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Assessing land-based mitigation implications for biodiversity

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ABSTRACT

The Paris Agreement to keep global temperature increase to well-below 2 °C and to pursue efforts to limit it to 1.5 °C requires to formulate ambitious climate-change mitigation scenarios to reduce CO_2 emissions and to enhance carbon sequestration. These scenarios likely require significant land-use change. Failing to mitigate climate change will result in an unprecedented warming with significant biodiversity loss. The mitigation potential on land is high. However, how land-based mitigation options potentially affect biodiversity is poorly understood. Some land-based mitigation options could also counter the biodiversity loss. Here we reviewed the recently scientific literature to assess twenty land-based mitigation options that are implemented in different mitigation pathways to comply with the Paris Agreement for their biodiversity impacts by using the Mean Species Abundance (MSA_{LU}) indicator for land use. We showed the likely land-use transition and potential MSA_{LU} changes for each option, compared their carbon sequestration opportunities (tC per ha) and assessed the resulting biodiversity change in two case scenarios. Our results showed that most options benefit biodiversity. Reforestation of cultivated and managed areas together with restoration of wetlands deliver the largest MSA_{LU} increases, if land is allowed to reach a mature state over time. A quarter of the assessed options, including intensification of agricultural areas and bioenergy with carbon capture and storage, decreased MSA_{LU}. Options, such as afforestation and reduced deforestation, either positively or negatively affected MSA_{LU}. This depends on their local implementation and adopted forest-conservation schemes. Comparing the different options showed that avoiding deforestation by implementing agroforestry at the expense of pastures delivered both the largest MSA_{LU} increases and the highest carbon sequestration opportunities. However, agroforestry that leads to deforestation, enhanced carbon sequestration slightly but with a marginal MSA_{LU} increase. This stresses the importance of avoiding forest conversion. Our study advances the understanding on current and future benefits and adverse effects of land-based mitigation options on biodiversity. This certainly helps biodiversity conservation and determines the regions with large land-based mitigation potential.

1. Introduction

Changes in climate are projected to further adversely affect biodiversity this century (Thomas et al., 2004; Pereira et al., 2010; Urban, 2015), including changes in species composition, distribution and extinctions, and in ecosystem structure and functioning. These impacts increase in extent and magnitude in the worst-case climate-change scenarios (Bellard et al., 2012). Global efforts to combat climate change are thus required to limit these adverse effects on biodiversity. These efforts include a global policy response to keep global temperature increase well-below 2 °C and to pursue efforts to limit it to 1.5 °C (i.e. The Paris Agreement; UNFCCC, 2015).

The climate targets from the Paris Agreement require, among others, further stringent climate-change mitigation to reduce CO_2 emissions in different sectors and regions. Without such additional efforts to reduce CO_2 emissions beyond those in place today, global emissions growth is expected to persist and the global mean temperature increase will likely range from 3.7 °C to 4.8 °C above pre-industrial levels by the end of the century (IPCC, 2014, 2018). Such temperature increase will unprecedentedly affect biodiversity (IPCC, 2014, 2018), as already at moderate warming (i.e. < 2 °C) significant change in species and ecosystems are expected. These changes are shown in a recent meta-analysis of the climate-change effects on biodiversity, where 14 % and 17 % of the originally occurring species and habitats, respectively, could be locally lost between 1 °C and 2 °C increase (Nunez et al., 2019). Grave impacts on biodiversity could potentially occur with 3 °C increase as over half of all ecosystem likely shift biome and a quarter (25 %) of the world's nature reserves consequently would not comply to their

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original conservation purposes any more (Leemans and Halpin, 1992).

The IPCC special report on Global Warming of 1.5 °C (IPCC, 2018) and recent climate-change mitigation assessments (Griscom et al., 2017; Rogelj et al., 2018a; van Vuuren et al., 2018v) reported mitigation pathways consistent with the Paris Agreement. Land-based mitigation is one of the options to hold the increase in the global average temperature to well-below the ambitious climate targets. This was agreed upon by the parties to the United Nations Framework Convention on Climate Change in their Paris Agreement.

The mitigation potential of the land-use sector is high with a likely contribution between 20%–60% of total cumulative abatement to 2030 and 15%–40% to 2100 (Smith et al., 2014). This contribution mainly comes from Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector (IPCC, 2018). Land-based mitigation actions to address climate change should however ensure the integrity of all ecosystems.

In 2010 the parties to the Convention on Biological Diversity (CBD) agreed upon the implementation of the Strategic Plan for Biodiversity, including the twenty so-called Aichi Targets (CBD, 2011). Targets include inter alia that the rate of loss of natural habitats should be brought to close to zero (target 5) and that ecosystems that provide essential services are restored and safeguarded (target 14) (CBD, 2010) (CBD, 2011). The Aichi Targets were set for 2020, and will be renewed under the CBD by the end of 2020. Projecting changes in land use is central to understand the ways in which land-based mitigation options will counter or promote biodiversity conservation efforts (Rudel et al., 2005). Consequently, mitigation options should not affect natural ecosystems to ensure achieving the biodiversity targets, which is in line with the Paris Agreement. How these land-based mitigation options will affect biodiversity is, however, poorly understood.

Priority areas to establish land-based mitigation will not always reflect biodiversity values (Miles and Kapos, 2008). Thus land-based mitigation options are unlikely to benefit all ecosystems equally and in some cases may be even harmful. For example, replacing degraded tropical forest by monoculture plantations can enhance terrestrial carbon storage in these ecosystems but the biodiversity value of monocultures is per definition low (Lal, 2008). Alternative options that promote degraded land to return to previous conditions, can be more beneficial to biodiversity. This land restoration can also translate into recovery (or improvement) of ecosystem services other than carbon sequestration, such as food, climate and water regulation. Other options such as forest conservation or reduced deforestation, can involve a geographic displacement of pressures (e.g. conversion of tropical forests into fields and pastures) to neighbouring locations (i.e. land-related leakage), particularly if prioritized forests storing the highest amounts of carbon do not coincide with those most important for biodiversity conservation (Meyfroidt et al., 2010; Popp et al., 2014). The challenge to identify and to select areas of high value for both climate change mitigation and biodiversity conservation urgently remains.

Our study aimed to assess the implications of land-based mitigation options on biodiversity. To this end, we identified mitigation options in the land-use sector that can substantially reduce and capture CO_2 emissions. These are AFOLU-related CDR options implemented in different climate change mitigation scenarios (IPCC, 2018). These options could largely contribute to achieve the 1.5 °C target from the Paris Agreement. We reviewed the scientific and policy literature on these different mitigation options and their land-use impacts to indicate whether they preserve, increase or deteriorate biodiversity. We used the Mean Species Abundance for land use (MSA; Alkemade et al., 2009) to quantify these impacts in a case scenario. As no single mitigation option sufficiently addresses climate change, we developed an approach to compare the carbon (C) storage (tC per ha) on land and the resulting biodiversity change of different mitigation options. This approach can be used to asses local, regional or global impacts and it shows baseline scenarios with underlying assumptions that negatively affect biodiversity, and alternative mitigation scenarios that, on the contrary, will likely benefit biodiversity. Our results and findings can be used for current and future biodiversity conservation in regions with presumably large land-based mitigation potential.

2. Methods

2.1. Selecting land-based mitigation options

Our study focused on climate-change mitigation options in the land sector. We first searched climate-change mitigation options that are consistent with scenarios limiting global temperature increases to 1.5 °C. These options were reported in Chapter 2 of the IPCC's Special Report on Global Warming of 1.5 °C (Rogelj et al., 2018b). Subsequently, we selected mitigation options that were implemented in agriculture and forestry and that endured changes in land management practices and technology. These are AFOLU-related CDR land-based mitigation options that will generally require greater land area under more stringent, ambitious mitigation pathways (Harper et al., 2018). We finally reviewed additional climate change mitigation studies in the context of the Paris Agreement to identify other potential land-based mitigation options (e.g. Harper et al., 2018; Rogelj et al., 2018a; van Vuuren et al., 2018v).

2.2. Determining changes in land use

We identified the potential land-use changes of each land-based mitigation option. To do this, we reviewed the scientific and policy literature of climate-change mitigation studies that assessed one or more selected options. These studies indicated the original land cover and/or use where the option is implemented. Land-based mitigation, which depends on the assumptions from the climate-change mitigation scenario in the original study, will likely result in land transition to achieve a substantial mitigation. In principle, this transition indicates land-cover and/or land-use change, but it can also indicate the same land cover and/or use with altered properties (e.g. land-use intensification). This land transition (or intensification) needed to achieve a substantial climate-change mitigation, was also indicated in the original study. We recorded the evidence on land changes from these studies to determine the initial and final land cover and/or use. This evidence helped to assess implications of these changes on biodiversity.

2.3. Assessing potential biodiversity change

To assess potential biodiversity change, we assigned MSA_{LU} values (Table S1 in Supplementary Material) to both the initial and final land cover and/or use for each mitigation option. The MSA_{LU} is an indicator that expresses the mean abundance of original species in disturbed conditions relative to their abundance in undisturbed habitats, as an indicator of the degree to which an ecosystem is intact (Alkemade et al., 2009, 2013). This indicator ranges between 0 in areas where original biodiversity has completely disappeared (e.g. from land transition due to climate-change mitigation), to 1 in areas where species composition and abundance is fully original (i.e. pristine). Relationships between MSA_{LU} and land use have been quantified in the GLOBIO model (Alkemade et al., 2009; Schipper et al., 2016). These relationships are based on studies and published datasets that reported species composition in a given type and intensity of land use and an undisturbed reference situation. Based on the MSA_{LU} values, we determined whether biodiversity increases, decreases or remains unchanged under the assumption of each mitigation option.

We further quantified biodiversity changes in a specific case-scenario analysis by comparing alternative mitigation scenarios that implement one or more land-based mitigation options, with corresponding baseline scenarios that assumed no mitigation. We showed two cases. The first baseline scenario (BAU-1) assumed a continuation of current trends in underlying socio-economic drivers, such as population,

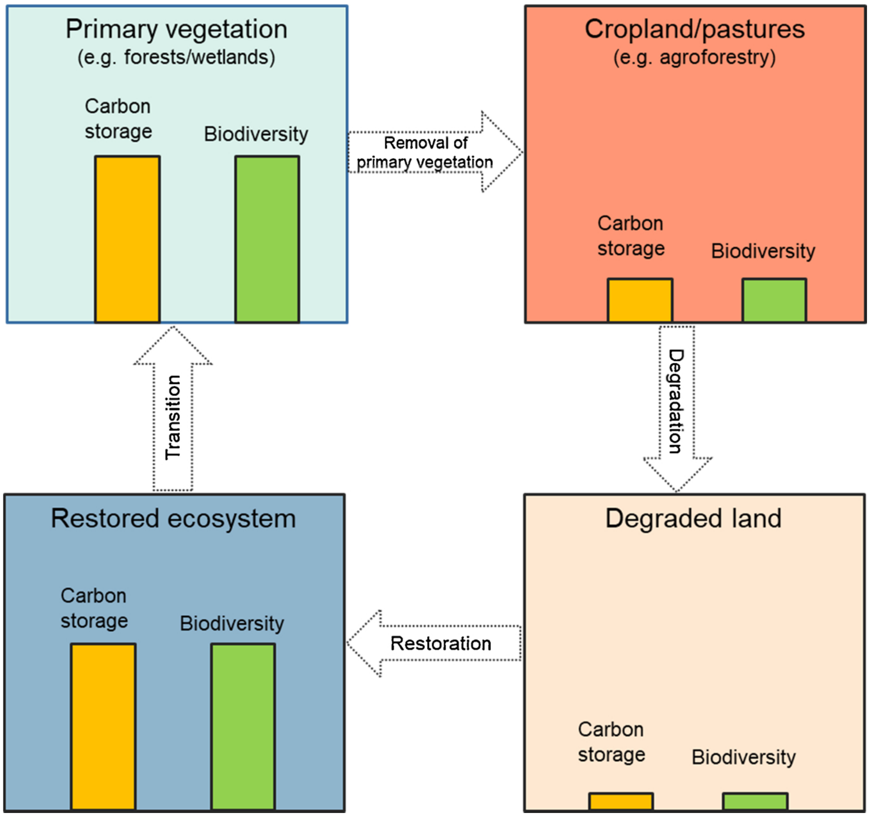

Fig. 1. Examples of mitigation options in different land cover and/or use. Potential carbon storage CS (tC per ha) and biodiversity (MSA_{LU}) of land cover and/or use.

technological and economic growth and consumption preferences. As a result, the demand for crop production (e.g. food and feed) increased (e.g. double) (Stehfest et al., 2019). This demand was realised by increasing cropland area onto forest areas. This resulted in deforestation. Alternative scenarios to BAU-1 offered the opportunity to assess avoid deforestation while fulfilling such crop demand. This was done by expanding cropland areas elsewhere (i.e. avoiding deforestation) in combination with other mitigation options. The second baseline scenario (BAU-2) also assumed that crop production doubles. This demand was realised by restoring degraded land into cropland. Alternative scenarios to BAU-2 assessed other possible restoration options.

Biodiversity changes that resulted from land-use transitions in each mitigation option were related to the carbon-storage (*CS;* tC per ha) potential of the land cover and/or use where these options occur (Fig. 1). We did this by calculating the total carbon storage CS_t for all baseline and alternative scenarios (Equation 5.1).

$$CS_{t,s} = \sum CS_i \,.a \quad (1)$$

where $CS_{t,s,}$ is the total carbon stored in scenario s, CS_i is the carbon storage capacity of land cover and/or land use i and a is the land cover and/or land use area (e.g. hectares). a and i vary depending on the mitigation option assumed in alternative scenarios. Subsequently, we calculated the absolute change between each alternative scenario and its corresponding baseline (Eq. 2).

$$\Delta CS_t = CS_{t,sx} - CS_{t,sb} \quad (2)$$

where ΔCS_t is the change in carbon stored between two scenarios, $CS_{t,sx}$ is the carbon stored in alternative scenario x and $CS_{t,sb}$ is the carbon stored in baseline scenario b. These carbon-storage estimates were derived from scientific evidence in the reviewed studies (Table S2 in Supplementary Material). We focused on the carbon storage of forests, croplands, pastures, peatlands and degraded lands.

Similarly, the MSA_{LU} values for both the initial and final land cover and/or use for each scenario were compared (Eq. 3).

$$\Delta MSA_{LU} = MSA_{LU,sx} - MSA_{LU,sb} \quad (3)$$

where ΔMSA_{LU} is the change in MSA_{LU} between two scenarios, $MSA_{LU,sx}$ is the MSA_{LU} value in alternative scenario x and $MSA_{LU,sb}$ is the MSA_{LU} value in baseline scenario b. We assumed that degraded lands, which have not been assigned MSA_{LU} estimates yet, were in early stages of secondary vegetation. The MSA_{LU} of degraded land was estimated to be 0.4. This was based on estimates for species richness in young secondary vegetation (Newbold et al., 2015). The MSA_{LU} for agricultural land was also assigned 0.4 (Alkemade et al., 2009). Our comparison determined which option(s) obtained the largest carbon storage with the largest benefit to biodiversity.

3. Results

We assessed twenty land-based mitigation options from AFOLU-related CDR. These options are presented in Table 1 together with their potential land cover and/or land use transitions. We found that more than half of these options could potentially benefit biodiversity by either maintaining (i.e. no change) or increasing the MSA value of the land cover and/or use where they occur. Mitigation options that increased its MSA included forest-related activities (i.e. forest restoration and afforestation), agriculture-related activities (i.e. agroforestry, urban and peri-urban agriculture and forestry and conservation agriculture) and degraded land-restoration options (i.e. reduced land degradation and restoration of wetlands). Restoration options included, for example, transitions from cleared or degraded land into primary vegetation. Land transitions into primary vegetation were indicated with MSA of 1. This means that those areas could potentially reach an original (or possibly natural) state over time. Thus, restoration of wetlands offered a large potential to increase biodiversity. These mitigation options, particularly forest-related activities, can derive moderate to high leakage effects that result from displacing land use or deforestation elsewhere, and consequently decreasing biodiversity.

Table 1
Land-based mitigation options and their land-cover and/or land-use transitions to indicate changes in Mean Species Abundance (MSA).

Mitigation option	Land-cover/land-use transitions *				Biodiversity changes	Potential leakage	Description	Reference to examples
	Initial	MSA	Final	MSA				
Reduced deforestation	Forest [a]	1	Forest [a]	1	No change	High	Reduced deforestation by enforcing existing land regulations	Ebeling and Yasué (2008)
	Pasture [g]	0.6	Cropland [e]	0.3	↑		Cropland expansion (mainly in tropics) in non-forested areas (e.g. grasslands) (i.e. leakage)	Popp et al. (2014); Miles and Kapos (2008); Aukland et al. (2003)
Forest protection	Forest [a]	1	Forest [a]	1	No change	High	Protection of forest areas by enforcing existing land regulations	Keith et al. (2009); Schmitt et al. (2009)
Avoided forest conversion	Forest [a]	1	Forest [a]	1	No change	High	Avoided forest conversion with land-use planning	Gaveau et al. (2016)
	Pasture [g]	0.6	Cropland [e]	0.3	↓		Cropland expansion (mainly in tropics) in non-forested areas (e.g. grasslands) (i.e. leakage)	Aukland et al. (2003)
Forest management	Forest [b]	0.3	Forest [b]	0.3	No change	Low	Traditional management that includes measures such as replacing dying or low-productivity forests	Bellassen and Luyssaert (2014)
	Forest [b]	0.3	Forest [d]	0.7	↑		Forest management that includes preserving mature forests	Bellassen and Luyssaert (2014)
	Forest [b]	0.3	Forest [c]	0.5	↑		Forest regeneration after natural disturbances that contributes to critical ecosystem values not found in timber producing forests	Lippke et al. (2011)
Reduced land degradation and forest restoration	Degraded land	0.4	Forest [a]	1	↑	Low	Degraded land changes through agricultural land and secondary forest, to primary forests	Foley et al. (2005); Koh and Ghazoul (2010); Lewis et al. (2019)
Agroforestry	Cropland [e,f]	0.3	Agroforestry	0.5	↑	Medium	Reintroduction of trees to agricultural lands to be managed together with crops and/or animals	Zomer et al. (2016); Albrecht and Kandji (2003); Ramachandran Nair et al. (2009)
Silviculture	Forest [b]	0.3	Forest [b]	0.3	No change	Low	Growth, health and quality control of forests so that they could be regenerated and managed for desirable outcomes	D'Amato et al. (2011)
Urban and peri-urban agriculture and forestry	Urban areas	0.1	Agricultural and forestry	0.3	↑	Medium	Opportunities for urban forests to deliver ecosystem services critical to human wellbeing and biodiversity	Endreny (2018)
Fire management and (ecological) pest control	Forest - Multiple types	1	Forest - Multiple types	1	No change	Low	Fire management involves prevention, detection, control, restriction and suppression of fire in forest	Seidl et al. (2017)
Changing agricultural practices enhancing soil carbon	Pasture [g]	0.6	Pasture [h]	0.3	↓	Low	Practices that aim at improving grazing management, legume sowing and N fertilization	Henderson et al. (2015) Smith et al. (2008)
Conservation agriculture	Cropland [f]	0.1	Cropland [e]	0.3	↑	Medium	Practices such as minimum soil disturbance, retention of crop residues and crop diversification, reduce soil degradation and improve agricultural sustainability	(Powlson et al., 2016)
Increasing agricultural productivity	Cropland [e] Pasture [g]	0.3 - 0.6	Cropland [f] Pasture [h]	0.1 - 0.3	↓	Low	Higher agricultural productivity increases to compensate for reduced land availability for agricultural use	Popp et al. (2014)
Methane reductions in rice paddies	Cropland [f]	0.1	Cropland [f]	0.1	No change	Low	Practices such as draining the wetland rice once or several times during the growing season, rice cultivars with low exudation rates, adjusting the timing of organic residue additions	Smith et al. (2008)
Nitrogen pollution reductions	Cropland [f]	0.1	Cropland [e]	0.3	↑	Low	Practices such as fertilizer reduction, increasing nitrogen fertilizer efficiency and use of sustainable fertilizers	Smith et al. (2008); Bouraoui and Grizzetti (2014)
Livestock and grazing management	Pasture [g]	0.6	Pasture [g]	0.6	No change	Low	Practices such as methane and ammonia reductions in ruminants through feeding management or feed additives, or manure management for local biogas production to replace traditional biomass use	Herrero et al. (2016)
Manure management	Pasture [g]	0.6	Pasture [g]	0.6	No change	Low	Manure management involves various technologies for collection, handling, storage, treatment and land application	Smith et al. (2008)
Bioenergy with Carbon Capture and Sequestration (BECCS)	Cropland [e]	0.3	Cropland [f]	0.1	↓	Low	Bioenergy production using biomass, and coupled with the harvesting and subsequent storing of carbon dioxide. This practice seeks for higher yields through improving agricultural efficiency and land expansion	Harper et al. (2018); Smith et al. (2008) van Vuuren et al. (2018) Fajardy and Mac Dowell (2017)
Afforestation	Degraded land	0.4	Forest [d]	0.7	↑	Low	Afforestation of treeless land (planting new trees)	Griscom et al. (2017)
Reforestation	Cropland [e] Pasture [g]	0.3 - 0.6	Forest [a]	1	↑	Medium	Forest regrowth achieved with replanting trees where they previously existed	Griscom et al. (2017)
	Cropland [e] Pasture [g]	0.3 - 0.6	Forest [a]	1	↑		Reforestation of agricultural land that involves approaches such as plantations of productive native tree species for both C sequestration and biodiversity	Cunningham et al. (2015)

(*continued on next page*)

Table 1 (*continued*)

Mitigation option	Land-cover/land-use transitions *				Biodiversity changes	Potential leakage	Description	Reference to examples
	Initial	MSA	Final	MSA				
Restoration of wetlands	Cropland [e] Pasture [g]	0.3 - 0.6	Primary vegetation	1	↑	Medium	Restoration activities that promote a return to previous conditions as well as those that improve the functioning of a wetland without necessarily seeking to return it to its pre-disturbance condition	Warren et al. (2017); Alongi (2012); Yule (2008)

[*] The land transitions are determined by the original study's methods (e.g. scenarios assumptions and models), and thus do not show the full range of possible land cover and/or land-use changes.
[a] Primary vegetation (natural).
[b] Plantation.
[c] Cleared-cut harvesting (secondary).
[d] Selective logging.
[e] Low input agriculture.
[f] Intensive agriculture.
[g] Moderately to intensively used.
[h] Man-made.

Land-based mitigation options in the livestock sector, such as grazing and manure management, did not require land-use change. Similarly, lands where silviculture, fire-management and pest-control options occurred did not transition into different land cover and/or use, and thus their MSA remained unchanged. These options helped to conserve forest structure and composition. The potential land-related leakage for these options is low.

The mitigation options that reduced the MSA of land cover and/or use included changes in agricultural practices to enhance soil carbon, which increased agricultural productivity. Such BECCS options are one of the largest contributors to remove emissions from the atmosphere during this century (Harper et al., 2018). Reduced deforestation and avoided forest conversion benefited biodiversity through maintaining the forest-land cover. However, they can also be detrimental to biodiversity as these options could lead to large biodiversity declines through 'leakage' issues if forest conservation is not adequately implemented (e.g. leakage effects into non-forest ecosystems) (Aukland et al., 2003; Popp et al., 2014).

The scenario comparison showed the baseline and alternative mitigation scenarios for two cases: deforestation and restoration of degraded land into cropland (Table 2 and Tables S3 and S4 in Supplementary Material). In the first case, we defined six alternative scenarios that contain options from Table 1, with the underlying assumption that food production doubles while avoiding deforestation (Table 2). These alternative scenarios showed different combinations of land-based mitigation in different land-cover/land-use types. We compared these scenarios with the baseline to determine which option derives both the highest carbon storage and MSA_{LU}. We found that agroforestry is by far the best option to avoid deforestation while maintaining, and even increasing, cropland production at the expense of pastures (Fig. 2 a). Both carbon storage and MSA_{LU} increased under this alternative option by 3185 MtC and by 7 %, respectively. The least desired option to avoid deforestation was agroforestry at the expense of forest. The second case showed minimal benefits on biodiversity when land is restored into cropland (Fig. 2 b). We found that restoration of peatlands is the best alternative option for degraded land.

4. Discussion and conclusions

We assessed the implications of twenty land-based mitigation options on biodiversity. Our results showed that fifteen of the assessed options benefit biodiversity by either maintaining or increasing the MSA of the land use where they occur. Options that increased biodiversity included agroforestry, conservation agriculture, reforestation of croplands and pastures and restoration of degraded land (e.g. wetlands). Reforestation and restoration options could potentially allow land to reach a primary vegetation state (i.e. MSA of 1) over time, while improving the land carbon-storage capacity and other ecosystems services such as water and climate regulations. Wetlands such as peatlands, which have some of the highest annual carbon sequestration rates (i.e. peat accumulates at rates of 0.5–1.0 mm yr-1; Ramsar, 2018), could return to important habitats and refuge for many rare and endangered species (Warren et al., 2017). This is particularly important to prevent wetlands from releasing methane, a potent greenhouse gas (Ramsar, 2018).

We found that avoided deforestation offered large benefits to biodiversity as it will preserve habitats for many species, especially in the tropics. However, avoided deforestation is contested as it creates a competing demand between climate-change mitigation and enhancing food security (i.e. demand for agricultural land) (Aukland et al., 2003; Miles and Kapos, 2008). This competing demand between agricultural land and more specifically croplands (e.g. SSP2; Popp et al., 2017; Stehfest et al., 2019), and forests was apparent in the baseline scenario for avoided deforestation. The expansion of cropland onto forest resulted in a 7 % MSA decrease and a loss of 1660 MtC, whereas implementing agroforestry with increasing agricultural productivity at the expense of pastures increased both carbon storage (i.e. with 2236 MtC) and MSA (i.e. with 7 %). Such land-related leakage can significantly impact biodiversity (Popp et al., 2014). Previous studies show that leakage is particularly likely if climate policies in the agricultural sector are implemented in isolation from climate policies in other sectors with large abatement potentials, including forestry (Golub et al., 2013). Similarly, afforestation either positively or negatively affects MSA. This depends on their spatial implementation and forest-conservation schemes. All other mitigation options will negatively affect biodiversity due to intensification of cultivated and managed areas to increase soil carbon and to promote the deployment of BECCS.

Land-based mitigation potentially limit global temperature increase to 1.5 °C above pre-industrial levels, with major contributions from BECCS and large-scale afforestation (Rogelj et al., 2018a; van Vuuren et al., 2018v). The deployment of BECCS in the scenarios that are consistent with the Paris Agreement, is projected to range from 0 to 4.5 GtC per year in 2100. This assumes that BECCS occurs worldwide (IPCC, 2018) and it would require a large amount of land (i.e. up to 550 Mha by 2060 in the Shared Socio-economic Pathway 2, SSP2-RCP1.9) (Harper et al., 2018) to cultivate the biomass required for bioenergy, competing not only with producing food to support a growing population but also biodiversity conservation. This was previously shown in an assessment on the effects of changes in agricultural efficiency and consumption patterns on biodiversity loss (Powell and Lenton, 2013). This assessment showed a substantial biodiversity loss due to increasing intensity of biomass harvests.

We found that the carbon mitigation potential and opportunity to increase MSA of forest management options is high. Globally, managed forest area is increasing and accounts for 7 % of the world's forest area, or 290 Mha (FAO, 2015). Managed forests supply timber (including woodfuel), non-wood forest products and many of the environmental services provided by natural forests. These forest products are long living and store carbon when used in structures (UNECE/FAO, 2019). In 2011 about half of the annual wood removals was for woodfuel. Only a small proportion of harvested wood ends up in durable products like furniture and building material (e.g. wooden houses). A recent study (Johnston and Radeloff, 2019) estimated that the global harvested wood product pool sequestered 335 Mt of CO2e-1 in 2015, and due to the increasing managed forest area could sequester as much as 441 Mt CO2e-1 in 2030.

Afforestation to mitigate climate change potentially increases biodiversity of degraded lands by growing new forests. Generally, these forests are plantations of non-native species that sequester carbon faster than native trees. However, afforestation could also be detrimental for biodiversity if implemented on non-degraded land. In such a case, reforestation by native trees on originally forested land is best for biodiversity (Cunningham et al., 2015).

While many studies assessed the climate-change mitigation potential of these options (e.g. Smith et al., 2008; Herrero et al., 2016; Zomer et al., 2016), only few addressed the likely impacts on biodiversity (Díaz et al., 2009; Powell and Lenton, 2013; Griscom et al., 2017; Smith et al., 2018). Yet, this limited number of studies focused mainly on impacts from individual land-based mitigation options or only qualitatively assessed biodiversity change. Our results advanced the findings of especially the recent study (Smith et al., 2018). We showed that cropland and agroforestry have a replacement effect if implemented in combination, whereas restoration of degraded land mostly increased biodiversity. However, restoration of severely degraded land is difficult and in some cases constrained by its short-term cost-effectiveness (Griscom et al., 2017).

We assessed land-based mitigation options implemented in scenarios that limit warming to 1.5 °C (e.g. van Vuuren et al., 2017v; Rogelj et al., 2018a; van Vuuren et al., 2018v). These mitigation scenarios differ in the deployment level of land-based mitigation options into the energy system, on the assumed development of socio-economic drivers (e.g. population growth and economic development), implementation costs and uncertainties in future land projections due to differences in modelling approaches in current land-use models (Popp et al., 2014; IPCC, 2018). These differences affect the time before benefits to biodiversity become visible. This means that land-based mitigation options that deliver an early high mitigation potential (e.g. BECCS) do not necessarily benefit biodiversity by increasing the land-use's MSA. Also, critical transitions of ecosystems at tipping points in response to altered climate or other drivers (e.g. land-use change) might limit the implementation of some mitigation options (Scheffer et al., 2009; Moore, 2018). For example, restoration of pastures into tropical

Table 2

Alternative mitigation scenarios for i) BAU-1 'deforestation' and ii) BAU-2 'restoration of degraded land into cropland'. The main underlying assumption for these scenarios is that cropland area increases to achieve the desired food production.

Scenarios	Short description
BAU 1 - deforestation	BAU shows continuation of current socio-economic trends that result in increasing food demand. Cropland area expands onto forest (deforestation)
Alternative 1 - cropland area increases at the expense of pastures[a]	Food production increases by cultivating the established units of cropland and additional units of pasture (i.e. moderately used rangelands; Alkemade et al., 2013)
Alternative 2 - food production increases due to agricultural productivity increase per area	Food production increases as technological change will result in increasing crop productivity (yield/ha) (Stehfest et al., 2014), and therefore no additional land is require.
Alternative 3 - agroforestry at the expense of forest	Reintroduction of trees to agricultural land will decrease land productivity by 25 %. To compensate the productivity loss and to achieve the desired level of food production, cropland area increases at the expense of forest area
Alternative 4 - agroforestry at the expense of pastures[a]	Reintroduction of trees to agricultural land will decrease land productivity by 25 %. To compensate the productivity loss and to achieve the desired level of food production, cropland area increases at the expense of pastures
Alternative 5 - agroforestry with agricultural productivity increase at the expense of forest	Reintroduction of trees to agricultural land will decrease land productivity by 25 %. By means of technological change, agricultural productivity increases in the agroforestry system. To compensate the original productivity loss and to achieve the desired level of food production, cropland area increases at the expense of forest area
Alternative 6 - agroforestry with agricultural productivity increase at the expense of pastures[a]	Reintroduction of trees to agricultural land will decrease cropland productivity by 25 %. By means of technological change, agricultural productivity increases in the agroforestry system. To compensate the original productivity loss and to achieve the desired level of food production, cropland area increases at the expense of pastures area
BAU 1 - restoration of degraded land	Degraded land is restored into cropland to fulfil food demand
1- forest increase	Degraded land is restored into forest
2- peatland increase	Degraded land is restored into peatlands
3- pastures increase [a]	Degraded land is restored into pastures

[a] This option assumes large changes in human diet (e.g. less meat) and consumption patterns that likely reduce the demand for livestock products.

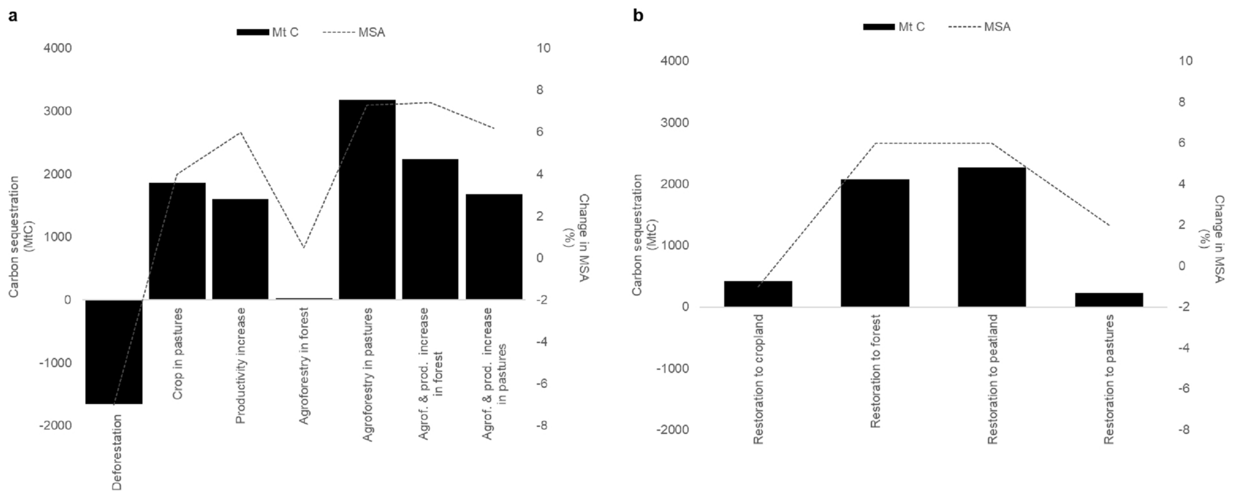

Fig. 2. Potential carbon storage and biodiversity changes in different land-based mitigation scenarios. (a) shows the results for total Carbon storage (MtC) and MSA respectively, in the case ‘avoided deforestation’; (b) shows the results for total Carbon storage (MtC) and MSA respectively, in the case ‘restoration of degraded land’.

forest might just not be possible as the climate suitability of the original species has changed and the ecosystem cannot restore to its original condition. Considerable research still is needed to comprehensively analyse the best options that favour both climate change mitigation and biodiversity protection. This desired combination will contribute to achieve the climate target, while reducing detrimental biodiversity decline by unsuitable land-based mitigation options.

Various studies and assessments show that land-use change and climate change are the dominant drivers of biodiversity loss (Sala et al., 2000; Alkemade et al., 2009; Pereira et al., 2010; IPBES, 2019). Our approach allows to analyse land-based mitigation options for their contribution to climate mitigation and biodiversity conservation. Implementing land-based mitigation options that lead to a win-win situation should be promoted while options that are harmful for biodiversity should be avoided. This means implementing options that increase carbon sequestration potential to combat climate change while achieving a high biodiversity conservation.

Overall, we showed that opportunities to mitigate climate change by land-use based options will largely benefit biodiversity. However, biodiversity protection strategies should also be considered. For example, implementation of forest-related efforts simultaneously reduce the pressures on biodiversity conservation and other ecosystem values (Miles and Kapos, 2008). A unique solution does not exist. With more claims on land, more pressure and higher potential biodiversity losses will occur. Yet, finding workable synergies requires solutions that are less effective for separate goals. The Paris Agreement call to limit global temperature increase can become a major risk to biodiversity conservation if the beneficial land-based mitigation options are not selected and implemented effectively. Thus addressing the impacts of different land-based mitigation with alternative mitigation options (e.g. van Vuuren et al., 2018v), like we did in this study, on biodiversity and other co-benefits of nature, is essential.

CRediT authorship contribution statement

Sarahi Nunez: Conceptualization, Methodology, Investigation, Visualization, Writing - original draft. **Jana Verboom:** Methodology, Writing - review & editing. **Rob Alkemade:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envsci.2020.01.006.

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