for. First, it ignores the fact that species may migrate due to a disturbance in their habitat. This could be specially misleading for birds that can easily move to a different geographical location. Second, because it is on the species level, it does not account for effects on populations, i.e. the effect of land use change on species abundance. For example, it could happen that there is reduction in habitat loss that decimate most of the individuals of a particular species, while there is one individual of that species, the biodiversity measure will remain unchanged, therefore only in the no-returning point where no individuals of a species are left, i.e. when the species becomes extinct, will the indicator reflect a change in biodiversity status. Third, the SAR models do not give information about *which* species in the taxonomic group are most vulnerable to the land use change .Fourth, it indeed assumes that all species within the taxonomic group are equal (through the same affinity value) so it does not give information about the relative differences in vulnerability to extinction. Fifth, the temporal scale, the model does not say anything about the amount of time it will take to lose the estimated amount of species. It only informs about the potential species loss due to the assessed scenario of habitat loss. This is why it is important to couple the results with other biodiversity measures.

Being aware of these limitations, there have been attempts to improve the biodiversity assessment, as a response to land use change, by incorporating more than one indicator of biodiversity. For example [Leclere et al., 2020] included the extent of suitable habitat, the Living Planet Index (LPI), the Mean Species Abundance (MSA), the Biodiversity Intactness Index (BII) and the regional and global potential species loss using cSAR model. However, because of the simplicity of the cSAR model that facilitates its incorporation with GLOBIOM-forest, and data availability on a global basis, the cSAR model will be used as a starting point.

2.2.1 Data for biodiversity model

In terms of data, the information on affinity factors $h_{g,i,j}$ were derived from [Chaudhary et al., 2016] using equation

$$h_{g,i,j} = \text{Response Ratio}^{1/z_j} \tag{2}$$

where Response Ratio $= {}^{X_e}/_{X_c}$. X_e is the mean species richness in the disturbed(managed) forest sites and X_c is the mean species richness in the reference (unmanaged) forest sites. For cases for which 2 resulted in numbers greater than 1, a 1 was assigned indicating that that management type is as good as the primary forest, which is the same as saying that species can use all of the modified habitat, and follows [Chaudhary et al., 2016].

Since the model intends to estimate the effect of forest management on biodiversity loss, $Aorg_j$ in this paper does not correspond to the area of the whole ecoregion, but only to forest area in the ecoregion.These areas were calculated using data from GLOBIOM-forest and a mapping between GLOBIOM-forest spatial units and the ecoregions. The mapping correspond to the intersection between the ecoregions map and the GLOBIOM-forest spatial units (on a 200km x 200 km basis) map done in ArcGIS. From it, weights of spatial unit s in ecoregion j, $mW_{s,j}$, were estimated. Then,

$$Aorg_j = \sum_s FOREST\_AREA_s \cdot mW_{s,j}, \, \forall j \in L \tag{3}$$

Similarly, $A_{i,j}$ was estimated according to 4. This is indeed the connection between the biodiversity model and the forestry model.

Data on $Sorg_{g,j}$ [4] comes from [Chaudhary and Brooks, 2018]. Finally, $z_j = 0.344$, $\forall j \in L$, that corresponds to the mean value for forests according to [de Baan et al., 2013].

Only amphibians, birds, mammals, plants are considered in the set of taxa due to data limitations.

[4] For consistency, $Sorg_{g,j}$ should also be adjusted to only include the number of species that live on forests. However, this was not possible dut to data limitations. This imply that the number of species loss may be an overestimation of the real number.

2.3 Integration of the models

There are two main components of the integration between cSAR model and GLOBIOM-forest, the data mappings and the methodology to incorporate biodiversity.

2.3.1 Data Mappings

There are three main data components related to the models that have to be considered: the spatial units, the forest management types and the time periods.

Spatial units As described in section 2.2, the biodiversity impact indicator is calculated on an ecoregion basis. On the other hand, the data for affinities in the biodiversity model (from [Chaudhary et al., 2016]), is on a continental level (excluding Antarctica). This implied the creation of a mapping between continents and ecoregions. The assignment of an ecoregion to a continent is through countries, therefore an initial mapping between ecoregions and countries is required. This was done in ArcGIS using the UIA World Country Boundaries Layer and the WWF ecoregions' layer. It is assumed that the affinity value h for the ecoregion will correspond to affinity value assigned to the continent to which the ecoregions belongs. If an ecoregion has area on more than one country, a weighted average of the affinity factors of the continents was calculated, based on the proportion of the ecoregion area in each continent.

With respect to GLOBIOM-forest model, the model was ran on a 200km x 200km (2^{o}) grid resolution for all countries. The spatial units in GLOBIOM-forest correspond to the intersection between country boundaries and this grid. To connect between the ecoregion level and these spatial units, an intersection of the two layers was done in ArcGIS. From it, a mapping was created. It includes (1) if the combination between ecoregion and spatial unit exists, and (2) the weight $mW_{s,j}$ used in equations 3,4.

Management Types Chaudhary et al. [2016] contains information on the response ratios, and therefore affinities, for ten Management types, whereas GLOBIOM-forest includes three management types. The mapping used is presented on Table 1. See table 2 in the Annex section for the definition of each forest management in GLOBIOM-forest.

[Chaudhary et al., 2016] management type	GLOBIOMf management type
Clear-cutting	High: CurC, CurNC
Retention	Low: CurC_L, CurNC_L
Selection system	Low: CurC_L, CurNC_L
Selective logging	Medium: CurC_M, CurNC_M
Reduced Impact Logging (RIL)	Low: CurC_L, CurNC_L
Plantation-timber	High: CurC, CurNC
Plantation-fuel	High: CurC, CurNC
Plantation-non timber	Not apply
Agroforestry	Not apply
Slash & Burn	Not apply

Table 1: Mapping between [Chaudhary et al., 2016] and GLOBIOM-forest management types

It is assumed that affinity factors will not change between tree species (coniferous and non- coniferous) and the affinity factor for a GLOBIOM-forest management intensity will correspond to the average between the [Chaudhary et al., 2016] management types according to mapping in Table 1.

Time periods The biodiversity cSAR model estimate potential regional species loss by comparing a reference scenario to a future scenario. To combine this with the 11 years periods (from 2000-2100) of GLOBIOM-forest, the "pristine" reference scenario remained the same for all GLOBIOM-forest time periods, while the future scenario correspond to each of the GLOBIOM-forest runs. This means that the potential species loss estimated is always with respect to the reference scenario.

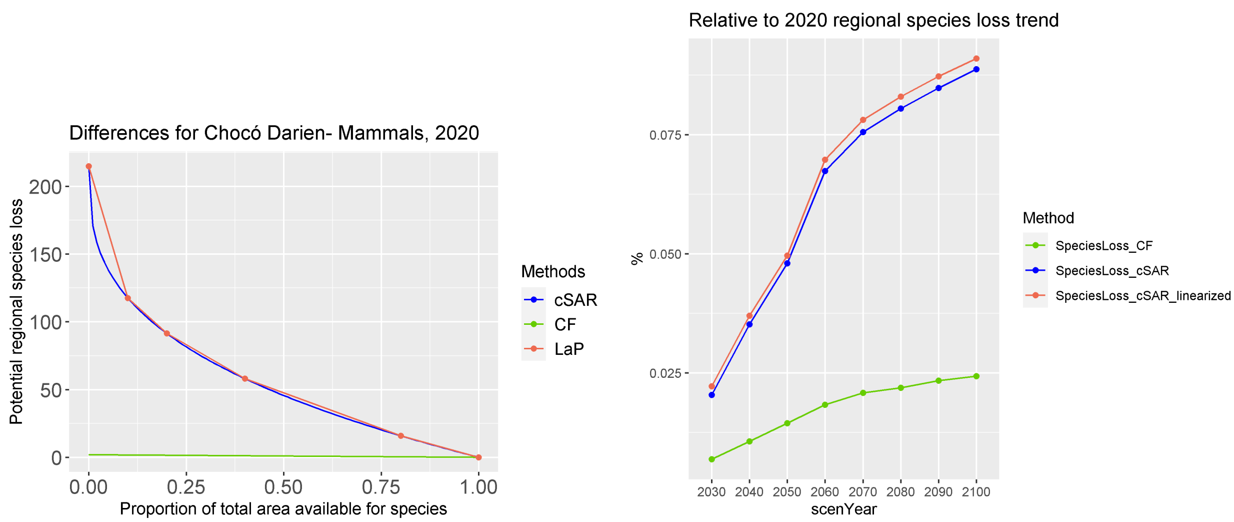
2.3.2 cSAR model incorporation methodology

There are 6 ways to incorporate the cSAR model into GLOBIOM-forest which are shown in Figure 1. The first criteria is how to represent the cSAR model. Currently, GLOBIOM-forest is a Linear Programming (LP) model because of the computational efficiency and running time improvement of using an LP versus a Non-Linear Programming Model (NLP). Considering this, there are three potential ways to include cSAR model. The first is to use characterization factors (CFs) that are derived from the cSAR model [Chaudhary and Brooks, 2018], this will be a linear version. The second alternative is to use a linear approximation of the cSAR function. This is the same approach taken in GLOBIOM and GLOBIOM-forest for areas under the non-linear demand functions and costs functions (trade, land use change, supply). The third approach is to change GLOBIOM-forest to a NLP and incorporate the cSAR function as defined in 1.

	cSAR model representation		
Biodiversity impact incorporation	Constraint Characterization Factors	Constraint Linear Approximation	Constraint Non-Linear
	Objective Function Characterization Factors	Objective Function Linear Approximation	Objective Function Non-Linear

Figure 1: 6 ways to incorporate biodiversity model into GLOBIOM-forest

To determine the best representation for the cSAR model both computational efficiency and accuracy of the biodiversity indicator were considered. Figure 2 show differences in the biodiversity loss estimation between the three methods. In Figure 2a we can see the estimation of the potential regional species loss for one ecoregion (Chocó Darien in Colombia), one taxon (Mammals) and one type of forest management change (from primary or secondary forest to high intensity management), as a response of changes in the ratio of available area for species. In this graph, a ratio of zero means that no area remains available for species, and a ratio of one, means that all area in the ecoregion remains available. On the other hand, Figure 2b shows the relative differences (with respect to 2020) of the biodiversity impacts for the three methods on an ex-Post basis, i.e. evaluating the biodiversity impacts for the baseline model that does not include biodiversity in the decision making. From both graphs it is clear that the characterization factors method subestimates significantly the impact on biodiversity. It is important to mention that whereas the subestimation is expected, because of the linear nature, the magnitude of the subestimation may be bigger than expected because of data limitations [5]. Furthermore, we can see how the linear approximation results in a good estimation, comparing it to the original non-linear model. Because of the computational advantages of keeping GLOBIOM-forest as an LP model, the cSAR model representation chosen is via the linear approximation with 6 steps (0, 0.1, 0.2, 0.4, 0.8, 1.0).



(a) **(b)**

Figure 2: Comparison between three ways of representing cSAR function

The second criteria is on how to incorporate the biodiversity impact. The first alternative is to use a constraint on biodiversity loss. This will mean that the model will allocate land based on the economic benefits, but will be limited on a threshold of species loss defined exogenously. The second alternative is to assign an economic value to biodiversity, that could be interpreted as a tax on biodiversity loss, to internalize the externality and have an efficient allocation. The advantage of the first approach is to avoid assigning an economic value to the regional extinction of one specie. The advantage of the second approach is that it allows for a clearer interpretation of a solution in terms of public policy. In this report, the results presented correspond to the first approach.

2.4 Mathematical formulation changes to GLOBIOM forest

As mentioned in section 2.3.2, biodiversity impacts can be included in GLOBIOM-forest in two different ways, as an additional constraint on biodiversity loss and as an additional cost in the objective function. The required changes to the partial equilibrium model mathematical formulation are explained next and the differences in the formulation for the two ways,

[5]See footnote 4

specified in each case.

Sets:

Add the following sets:
G: set of taxonomic groups indexed in g. Includes {Mammals, Birds, Amphibians, Plants}.
L: set of ecoregions of the world indexed in j.

Note: In GLOBIOM forest, the spatial units corresponds to the intersection of the indices that correspond to the sets COUNTRY, ALLCOLROW, AltiClass, SLPCLASS, SOILCLASS and AEZCLASS. In these ones ALLCOLROW, represents the gridcell which can be defined and used under two different resolutions 200km x 200km (2°) or 50km x 50km (0.5°). The other sets represent Altitude, Slope, Soil and Agro-ecological zones (AEZ) categories, respectively.

For the effects of this mathematical formulation, s will index the spatial units in GLOBIOM forest.

Parameters:

Add the following parameters:

- $Sorg_{g,j}$: Number of species of taxa g present in ecoregion j in reference scenario.
- $Aorg_j$: Natural habitat area in reference scenario in ecoregion j. See assumptions on 2.2 section.
- z_j: The slope of the log-log plot of the power-law that describes how rapidly species are lost as habitat is lost in SAR models. Defined for each ecoregion j.
- $h_{g,i,j}$: SAR model parameter that reflects the affinity of taxonomic group g to management type i in ecoregion j.
- $Bmax$: max number of species we are willing to lose due to habitat loss caused by forest management decisions.
- $mW_{s,j}$: weight of spatial unit s in ecoregion j. Based on areas.

Decision variables:

The decision variable from GLOBIOM forest that will be connected with the biodiversity model Countryside SAR is:

HARVEST_VAR(COUNTRY, ALLCOLROW, AltiClass, SLPCLASS, SOILCLASS, AEZCLASS, ForMngType)

This variable represents the area of forest that will be harvested in each spatial unit under each forest management type during the rotation time, measured in (1000 ha).

Auxiliary variables:

$A_{i,j}$: is the area under each forest management type i in each ecoregion j in the scenario being analyzed.

$speciesLoss_{g,j}$: corresponds to the calculation from Countryside SAR model for taxon g and spatial unit j.

Constraints:

1. Defines $A_{i,j}$. Adds over the spatial units that belong to each ecoregion.

$$A_{i,j} = \sum_{s} HARVEST\_VAR_{s,i} \cdot mW_{s,j} \; \forall i \in ForMngType, j \in L \tag{4}$$

2. Defines $cSAR\_calc$ auxiliary variable.

$$speciesLoss_{g,j} = Sorg_{g,j} \left[1 - \left(\frac{\sum_{i \in ForMngTypes} h_{g,i,j} A_{i,j}}{Aorg_j} \right)^{z_j} \right] \; \forall g \in G, j \in L \tag{5}$$

3. **Constraint methodology** Defines an upper limit for biodiversity loss of current forest management allocation

$$\sum_{\substack{g \in G, \\ j \in L}} speciesLoss_{g,j} \leq Bmax \tag{6}$$

About *Bmax* For the results presented here $Bmax$ was defined in function of the total biodiversity loss, calculated on an ex-Post basis, of the baseline scenario (without the incoporation of biodiversity). First, the baseline model is run. Second, using the results for the harvest areas under each type of management ($HARVEST\_VAR$), biodiversity impact for baseline model ($Bmax_0$) is estimated using the same cSAR model representation that is then going to be used in the model that includes biodiversity. Third, $Bmax$ is defined according to equation 7.

$$Bmax = (1 - \%)Bmax_0 \tag{7}$$

where % corresponds to the percentage of reduction desired. Here 10%, 20% and 30% were used.

Objective function methodology: If the methodology used is to add an additional cost to the objective function, constraint 6 must be excluded and instead τ cost of losing an additional regional specie should be added to the objective function following equation 8.

$$-\sum_{g,j} speciesLoss_{g,j} \cdot \tau \tag{8}$$

2.4.1 Linear approximation for cSAR

For computational efficiency purposes, GLOBIOM forest is modeled as an LP. With constraint 5 the model became non-linear. The following is a proposed way to linearize the problem using a linear approximation for the countryside SAR model.

First, some new auxiliary variables will be added:

Auxiliary variables:

$cSAR1_{g,j}$: corresponds to ratio between areas available for species relationship on SAR model.

then, the following constraints are added,

Constraints:

1. Defines $cSAR1$.

$$cSAR1_{g,j} = \frac{\sum_{i \in ForMngTypes} h_{g,i,j} A_{i,j}}{Aorg_j} \; \forall g \in G, j \in L \tag{9}$$

With constraint 9, the countryside SAR model (constraint 5) becomes

$$cSAR\_calc_{g,j} = Sorg_{g,j} \left[1 - (cSAR1_{g,j})^{z_j}\right] \; \forall g \in G, j \in L \tag{10}$$

Now, the purpose is to replace $cSAR1^{z_j}_{g,j}$ with a linear approximation $L(cSAR1^{z_j}_{g,j})$ and then the model becomes

$$cSAR\_calc_{g,j} = Sorg_{g,j}[1 - L(cSAR1^{z_j}_{g,j})] \; \forall g \in G, j \in L \tag{11}$$

About $L(cSAR1^{z_j}_{g,j})$

Let $f(x_{g,j}) = x^{z_j}_{g,j}$ where $x_{g,j} = cSAR1_{g,j}$. Also, $x_{g,j}$ is defined over interval $[a_1, a_m]$. Denote $a_k, (k = 1, 2, ..., m)$ as the break points of $f(x_{g,j})$, where $a_1 < a_2 < ... < a_m$. Then $f(x_{g,j})$ can be linearly approximated on interval $[a_1, a_m]$ according to

$$L(f(x_{g,j})) = \sum_{k=1}^{m} f(a_{k,g,j}) t_{k,g,j} = \sum_{k=1}^{m} a^{z_j}_{k,g,j} t_{k,g,j} \tag{12}$$

where $x_{g,j} = \sum_{k=1}^{m} a_{k,g,j} t_{k,g,j}$, $\sum_{k=1}^{m} t_{k,g,j} = 1$, $t_{k,g,j} \geq 0$ and only two adjacent $t_{k,g,j}$'s are allowed to be nonzero. t_k can be thought as the weight.

To represent this in the LP model the following must be added/modified:

Set:

K: $\{1, 2, ..., m\}$ Number of breakpoints for linearization.

Auxiliary variables:

$t_{k,g,j}$: weight given to k break point for each combination of ecoregion j and taxon g.
$y_{k,g,j}$: Binary variables that control that only two adjacent weights are allowed to be nonzero.

Constraints:

1. Define the linearization.

$$L(f(x_{g,j})) = \sum_{k=1}^{m} f(a_{k,g,j})t_{k,g,j} = \sum_{k=1}^{m} a_{k,g,j}^{z_j} t_{k,g,j} \tag{13}$$

2. Define $cSAR1_{g,j}$ as the convex combination of break points.

$$cSAR1_{g,j} = x_{g,j} = \sum_{k=1}^{m} a_{k,g,j}t_{k,g,j}, \qquad \forall g \in G, j \in L \tag{14}$$

$$\sum_{k=1}^{m} t_{k,g,j} = 1, \qquad \forall g \in G, j \in L \tag{15}$$

3. Define that only two adjacent $t_{k,g,j}$'s are allowed to be nonzero.

$$t_{1,g,j} \leq y_{1,g,j}, \qquad \forall g \in G, j \in L \tag{16}$$

$$t_{k,g,j} \leq y_{k-1,g,j} + y_{k,g,j}, \qquad \forall g \in G, j \in L, k = \{2, ..., m-1\} \tag{17}$$

$$t_{m,g,j} \leq y_{m-1,g,j}, \qquad \forall g \in G, j \in L \tag{18}$$

4. Define lower bound on $t_{k,g,j}$

$$t_{k,g,j} \geq 0, \ \forall g \in G, j \in L, k = \{1, 2, ..., m\} \tag{19}$$

5. Only one of the binary variables can take the value of 1 to guarantee the consecutiveness.

$$\sum_{k=1}^{m-1} y_{k,g,j} = 1, \ \forall g \in G, j \in L \tag{20}$$

6. Define binary variables. Creates from 1 to $m-1$, therefore $m-1$ variables.

$$y_{k,g,j} \in \{0, 1\}, \ \forall g \in G, j \in L, k = \{1, 2, ..., m-1\} \tag{21}$$

The formulation presented here includes $m-1$ binary variables $y_{k,g,j}$ turning this into a Mixed Integer Program (MIP). However, if the function to linearize is a concave function, the binary variables are not required to guarantee that only two adjacent points are nonzero. Since $y = cSAR1^{z_j}$ is a concave function when $0 \leq h \leq 1$, we can omit constraints in 16-18. We defined $m = 6$ and the domain of cSAR1 as $[a_1 = 0, a_6 = 1]$.

3 Results

Since the main interest is to understand the differences between forest management decision making between incorporating and omitting biodiversity impact in the model, the results presented here correspond to the differences in the indicators of interest for the year 2100 between the model that includes biodiversity vs the baseline model that omits biodiversity. The results were calculated for a total of 6 scenarios that correspond to the combination of 3 different biodiversity loss thresholds and 2 climate change scenarios (that correspond to 2 different Representative Concentration Pathways (RCPs) in conjunction with one Shared Socio-economic Pathway(SSP), the SSP2) as presented in Figure 3.

	Biodiversity thresholds ($Bmax$)		
Climate Change scenario	RCP1.9 10% reduction w.r.t. baseline	RCP1.9 20% reduction w.r.t. baseline	RCP1.9 30% reduction w.r.t. baseline
	RCPref 10% reduction w.r.t. baseline	RCPref 20% reduction w.r.t. baseline	RCPref 30% reduction w.r.t. baseline

Figure 3: 6 scenarios assessed

The climate change mitigation scenarios chosen are RCPref (which refers to RCP7.0) and RCP1.9. RCPref is a no mitigation scenario, with very high greenhouse gas emissions, where harvest volumes do not increase much over time. This correspond to the business as usual. In contrast, RCP1.9 correspond to a high mitigation scenario consistent with an overshoot scenario that pushes harvest volumes to increase after 2050. In it, there is a significant increase in bioenergy demand, which for GLOBIOM-forest, is exogeneously defined according to bioenergy demand from MESSAGEix integrated assessment model. In this way, by using RCPref and RCP1.9 we have two extremes on the spectrum of climate change mitigation pathways.

Regarding the percentage reduction in the biodiversity threshold, a main result that was found is that under current economic assumptions in GLOBIOM-forest, that means, functional forms for demand functions and costs, the costs incorporated and exogeneous information, such as bioenergy demand for wood, the model is infeasible for percentages of biodiversity loss reduction of 40% or more. This is why, the scenarios presented here correspond to 10%, 20% and 30% reduction with respect to baseline model. When interpreting the results it must be noted that an increase in the percentage of reduction represent a tighter constraint for biodiversity loss. This means the scenario with 30% reduction has a smaller feasible area compare to that of the 10% reduction scenario.

The indicators of interest related to forest management decisions include (1) amount of harvested areas under each level of intensity on a spatially explicit level, (2) harvested volumes for selected products and (3) market prices of selected products. With respect to biodiversity the indicators of interest are (1) Total regional species loss and (2)regional species loss per taxa and ecoregion.

Economic impacts With respect to the economic impacts of the forestry sector and the forest industry, two main variables were evaluated, the harvest volumes of roundwood and the world market prices for both harvested and final products. Figure 4and 5 show the results, respectively. In terms of harvested volumes, we can see that across biodiversity threshold scenarios and for all regions (boreal, temperate, tropical, and the whole world), the harvest volumes are greater under the RCP1.9 scenario compared to the RCPref scenario, this is expected due to the increased demand for bioenergy in the former versus the latter. Similarly, we see an interesting pattern in which boreal zone harvest volumes go down as the biodiversity constraint gets tighter, for both RCPref and RCP1.9, whereas it seems that for RCPref harvest volumes in temperate region slightly increase. Nevertheless, the world harvest volumes remain mostly unchanged both when biodiversity constraint is introduced and when it gets tighter.

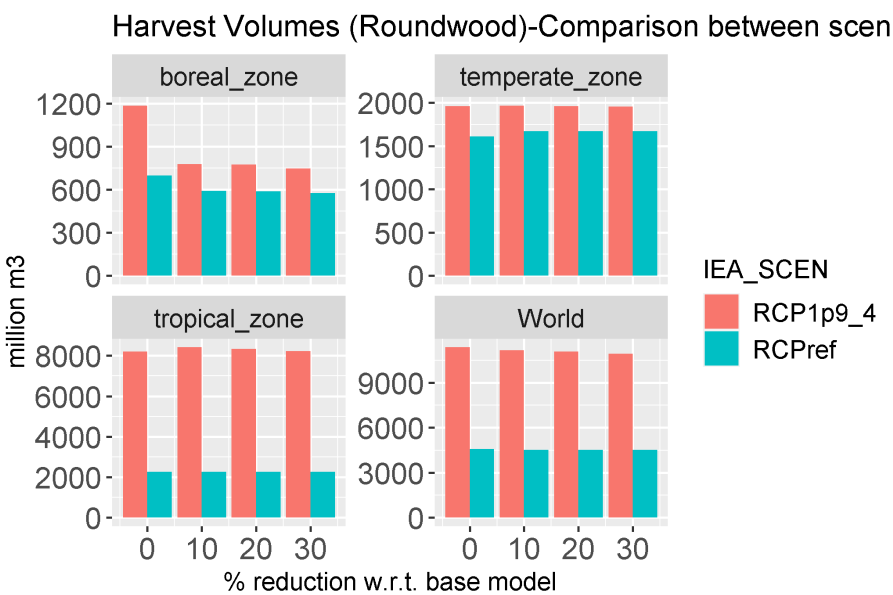
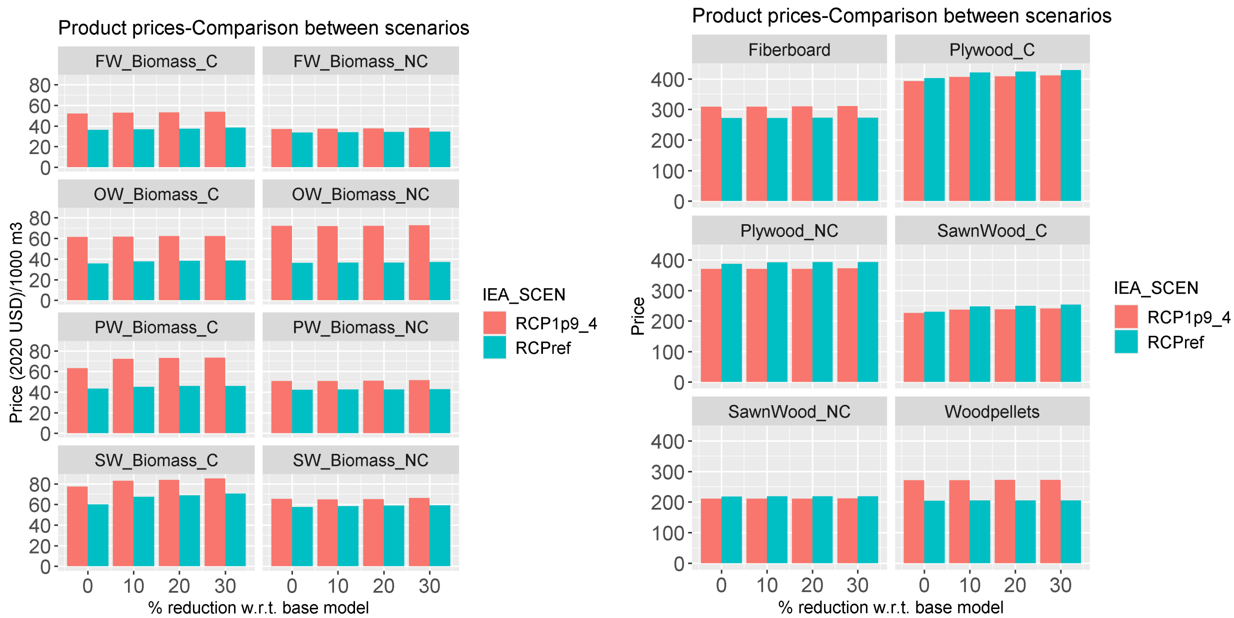


Figure 4: Harvest volumes under each of the 6 assessment scenarios plus exPost results for both RCPref and RCP1.9.

Given that global harvest volumes do not change much, it is interesting to understand how prices are changing. On a global basis, prices results are shown in Figure 5. These world prices correspond to a weighted average of regional prices, where the weight is calculated based on demanded quantities for each product in each region. Here we can see that for RCPref scenario, prices for all harvest products remain mostly unchanged through biodiversity threshold scenarios. An exception are the softwood sawlogs whose price increases as biodiversity constraint gets tighter. Under the RCP1.9 scenario, the trend is similar, but in it, softwood pulplogs prices also increase. This last result is also reflected in the plywood and sawnwood final products that comes from softwood. Besides this, all harvest products prices are higher under the RCP1.9 scenario, which may be a result of higher demands, but also of a higher difficulty to satisfy those under the biodiversity loss contraint.

It is worth mentioning that current products demands are highly inelastic with values between -0.1 and -0.3, which explains why harvested volumes do not decrease more when prices go up.



(a) **(b)**

Figure 5: Prices for harvested products (5a) and final products 5b under each of the 6 assessment scenarios, plus exPost results for both RCPref and RCP1.9 for 2100. C refers to products from coniferous species and NC to those from non-coniferous species.

Forest management intensities Another result of interest is how forest management intensities change on a worlwide basis with the introduction of the biodiversity loss constraint. First lets see how total area worldwide under each intensity level changes for each scenario. From Figure 6 we can see that between RCP1.9 and RCPref, RCP1.9 has more area worldwide under high intensity management, and less area under low and medium intensity management, when compared to RCPref. This may be a consequence of the higher demanded quantities due to higher bioenergy demand on RCP1.9. In addition, for RCP1.9 there is an interesting tendency as the biodiversity threshold gets tighter. With the introduction of the biodiversity constraint, in fact there is more area under high intensity management, but as the threshold increases to 20% or 30% high intensity management areas begin to decrease again. In the low and medium intensity management there is an interesting behavior. With the introduction of the biodiversity constraint, low intensity management increased significantly and medium intensity management drop down. Also, when the biodiversity constraint gets tighter, low intensity management areas continue increasing, while medium intensity areas decrease. This behaviour occurs for both RCPref and RCP1.9.

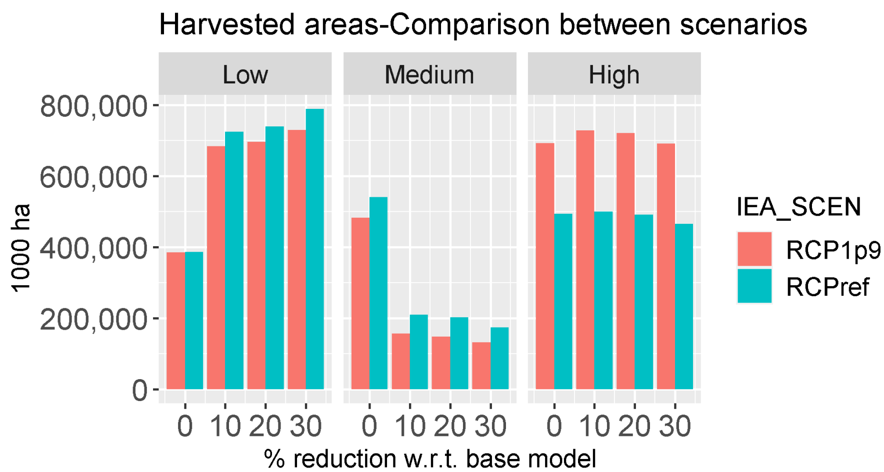
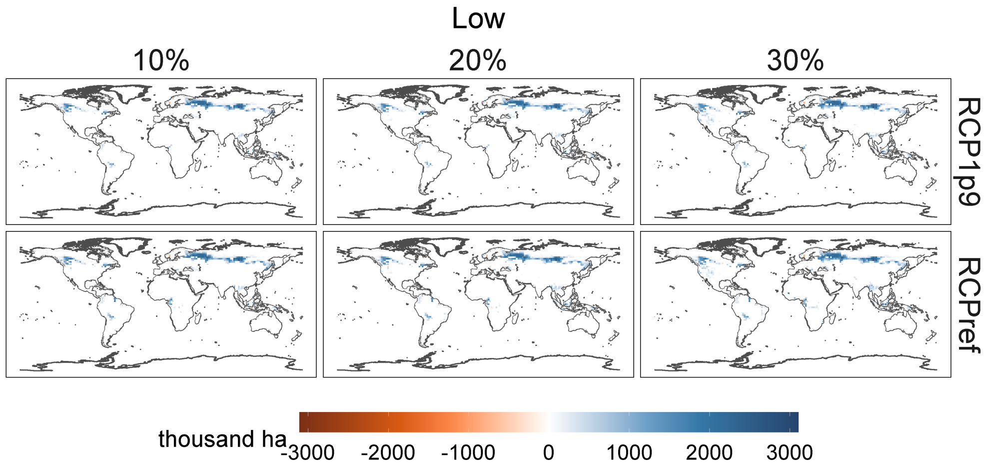


Figure 6: Harvested areas under each management intensity for each of the 6 assessment scenarios, plus exPost results for both RCPref and RCP1.9 for 2100.

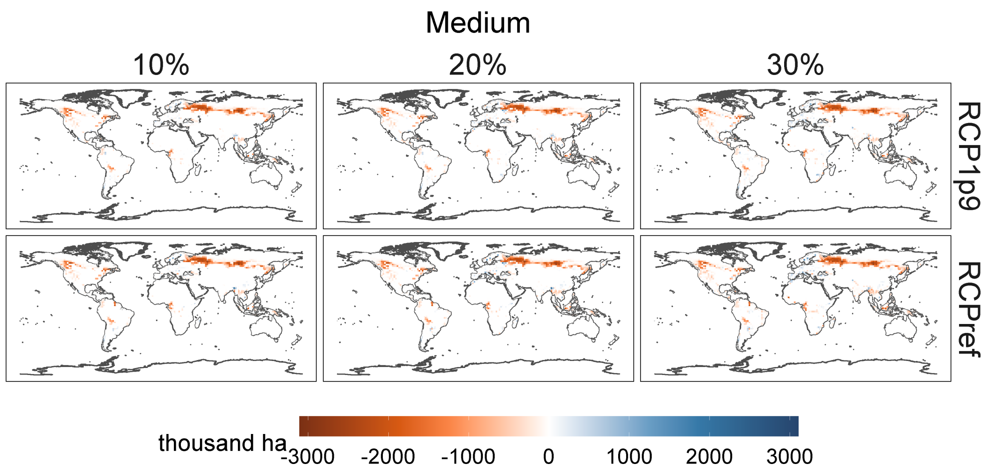
Next, lets see how the worldwide allocation of management intensities is distributed on a spatial level in Figure 7. These maps show the differences in the areas under each management intensity in the scenario that included biodiversity minus the areas under each management intensity on the baseline model. This means that if the number is positive (or the color is blue), the scenario that includes biodiversity has more area under that management type than the scenario without biodiversity. Similarly, if the number is negative (or the color is orange) it means that the scenario that includes biodiversity has less area under that management type, compared to baseline model. The most significant result is that under all scenarios, when introducing biodiversity, there is more area under low intensity management and less area under medium intensity management. Because of the spatial location, this may be interpreted as the model reallocating medium intensity towards low intensity, since biodiversity impact is always higher for higher intensity managements for all taxa. Regarding location, this effect is seen on boreal areas, western US, Guyana, Bolivia, eastern Brazil, Colombia, Myanmar, Indonesia, Philippines, Papua New Guinea, Gabon and Cameroon.

Besides this, there is also less high intensity management in several areas of Europe, specially between Latvia and Estonia and the magnitude of the reduction becomes bigger as the biodiversity threshold increase. There is also less high intensity management in Morocco, Pakistan, northern India and Madagascar, whereas there is more high intensity management in southeastern US across all scenarios. It is interesting that high intensity management in western US is higher when the biodiversity threshold is of 10% and 20% reduction, but become less when 30% reduction in biodiversity loss is required. Also there is more high intensity management in eastern Brazil under RCP1.9, which does not occur under RCPref. The magnitude of the increase becomes bigger as biodiversity threshold increases from 10% to 30% reduction.

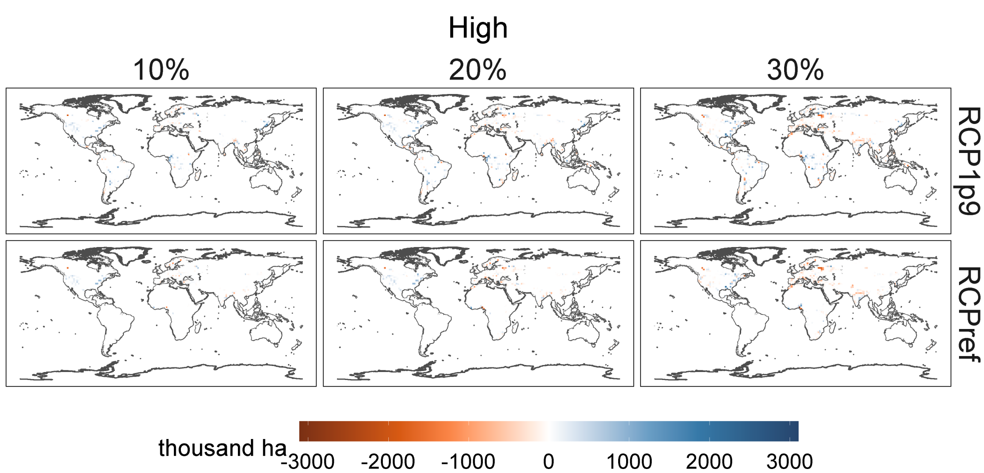
Of interest is also that under RCPref most of the changes in high intensity are concentrated on global north, whereas when bioenergy demand increases, under RCP1.9, there are changes (mostly reductions) in the global south.



(a)



(b)

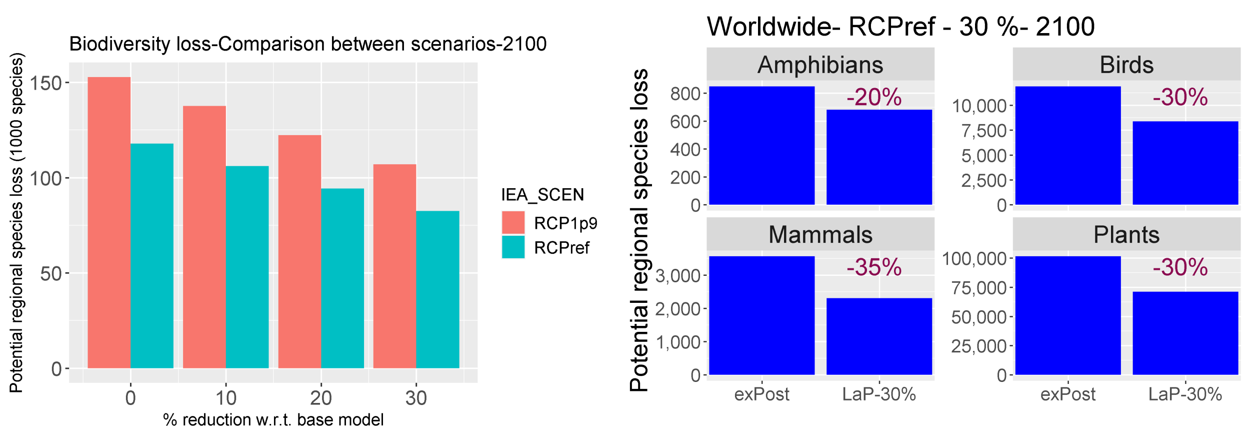


(c)

Figure 7: The maps indicates the differences in harvest areas for low(a), medium (b) and high (c) intensity levels of forest management practices.

Biodiversity impacts Biodiversity impacts are presented for each taxon (Amphibians, Birds, Mammals, Plants) for each of the 6 scenarios. Similar to management intensity maps, maps in figures 9, 10, 11 and 12 shows the differences in potential regional species loss of the different scenarios that include biodiversity compared to the baseline scenario. In this case, if the number is positive (color red) there is more biodiversity loss, whereas if the number is negative (color green), there is less biodiversity loss in the scenario that includes biodiversity versus the baseline model.

In here, one of the main results is the difference between RCP1.9 and RCPref. In general, for all taxa, RCP1.9 shows more species loss in the scenarios with biodiversity for some areas, whereas RCPref shows mostly reductions in biodiversity loss, in other words, there is more green with RCPref. The results vary by ecoregion and taxa, but follow patterns of harvest intensities. A second main result, that is expected, is that broadly when incorporating a constraint on biodiversity loss, there is total less biodiversity loss compared to the baseline model. This is shown if Figure 8a where as expected, as the constraint on biodiversity loss gets tighter, total potential regional species loss decreases. This is also true if the results in species loss are observed by taxa as in Figure 8b. In here results are presented for just one scenario, the one with RCPref and a 30% reduction on biodiversity loss constraint. We can see that even when total biodiversity loss have to be at most 30% of the total biodiversity loss for baseline model, amphibians have less reduction in species loss compared to mammals.



(a) (b)

Figure 8: In (a) Total potential regional species comparison between scenarios. In (b) total potential regional species loss by taxa for scenario with RCPref and a biodiversity threshold of 30%

Analyzing the impacts by taxa, we can see there is more amphibians species loss in western US for both RCP1.9 and RCPref when biodiversity constraint is 20% or less, but less under 30%. Note that there is always more species loss in southeastern US, responding to the increases in high intensity management under bith RCPref and RCP1.9. Also, under RCP1.9 there is always more amphibians species loss in the ecoregion "Dry Chaco", that covers area in Bolivia, Paraguay and Argentina, which is explained by more area under high intensity management. On the other hand, there is less amphibians species loss in Uruguay for the RCP1.9 scenario which increases in magnitude as the biodiversity constraint gets tighter. An interesting fact is that the neighboring ecoregion in Brazil has more amphibians species loss under the RCPref scenario. In some ecoregions of west and central Africa, there is also more amphibians species loss.

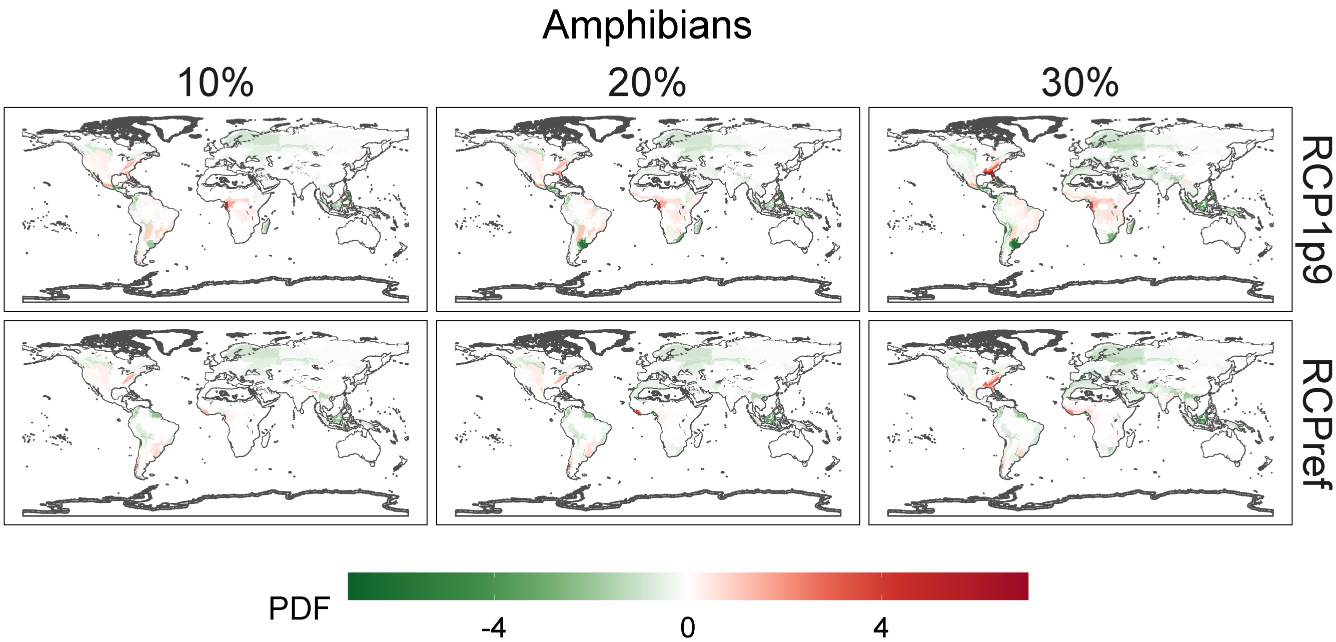


Figure 9: Amphibians difference in regional species loss

When analyzing birds, we see there is less species loss in the boreal areas in Canada, Europe and Russia, in northern Africa, the Arabic peninsula and Indonesia for all scenarios. These seems to be a result of the decrease in medium intensity management and the increase in low intensity management in those areas. Following the amphibians result, birds in western US have more species loss if the biodiversity threshold is less that 20% and less if it is 30%.

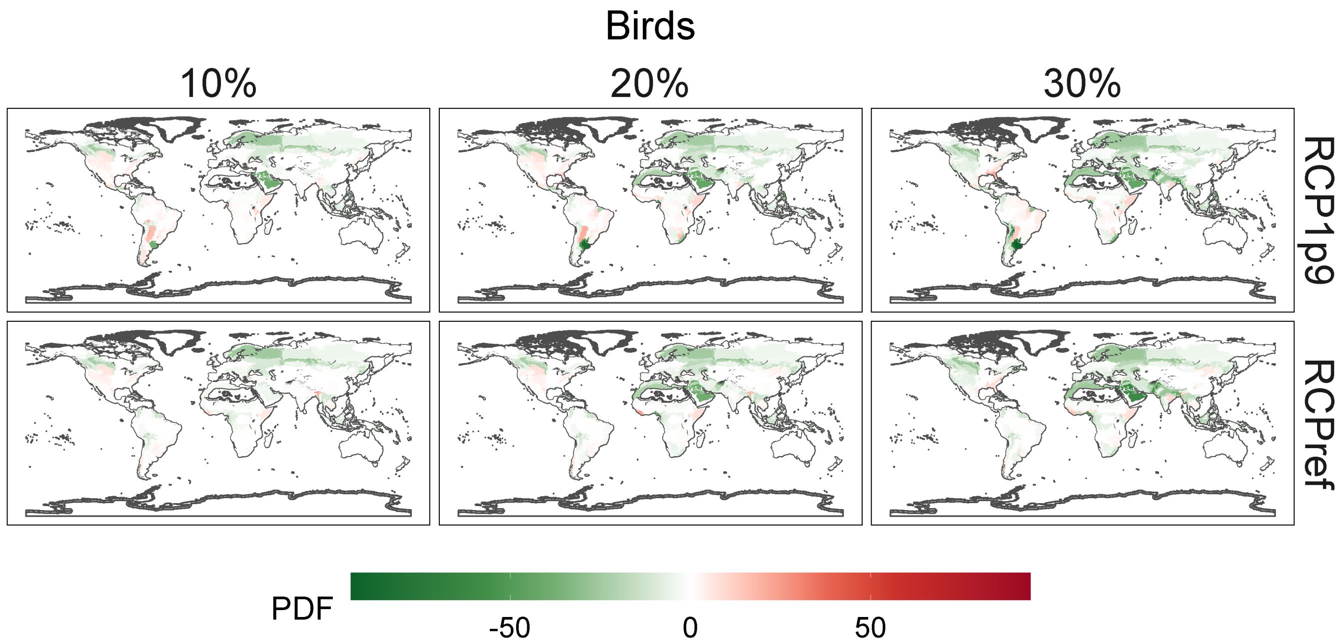


Figure 10: Birds difference in regional species loss

Regarding mammals, one interesting result is that in western US mammals are always better in all scenarios that include biodiversity loss. This is also true for northern Europe, norther Africa, the Arabic peninsula and Indonesia. On the RCP1.9 if the threshold is 10% there is more mammals species loss in Argentina, but if the threshold increases, there is no difference between the scenarios with biodiversity and the baseline. For central an east Africa, the result is the reverse, there magnitude of the increase in mammals species loss gets bigger as the threshold gets bigger.

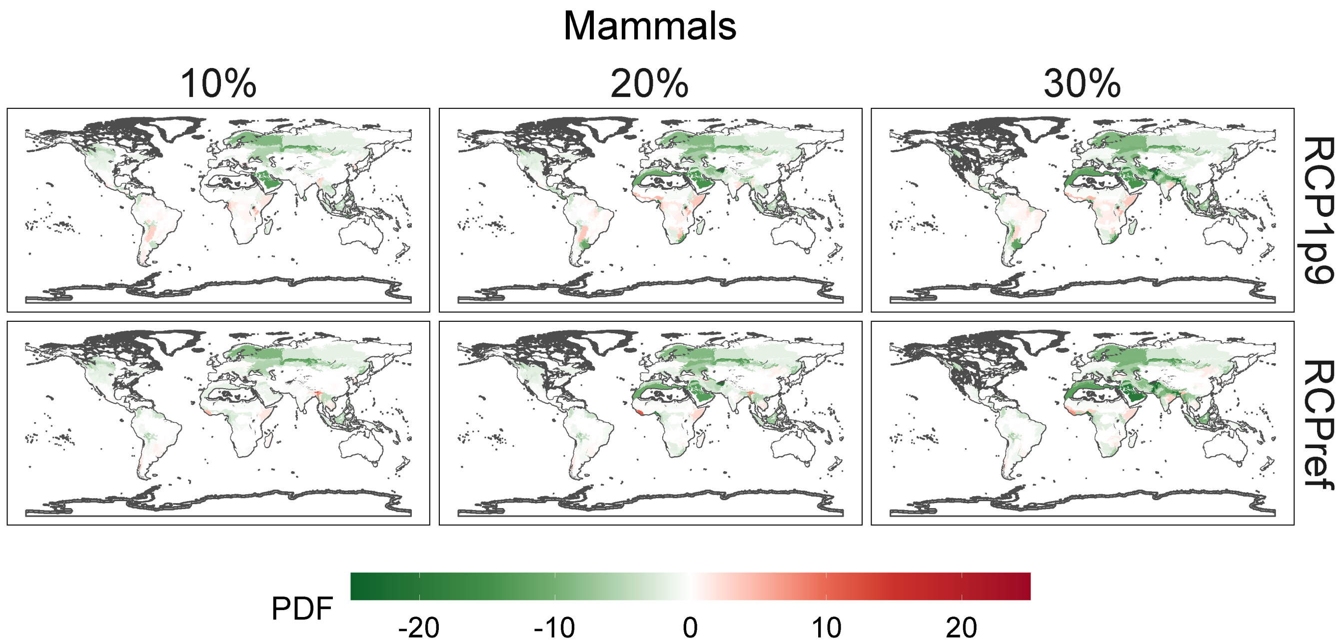


Figure 11: Mammals difference in regional species loss

Finally plants species loss is reduced in all the northern hemisphere compared to the baseline, except in some ecoregions close to North Korea and South Korea, for all scenarios. In the southern hemisphere, there is more plants species loss in Africa under RCP1.9 scenarios due to increases in high intensity management.

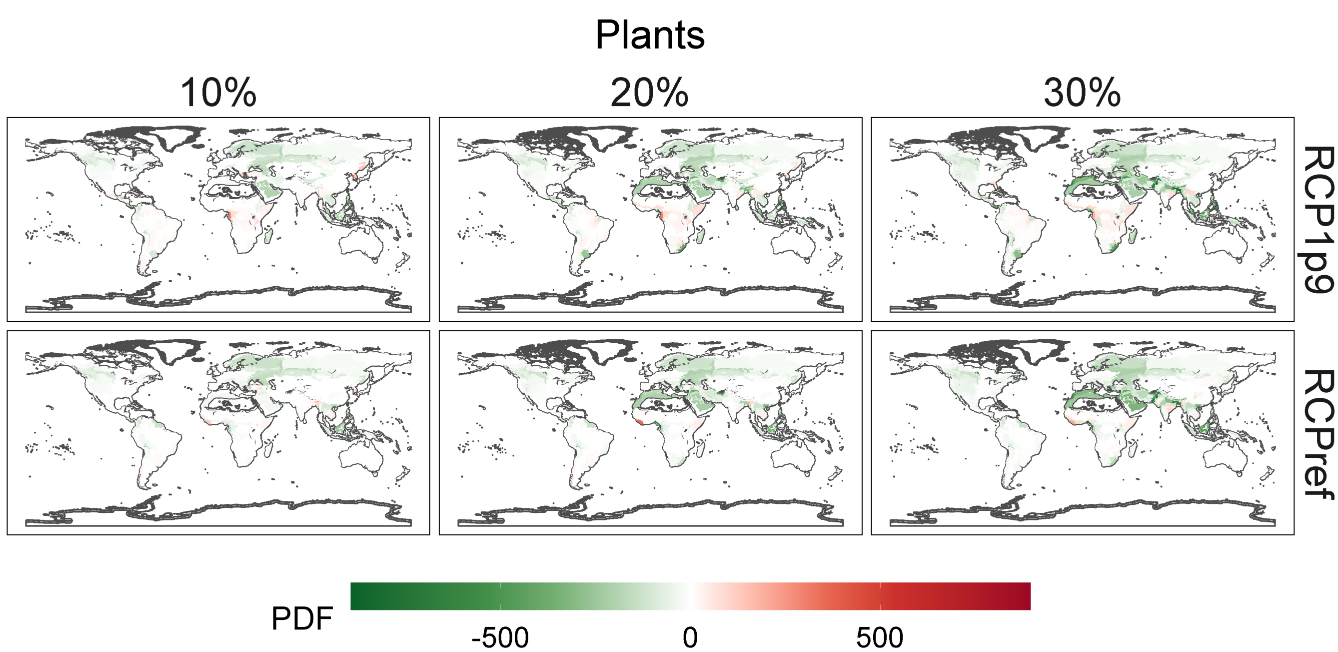


Figure 12: Plants difference in regional species loss

Considering the spatially explicit results for biodiversity loss per taxa a third key result arises. Even when biodiversity is incorporated in the forest management decision making model, there are ecoregions and taxa with more potential regional species loss in comparison with the baseline model that excluded biodiversity. This is due to the fact that the current biodiversity loss constraint is adding an upper bound to global total species loss, this means that it can reduce the global biodiversity loss by "trading" species loss between both ecoregions and taxa. If the "trading" between taxa wants to be avoided, a biodiversity constraint per taxa could be added, if the "trading" between ecoregions wants to be avoided, a biodiversity constraint per ecoregion could be added. However, it is important to mention that these proposed constraints will reduce the flexibility of the model to reallocate forest management decisions so the economic constraints are still satisfied, which could more easily result in an infeasible model.

4 Discussion

When interpreting the results of this paper, it is important to acknowledge various characteristics and limitations of the modeling framework. First, the indicator presented here correspond to potential regional species loss and not potential global species loss. This imply that when summing up regional species loss between ecoregions, the same species could be counted twice if for example is becomes potentially extinct in two different ecoregions. Recall, it will only be globally extinct if it becomes extinct in all ecoregions that it inhabits, but this is not included in the scope of this model.

Second, as mentioned in section 2.2, there are several limitations to the cSAR model used here. The main ones include (1) that it ignores that species may migrate due to disturbance in their habitats, (2) that it does not account for effect on populations levels and (3) that it does not inform about which species in the taxonomic group are more vulnerable or the time scale in which the extinctions are expected. Similarly, there are additional limitations due to how the biodiversity impact is included, (1) the fact that only one dimension of biodiversity is assessed, (2) that only one driver (habitat loss) of biodiversity loss is included, which omits that there are other mechanisms through which forest management decisions can affect biodiversity loss, (3) data limitations that may result in overestimation of the biodiversity impact and (4) the way in which the constraint of biodiversity is added.

With respect to the last point, because the constraint is on the sum of all ecoregions and taxa potential species loss, the model is allowed the flexibility to "trade" between losing species from one taxon versus the other and/or between one ecoregion versus the other. Of course, deciding on trading species loss goes into the moral and ethical framework. In the context of a world where there are constraints on economic, social and environmental implications, is it acceptable to loss more species of one taxon to avoid losing more species of another one? is it acceptable to loss more species in one region of the planet to lose less species on a global basis? This paper does not intend and cannot answer these questions, however it makes us aware that in the context of the decisions that we have to face today, under today's assumptions we may need to start thinking about this. From a modeling perspective, assigning the constraint per taxon, or per ecoregion, or per taxon an ecoregion, implies additional constraints on the model and therefore less flexibility to determine feasible solutions. It goes without saying that this effect could be extrapolated outside the modeling framework.

Also, there are limitations due to the assumption in GLOBIOM-forest that total forest area remains constant for each spacial unit, i.e, that no afforestation or deforestation decisions are incorporated in this version of the model and therefore not considered in the biodiversity assessment. This needs to be considered when assessing RCP1.9, because afforestation could benefit biodiversity.

Future research includes the evaluation of different ways to incorporate biodiversity loss in the model, this include (1) comparison with the results from the objective function approach, (2) changing the biodiversity constraint to be on a taxa level and (3) extending it to also include impacts from land use change. Besides this, biodiversity impact estimates could be improved by adding more dimensions of biodiversity or using more indicators that give us a better picture of how biodiversity is being affected.

5 Conclusion

Biodiversity loss due to forest management decisions have been assessed on an ex-Post basis, but has not been incorporated into the decision making. As far as we know, this is the first attempt to incorporate biodiversity impacts into forest management decision making. In this paper, we integrated the cSAR model, into the partial equilibrium GLOBIOM-forest model. Using cSAR, potential regional species loss was estimated for each ecoregion and taxon on a global basis, as a response to changes in forest management intensities (low, medium and high). We assessed the effects of constraining biodiversity in comparison with a baseline run of the model. We run six scenarios that correspond to 3 different biodiversity loss thresholds (10%, 20% and 30% of reduction in species loss compared to baseline scenario) and 2 climate change scenarios (RCPref and RCP1.9). Indicators of interest included, harvested volumes, location and forest management type used, prices of forest products, and species loss.

The main research question of the paper is to understand how forest management decisions change when incorporating biodiversity and to propose a methodology to incorporate it. We found five main results. First, omitting biodiversity loss in forest management decision making results in significantly higher impacts on biodiversity, compared to the scenarios where biodiversity loss is incorporated. Second, this is also true if we assess the results by taxa on a global basis. However, the magnitude of the reduction varies between taxa. For example, for the scenario with a 30% reduction with respect to baseline model biodiversity loss and under RCPref, mammals have a reduction in total species loss of 35% whereas amphibians have a reduction of 20%. Third, on a spatial explicit basis, there are ecoregions and taxa for which the scenarios that include a constraint on biodiversity loss resulted in more species loss compared to baseline scenario, whereas other ecoregions and taxa resulted in less species loss. The main reason is the reallocation in species loss between ecoregions and taxa that is allowed in the model because of the way the biodiversity constraint was introduced. Fourth, RCP1.9, the scenario of higher mitigation efforts with high bio-energy demand for wood, resulted in higher biodiversity loss than the RCPref. This is due to the increases harvested volumes, which at the end result in more high intensity management area in the RCP1.9 versus RCPref for all biothreshold scenarios. This suggests there is a trade-off between climate change mitigation with increased woody biomass and biodiversity conservation. Fifth, global harvested volumes of roundwood do not change significantly with the introduction of biodiversity constraint. Still, there are differences between the type of forests with decreased harvest volumes in boreal and increased harvest volumes in temperate zones.

Besides this, a model of this kind is consistent with view of forests as natural ecosystems and moves away from the forest management models that only reflect a view of forests as providers of timber. Then, when a model as the one presented here is introduced in the framework of climate change decision making, as is with Integrated Assessment Models (IAMs), it could help identify solutions for climate change that already consider biodiversity impacts of forest management decision making. This could be used to assess for example, increased bioenergy demands using wood, as shown here with the assessment of RCPref and RCP1.9. In this way, by incorporating biodiversity in forest management decisions, it allows to identify solutions that favor both biodiversity conservation and economic goals.

It also allows to understand the limits of assumptions made on forestry and forest industry.

For example, under the economic assumptions of forestry sector in the current GLOBIOM-forest model, a biodiversity threshold with a reduction in total species loss of 40% or more with respect to the baseline model, is infeasible. For the scenarios presented here this means that with the assumed functional forms of demand functions, the representation of costs and bioenergy demands from climate change scenarios, it is not possible to reduce biodiversity loss in 40% or more compared to the scenario where biodiversity is not considered in the decision making. Nonetheless, from a general perspective it allows to see the conflicts in the underlying assumptions between the biodiversity impact estimation and forest management decisions.

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6 Annex

ID GLOBIOMf	Management Intensity	Description
CurC_L, CurNC_L	Low	Low intensity management. 50% of increment harvested. Its a mix of several low intensity management types: Retention forestry, "Nature" management, Selective logging with uneven age management. Requirement of deadwood from remaining increment= 0 Logging residues share= 0
CurC_M, CurNC_M	Medium	Medium intensity management. 75% of increment harvested. Could be considered Multifunctional management. Requirement of deadwood from remaining increment= 0 Logging residues share= 0.25
CurC, CurNC	High	High intensity management. 100% of increment is harvested. Its a mix of several high intensity management types: Planted forest, clear-cut management, even aged monoculture. Requirement of deadwood from remaining increment= 0 Logging residues share = 0.5

Table 2: Description of forest management intensities in GLOBIOM forest