Impact of land-use-based climate mitigation policies on biodiversity and food security

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Abstract

Agriculture faces three great challenges: feeding a growing population, reducing its impact on biodiversity and minimizing greenhouse gas (GHG) emissions. Therefore, it is important to assess synergies and trade-offs in meeting these challenges. 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: biofuel crop production, dietary change and reforestation of pasture. We evaluated the impacts of these scenarios on food security and biodiversity conservation. We find that focusing mitigation on a single policy can lead to positive results for one indicator, but with significant negative side effects on others. For example, mitigation dominated by reforestation favors biodiversity criteria, but is projected to lead to sharp increases in food prices. Mitigation scenarios focusing on biofuels have strong adverse effects on both biodiversity and food security indicators. 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 projected impact of mitigation policies are similar to proection at global scale, except for Canada and Middle-East. Due to the small area of agricultural land in these regions, their average regional levels of biodiversity are mainly influenced by the state of their natural areas and not by agricultural land-use changes.

Keywords: Mitgation policies | Global land-use system | Biodiversity | PREDICTS

1 Introduction

Land is a multi-purpose asset that may involve conflicts in its use. Formerly restricted to the local level, global conflicts have emerged over the last few decades because of the rapid intensification of international exchanges [Liu et al., 2013]. Today, 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 strenghtening the global dimension.

Assessments based on global land-use models show that mitigation policies relying on large-scale biofuel production have important environmental implications as well as adverse impact on food prices especially if forest protection measures are implemented [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] while dietary change policies may have the opposite effect, with a reduction in the price of calories when implemented [Stevanović et al., 2017]. Combining measures appears to be an appropriate solution to minimize negative effects, but the nature of the combinations does matter [Humpenöder et al., 2018, Obersteiner et al., 2016, Visconti et al., 2016].

This picture can be made more complex by taking into account the trade-offs between biodiversity and climate mitigation. While some mitigation policies such as carbon storage in forests can maintain biodiversity when appropriately implemented [Watson et al., 2018], other options could increase pressure on biodiversity indices. Mitigation policies in integrated scenarios of climate change (Representative Concentration Pathways) and human development (Shared Socio-economic Pathways) seem to be mostly harmful to biodiversity [Hill et al., 2018] with regard to numerous indicators and at the level of biodiversity hot-spots [Jantz et al., 2015]. Ambitious mitigation scenarios involving substantial land use change or scenarios with strong climate change are particularly associated with high impacts on biodiversity [Newbold, 2018].

This study provides a unique framework for understanding (i) the impact of different GHG mitigation policies (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.

The food system [Erb et al., 2017] is represented by the Nexus Land Use (NLU) model [Souty et al., 2012]. This global agricultural intensification model 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 wuth respect to GHG emission goals and generates land-use maps.

The PREDICTS models are used to convert these land-use maps into impacts on biodiversity through computation of the local Biodiversity Intactness Index (BII) [Scholes and Biggs, 2005] and Species Richness indicator (SR) using a mixed-effect modelling structure [Hill et al., 2018]. BII is an indicator of ecosystem naturalness and measures the proportion of species present in the ecosystem that are similar to the natural reference ecosystem. The SR reports the number of species present in the ecosystem. These two indicators are complementary because they provide an insight into the overall health of the ecosystemś specific diversity and the type of biodiversity present. To clarify the impacts of GHG mitigation policies on these indicators, we make some changes to the framework presented by Hill et al (2018) [Hill et al., 2018] by separating rangeland from other pasture and representing grassy and woody biofuel crops as highly intensified perennials.

With this framework, we assess the impact on biodiversity and food security of land-use-based mitigation scenarios that provide mitigation of 4.3 $GtCO_2$/year in 2100 (target for the AFOLU sector to reach 2° of global warming obtained by extrapolating the 2030 results to 2100 [Wollenberg et al., 2018]). To mitigate these 4.3 $GtCO_2$/year in 2100, we build scenarios that are combinations of second-generation biofuel production (between 0 and 112 EJ/year in 2100), dietary change (reduction of the proportion of animal products in food down to 314 kcal/cap/day except in Africa for nutritional reasons) and reforesting pastures (between 0 and 31% of global pasture reforested). 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 (See Section.5.2.1 in supporting information). To cover a broad range of scenarios and represent a uniform distribution of mitigation policies (biofuel dietary change and reforestation), the scenarios are constructed according to a complete factorial plan (See Section.5.3 in supporting information). 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%.

We infer from these scenarios whether the relationship between biodiversity and food security in

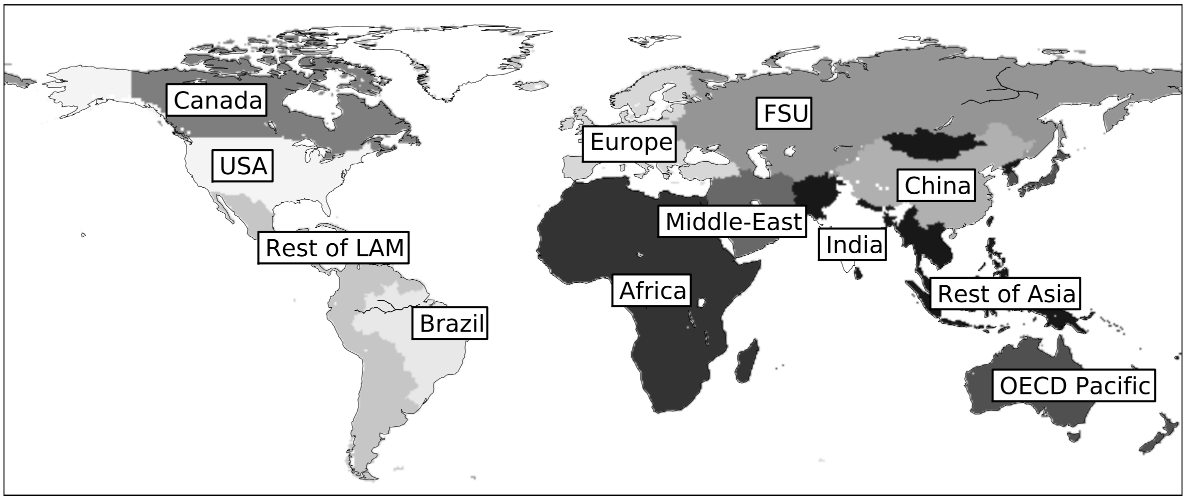

Figure 1: Map of the 12 regions as defined in NLU

the presence of mitigation policies is synergistic or antagonistic and how the policy mix influences this relationship.

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 but depends on the amount of pasture 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 supporting information for details of these indicators).

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

2 Material and methods

2.1 Estimating agricultural production

Here, we provide a general description of the version of NLU before this thesis. More details can be found in Souty et al. [2012] and Brunelle et al. [2015].

NLU model is a partial equilibrium model in which the agricultural sector is divided into 12 regions of the world (Fig.1), inter-connected with each other by international trade.

Model inputs are scenarios of population, diet, agrofuel production, deforestation rate and fertilizer prices and its outputs are cropland area, mixed crop-livestock system area, pastoral area, crop yield, fertilizer consumption, land price and calorie price (See Fig.2). NLU provides a simple representation of the main processes of agricultural intensification for crop and livestock production: the substitution between (i) land and fertiliser for the crop sector and (ii) grass, food crops, residues and fodder for the livestock sector. It does so by minimising the total production cost under a supply-use equilibrium for food and biofuel markets. A detailed description can be found in Brunelle et al. [2015].

The NLU model simulates changes in the agricultural sector at the global scale (food price, land rent, profit, crop yield and cropland as a percentage of total agricultural land) with a non-linear response of yield to fertilizer prices, as well as an explicit representation of livestock systems and international trade.

For the base year, a representative potential yield is computed on a $0.5° \times 0.5°$ grid from the potential yields given by the vegetation model LPJmL for 11 crop functional types (CFT). Land classes are

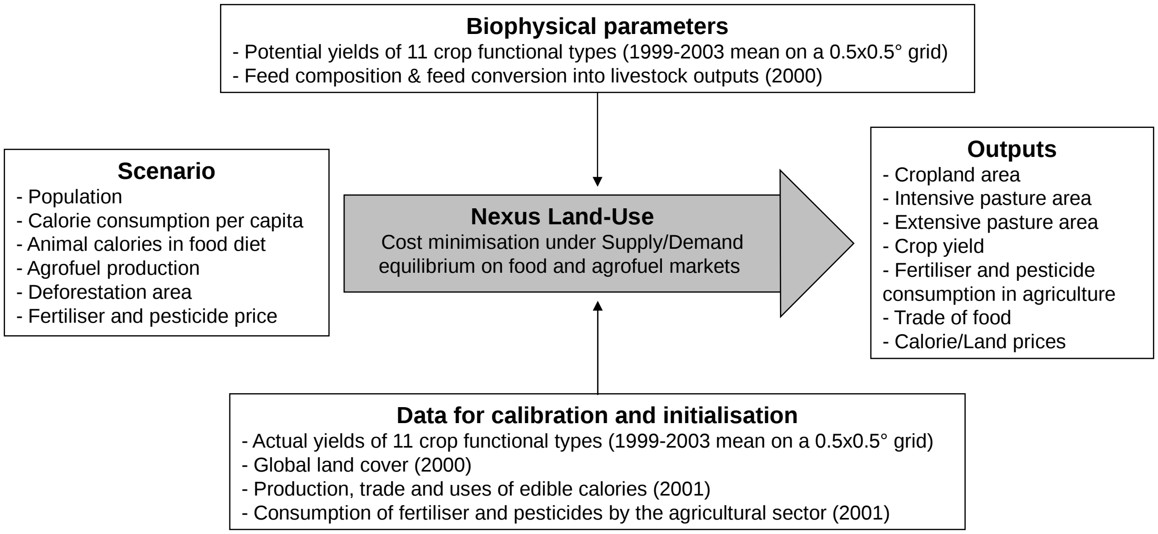

Figure 2: General description of the modelling system in NLU.

set up that group together grid points with the same potential yield. Yield in each land class is dynamically determined by a fertilizer function for the 11 CFT (hereafter referred to as dynamic crops). This function asymptotes toward the potential yield and is characterised by decreasing returns. In each land class, consumption of chemical inputs and associated yield are determined by cost minimization under the constraint of a global supply-demand balance for plant food (Eq. 3) and ruminant calories (Eqs. 4–7) and a land constraint (Eq. 9).

Indices

j	Land class number.
j_{limit}	Limit land class between the mixed crop-livestock and the pastoral production systems.
j_{max}	Index of the highest land class.

Parameters in each region

$\omega^{\mathrm{fc}}_{\mathrm{swo}}$, $\omega^{\mathrm{m}}_{\mathrm{swof}}$, $\omega^{\mathrm{r}}_{\mathrm{swof}}$	Ratio of Seed, Waste at the farm level, Other uses of food crops (excluding Feed) in total production of Food Crop, Monogastric and Ruminant products.
$Q^{\mathrm{fc}}_{\mathrm{other\ crop}}$	*Other* production of food crops which is not dynamically modelled (i.e. difference between the total production from Agribiom and LPJmL production in 2001).
α_{IC}	Initial slope of the intermediate consumption function in $\$\,\mathrm{kcal}^{-1}$.
$\mathrm{FC_{tot}}$	Fixed cost per hectare in $\$\,\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ corresponding to capital, labour, business services, pesticides and energy consumption for vehicles, buildings (heating, etc.) and other on-farm operations (drying of crops, etc.). Recalibrated to account for the costs of the mixed crop-livestock system and the pastoral systems.
$\rho^{\mathrm{grass}}_{\mathrm{past,int}}$, $\rho^{\mathrm{grass}}_{\mathrm{past,ext}}$	Grazed grass per hectare of pastures in the mixed crop-livestock and pastoral systems in $\mathrm{kcal\,ha^{-1}\,yr^{-1}}$.
$\rho^{\mathrm{r,int}}_{\mathrm{past}}$, $\rho^{\mathrm{r,ext}}_{\mathrm{past}}$	Production of ruminant product per hectare of pasture in the mixed crop-livestock and pastoral systems in $\mathrm{kcal\,ha^{-1}\,yr^{-1}}$ ($\rho^{\mathrm{r,int/ext}}_{\mathrm{past}} = \frac{\rho^{\mathrm{grass}}_{\mathrm{past,int/ext}}}{\beta_{\mathrm{r,int/ext}}\phi^{\mathrm{grass}}_{\mathrm{r,int/ext}}}$).
$\mathrm{Imp^m}$, $\mathrm{Exp^m}$	2001 imports and exports of monogastric products in $\mathrm{kcal\,yr^{-1}}$.
$\rho^{\max}_j$, $\rho^{\min}_j$	Potential yield and minimum (no inputs) yield in $\mathrm{kcal\,ha^{-1}\,yr^{-1}}$.
β_{m}, $\beta_{\mathrm{r,int}}$, $\beta_{\mathrm{r,ext}}$	Feed conversion factor for monogastrics, ruminants from the mixed crop-livestock and the pastoral systems in kcal of feed/kcal of animal product.
$\phi^{\mathrm{fc}}_{\mathrm{m}}$, $\phi^{\mathrm{fodder}}_{\mathrm{m}}$, $\phi^{\mathrm{fc}}_{\mathrm{r,int}}$, $\phi^{\mathrm{fodder}}_{\mathrm{r,int}}$, $\phi^{\mathrm{grass}}_{\mathrm{r,int}}$, $\phi^{\mathrm{grass}}_{\mathrm{r,ext}}$	Share of feed categories in animal rations (fc: food crops, fodder: residues and fodder, grass: pasture grass, monog: monogastrics, r,int: ruminants from the mixed crop-livestock system, r,ext: ruminants from the pastoral system).

World level variables

$p^{\mathrm{w}}_{\mathrm{cal}}$	World calorie price in $\$\,\mathrm{kcal}^{-1}$ (endogenous).
p_χ	Index of fertilizer and pesticide price (exogenous).

Exogenous regional variables

$D^{\mathrm{fc}}_{\mathrm{h}}$, $D^{\mathrm{m}}_{\mathrm{h}}$, $D^{\mathrm{r}}_{\mathrm{h}}$	Demand of food crops (fc), monogastrics (m) and ruminants (r) products for humans (h) in $\mathrm{kcal\,yr}^{-1}$.
$D^{\mathrm{fc}}_{\mathrm{agrofuel}}$	Demand of food crops for agrofuel production in $\mathrm{kcal\,yr}^{-1}$.
S_{surf}	Supply of agricultural area excluding *other* croplands, including *dynamic* croplands, residual pastures and pastures from the crop-livestock and pastoral systems in ha.

Endogenous regional variables in each land class

ρ_j	Yield of the land class j minimizing farmer's production cost in $\mathrm{kcal\,ha}^{-1}\,\mathrm{yr}^{-1}$.
IC_j	Intermediate consumption of chemical and mineral inputs of the land class j in $\$\,\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$.
f^{crop}_j, f^{Pint}_j, f^{Pres}_j, f^{Pext}_j	Area of *dynamic* cropland (i.e. where crops modelled in the LPJmL model are grown), pastures from the crop-livestock system, residual pastures, pastures of the pastoral system of the land class j expressed as a fraction of D_{surf}.

Endogenous regional variables

p_{cal}	Food crop calorie price in $\$\,\mathrm{kcal}^{-1}$.
λ	Land rent in $\$\,\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$.
p_{r}	Price of ruminant calories in $\$\,\mathrm{kcal}^{-1}$.
D_{surf}	Demand of agricultural area excluding *other* croplands, including *dynamic* croplands, pastures from the crop-livestock system, residual pastures and pastures of the pastoral system in ha.
$Q_{\mathrm{r,int}}$, $Q_{\mathrm{r,ext}}$	production ruminant from the crop-livestock system and the pastoral system in $\mathrm{kcal\,yr}^{-1}$.
$D^{\mathrm{fc}}_{\mathrm{m}}$, $D^{\mathrm{fc}}_{\mathrm{r,int}}$	Demand of food crops for monogastrics and ruminant production from the crop-livestock system in $\mathrm{kcal\,yr}^{-1}$.
D^{fc}	Total demand of food crops in $\mathrm{kcal\,yr}^{-1}$.
$\mathrm{Imp}^{\mathrm{fc}}$, $\mathrm{Exp}^{\mathrm{fc}}$	Imports and exports of food crops in $\mathrm{kcal\,yr}^{-1}$.
$\mathrm{Imp}^{\mathrm{r}}$, $\mathrm{Exp}^{\mathrm{r}}$	Imports and exports of ruminant products in $\mathrm{kcal\,yr}^{-1}$.

Yield-fertilizer function:

$$\mathrm{IC}_j(\rho_j) = \alpha_{\mathrm{IC}}(\rho_j^{\max} - \rho_j^{\min}) \left(\frac{\rho_j^{\max} - \rho_j^{\min}}{\rho_j^{\max} - \rho_j} - 1 \right) \tag{1}$$

Objective function: Cost minimization of total production costs in each region:

$$\underset{\substack{\rho_j, j_{\mathrm{limit}}, D^{\mathrm{fc}}_{\mathrm{r,int}} \\ Q_{\mathrm{r,int}}, Q_{\mathrm{r,ext}}, D_{\mathrm{surf}}}}{\mathrm{Min}} \left(\int_{j_{\mathrm{limit}}}^{j_{\max}} (p_\chi \mathrm{IC}_j(\rho_j) + \mathrm{FC}_{\mathrm{tot}}) f^{\mathrm{crop}}_j \mathrm{d}j \right) D_{\mathrm{surf}} \tag{2}$$

Regional constraints:

$$Q_{\text{other}}^{\text{fc}} + \int_{j_{\text{limit}}}^{j_{\max}} f_j^{\text{crop}} \rho_j dj D_{\text{surf}} =$$

$$(D_{\text{r,int}}^{\text{fc}} + D_{\text{h}}^{\text{fc}} + D_{\text{m}}^{\text{fc}} + D_{\text{agro}}^{\text{fc}} + \text{Exp}^{\text{fc}} - \text{Imp}^{\text{fc}})(1 + \omega_{\text{swo}}^{\text{fc}}) \tag{3}$$

$$D_{\text{h}}^{\text{r}} + \text{Exp}^{\text{r}} - \text{Imp}^{\text{r}} = Q_{\text{r,int}} + Q_{\text{r,ext}} \tag{4}$$

$$D_{\text{h}}^{\text{m}} + \text{Exp}^{\text{m}} - \text{Imp}^{\text{m}} = Q_{\text{m}} \tag{5}$$

$$Q_{\text{r,ext}} = \left(\int_0^{j_{\text{limit}}} f_j^{\text{Pext}} dj + \int_{j_{\text{limit}}}^{j_{\max}} f_j^{\text{Pres}} \text{d}j \right) \rho_{\text{past}}^{\text{r,ext}} D_{\text{surf}} \tag{6}$$

$$Q_{\text{r,int}} = \frac{D_{\text{r,int}}^{\text{fc}}}{\beta_{\text{r,int}} \phi_{\text{r,int}}^{\text{fc}}} \tag{7}$$

$$Q_{\text{m}} = \frac{D_{\text{m}}^{\text{fc}}}{\beta_{\text{m}} \phi_{\text{m}}^{\text{fc}}} \tag{8}$$

$$S_{\text{surf}} = D_{\text{surf}} \tag{9}$$

The constraint on food crop production (Eq. 3) is associated with the Lagrangian multiplier interpreted as the calorie price p_{cal}. The constraints on total ruminant production (Eq. 4), ruminant production from the pastoral system (Eq. 6) and ruminant production from the mixed crop-livestock system (Eq. 7) are associated with Lagrangian multipliers that are all equal and can be interpreted as the ruminant price p_{r}. The constraints on monogastric production (Eq. 5 and 8) are associated with Lagrangian multipliers that are all equal and can be interpreted as the ruminant price p_{m}. Finally, the land constraint (Eq. 9) is associated with the Lagrangian multiplier interpreted as the land rent λ.

First order conditions yields:

$$p_{\text{cal}} = p_\chi \text{IC}_j'(\rho_j)(1 + \omega_{\text{swo}}^{\text{fc}}) \tag{10}$$

$$p_{\text{r}} = p_{\text{cal}}(1 + \omega_{\text{swo}}^{\text{r}}) \beta_{\text{r,int}} \phi_{\text{r,int}}^{\text{fc}} \tag{11}$$

$$p_{\text{m}} = p_{\text{cal}}(1 + \omega_{\text{swo}}^{\text{m}}) \beta_{\text{m}} \phi_{\text{m}}^{\text{fc}} \tag{12}$$

$$p_{\text{r}} f_{j_{\text{limit}}}^{\text{Pext}} \rho_{\text{past}}^{\text{r,ext}} =$$

$$(p_{\text{cal}} \rho_{j_{\text{limit}}} - p_\chi \text{IC}_{j_{\text{limit}}}(\rho_{j_{\text{limit}}}) - \text{FC}_{\text{tot}}) f_{j_{\text{limit}}}^{\text{crop}} + p_{\text{r}} f_{j_{\text{limit}}}^{\text{Pres}} \rho_{\text{past}}^{\text{r,ext}} \tag{13}$$

$$\lambda = p_{\text{cal}} \int_{j_{\text{limit}}}^{j_{\max}} f_j^{\text{crop}} \rho_j \text{d}j - \int_{j_{\text{limit}}}^{j_{\max}} (p_\chi \text{IC}_j(\rho_j) + \text{FC}_{\text{tot}}) f_j^{\text{crop}} \text{d}j \dots \tag{14}$$

$$\dots + p_{\text{r}} \left(\int_0^{j_{\text{limit}}} f_j^{\text{Pext}} dj + \int_{j_{\text{limit}}}^{j_{\max}} f_j^{\text{Pres}} dj \right) \rho_{\text{past}}^{\text{r,ext}} \tag{15}$$

The land rent λ is the sum of the scarcity rent, denoted μ, and the differential rent, denoted δ, defined as following:

$$\mu = p_{\text{cal}} f_{j_{\text{limit}}}^{\text{crop}} \rho_{j_{\text{limit}}} - (p_\chi \text{IC}_{j_{\text{limit}}}(\rho_{j_{\text{limit}}}) + \text{FC}_{\text{tot}}) f_{j_{\text{limit}}}^{\text{crop}} + p_{\text{r}} f_{j_{\text{limit}}}^{\text{Pres}} \rho_{\text{past}}^{\text{r,ext}} \tag{16}$$

$$\delta = \lambda - \mu \tag{17}$$

The global land-use model known as NLU 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 the 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.

2.2 Estimating agricultural emissions

Agricultural emissions are calculated by the NLU model 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 based on Le Quéré et al. [2009] and for fossil fuel substituted by second-generation biofuel (detailed in the description of biofuel scenarios in supporting information).

2.3 Estimating biodiversity impacts

Biodiversity impacts are estimated by the PREDICTS modeling framework [Purvis et al., 2018] which considers land-use to be the main driver of biodiversity losses [Foley et al., 2005].

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 [Hudson et al., 2017]. Among the biodiversity models provided by the PREDICTS framework [Purvis et al., 2018], we chose BII because of its use in the Planetary Boundaries framework [Steffen et al., 2015] 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 (Table.1). The total abundance model computes the sum of all individuals of all species presentin the ecosystem. The compositional similarity model computes the percentage of individuals common to the studied ecosystem and the reference ecosystem [De Palma et al., 2018] 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 [Newbold et al., 2016]. 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).

2.4 Estimating the link between PREDICTS and NLU

In the NLU, 60 land classes are defined in the reference year according to their potential yield [Brunelle et al., 2018]. Different crop types are defined for each land-class: "Dynamic" crops and "other" crops (See supporting information). In PREDICTS, three levels of intensification break down perennial crops, annual crops and nitrogen-fixing crops into a "minimal", "light" and "intense" use category [Hudson et al., 2014]. 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. In 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 supporting information, Fig.**??**). Pastures in the 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 the rangeland map produced by Hurtt et al. [2011]. For the remaining pastures, livestock density is defined on the basis of livestock density maps produced by 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 supporting information, Fig.**??**).

Table 1: Abundance,composition similarity and species richness models based on the PREDICTS data base

Land-Use	Abundance model	Species richness model	Composition model
Intercept	0.65895	2.65435	2.189599
Secondary	-0.01415	-0.15875	-0.223229
Rangelands	-0.03463	-0.09300	-1.122190
Pasture Light use	-0.05364	-0.23153	-3.398944
Pasture Intense use	-0.08303	-0.21634	-3.398944
Annual Minimal use	-0.12289	-0.37063	-1.557422
Annual Light use	-0.11470	-0.47360	-1.557422
Annual Intense use	-0.15255	-0.41606	-1.557422
Perennial Minimal use	0.02072	-0.21912	-0.294046
Perennial Light use	-0.09749	-0.42456	-1.063739
Perennial Intense use	-0.06351	-0.51682	-1.801390
Nitrogen Minimal use	-0.04453	-0.37003	-1.280273
Nitrogen Light use	-0.16470	-0.72871	-1.280273
Nitrogen Intense use	-0.23775	-0.67512	-1.280273
Urban Minimal use	-0.01684	-0.15043	1.319501
Urban Light use	-0.10958	-0.34365	1.319501
Urban Intense use	-0.15866	-0.39866	1.319501

2.5 Estimating the baseline

The population follows changes in the Shared Socio-economic Pathway (SSP2) [Riahi et al., 2017]. Food demand follows FAO projections [Alexandratos and Bruinsma, 2012] with a global mean consumption in 2100 of 2585 kcal/cap/day of vegetable products and 615 kcal/cap/day of animal products. International trade parameters are kept constant. The forest, which is exogenous in the model, follows current trends described in Hurtt et al. [2011] until 2050 and then stabilizes. Fertilizer prices are computed using the method described in Brunelle et al. [2015] based on energy prices taken from the baseline of IMACLIM-R [Waisman et al., 2012].

2.6 Mitigation scenarios to achieve 2°C of global warming in 2100.

We combine 3 mitigation policies in mitigation scenarios to achieve 4.3GtCO_2/year of mitigated emissions in 2100 (the target for the AFOLU sector to achieve 2° of global warming according to an extrapolation of the 2030 results to 2100 Wollenberg et al. [2018]).

To obtain a broad representation of the possible combinations between second-generation biofuel production, dietary change and reforestation, we use a complete factorial design (See Fig.6 in supporting information) which covers second-generation biofuel production of between 0 and 112 EJ, animal product consumption of between FAO trends [Alexandratos and Bruinsma, 2012] and a convergence towards 432 kcal/cap/year (See supporting information, Table.S2), and pasture reforestation of between 0% and 31% (See supporting information, Table.S3). To achieve 4.3 GtCO_2 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., 2011]. This leads to a convergence of the overall animal consumption towards 432 kcal/cap/day in all regions. The consumption of ruminant products obtained is 183 kcal/cap/year in 2050 for Brazil, Canada, Europe, USA, FSU, OECD Pacific and Rest of LAM, 91 kcal/cap/year in 2050 for India, Rest of Asia and China, 154 kcal/cap/year for Middle-East and 65 kcal/cap/year for Africa. The rest of animal product consumption (in the 432 kcal/cap/day) is composed of monogastric and aquatic products (See supporting information, Table.S2).

The reforestation scenario follows the same philosophy as the natural climate solutions reforestation scenario presented in [Griscom et al., 2017] by reforesting pastures. The figure of 31 % of pastures reforested in the world corresponds to a reduction of 4.3 $GtCO_2$ of mitigated emissions by the AFOLU sector in 2100 (See supporting information, Table.S3). In Europe and the USA, second-generation biofuels are produced in the form of grassy crops; in the rest of the world they are woody crops.

3 Results

3.1 Trade-off between biodiversity and food security

The scatter of points representing the impacts of land-use 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 given climatic objective (Fig.3 and see supporting information for other indicators).

Scenarios with high second-generation biofuel production are located largely within the envelope indicating 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 (Fig.3 and see supporting information for other indicators). Moreover, scenarios with low levels of biodiversity (especially low SR) are linked with scenarios including high levels of second-generation biofuel production (Fig.4).

Mitigation scenarios focusing on dietary change or reforestation are at one edge of the envelope, indicating that they are performing well in relation to one indicator but have negative side effects on at least one of the other indicators (Fig.4). The reforestation of large proportions of the worldś pastures is beneficial to biodiversity whichever indicator is chosen, but causes a sharp increase in food prices and food cost, thus threatening food security (Fig.4). On the contrary, scenarios with significant dietary changes have a lower performance in terms of biodiversity but have lower impacts on food prices and food production costs (Fig.4).

Finally, it should be noted that some mitigation scenarios (mainly involving reforestation and dietary change) can improve the protection of biodiversity and food security in 2100 compared to a scenario without mitigation policies (scenarios in the upper left-hand quadrant of the Fig.3).

3.2 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. Scenarios with higher levels of biodiversity and food security than the baseline 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 animal consumption of 150 kcal/cap/day (50% of the mitigation effort) decrease the food price by 13% compared to the baseline and increase BII by 1.2% compared to the baseline (Fig.3 and see supplmentary information for other indicators).

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

The trade-offs and synergies between biodiversity conservation and food security protection observed at the global level can be found in most regions of the world. Former Soviet Union countries (FSU),

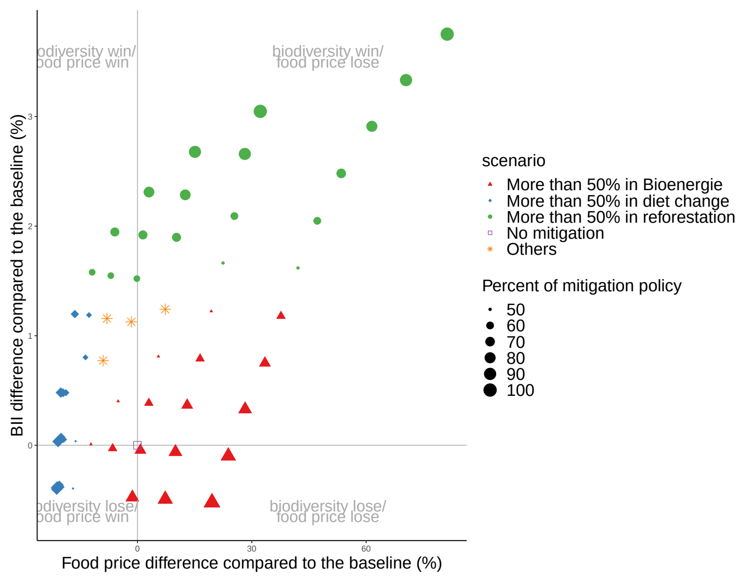

Figure 3: Impacts of mitigation scenarios achieving 4.3 $GtCO_{2_{eq}}$ of mitigated emissions in 2100 based on combinations of second-generation biofuel production, dietary change and reforestation. Outputs are presented as the relative change in BII and food price with respect to the scenario without any mitigation policy (baseline) with respect to the relative change in mitigated emissions. The relative changes in BII and food prices can be deduced from this graph by multiplying the values obtained by the relative change in emissions for each scenario, which is constant at $\frac{\text{Mitigated emissions}}{\text{Baseline emissions}} = \frac{4.3\text{GtCO}_{2_{eq}}}{13.87\text{GtCO}_{2_{eq}}} = 0.3$ The mitigation effort of each policy (second-generation biofuel production, dietary change and reforestation) is expressed in the legend as the percentage of mitigated emissions due to the policy in total mitigated emissions. "Others" in the legend represents scenarios without an option accounting for more than 50% of the mitigation effort.

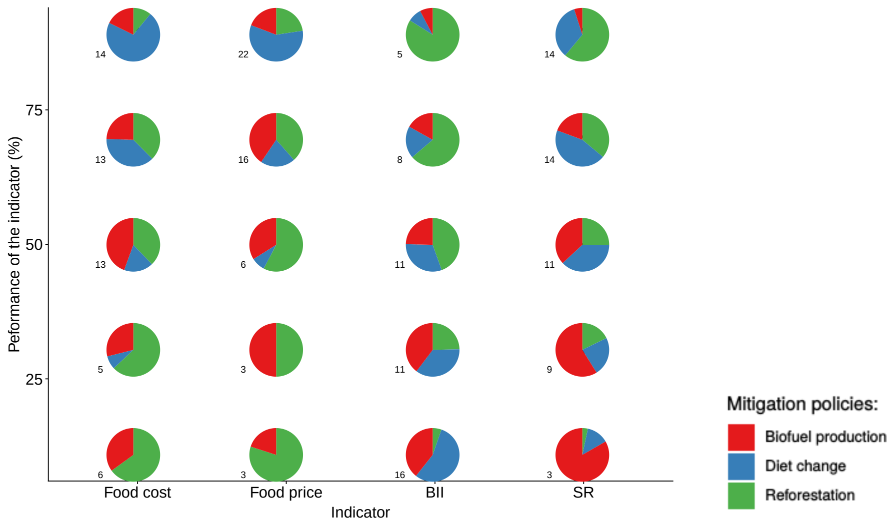

Figure 4: Influence of the distribution of mitigation effort between reforestation, biofuel production and dietary change on biodiversity (SR and BII) and food security (food price and food cost) indicators. Each indicator is linearly rescaled between 0 and 100. We group the mitigation scenarios into quintiles according to their impact on the indicator and calculate for each quintile the average percentage of mitigation achieved by biofuel production, dietary change and reforestation. Because averages are used, it cannot be deduced from this graphic that a mix of mitigation policies is optimal.

the Rest of Latin America (LAM) and Brazil are exceptions as they present a synergetic relationship between SR and food security indicators under mitigation scenarios (Fig.10 and Fig.12 in supporting information). In this case, dietary change is the optimal policy whichever indicator is considered.

However, regional contexts affect the influence of mitigation strategies on the protection of biodiversity and food security. Canada and the Middle-East are subject to limited changes in their biodiversity indicators(Fig.5). Due to the small area 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 (Fig.5). To reduce malnutrition in Africa, the dietary change mitigation scenario consists of increasing consumption of animal products, unlike other regions (See Table.2). This particular dietary change scenario explains the high levels of biodiversity in this region with significant dietary change (Fig.5). Finally, in India, any reduction or increase in pressure on land and the agricultural system through a constraining mitigation policy significantly influences biodiversity and food security (Fig.5).

4 Discussion

4.1 Impacts of mitigation scenarios on biodiversity conservation objectives

The major contribution of this study is to represent not only the impact of mitigation policies on habitats of high ecological value such as "biodiversity hot spots" [Obersteiner et al., 2016] or forests [Humpenöder et al., 2018], but also to represent the impact of agricultural intensification and land use changes within the agricultural sector (conversion of the pastoral system into a mixed path-and-crop system). For example, the inclusion of the impact of agricultural intensification on biodiversity in this study mitigates the BII increase resulting from a reforestation scenario by taking into account the impact of the intensification resulting from this forest scenario [Stevanović et al., 2017]. Also, the reduction in extent of the crop-pasture mix system in favour of the pastoral system in scenarios

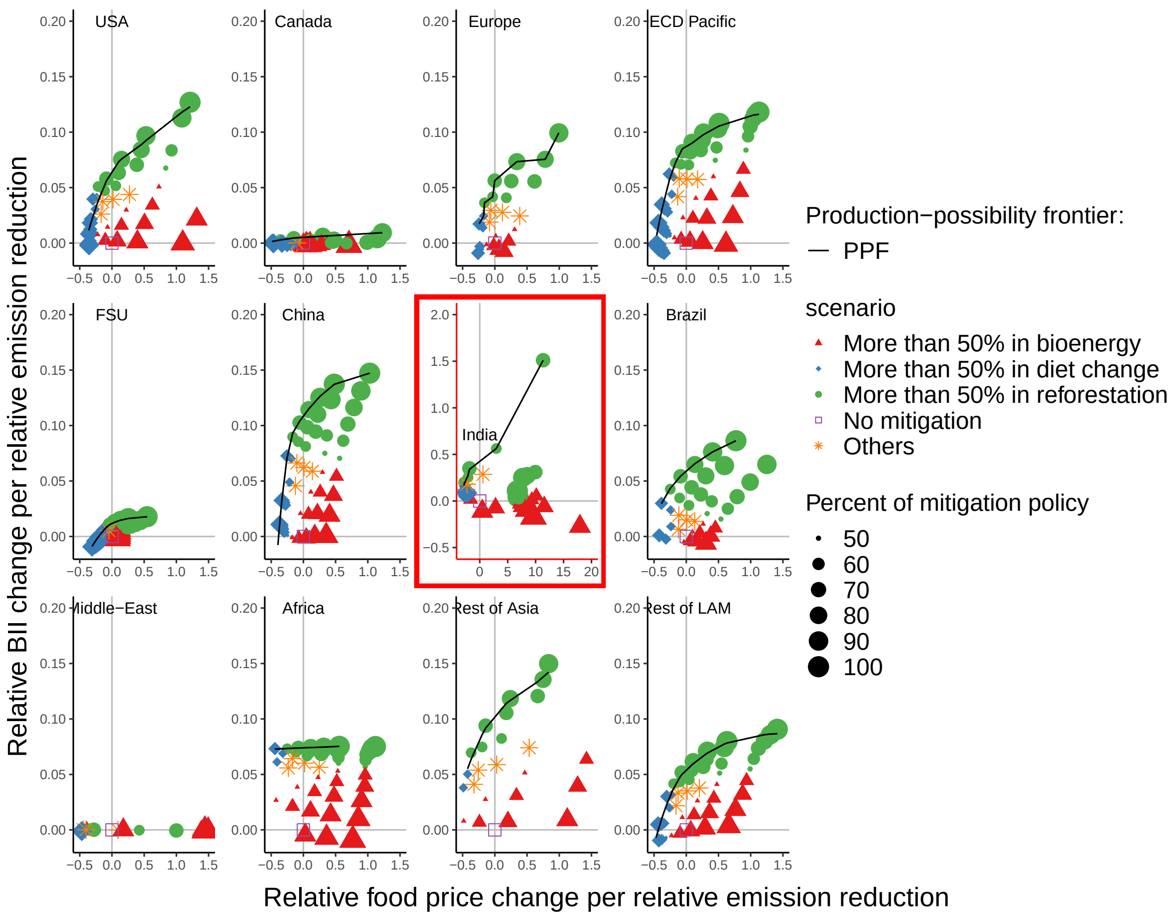

Figure 5: Relative change in BII and food price with respect to relative change in GHG emission reduction at the regional level. This ratio takes into account the different emission changes within a region from one mitigation scenario to another and the unequal distribution of mitigation efforts between regions within a scenario. A relative change in BII of 0.2 therefore indicates that a 10% reduction in regional emissions means a 2% reduction in biodiversity. To compare the regions with each other, a common range is chosen for the axes of each region. An unzoom is provided for India with extreme BII and food indicator change for mitigation scenarios (red rectangle). These indicators are also privided at the global scale in Fig.3. Similar graphs for other biodiversity and food security indicators are provided in supporting information.

of significant dietary change has consequences for biodiversity, as evidenced by the reduction in BII (Fig.3).

Another major interest of this framework is to study the impacts of different land-use-based mitigation scenarios on different biodiversity values: (i) the "naturalness" of ecosystems through the BII and (ii) the "extirpation risk" through the BII and SR according to the classification described by Karp et al. [2015]. By making assumptions about the ecological functions provided by new individuals in non-primary ecosystems, the BII also makes it possible to estimate the risks of loss of ecosystem services previously provided by the replaced biodiversity [Newbold et al., 2016]. Combined with the extinction risk studied by Obersteiner et al. [2016] through global biodiversity hotspots, 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.

In addition, 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 can significantly change the relationship between biodiversity protection and food security [FAO, 2019].

4.2 Trade-off and synergies between food security and biodiversity conservation under mitigation scenarios

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 [Bertram et al., 2018, Humpenöder et al., 2018, Minx et al., 2018, Obersteiner et al., 2016]. For example reforestation of 22% of pasture (70% of the mitigation effort) and a dietary change of 90 kcal/cap/day (30% of the mitigation effort) is the best scenario to minimize the worst criteria among 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 and using that land both for storing carbon and preserving biodiversity [Herrero et al., 2016, Stevanović et al., 2017, Ewers et al., 2018]. 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 compared to Searchinger et al. [2018].

4.3 Regional impacts of mitigation policies on biodiversity and food security

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 without taking into account the equitablity or mitigation cost of this distribution of the mitigation effort. The relationships between biodiversity and food security established in this study could change when these allocation criteria are taken into account. Moreover, the potential for mitigation of emissions, food insecurity and biodiversity loss in the AFOLU sector, although very high [Tubiello et al., 2015, Heck et al., 2018b, Tilman et al., 2017], may not be exploited due to equitability of the allocation of effort or high mitigation costs [van den Berg et al., 2019, Markel et al., 2018, Tilman et al., 2017].

In this study, we show the importance of taking into account the regional context, which strongly nuances the trade-offs between biodiversity protection and food security protection on a global scale. This study should therefore be complemented by other mitigation scenarios that take into account the regional context more specifically, such as 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) [Zhang et al., 2015, Bodirsky et al., 2014] in regions with low NUE such as China or India.

4.4 Scenarios in the policy agenda

In this study, we show the importance of going back and forth between exploratory and target-seeking scenarios to include new objectives as we have done here with biodiversity. In the literature, climate scenarios are currently at the target-seeking scenario stage according to the framework proposed by Pichs-Madruga et al. [2016] while global biodiversity impact scenarios are still exploratory scenarios. Here we do seek to quantify exploratory scenarios without sticking to a cost-efficiency criterion that would lead to choosing the scenario with the lowest implementation cost. This approach allows the assessment of a wider variety of combinations of mitigation policies than optimized mitigation scenarios and does not make implicit assumptions about preferences between biodiversity and food security. For example, the RCP2.6 scenario proposed in Vuuren et al. [2011] implies that an important part of the mitigation effort (equivalent to 181 Ej) is assumed by second-generation biofuel production. The rest of the mitigation effort is shared between dietary change, reforestation and a carbon tax on agricultural emissions. This cost-optimal approach leads to relatively low food prices at the expense of low SR levels (See Fig.4). The negative effect on biodiversity is mainly due to the significant production of second-generation biofuel [Hill et al., 2018, Jantz et al., 2015].

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5 Supporting information

5.1 Indicators

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

- Global food price (\$/Mkcal): The price of food is used here as an indicator of the extent to which global food demand is satisfied by production. This indicator is calculated by taking the output-weighted average of regional prices. There is no price equalization across regions in NLU because trade rigidities constrain the regional supply.
- Crop production cost per unit of food energy produced: food production costs include (i) fertilizer and pesticides which are substitutable to land according to relative prices and (ii) labor and capital (excluding fertilizer and pesticides) which are complementary inputs for each hectare of land.
- Species richness: We focus on species richness because of its wide use and easy interpretation. Local species richness is calculated by projecting a model linking the intensity and the different land-uses onto a world map ($0.5° \times 0.5°$ grid cell) with this indicator (see Table.1 for a presentation of the coefficients of the model). The species richness model is based on between-site comparisons of ecological assemblage composition collated from the literature as part of the PREDICTS project (Hudson et al. [2014]). Random effects in PREDICTSś models accounted for study-level differences in response variables and sampling methods, and for the within-study spatial arrangement of sites.
- Biodiversity intactness index (BII): As defined in Newbold et al. [2015], the BII-abundance indicator results from the multiplication of abundance by the change in composition due to change in land uses and the change in intensity of these uses. It allows us to take into account the effects of human activities on the replacement of original species by newcomers [Dornelas et al., 2014]

5.2 Mitigation scenarios

5.2.1 Definition of the mitigation effort

The mitigation effort provided by a mitigation policy (reforestation, dietary change or second-generation biofuel production) is the proportion of emissions mitigated by that policy. The sum of the mitigation efforts of the 3 policies in a scenario is therefore 100% by addition. These mitigation policies interact with each other within the food system when implemented simultaneously. The attribution of given mitigated emissions to one specific mitigation policy is therefore not straightforward. For example, second-generation biofuel production increases the pressure on the food system through an increase in the area under cultivation and an increase in yield [Brunelle et al., 2015]. The simultaneous deployment of a pasture reforestation policy also increases the pressure on the agricultural system, which is also reflected in an increase in yields. The attribution of emissions to different mitigation policies (reforestation, dietary change or second-generation biofuel production) is therefore carried out ex-post.

First, we calculate the emission mitigation factor per unit of forest area introduced ($\mathrm{EA}_{f,0}$), per unit of second-generation biofuel energy produced ($\mathrm{EA}_{b,0}$) and per unit of substituted annual product ($\mathrm{EA}_{d,0}$) for the reforestation scenarios of 31% pasture (Forest_0), 112 EJ second-generation biofuel production ($\mathrm{Biofuel}_0$) and change in diet (-301 kcal/cap/day global average of animal products (Diet_0). These 3 scenarios make it possible to achieve 4.3 $GtCO_2$ of attenuated emissions in 2100 with reforestation, second-generation biofuel production and dietary change respectively.

Then, for mitigation scenarios mixing the 3 policies (involving a dietary change of Diet_i, second-generation biofuel production of $\mathrm{Biofuel}_i$ and reforestation of Forest_i), we apply these mitigation factors to each of the policies to calculate theoretical mitigated emissions without interaction between the policies:

$$E_{Tot,theoretical} = EA_{f,0} \times Forest_i \tag{18}$$
$$+ EA_{b,0} \times Biofuel_i \tag{19}$$
$$+ EA_{d,0} \times Diet_i \tag{20}$$
$$\tag{21}$$

Because of the interactions between these mitigation policies, $E_{Total,theoretical}$ is different to the emissions mitigated by the policy mix scenario calculated by the NLU $E_{Total,NLU}$. In the policy mix scenario, mitigated emissions result from mitigation efforts related to reforestation ($Effort_{Forest}$), second-generation biofuel production ($Effort_{Biofuel}$) and diet change ($Effort_{Diet}$) as follows:

$$E_{Tot,NLU} = \frac{E_{Tot,NLU}}{E_{Tot,theoretical}}(EA_{f,0} \times Forest_i \tag{22}$$
$$+ EA_{b,0} \times Biofuel_i \tag{23}$$
$$+ EA_{d,0} \times Diet_i) \tag{24}$$

We deduce the efforts related to reforestation ($Effort_{Forest}$), second-generation biofuel production ($Effort_{Biofuel}$) and dietary change ($Effort_{Diet}$):

$$Effort_{Forest} = \frac{E_{Tot,NLU}}{E_{Tot,theoretical}} EA_{f,0} \times Forest_i \times \frac{1}{E_{Tot,NLU}} \tag{25}$$
$$= \frac{E_{Tot,NLU}}{E_{Tot,theoretical}} \frac{\frac{E_{Tot,NLU}}{Forest_0} \times Forest_i}{E_{Tot,NLU}} \tag{26}$$
$$= \frac{E_{Tot,NLU}}{E_{Tot,theoretical}} \frac{Forest_i}{Forest_0} \tag{27}$$
$$Effort_{Biofuel} = \frac{\frac{E_{Tot,NLU}}{E_{Tot,theoretical}} EA_{b,0} \times Biofuel_i}{E_{Tot,NLU}} \tag{28}$$
$$= \frac{E_{Tot,NLU}}{E_{Tot,theoretical}} \frac{Biofuel_i}{Biofuel_0} \tag{29}$$
$$Effort_{Diet} = \frac{\frac{E_{Tot,NLU}}{E_{Tot,theoretical}} EA_{d,0} \times Diet_i}{E_{Tot,NLU}} \tag{30}$$
$$= \frac{E_{Tot,NLU}}{E_{Tot,theoretical}} \frac{Diet_i}{Diet_0} \tag{31}$$

Through this formalization, we hypothesize that mitigation policies mitigate emissions linearly according to the mitigation factors $EA_{f,0}$,$EA_{d,0}$ and $EA_{b,0}$ for reforestation, dietary change and second-generation biofuel production respectively. This assumption is corrected by the ratio $\frac{E_{Tot,NLU}}{E_{Tot,theoretical}}$ which changes in the different scenarios to obtain 4.3 $GtCO_2$ of mitigated emissions in 2100. Finally only scenarios that mitigate 4.3 $GtCO_2$ ($\pm 5\%$) are retained.

5.2.2 Complete factorial experiment

The scenario sampling plan defines which scenarios will be simulated. The type of sampling is important to avoid biased sampling. For this reason we chose to sample using a complete factorial plan that avoids scenario sampling bias.

A complete factorial plan consists of sampling scenarios defined by several variables (here reforestation effort, dietary change effort and second-generation biofuel production effort) on a regular basis throughout the set of values taken by these variables. In this plan, the efforts of each of three mitigation policies therefore take values between 0% and 100% in 10% steps with the constraint that the sum of hte efforts must be equal to 100%.

In the following sections, we define how scenarios are built when 100% of the mitigation effort is provided by a single mitigation policy (reforestation, dietary change or second-generation biofuel production).

5.2.3 Dietary change scenario

The mitigation scenario composed exclusively of a dietary change (called here DC) is inspired by the Agrimonde scenario called AG1 [Paillard et al., 2011] which aims to describe a sustainable diet. We modified the plant, ruminant and monogastric demand of AG1 to reach the 4.3GtCO$_{2,eq}$ mitigated emissions target by substituting plant food calories (low emission intensive product) for ruminant calories (intensive emissions product). This substitution occurs in the same proportion in all regions unless a lower limit of ruminant consumption of 65 kcal/cap/day is reached (as in Africa in the DC scenario). In that case, ruminant calorie substitution continues in other regions (excluding Africa) until 4.3 GtCO$_{2,eq}$ of mitigated emissions are achieved. DC scenario regional diets are presented in Table.2.

Table 2: Regional diet in 2050 (kcal/cap/day)

	Baseline				DC[1]			
Regions	Plant Food	Ruminant*	Monogastric	Aquatic[2]	Plant Food	Ruminant[3]	Monogastric[3]	Aquatic[2][3]
Africa	2586	111	27	-	2564	65	350	21
Brazil	2466	382	331	-	2568	183	253	42
Canada	2543	516	389	-	2568	183	200	49
China	2682	161	334	-	2568	91	253	88
Europe	2543	516	389	-	2568	183	200	49
FSU	2543	516	389	-	2568	183	212	37
India	2517	230	64	-	2568	91	253	88
Middle-East	2837	274	74	-	2568	154	207	40
OECD Pacific	2543	516	389	-	2568	183	200	49
Rest of Asia	2682	161	334	-	2568	91	253	88
Rest of LAM	2466	382	331	-	2568	183	207	42
USA	2543	516	389	-	2568	183	200	49

[1] DC is a diet based on AG1 and modified to achieve 4.3GtCO$_2$/year in 2100

[2] Aquatic products are not computed by NLU

[3] Sum of aquatic, ruminant and mongastric products is 432kcal/cap/day in all regions

In mitigation scenarios composed of a change in diet mixed with reforestation and production of second generation biofuel, we take intermediate diets between the DC and the FAO diet used in the baseline [Alexandratos and Bruinsma, 2012]. In these intermediate diets, the consumption of monogastric and aquatic products is set to those of the DC diet and the consumption of ruminant and plant products are linear interpolations between the respective consumptions of DC and FAO.

The diets in the scenarios change between 2020 and 2050. Between 2001 and 2020, actual trends are used [Alexandratos and Bruinsma, 2012] and between 2050 and 2100, the diets are kept constant.

5.2.4 Second-generation biofuel scenario

Ligno-cellulosic biofuels are produced in NLU from dedicated energy crops (woody or grassy crops). Dedicated energy crops correspond to short rotation coppice such as eucalyptus, willow or poplar and grasses such as miscanthus or switchgrass. The increase in second-generation biofuel production is linear between 2005 and 2100.

A global yield of 230GJ/ha in 2020, rising to 340GJ/ha (or 72Mkcal/ha) in 2050, is assumed for dedicated energy crops based on our literature review cross-checked with experts' views. This value is then distributed regionally based on the land distribution of potential yield used in NLU (see Souty et al. [2012]).

Energy crops are allocated homogeneously over the different categories of land quality. They expand over agricultural areas without affecting forested land. In so doing they increase the scarcity of agricultural land and spur intensification of crop and livestock production. In the scenario with only biofuel production to mitigate 4.3 $GtCO_2$, 112 EJ are produced worlwide.

Emissions from biofuel fertilization and from conversion of pasture to cropland are computed based respectively on emissions from crop fertilization as described in Tier 1 of IPCC [2006] and emissions from land-use change as described in Le Quéré et al. [2009]. With a global yield of 230 GJ/ha, a NUE of 0.5, a fertilization rate of 93 kgN/ha and an emission factor of 0.03 $kgCO_{2,eq}$/kgN, we deduce an emission factor of 6 g CO_2/MJ due to biofuel fertilization. Emissions saved due to the use of biofuel instead of fossil fuel are also computed. First, we convert primary energy included in grassy and woody crops into energy included in biofuel after refining with a coefficient of 0.481 MJ/MJ. We made the assumption that biofuel is used in the transport sector instead of a mix of diesel (50%) and ethanol (50%) with an emission factor of 87.85 gCO_2/MJ [Hoogwijk et al., 2009]. Finally we removed emissions produced during refining (0.6 gCO2/MJ) and transport to the refinery (0.6 gCO_2/MJ) [Hoogwijk et al., 2009]. The final emission coefficient is 41 gCO2/MJ of saved emissions per MJ of biofuel minus 6 gCO_2/MJ due to biofuel fertilization. By computing the difference betwenn fossil fuel emissions of 86 gCO_2/MJ [Hoogwijk et al., 2009] and emissions from second-generation biofuel production between 26 and 65 gCO_2/MJ Jungbluth et al. [2008], our estimation of saved emissions due to the production of second-generation biofuel instead of fossil fuel (35 gCO2/MJ) is in the middle of the range 21-60 gCO_2/MJ. By taking into account uncertainty around this coefficient, more pessimistic assumptions about the mitigation potential of second-generation biofuel would lead to worse impacts on biodiversity and food prices in NLU due to the requirement to produce a higher amount of biofuel in order to mitigate 4.3 $GtCO_{2,eq}$ and vice-versa. Use of carbon capture and storage, or use of co-production in bioelectricity production could improve the mitigation potential of second-generation biofuel [Whitaker et al., 2010] and reduce its negative impacts on biodiversity and food prices.

5.2.5 Forest scenario

The forest scenario used as a baseline is the continuation of current trends until 2050 and a stabilization of forest areas after 2050. The alternative scenario is inspired by the reforestation scenario in the Natural Climate Solution presented in [Griscom et al., 2017]. In this scenario, forest lands expand at the expense of pastures to reach the climate target. The distribution of the reforested area between regions is therefore proportional to the area of pasture present in each region.

The area of forest follows historical trends between 2001 and 2020. The increase in forest area at the expense of pasture occurs between 2020 and 2100.

5.3 Scenario sampling plan

In this section, we present a set of policies allowing us to reach 2° by making the necessary mitigations in the AFOLU sector. The experimental design follows a complete factorial design to address a wide range of adequate mitigation scenarios.

The holes in the complete factorial design correspond to scenarios that do not mitigate 4.3 $GtCO_2$ with a 5% error.

Table 3: Regional reforestation rate in 2020 and 2050. A negative reforestation rate indicates deforestation.

	Baseline		Reforestation	
Regions	Reforestation rate (%)	Forest change (Mha)	Reforestation rate (%)	Forest change (Mha)
Africa	-0.032	-11.042	0.213	71.409
Brazil	-0.029	-13.471	0.021	9.393
Canada	-0.001	-0.526	0.002	1.318
China	0.086	13.824	0.290	44.767
Europe	0.029	3.642	0.101	12.244
FSU	0.005	4.215	0.052	43.241
India	0.044	1.284	0.085	2.388
Middle-East[1]	0.000	0.000	0.000	0.000
OECD Pacific	-0.022	-1.353	0.464	27.650
Rest of Asia	-0.016	-5.616	0.041	14.094
Rest of LAM	-0.027	-9.586	0.082	28.343
USA	0.011	2.973	0.106	27.167

[1] In [Hurtt et al., 2011], there is no forest in the Middle-East in the reference year

5.4 Results

Biodiversity indicators and food indicators relations at global scale

5.4.1 Relationships between biodiversity indicators and food indicators at the regional scale

5.4.2 Mitigation scenarios

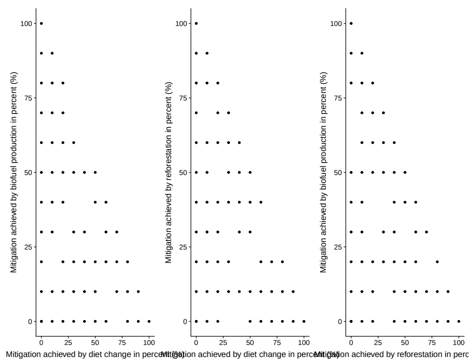

Figure 6: Complete factorial design to address a wide range of mitigation scenarios

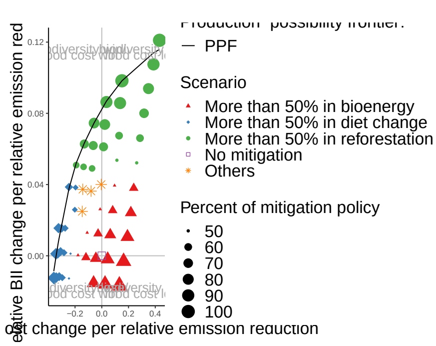

Figure 7: Impacts of mitigation scenarios reaching 4.3 $GtCO_{2_{eq}}$ in 2100 of mitigated emissions based on combinations of second-generation biofuel production, dietary change and reforestation on global BII average and global food production cost. BII and food production cost are presented as a relative difference to the scenario without any mitigation policy (baseline). The mitigation effort of each policy (second-generation biofuel production, dietary change and reforestation) is expressed in the legend as a percentage of the overall mitigation effort.

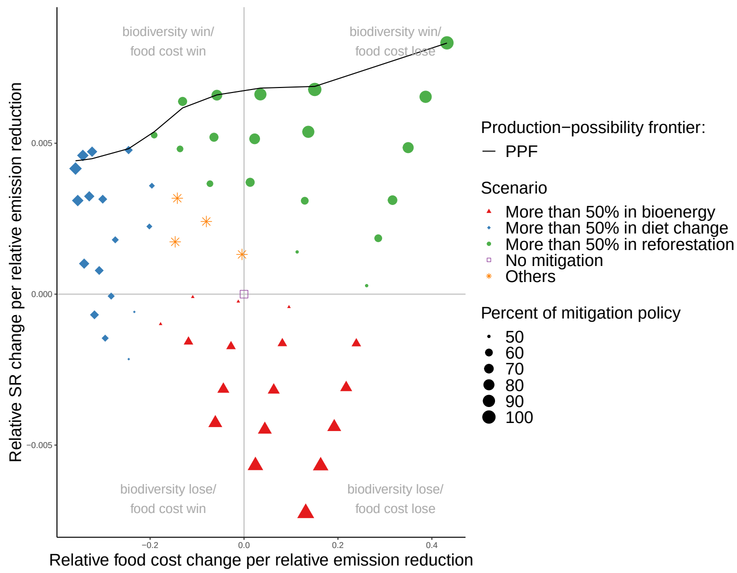

Figure 8: Impacts of mitigation scenarios reaching 4.3 $GtCO_{2_{eq}}$ in 2100 of mitigated emissions based on combinations of second-generation biofuel production, dietary change and reforestation on global SR average and global food production cost. SR and food production cost are presented as a relative difference to the scenario without any mitigation policy (baseline). The mitigation effort of each policy (second-generation biofuel production, dietary change and reforestation) is expressed in the legend as a percentage of the overall mitigation effort.

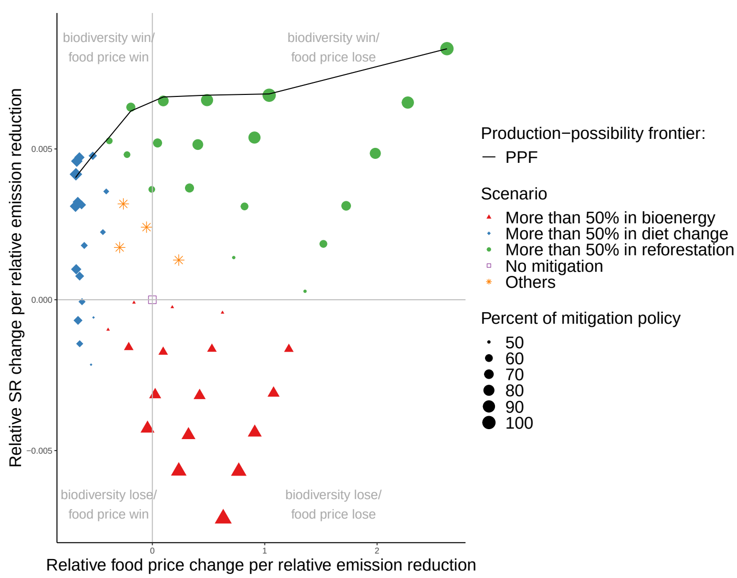

Figure 9: Impacts of mitigation scenarios reaching 4.3 $GtCO_{2_{eq}}$ in 2100 of mitigated emissions based on combinations of second-generation biofuel production, dietary change and reforestation on global SR average and global food price. SR and global food price are presented as a relative difference to the scenario without any mitigation policy (baseline). The mitigation effort of each policy (second-generation biofuel production, dietary change and reforestation) is expressed in the legend as a percentage of the overall mitigation effort.

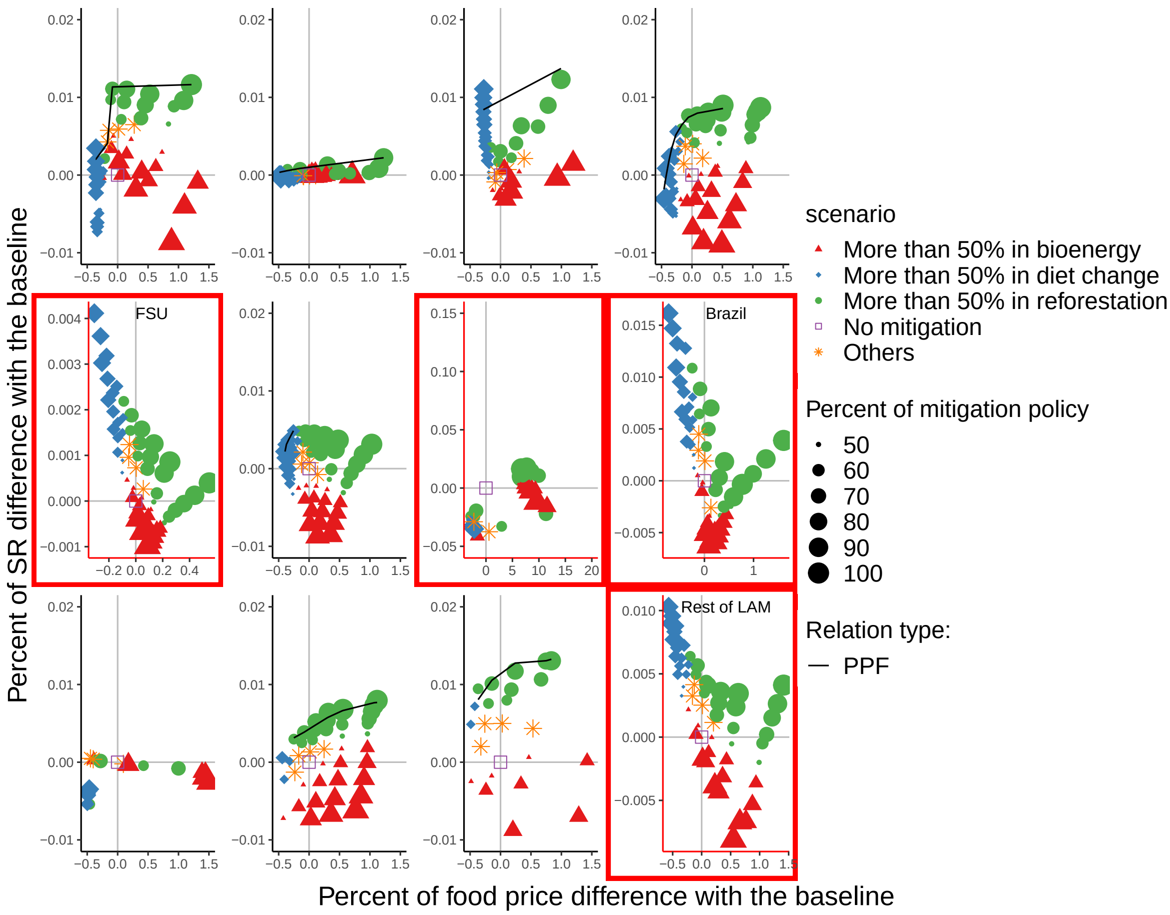

Figure 10: Relative change in SR and food price with respect to relative change in GHG emission reduction at the regional level. This ratio takes into account the different emission changes within a region from one mitigation scenario to another and the unequal distribution of mitigation efforts between regions within a scenario. A relative change in the SR of 0.2 therefore indicates that a 10% reduction in regional emissions means a 2% reduction in biodiversity. To compare the regions with each other, a common range is chosen for the axes of each region. An unzoom is provided for FSU, India, Brazil and Rest of LAM with extreme BII and food indicator change for mitigation scenarios (red rectangles).

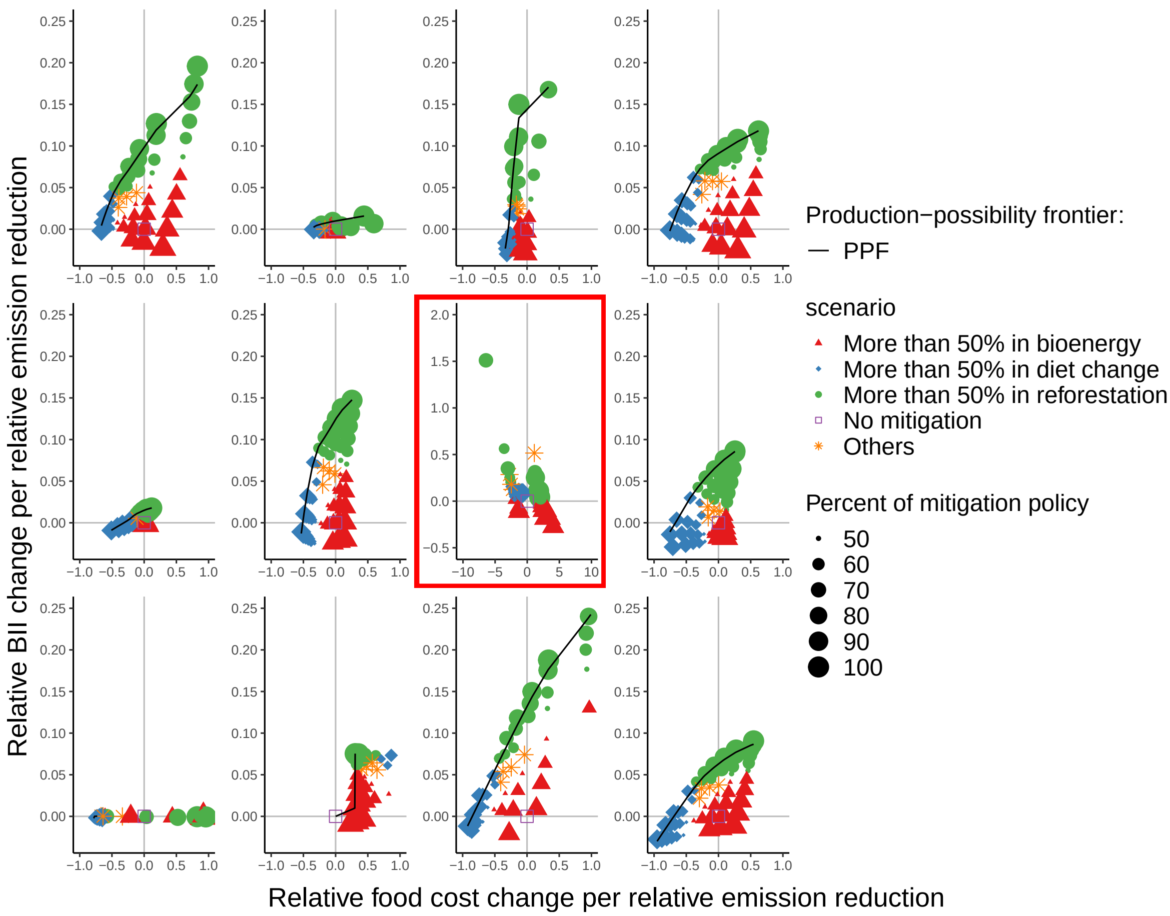

Figure 11: Relative change in BII and food cost with respect to relative change in GHG emission reduction at the regional level. This ratio allows takes into account the different emission changes within a region from one mitigation scenario to another and the unequal distribution of mitigation efforts between regions within a scenario. A relative change in the BII of 0.2 therefore indicates that a 10% reduction in regional emissions means a 2% reduction in biodiversity. To compare the regions with each other, a common range is chosen for the axes of each region. An unzoom is provided for India with extreme BII and food indicator change for mitigation scenarios (red rectangle).

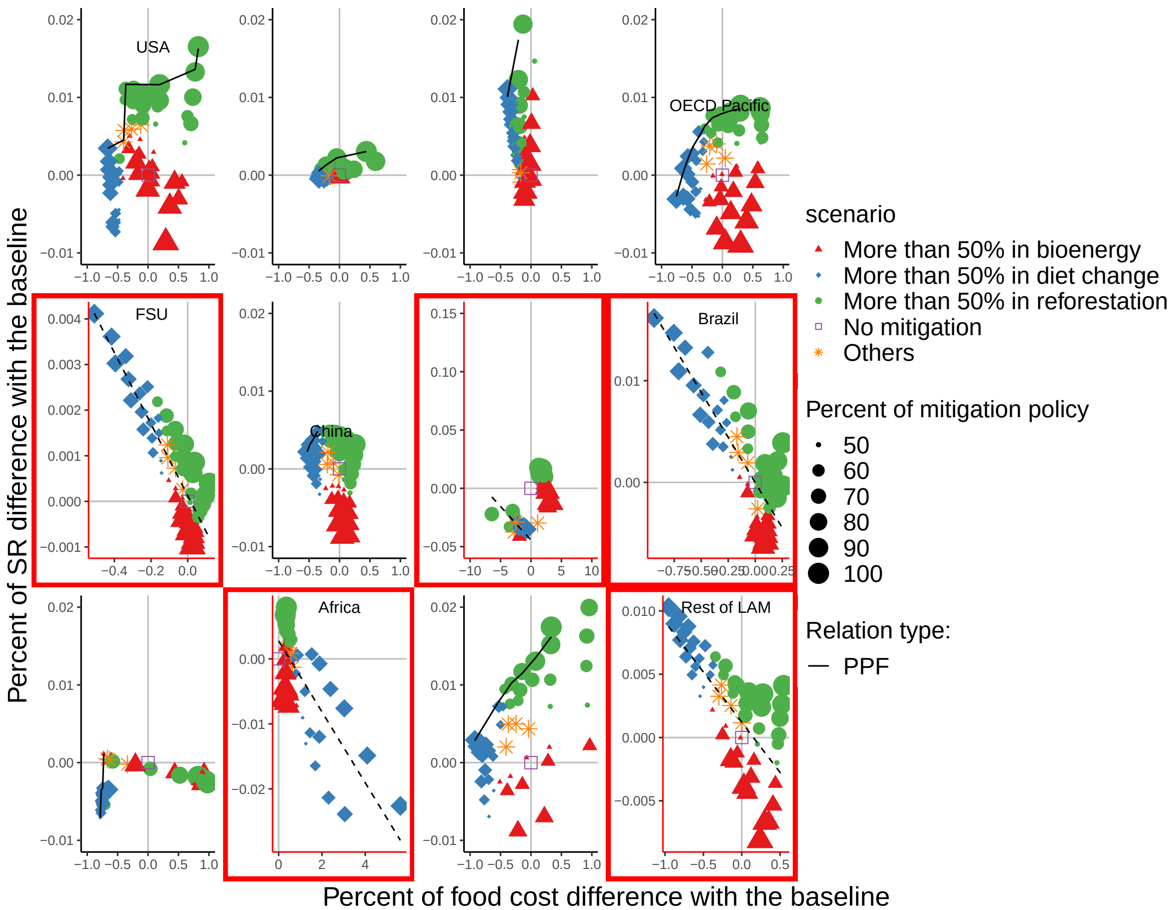

Figure 12: Relative change in SR and food production cost with respect to relative change in GHG emission reduction at the regional level. This ratio takes into account the different emission changes within a region from one mitigation scenario to another and the unequal distribution of mitigation efforts between regions within a scenario. A relative change in the SR of 0.2 therefore indicates that a 10% reduction in regional emissions means a 2% reduction in biodiversity. To compare the regions with each other, a common range is chosen for the axes of each region. An unzoom is provided for FSU, India, Brazil and Rest of LAM with extreme BII and food indicator change for mitigation scenarios (red rectangles).

Table 4: Global food security and biodiversity indicators for the sampled mitigation scenarios in 2100. Indicators are rescaled between 0 and 100 for each indicator. 0 means a high price, a high cost, low BII and a low SR. On the contrary, 100 means a low price, a low production cost, a high SR and high BII. Scenarios are described by the mitigation effort (in %) of second-generation biofuel production, reforestation of pasture and dietary change.

Scenario			Food Cost ($/Mk-cal)	Food Price ($/Mk-cal)	BII	SR
Biofuel*	Forest*	Diet*				
40	40	20	4197	85.2	0.831	2.54
30	40	30	4098	78.1	0.830	2.54
60	10	30	4049	74.2	0.820	2.53
0	100	0	4766	143.9	0.851	2.54
80	20	0	4453	101.8	0.823	2.53
50	40	10	4328	94.7	0.830	2.53
90	10	0	4415	98.3	0.820	2.53
30	0	70	3788	63.1	0.817	2.53
100	0	0	4374	94.9	0.816	2.53
10	90	0	4707	135.3	0.848	2.54
20	10	70	3801	63.5	0.821	2.53
30	30	40	4012	72.2	0.827	2.54
20	0	80	3759	62.7	0.817	2.54
0	50	50	3953	70.0	0.833	2.54
80	10	10	4261	87.3	0.820	2.53
10	10	80	3773	63.1	0.821	2.54
50	20	30	4061	75.4	0.824	2.53
50	30	20	4187	83.8	0.827	2.53
20	80	0	4658	128.2	0.844	2.54
20	50	30	4108	79.3	0.833	2.54
0	80	20	4248	91.4	0.842	2.54
90	0	10	4234	85.2	0.816	2.53
10	60	30	4119	80.5	0.836	2.54
10	70	20	4232	89.3	0.839	2.54
60	20	20	4167	81.8	0.824	2.53
30	10	60	3834	64.0	0.821	2.53
70	10	20	4145	80.0	0.820	2.53
80	0	20	4123	78.3	0.817	2.53
0	60	40	4032	74.7	0.836	2.54
0	70	30	4127	81.8	0.839	2.54
10	20	70	3811	63.9	0.824	2.54
40	50	10	4350	97.2	0.834	2.54
0	10	90	3756	62.8	0.821	2.54
10	0	90	3741	62.6	0.817	2.54
0	40	60	3882	66.3	0.830	2.54
20	60	20	4220	87.5	0.836	2.54
20	20	60	3845	64.5	0.824	2.54
50	50	0	4543	112.8	0.834	2.53
0	90	10	4399	105.0	0.845	2.54
20	30	50	3940	68.6	0.827	2.54
60	40	0	4514	109.3	0.830	2.53
30	70	0	4615	121.8	0.841	2.54
70	30	0	4486	105.9	0.827	2.53

10	50	40	4025	73.8	0.833	2.54
30	60	10	4371	99.6	0.838	2.54
70	20	10	4285	89.7	0.823	2.53
40	0	60	3818	63.5	0.817	2.53
60	30	10	4309	92.4	0.827	2.53
10	40	50	3947	69.3	0.830	2.54
50	10	40	3971	69.7	0.821	2.53
0	20	80	3781	63.4	0.824	2.54
0	0	100	3735	62.6	0.817	2.54
40	10	50	3898	66.5	0.821	2.53
20	40	40	4018	73.0	0.830	2.54
50	0	50	3883	66.0	0.817	2.53
10	80	10	4381	101.7	0.842	2.54
40	60	0	4575	116.8	0.837	2.54
0	0	0	4203	79.4	0.820	2.53