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Combining mitigation strategies to increase co-benefits for biodiversity and food security

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Abstract

World agriculture needs to find the right balance to cope with the trilemma between feeding a growing population, reducing its impact on biodiversity and minimizing greenhouse gas (GHG) emissions. In this paper, we evaluate a broad range of scenarios that achieve 4.3 $GtCO_{2,eq}$/year GHG mitigation in the Agriculture, Forestry and Other Land-Use (AFOLU) sector by 2100. Scenarios include varying mixes of three GHG mitigation policies: second-generation biofuel production, dietary change and reforestation of pasture. We find that focusing mitigation on a single policy can lead to positive results for a single indicator of food security or biodiversity conservation, but with significant negative side effects on others. A balanced portfolio of all three mitigation policies, while not optimal for any single criterion, minimizes trade-offs by avoiding large negative effects on food security and biodiversity conservation. At the regional scale, the trade-off seen globally between biodiversity and food security is nuanced by different regional contexts.

1. Introduction

Land is a multi-purpose asset that may involve conflicts in its use. Formerly restricted to the local level, conflicts have become increasingly global over the last few decades because of the rapid intensification of international exchanges (Liu *et al* 2013). Currently, the joint challenges of global food security, climate change mitigation and conservation of biodiversity give a new dimension to this issue, involving new types of trade-offs and synergies while strengthening the global dimension.

Assessments based on global land-use models have shown that mitigation policies relying on large-scale second-generation biofuel production have important environmental implications and, especially if forest protection measures are implemented, adversely impact food prices (Popp *et al* 2011, Humpenöder *et al* 2018, Heck *et al* 2018a). Afforestation is also associated with significant increase in food prices (Kreidenweis *et al* 2016) whereas dietary change policies may have the opposite effect (Stevanović *et al* 2017). Combining measures appears to be an appropriate solution to minimize negative effects, but the nature of the combinations promotes either biodiversity or food security (Obersteiner *et al* 2016, Visconti *et al* 2016, Humpenöder *et al* 2018).

Trade-offs between biodiversity and climate mitigation needed to be considered. While some mitigation policies such as carbon storage in forests can maintain biodiversity (Watson *et al* 2018), other options could increase pressure on biodiversity. Strong climate change mitigation scenarios relying on bioenergy are typically harmful to biodiversity either due to land-use change related to second-generation biofuel production (Hill *et al* 2018, Newbold 2018, Shukla *et al* 2019) or due to increased wood harvest for fuel in biodiversity hotspots (Jantz *et al* 2015). However, scenarios without strong climate mitigation are also associated with high impacts of climate change on biodiversity, especially in the second part of the century (Newbold 2018).

Combining on a global scale a model of agricultural intensification with a statistical model of biodiversity provides a unique framework for understanding (i) the impact of different GHG mitigation policies (second-generation biofuel production, dietary change and reforestation of pastures) on both biodiversity and food security and (ii) the degree of conflict or synergy between such policies.

2. Method

2.1. Overview of the modelling framework

The food system is represented by the Nexus Land-Use (NLU) model (Souty *et al* 2012). This global model of agricultural intensification describes the worldwide land-use system, computes cost-optimal food security indicators (average cost of production per calorie produced and food price per calorie produced), calculates associated agricultural and land-use change with respect to GHG emission goals and generates land-use maps (Souty *et al* 2012).

These land-use maps are converted into impacts on biodiversity through global estimation of two indicators of local biodiversity—Biodiversity Intactness Index (BII) (De Palma *et al* 2019) and within-sample species richness (SR)—applying a mixed-effect modelling structure based on the PREDICTS database (Hudson *et al* 2017). BII indicates the average abundance of a large, diverse set of native species in a given area, relative to their abundance in a pristine reference condition (Scholes and Biggs 2005) (see the Method section). The SR reports the number of species, relative to the number expected in a natural system (section 6 in the supporting information (SI), which can be found online at stacks.iop.org/ERL/15/114005/mmedia). These two indicators can provide complementary insights as they address both the number of species and differences in the composition of ecological communities present in ecosystems (section 6 in the SI). To clarify the impacts of GHG mitigation policies on these indicators, we made some changes to the framework used in Hill *et al* 2018: represented grassy and woody second-generation biofuel as highly intensified perennials.

Using this framework, we assess the impact on biodiversity and food security of land-use-based mitigation scenarios that provide mitigation of 4.3 $GtCO_{2,eq}$/year in 2100 (which is the AFOLU sector's share of the mitigation needed to limit global warming to 2° in 2100: Wollenberg *et al* 2016). This mitigation target is calculated based on a methodology detailed in table 2 of the SI. We set a common target for every scenario to make their impacts on biodiversity and food security comparable.

We infer from these scenarios whether the relationship between biodiversity and food security in the presence of mitigation policies is synergistic or antagonistic and how the policy mix influences this relationship.

To mitigate the 4.3 $GtCO_{2,eq}$/year in 2100, we built scenarios that are combinations of second-generation biofuel production (between 0 and 112 EJ/year in 2100), dietary change (a convergence towards the consumption of 432 kcal/capita/day of animal products which is a reduction except in Africa for nutritional reasons) and reforesting pastures (between 0 and 31% of global pasture reforested). Each mitigation scenario is detailed in the SI. The mitigation effort of each of these policies (second-generation biofuel production, dietary change and reforestation of pastures) is then defined as the percentage of each policy in total mitigated emissions (section 7 in the SI). To cover a broad range of scenarios and represent a uniform distribution of mitigation policies (second-generation biofuel, dietary change and reforestation), the scenarios are constructed according to a full factorial design (sections 8 and 9 the in SI). The experimental design involves taking mitigation efforts ranging from 0% to 100% for each policy in 10% steps while keeping the sum of efforts equal to 100% (section 8 in the SI).

Finally, we detail the distribution of these impacts across 12 large regions of the world. In this study, the mitigation effort is unequally distributed among the regions and depends on the amount of pasture available to reforest, the current diet and the regional cost of second-generation biofuel production. To compare the impacts of these heterogeneous mitigation efforts between regions and with the global figures, we calculate the relative change in biodiversity and food security divided by the relative change in regional emissions (see section 6 in the SI for details of these indicators).

This downscaling highlights the influence of the regional context on the sensitivity of responses of both regional biodiversity and food security to mitigation policies.

2.2. Description of the NLU and PREDICTS models

2.2.1 Estimating agricultural production.

The global NLU model is used to represent the agricultural sector (see Souty *et al* 2012 for more details). It allows us to represent agricultural intensification and the distribution of cropland, pastures and forest at the global scale. Crop intensification is explicitly represented in NLU with a concave production function and fertilizer prices are computed from energy prices (Brunelle *et al* 2015). Two livestock systems are considered: a grass-based system and a mixed crop-livestock system.

Regional production cost is minimized under a supply-use equilibrium with a simplified representation of international trade. Based on an interpretation of the Ricardian theory, the boundary between the mixed crop-livestock system and the grass-fed livestock system changes according to the equalization of rent. In the mixed crop-livestock system, cropland distribution is based on potential yield, with rent increasing with land quality. In this model forest area is exogenously defined by scenarios. A detail description of these elements is provided in section 1 in the SI.

2.2.2 Estimating agricultural emissions.
Agricultural emissions are calculated by NLU using the IPCC Tier 1 method for production in the plant food sector and the IPCC Tier 2 method for the livestock sector (IPCC 2006). In the livestock sector, emissions from manure management (CH_4 and N_2O) and enteric fermentation (CH_4) are computed. In the plant food sector, emissions from fertilization (N_2O) and rice cultivation (CH_4) are computed. Carbon dioxide (CO_2) emissions are also computed for land-use changes (Le Quéré *et al* 2009) and for fossil fuel substituted by second-generation biofuel (detailed in the description of biofuel scenarios in the SI).

2.2.3 Estimating biodiversity impacts.
Biodiversity impacts are estimated by the PREDICTS modelling framework (Purvis *et al* 2018) which considers land-use to be the main driver of biodiversity losses (Díaz *et al* 2019).

The statistical models linking biodiversity to drivers are underpinned by a large, global and taxonomically broad database of terrestrial ecological communities facing land-use pressures. Among the biodiversity models provided by the PREDICTS framework, we chose BII because of its use in the Planetary Boundaries framework and SR because of its wide use despite its known limitations. The species richness model (SR) is a mixed-effect model computing the number of species present in a given area. The total abundance model computes the sum of all individuals of all species present in the ecosystem. The compositional similarity model computes the percentage of individuals common to the studied ecosystem and the reference ecosystem for each grid of a 0.5° map. The abundance map was then multiplied by the compositional similarity map to produce the map of abundance-based BII (De Palma *et al* 2019) (section 6 in the SI). These three PREDICTS models include different levels of management (intensive, light or minimal) and different types of land cover (forest, pasture, rangeland, annual cropland, perennial cropland and urban zones).

2.2.4 Linking PREDICTS and NLU.
In NLU, 60 land classes are defined in the reference year according to their potential yield. Different crop types are defined for each land-class: 'Dynamic' crops and 'other' crops (see the SI).

In PREDICTS, three levels of intensification break down perennial crops, annual crops and nitrogen-fixing crops into a 'minimal', 'light' and 'intense' use category.

NLU crop types are aggregated into a single category and then split into PREDICTS crops categories (perennial, annual and nitrogen-fixing crops) based on their relative proportion of the crop mix in the reference year.

For the reference year, a generalized additive model (GAM) is computed to match the relative proportion of 'minimal', 'light' and 'intense' cropland with the 60 NLU land classes (see the SI, figure 7). A GAM is used to avoid making assumptions about the form of the relationship between the intensification in PREDICTS and the land classes of NLU and to avoid giving too much weight in the relationship to uncertain extreme values (section 4 in the SI).

Pastures in NLU mixed crop-livestock and pastoral production systems are aggregated into a single pasture category. In PREDICTS, pastures include rangeland, 'light' and 'intense' pastures. Among the aggregated pasture category of NLU, rangeland areas are defined on the basis of reference rangeland map (Hurtt *et al* 2011). For the remaining pastures, livestock density is defined on the basis of livestock density maps (Robinson *et al* 2014). In the reference year, a GAM is computed to match the relative proportion of 'light' and 'intense' pasture with livestock density maps (see the SI, figure 8).

2.2.5 Baseline scenario.
The population follows changes in the Shared Socioeconomic Pathway (SSP2) (Riahi *et al* 2017). Food demand follows FAO projections (Alexandratos and Bruinsma 2012a) with a global mean food supply at the household level in 2100 of 2585 kcal/capita/day of vegetable products and 615 kcal/capita/day of animal products. International trade parameters are kept constant. Forest, which is exogenous to the model, follows current trends (Hurtt *et al* 2011) until 2050 and then stabilizes. Fertilizer prices are computed based on energy prices (Brunelle *et al* 2015) taken from the baseline of IMACLIM-R (Waisman *et al* 2012). This leads to a global average calorie price of 79$/Mkcal, a global average production cost of 43$/Mkcal, a 14% reduction of BII by land-use change occurring between 2001 and 2100 and a 15% reduction of species richness by land-use change occurring between 2001 and 2100 compared to the biodiversity levels in 2001.

2.2.6. Mitigation scenarios to achieve 2 °C of global warming in 2100.
We combine three mitigation policies in mitigation scenarios to achieve 4.3 $GtCO_{2,eq}$/year of mitigated emissions in 2100. 4.3 $GtCO_{2,eq}$/year is the target for the AFOLU sector to achieve 2 °C of global warming. We deduced this target by applying the share of

mitigated emissions by the AFOLU sector in overall mitigated emissions between the RCP2.6 and the baseline 2030 (Wollenberg *et al* 2016) to mitigated emissions between the RCP2.6 and the baseline of the marker model IMAGE (Gidden *et al* 2019) in 2100 (See table 2 in the SI) .

To obtain a broad representation of the possible combinations between second-generation biofuel production, dietary change and reforestation, we use a full factorial design (see figure 11 in the SI), which covers second-generation biofuel production ranging from 0 to 112 EJ, animal product consumption ranging from FAO trends (Alexandratos and Bruinsma 2012b) to a convergence towards 432 kcal/capita/year (see the SI, table 2), and pasture reforestation ranging from 0% to 31% (see the SI, table 3).

To achieve 4.3 $GtCO_{2,eq}$/year of mitigated emissions by means of dietary change, we replace the consumption of animal products by plant products in the Agrimonde scenarios called AG1 (Paillard *et al* 2014). This leads to a convergence of the overall animal consumption towards 432 kcal/capita/day in all regions. The consumption of ruminant products obtained is 183 kcal/capita/year in 2050 for Brazil, Canada, Europe, USA, FSU, OECD Pacific and Rest of LAM, 91 kcal/capita/year in 2050 for India, Rest of Asia and China, 154 kcal/capita/year for Middle-East and 65 kcal/capita/year for Africa (section 10.1 in the SI). The rest of animal product consumption (in the 432 kcal/capita/day) is composed of monogastric and aquatic products (see the SI, table 2).

The reforestation scenario follows the same philosophy as the natural climate solutions reforestation scenario presented in (Griscom *et al* 2017) by reforesting pastures (section 10.3 in the SI). The 31% of pastures reforested in the world corresponds to the reforestation of 186 Mha with a carbon sequestration of 23 tCO_2/ha in global average (see table 5 in the SI). This reforestation area is in the lower range of afforestation potential in baseline (Intergovernmental Panel on Climate Change 2014) (see the SI for more details about the regional distribution, table 3).

The second-generation biofuel production of 112 EJ is coherent with the literature that agrees on a technical bioenergy potential of at least 100 EJ (Edenhofer *et al* 2011, Creutzig *et al* 2015). To limit the competition of the biofuel production with food, second-generation biofuels in the scenarios are deployed in the form of grassy crops in Europe and the USA, and in the form of woody crops in the rest of the world (section 10.2 in the SI).

2.2.7. Indicators of food security and biodiversity.
We use four indicators to represent impacts of mitigation policies on biodiversity and food security:

– Global food price (\$/Mkcal) (section 6 in the SI).

– Crop production cost per unit of food energy produced (\$/Mkcal) (section 6 in the SI)

– Species richness (section 2.2.3 in the method section)

– BII (section 2.2.3 in the method section)

3. Results

The scatter of points representing the impacts of land-based mitigation scenarios is widely spread over the output space and has concave boundaries, indicating a moderate trade-off between biodiversity and food security for a greenhouse gas (GHG) reduction objective compatible with 2 degrees of global warming (figure 1 and see the SI for other indicators). A table presenting the values of the four indicators (calorie price, cost, BII and SR) for each scenario is provided in section 13 in the SI.

Scenarios with high second-generation biofuel production are located well inside the cloud of points. This shows that second-generation biofuel production is a less effective mitigation option for reconciling biodiversity and food security objectives than scenarios containing more reforestation or dietary change (figures 1 and 2 and see the SI for other indicators). Moreover, scenarios with low levels of biodiversity (especially low SR) tend to be those including high levels of second-generation biofuel production (SI, figure 17).

Mitigation scenarios focusing almost exclusively on dietary change or reforestation are either at the upper right hand or at the lower left hand of the cloud of points. This indicates that they perform well in relation to one indicator but have negative side-effects on at least one of the others (See figure 14 in supplementary information). The reforestation of large proportions of the world's pastures is positive for both biodiversity indicators but causes a sharp increase in food prices and food cost, thus threatening food security (SI, figure 14). By contrast, scenarios with significant dietary changes are less positive in terms of biodiversity but have lower impacts on food prices and food production costs (figure 1 and the SI, figure 17). The cost of food production and the price of food vary in the same direction across mitigation strategies but with larger change in price (section 11.1 of the SI for an explanation of the difference between response of food price and cost). The impacts of a dietary change on biodiversity vary according to the indicator under consideration with a reduction in BII (-0.7% per Gt $CO_{2,eq}$) and an increase in SR ($+0.3\%$ per Gt $CO_{2,eq}$) compared to the baseline. A major dietary change leads to less intensification of livestock farming, which in NLU model results in an increase in

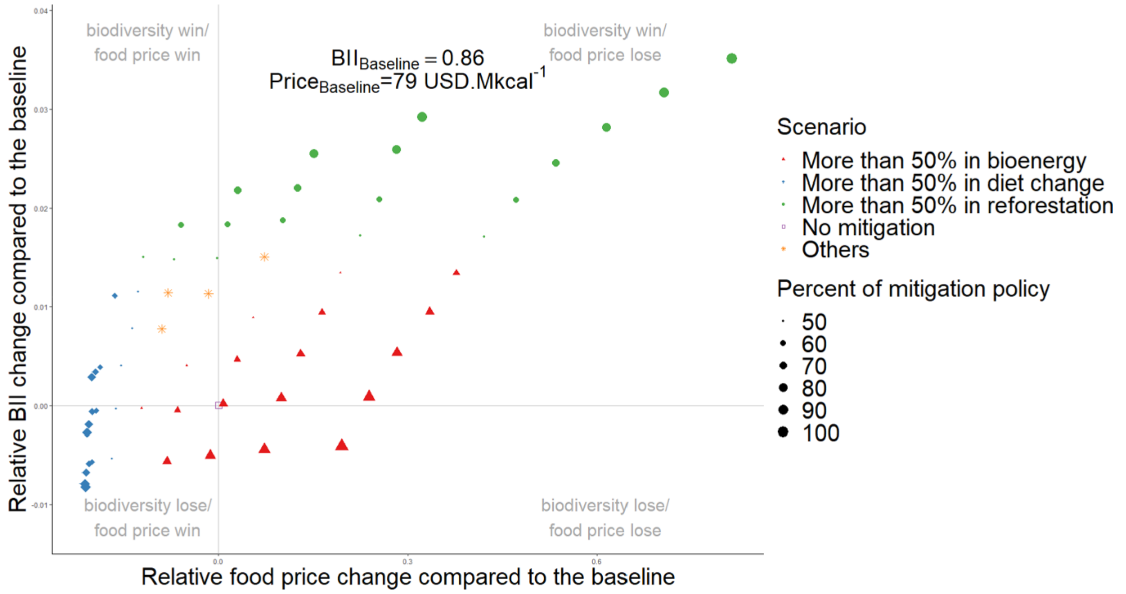

Figure 1. Impacts of mitigation scenarios achieving 4.3 GtCO2,eq/year of mitigated emissions in 2100 based on combinations of second-generation biofuel production, dietary change and reforestation. Outputs are presented as the relative change in BII and food price in the climate mitigation scenarios with respect to the baseline (no mitigation policy). At the global scale, all climate mitigation scenarios reduce emissions by construction of baseline emissions (13.9 GtCO2,eq in 2100) by around 4.3 GtCO2,eq/year in 2100. Each climate mitigation scenario is coloured according to the dominant mitigation policy. The dominant emission reduction policy in each scenario is the one that contributes the most to emissions reductions. 'Others' in the legend represents scenarios where no option accounts for more than 50% of the mitigation effort. The percent of mitigation policy is the share of mitigated emissions of the dominant mitigation policy (second-generation biofuel production, dietary change and reforestation). The food price and the BII in baseline in 2100 are also indicated.

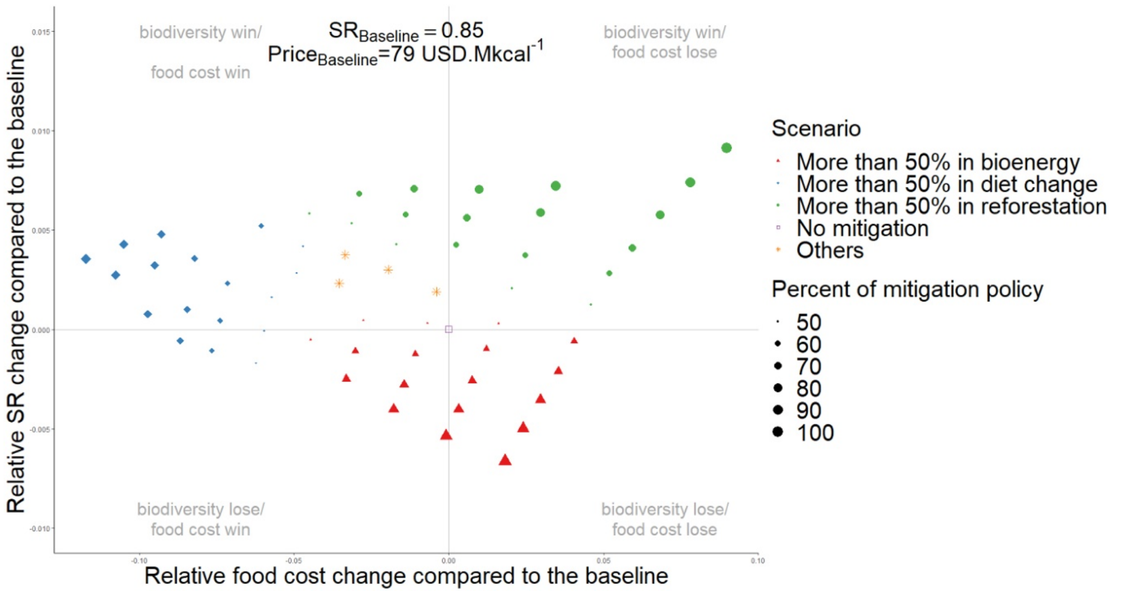

Figure 2. Impacts of mitigation scenarios reaching 4.3 GtCO2,eq/year in 2100 of mitigated emissions based on combinations of second-generation biofuel production, dietary change and reforestation. Outputs are presented as the relative change in SR and cost of food production in the climate mitigation scenarios with respect to the baseline (no mitigation policy). Each climate mitigation scenario is coloured according to the dominant mitigation policy. The dominant emission reduction policy in each scenario is the one that contributes the most of emissions reductions. 'Others' in the legend represents scenarios where no option accounts for more than 50% of the mitigation effort. For additional details, see figure 1. The food production cost and the SR in baseline in 2100 are also indicated. Impacts of mitigation on other indicators are provided in section 12 in the SI.

the pasture area without any influence on forest area (section 12.3 in the SI). Grazing land has a high species richness but its ecological communities have little similarity with those found in natural environments, which explains why there is a low BII and high SR in a dietary change scenario.

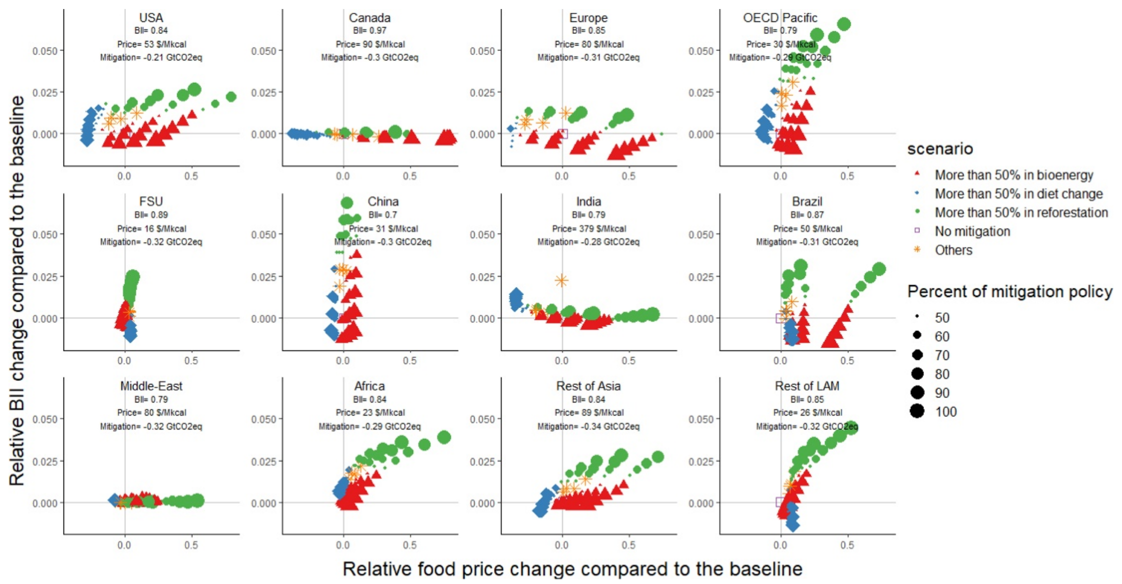

Figure 3. Regional impacts of mitigation scenarios reaching 4.3 GtCO2,eq/year in 2100 of mitigated emissions globally based on combinations of second-generation biofuel production, dietary change and reforestation. Outputs are presented as the relative change in BII and food price in the climate mitigation scenarios with respect to the baseline (no mitigation policy). These indicators compare changes in relative BII and relative food prices by considering different amounts of regionally mitigated emissions indicated for each region by an average of mitigated emission in the different mitigation scenarios. These indicators are also provided at the global scale in figure 1. Similar graphs for other biodiversity and food security indicators are provided in the SI.

3.1. Portfolios of land-use-based mitigation scenarios reduce the trade-off between biodiversity and food security

On a global scale, mitigation scenarios that spread mitigation efforts between several policies (reforestation, second-generation biofuel production and dietary change) avoid extreme negative side effects. Among these scenarios involving different emission mitigation policies, some mitigation scenarios can improve both the protection of biodiversity and food security in 2100 compared to the baseline without mitigation policies (scenarios in the upper left-hand quadrant of the figure 1).

These mitigation scenarios are mainly mixes of reforestation and dietary change associated with low second-generation biofuel production. For example second-generation biofuel production of 10 EJ/year in 2100 (10% of the mitigation effort) associated with reforestation of 11% of pasture (40% of the mitigation effort) and a low consumption of ruminant product of 150 kcal/capita/day (50% of the mitigation effort) decrease the food price by 13% compared to the baseline and increase BII by 1.2% for a decrease of 30% of emissions in the AFOLU sector compared to the baseline (figure 1).

3.2. Trade-off and synergies between food security and biodiversity conservation in mitigation policies at the regional scale

The trade-off between BII and food prices seen at a global scale is also found within some regions such as the region covering Japan, South Korea, Australia and New Zealand (OECD Pacific in figure 3), Europe, the USA and China, but differs in other regions because of the regional context. For example, food prices and BII are relatively insensitive to mitigation strategies in the former Soviet Union. In Canada and the Middle East, food prices, but not BII are very sensitive to mitigation strategies. Due to the small fraction of agricultural land in these regions (Hurtt *et al* 2011), their average regional levels of biodiversity are mainly influenced by the state of their natural areas and not by agricultural land-use changes (figure 3).

The choice of the optimal regional mitigation mix for BII and the food price varies from one region to another. On the one hand, large-scale bioenergy production systematically increases food prices and reduces biodiversity compared to a baseline without a mitigation strategy. On the other hand, the influence of reforestation and diet change in the mitigation strategy depends on the regional context. For example, a lower ruminant consumption decreases in the African dietary change (−46 kcal/capita/day) compared to the other regions (for example, − 199 kcal/capita/day in Brazil in Table 2) leads to high levels of BII and a low food price (figure 3). For other regions like Brazil and the rest of Latin America, both dietary change and reforestation mitigation scenarios lead to higher price than the baseline without a mitigation strategy.

4. Discussion and conclusion

The major contribution of this study is that it is the first explore the full range of combinations of key land-based climate mitigation options—bioenergy, reforestation and dietary change—on biodiversity and food systems. The model projections are not predictions of future outcomes but do provide insight into the synergies and trade-offs among land-based mitigation measures, as well as their respective advantages and drawbacks. Another important novelty of this study is that it provides a global perspective of the impact of agricultural intensification and land use changes within the agricultural sector on biodiversity of both agricultural intensification and land use changes within the agricultural sector (conversion of the pastoral system into a mixed pasture-and-crop system), while previous studies have focused on the impact of mitigation scenarios on habitats of high ecological value such as 'biodiversity hotspots' (Obersteiner *et al* 2016) or forests (Humpenöder *et al* 2018). Considering the impact of agricultural intensification on biodiversity provides several new insights. For example, the substantial agricultural intensification induced by a reforestation scenario mitigates the initial BII increase inside the reforested area. In addition, the reduction in extent of the crop-pasture mix system in favour of the pastoral system in scenarios of significant dietary change may lead to strong change in ecological community composition, as evidenced by the reduction in BII (figure 1). However, as the reforestation rates are exogenously set in NLU, the reduction in extent of the crop-pasture mix system is probably overestimated in this study, leading to an underestimation of the BII and the food price (see section 11 of the SI for a description of main mechanisms).

Another major contribution of this study is an understanding of the impacts of different land-use-based mitigation scenarios on different biodiversity indicators: (i) the 'naturalness' of ecosystems through the BII and (ii) the local 'extirpation risk' through the BII and SR (Karp *et al* 2015). Although we do not estimate extinction rates in this study, the biodiversity indicators computed in our mitigation scenarios provide additional and consistent information to the extinction risk in global biodiversity hotspots already studied by, e.g. Obersteiner *et al* 2016. Reforestation scenarios are beneficial to these three indicators, second-generation biofuel is detrimental to these three indicators and decreasing pressure on land through dietary change has a beneficial effect on SR and biodiversity hotspot preservation but decreases BII due to an increase in the area of pasture.

The inclusion of the impacts of these policies on biodiversity is a first step towards a deeper integration of biodiversity into the socio-ecological system used in environmental assessment of mitigation options. The crucial role of biodiversity in food production is well established and its integration into land-use models can significantly change the relationship between biodiversity protection and food security (Commission on Genetic Resources for Food and Agriculture and Food and Agriculture Organization of the United Nations 2019).

A portfolio of mitigation strategies reduces side-effects on biodiversity and food security compared to siloed strategies and allows several SDGs to be achieved simultaneously (Obersteiner *et al* 2016, Humpenöder *et al* 2018, Bertram *et al* 2018, Minx *et al* 2018). For example, reforestation of 22% of pasture (70% of the mitigation effort) and a dietary change of 90 kcal/capita/day from ruminant toward plant consumption (30% of the mitigation effort) is the best scenario to minimize negative impacts on our measures of biodiversity, food security and mitigation in the agricultural sector at the global scale. The portfolio effect is explained in this scenario by the complementarity of mitigation policies. The synergy is particularly strong between dietary change and reforestation strategies, as this combination allows for land to be spared through a reduction in overall food production, meaning it can both store carbon and preserve biodiversity (Ewers *et al* 2009, Herrero *et al* 2016, Stevanović *et al* 2017). On the other hand, the increase in second-generation biofuel production reduces the positive synergies between food security and biodiversity conservation even with an optimistic assumption about the quantity of emissions reduced per unit of second-generation biofuel produced (Searchinger *et al* 2018).

In this study, mitigation effort is allocated between regions according to reforestation potential, biofuel prices and the difference between local diet and a reference diet, but without considering the equitability or mitigation cost of this distribution of the effort. The relationships between biodiversity and food security we report could change when these allocation criteria are considered. Moreover, the potential for mitigation of emissions, food insecurity and biodiversity loss in the AFOLU sector, although very high (Tubiello *et al* 2015, Tilman *et al* 2017, Heck *et al* 2018b), may not be exploited due to equitability of the allocation of effort or high mitigation costs (Tilman *et al* 2017, Markel *et al* 2018, van den Berg *et al* 2019).

In this study, we show the importance of considering the regional context, which strongly nuances the global trade-offs between biodiversity protection and food security protection. This study should therefore be complemented by future work that take into account the regional context. More specifically, soil carbon sequestration (Lal 2004) in regions with degraded soils such as southern Europe, some parts of Asia and Africa, or increased nitrogen use efficiency (NUE) (Bodirsky *et al* 2014, Zhang *et al* 2015) in regions with low NUE such as China or India. Other important dimensions could be added to our analysis. For instance, the nutritional qualities and health benefits of food diets could be also considered in relation to recent work on the topic; and more location-sensitive measures of biodiversity, such as extinction rates or extinction risk, could usefully be added.

Our study shows the importance of combining exploratory with target-seeking scenarios to include new objectives such as we have done here with biodiversity. This approach differs from many others used in climate scenarios that select the scenario with the lowest implementation cost regardless of preferences toward other objectives, as biodiversity conservation or food security. For example, the RCP2.6 scenario (Vuuren *et al* 2011), implying an important second-generation biofuel production (equivalent to 181 E_j) leads to relatively low food prices at the expense of low SR levels (see table 3). In this scenario, the negative effect on biodiversity is mainly due to the significant production of second-generation biofuel (Jantz *et al* 2015, Hill *et al* 2018). In contrast, our approach allows the assessment of a wide variety of combinations of mitigation policies and does not make implicit assumptions about preferences between biodiversity and food security.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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