



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

Rémi Prudhomme, Adriana De Palma, Patrice Dumas, Ricardo Gonzalez, Paul Leadley, Harold Levrel, Andy Purvis, Thierry Brunelle

► To cite this version:

Rémi Prudhomme, Adriana De Palma, Patrice Dumas, Ricardo Gonzalez, Paul Leadley, et al.. Combining mitigation strategies to increase co-benefits for biodiversity and food security. *Environmental Research Letters*, 2020, 15 (11), pp.114005. 10.1088/1748-9326/abb10a . hal-03206590

HAL Id: hal-03206590

<https://hal.science/hal-03206590v1>

Submitted on 21 Feb 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

ACCEPTED MANUSCRIPT • OPEN ACCESS

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

To cite this article before publication: Rémi Prudhomme *et al* 2020 *Environ. Res. Lett.* in press <https://doi.org/10.1088/1748-9326/abb10a>

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is © 2020 The Author(s). Published by IOP Publishing Ltd.

As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 3.0 licence, this Accepted Manuscript is available for reuse under a CC BY 3.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence <https://creativecommons.org/licenses/by/3.0>

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the [article online](#) for updates and enhancements.

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

Rémi Prudhomme^{1,2}, Adriana De Palma³, Patrice Dumas¹, Ricardo Gonzalez^{3,4}, Paul Leadley², Harold Levrel¹, Andy Purvis^{3,4}, and Thierry Brunelle¹

¹ CIRED, AgroParisTech, CNRS, Ecole de Ponts ParisTech, CIRAD, EHESS, Université Paris-Saclay, 94130, Nogent-sur-Marne, France

² Ecologie Systématique Evolution, Université Paris-Saclay, CNRS, AgroParisTech, 91405 Orsay, France

³ Department of Life Sciences, Natural History Museum, Cromwell Road, London SW7 5BD, UK

⁴ Department of Life Sciences, Imperial College London, Silwood Park, Berkshire SL5 7PY, UK

E-mail : prudhomme@centre-cired.fr

Received xxxxxx

Accepted for publication xxxxxx

Published xxxxxx

Length:4143

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.

Keywords: Mitigation, Global scale, Land-use, Trade-off, Dietary change, Reforestation, Bioenergy, Food security, Biodiversity

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 (Humpenöder *et al* 2018, Obersteiner *et al* 2016, Visconti *et al* 2016).

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 supporting information). 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 supporting information). 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 supporting information Table 2. 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 supporting information. 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 supporting information). 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 (Section 8 and 9 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% (Section 8 in supporting information).

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 (Section 6 in supporting information 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 Nexus Land-Use model (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 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 supporting information.

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 (CH₄ and N₂O) and enteric fermentation (CH₄) are computed. In the plant food sector, emissions from fertilization (N₂O) and rice cultivation (CH₄) are computed. Carbon dioxide (CO₂) 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 supporting information).

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 supporting information). 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 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.

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 supporting information, Fig. 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 supporting information).

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 supporting information, Fig. 8).

2.2.5 Baseline scenario. The population follows changes in the Shared Socio-economic 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 supporting information).

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 Fig.11 in supporting information), 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 supporting information, Table 2), and pasture reforestation ranging from 0% to 31% (see supporting information, Table 3).

To achieve 4.3 GtCO_{2,eq}/year of mitigated emissions by means of dietary change, we replace the consumption

Journal **XX** (XXXX) XXXXXX

Author *et al*

1

2

3 of animal products by plant products in the Agrimonde

4 scenarios called AG1 (Paillard *et al* 2014). This leads to

5 a convergence of the overall animal consumption

6 towards 432 kcal/capita/day in all regions. The

7 consumption of ruminant products obtained is 183

8 kcal/capita/year in 2050 for Brazil, Canada, Europe,

9 USA, FSU, OECD Pacific and Rest of LAM, 91

10 kcal/capita/year in 2050 for India, Rest of Asia and

11 China, 154 kcal/capita/year for Middle-East and 65

12 kcal/capita/year for Africa (Section 10.1 in supporting

13 information). The rest of animal product consumption

14 (in the 432 kcal/capita/day) is composed of

15 monogastric and aquatic products (See supporting

16 information, Table 2).

17

18

19

20

21 The reforestation scenario follows the same philosophy

22 as the natural climate solutions reforestation scenario

23 presented in (Griscom *et al* 2017) by reforesting

24 pastures (Section 10.3 in supporting information). The

25 31 % of pastures reforested in the world corresponds to

26 the reforestation of 186 Mha with a carbon

27 sequestration of 23 tCO₂/ha in global average (See

28 Table 5 in supporting information). This reforestation

29 area is in the lower range of afforestation potential in

30 baseline (Intergovernmental Panel on Climate Change

31 2014) (See supporting information for more details

32 about the regional distribution, Table 3).

33

34

35

36 The second-generation biofuel production of 112 EJ is

37 coherent with the literature that agrees on a technical

38 bioenergy potential of at least 100EJ (Edenhofer *et al*

39 2011, Creutzig *et al* 2015). To limit the competition of

40 the biofuel production with food, second-generation

41 biofuels in the scenarios are deployed in the form of

42 grassy crops in Europe and the USA, and in the form of

43 woody crops in the rest of the world (Section 10.2 in

44 supporting information).

45

46

47 **2.2.7. Indicators of food security and biodiversity.** We

48 use four indicators to represent impacts of mitigation

49 policies on biodiversity and food security:

50

51 - Global food price (\$/Mkcal) (Section 6 in supporting

52 information).

53

54 - Crop production cost per unit of food energy produced

55 (\$/Mkcal) (Section 6 in supporting information)

56

57

58

59

60

- Species richness (Section 2.2.3 in the method section)

- Biodiversity intactness index (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 reduction objective compatible with 2 degrees of global warming (Fig. 1 and see supporting information 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 supporting information.

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 (Fig. 1 and see supporting information 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 (supporting information Fig. 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 Fig. 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 (supporting information Fig. 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 (Fig. 1 and supporting information Fig. 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 the pasture area without any influence on forest area (Section 12.3 in supporting information). 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.

[Insert Figure 1 here (See Figure section after the reference section)]

Figure 1. Impacts of mitigation scenarios achieving 4.3 GtCO_{2,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 biodiversity intactness index (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 GtCO_{2,eq} in 2100) by around 4.3 GtCO_{2,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.

[Insert Figure 2 here (See Figure section after the reference section)]

Figure 2. Impacts of mitigation scenarios reaching 4.3 GtCO_{2,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 Species Richness (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 Fig. 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 supporting information.

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 Fig. 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 (Fig. 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 Fig. 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 (Fig. 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 (Fig. 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.

[Insert Figure 3 here (See Figure section after the reference section)]

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 biodiversity intactness index (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 Fig. 1. Similar graphs for other biodiversity and food security indicators are provided in supporting information

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 (Fig. 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 (Section 11 of the supporting information 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 (Humpenöder *et al* 2018, Obersteiner *et al* 2016, 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 (Stevanović *et al* 2017, Herrero *et al* 2016, Ewers *et al* 2009). 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 (Heck *et al* 2018b, Tubiello *et al* 2015, Tilman *et al* 2017), may not be exploited due to equitability of the allocation of effort or high mitigation costs (Tilman *et al* 2017, van den Berg *et al* 2019, Markel *et al* 2018).

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) (Zhang *et al* 2015, Bodirsky *et al* 2014) 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 EJ) 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 (Hill

et al 2018, Jantz et al 2015). 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.

Acknowledgements

This work was supported by a doctoral school ABIES grant (provided by AgroParistech). This article has also benefited from the support of the LabEx BASC (ANR-11-LABX-0034), the Long-term modelling chair for sustainable development (Ponts Paristech-Mines Paristech) funded by ADEME, Grt-Gaz, Schneider Electric, EDF, French Environment Ministry, the aid from the French state managed by the ANR under the "Investissements d'avenir" programme (ANR-16-CONV-0003) and the funding by the NERC (award NE/M014533/1).

References

- Alexandratos N and Bruinsma J 2012a *World agriculture towards 2030/2050: the 2012 revision* (ESA Working paper FAO, Rome)
- Alexandratos N and Bruinsma J 2012b *World agriculture towards 2030/2050: the 2012 revision* (ESA Working paper FAO, Rome)
- van den Berg N J, van Soest H L, Hof A F, den Elzen M G J, van Vuuren D P, Chen W, Drouet L, Emmerling J, Fujimori S, Höhne N, Köberle A C, McCollum D, Schaeffer R, Shekhar S, Vishwanathan S S, Vrontisi Z and Blok K 2019 Implications of various effort-sharing approaches for national carbon budgets and emission pathways *Climatic Change* Online: <https://doi.org/10.1007/s10584-019-02368-y>
- Bertram C, Luderer G, Popp A, Minx J C, Lamb W F, Stevanović M, Humpenöder F, Giannousakis A and Kriegler E 2018 Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios *Environ. Res. Lett.* **13** 064038
- Bodirsky B L, Popp A, Lotze-Campen H, Dietrich J P, Rolinski S, Weindl I, Schmitz C, Müller C, Bonsch M, Humpenöder F, Biewald A and Stevanovic M 2014 Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution *Nature Communications* **5** 3858
- Brunelle T, Dumas P, Souty F, Dorin B and Nadaud F 2015 Evaluating the impact of rising fertilizer prices on crop yields *Agricultural Economics* **46** 653–66
- Commission on Genetic Resources for Food and Agriculture and Food and Agriculture Organization of the United Nations 2019 *The state of the world's biodiversity for food and agriculture*.
- Creutzig F, Ravindranath N H, Berndes G, Bolwig S, Bright R, Cherubini F, Chum H, Corbera E, Delucchi M, Faaij A, Fargione J, Haberl H, Heath G, Lucon O, Plevin R, Popp A, Robledo-Abad C, Rose S, Smith P, Stromman A, Suh S and Masera O 2015 Bioenergy and climate change mitigation: an assessment *GCB Bioenergy* **7** 916–44
- De Palma A, Sanchez-Ortiz K and Purvis A 2019 *Calculating the Biodiversity Intactness Index: the PREDICTS implementation* (Zenodo) Online: <https://zenodo.org/record/3518067#.XuOau6bgrIU>
- Díaz S, Settele J, Brondízio E S, Ngo H T, Agard J, Arneth A, Balvanera P, Brauman K A, Butchart S H M, Chan K M A, Garibaldi L A, Ichii K, Liu J, Subramanian S M, Midgley G F, Miloslavich P, Molnár Z, Obura D, Pfaff A, Polasky S, Purvis A, Razzaque J, Reyers B, Chowdhury R R, Shin Y-J, Visseren-Hamakers I, Willis K J and Zayas C N 2019 Pervasive human-driven decline of life on Earth points to the need for transformative change *Science* **366** Online: <https://science.sciencemag.org/content/366/6471/eaax3100>

- Edenhofer O, Madrugá R P, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S and Stechow C 2011 Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change* 1–1075
- Ewers R M, Scharlemann J P, Balmford A and Green R E 2009 Do increases in agricultural yield spare land for nature? *Global Change Biology* **15** 1716–26
- Gidden M J, Riahi K, Smith S J, Fujimori S, Luderer G, Kriegler E, van Vuuren D P, van den Berg M, Feng L, Klein D, Calvin K, Doelman J C, Frank S, Fricko O, Harmsen M, Hasegawa T, Havlik P, Hilaire J, Hoesly R, Horing J, Popp A, Stehfest E and Takahashi K 2019 Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century *Geosci. Model Dev.* **12** 1443–75
- Griscom B W, Adams J, Ellis P W, Houghton R A, Lomax G, Miteva D A, Schlesinger W H, Shoch D, Siikamäki J V, Smith P, Woodbury P, Zganjar C, Blackman A, Campari J, Conant R T, Delgado C, Elias P, Gopalakrishna T, Hamsik M R, Herrero M, Kiesecker J, Landis E, Laestadius L, Leavitt S M, Minnemeyer S, Polasky S, Potapov P, Putz F E, Sanderman J, Silvius M, Wollenberg E and Fargione J 2017 Natural climate solutions *PNAS* **114** 11645–50
- Heck V, Gerten D, Lucht W and Popp A 2018a Biomass-based negative emissions difficult to reconcile with planetary boundaries *Nature Climate Change* **8** 151
- Heck V, Hoff H, Wirsén S, Meyer C and Kreft H 2018b Land use options for staying within the Planetary Boundaries – Synergies and trade-offs between global and local sustainability goals *Global Environmental Change* **49** 73–84
- Herrero M, Henderson B, Havlík P, Thornton P K, Conant R T, Smith P, Wirsén S, Hristov A N, Gerber P, Gill M, Butterbach-Bahl K, Valin H, Garnett T and Stehfest E 2016 Greenhouse gas mitigation potentials in the livestock sector *Nature Climate Change* **6** 452–61
- Hill S L L, Gonzalez R, Sanchez-Ortiz K, Caton E, Espinoza F, Newbold T, Tylianakis J, Scharlemann J P W, Palma A D and Purvis A 2018 Worldwide impacts of past and projected future land-use change on local species richness and the Biodiversity Intactness Index *bioRxiv* 311787
- Hudson L N, Newbold T, Contu S, Hill S L L, Lysenko I, Palma A D, Phillips H R P, Alhusseini T I, Bedford F E, Bennett D J, Booth H, Burton V J, Chng C W T, Choimes A, Correia D L P, Day J, Echeverría-Londoño S, Emerson S R, Gao D, Garon M, Harrison M L K, Ingram D J, Jung M, Kemp V, Kirkpatrick L, Martin C D, Pan Y, Pask-Hale G D, Pynegar E L, Robinson A N, Sanchez-Ortiz K, Senior R A, Simmons B I, White H J, Zhang H, Aben J, Abrahamczyk S, Adum G B, Aguilar-Barquero V, Aizen M A, Albertos B, Alcalá E L, Alguacil M del M, Alignier A, Ancrenaz M, Andersen A N, Arbeláez-Cortés E, Armbrrecht I, Arroyo-Rodríguez V, Aumann T, Axmacher J C, Azhar B, Azpiroz A B, Baeten L, Bakayoko A, Báldi A, Banks J E, Baral S K, Barlow J, Barratt B I P, Barrico L, Bartolommei P, Barton D M, Basset Y, Batáry P, Bates A J, Baur B, Bayne E M, Beja P, Benedick S, Berg Å, Bernard H, Berry N J, Bhatt D, Bicknell J E, Bihn J H, Blake R J, Bobo K S, Bócon R, Boekhout T, Böhning-Gaese K, Bonham K J, Borges P A V, Borges S H, Boutin C, Bouyer J, Bragagnolo C, Brandt J S,

- Brearley F Q, Brito I, Bros V, Brunet J, Buczkowski G, Buddle C M, Bugter R, Buscardo E, Buse J, Cabra-García J, et al 2017 The database of the PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) project *Ecology and Evolution* **7** 145–88
- Humpenöder F, Popp A, Bodirsky B L, Weindl I, Biewald A, Lotze-Campen H, Dietrich J P, Klein D, Kreidenweis U, Müller C, Rolinski S and Stevanovic M 2018 Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environ. Res. Lett.* **13** 024011
- Hurtt G C, Chini L P, Frolking S, Betts R A, Feddema J, Fischer G, Fisk J P, Hibbard K, Houghton R A, Janetos A, Jones C D, Kindermann G, Kinoshita T, Goldewijk K K, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, Vuuren D P van and Wang Y P 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands *Climatic Change* **109** 117
- Intergovernmental Panel on Climate Change 2014 *Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) Online: <http://ebooks.cambridge.org/ref/id/CBO9781107415416>
- IPCC 2006 2006 *IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use* vol 4 (Simon Eggleston and Leandro Buendia and Kyoko Miwa and Todd Ngara and Kiyoto Tanabe) Online: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html>
- Jantz S M, Barker B, Brooks T M, Chini L P, Huang Q, Moore R M, Noel J and Hurtt G C 2015 Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation *Conservation Biology* **29** 1122–31
- Karp D S, Mendenhall C D, Callaway E, Frishkoff L O, Kareiva P M, Ehrlich P R and Daily G C 2015 Confronting and resolving competing values behind conservation objectives *PNAS* **112** 11132–7
- Kreidenweis U, Humpenöder F, Stevanović M, Bodirsky B L, Elmar Kriegler, Lotze-Campen H and Popp A 2016 Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects *Environ. Res. Lett.* **11** 085001
- Lal R 2004 Soil Carbon Sequestration Impacts on Global Climate Change and Food Security *Science* **304** 1623–7
- Le Quéré C, Raupach M R, Canadell J G, Marland G, Bopp L, Ciais P, Conway T J, Doney S C, Feely R A and Foster P 2009 Trends in the sources and sinks of carbon dioxide *Nature geoscience* **2** 831
- Liu J, Hull V, Batistella M, DeFries R, Dietz T, Fu F, Hertel T, Izaurralde R C, Lambin E, Li S, Martinelli L, McConnell W, Moran E, Naylor R, Ouyang Z, Polenske K, Reenberg A, de Miranda Rocha G, Simmons C, Verburg P, Vitousek P, Zhang F and Zhu C 2013 Framing Sustainability in a Telecoupled World *Ecology and Society* **18** Online: <https://www.ecologyandsociety.org/vol18/issue2/art26/>
- Markel E, Sims C and English B C 2018 Policy uncertainty and the optimal investment decisions of second-generation biofuel producers *Energy Economics* **76** 89–100
- Minx J C, Lamb W F, Callaghan M W, Fuss S, Hilaire J, Creutzig F, Thorben Amann, Beringer T, Garcia W de O, Hartmann J,

- Khanna T, Lenzi D, Gunnar Luderer, Nemet G F, Rogelj J, Smith P, Vicente J L V, Wilcox J and Dominguez M del M Z 2018 Negative emissions—Part 1: Research landscape and synthesis *Environ. Res. Lett.* **13** 063001
- Newbold T 2018 Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios *Proceedings of the Royal Society B: Biological Sciences* **285** Online: <http://rspb.royalsocietypublishing.org/content/royprsb/285/1881/20180792.full.pdf>
- Obersteiner M, Walsh B, Frank S, Havlík P, Cantele M, Liu J, Palazzo A, Herrero M, Lu Y, Mosnier A, Valin H, Riahi K, Kraxner F, Fritz S and Vuuren D van 2016 Assessing the land resource–food price nexus of the Sustainable Development Goals *Science Advances* **2** e1501499
- Paillard S, Treyer S and Dorin B 2014 *Agrimonde -- scenarios and challenges for feeding the world in 2050* (Dordrecht ; New York: Springer)
- Popp A, Dietrich J P, Lotze-Campen H, Klein D, Bauer N, Krause M, Beringer T, Gerten D and Edenhofer O 2011 The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system *Environmental Research Letters* **6** 034017
- Purvis A, Newbold T, De Palma A, Contu S, Hill S L L, Sanchez-Ortiz K, Phillips H R P, Hudson L N, Lysenko I, Börger L and Scharlemann J P W 2018 Modelling and projecting the response of local terrestrial biodiversity worldwide to land use and related pressures: the PREDICTS project *Advances in Ecological Research* vol 58 (Elsevier) pp 201–41 Online: <https://doi.org/10.1016/bs.aecr.2017.12.003>
- Riahi K, van Vuuren D P, Kriegler E, Edmonds J, O'Neill B C, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Cuaresma J C, KC S, Leimbach M, Jiang L, Kram T, Rao S, Emmerling J, Ebi K, Hasegawa T, Havlik P, Humpenöder F, Da Silva L A, Smith S, Stehfest E, Bosetti V, Eom J, Gernaat D, Masui T, Rogelj J, Strefler J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Baumstark L, Doelman J C, Kainuma M, Klimont Z, Marangoni G, Lotze-Campen H, Obersteiner M, Tabeau A and Tavoni M 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview *Global Environmental Change* **42** 153–68
- Robinson T P, Wint G R W, Conchedda G, Boeckel T P V, Ercoli V, Palamara E, Cinardi G, D'Aiotti L, Hay S I and Gilbert M 2014 Mapping the Global Distribution of Livestock *PLOS ONE* **9** e96084
- Scholes R J and Biggs R 2005 A biodiversity intactness index *Nature* **434** 45–9
- Searchinger T D, Beringer T, Holtsmark B, Kammen D M, Lambin E F, Lucht W, Raven P and Ypersele J-P van 2018 Europe's renewable energy directive poised to harm global forests *Nature Communications* **9** 3741
- Shukla P R, Skeg J, Buendia E C, Masson-Delmotte V, Pörtner H-O, Roberts D C, Zhai P, Slade R, Connors S and van Diemen S 2019 Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems
- Souty F, Brunelle T, Dumas P, Dorin B, Ciais P, Crassous R, Müller C and Bondeau A 2012 The Nexus Land-Use model version 1.0, an approach articulating biophysical potentials and economic dynamics to model competition for land-use *Geoscientific Model Development* 1297–322

- Stevanović M, Popp A, Bodirsky B L, Humpenöder F, Müller C, Weindl I, Dietrich J P, Lotze-Campen H, Kreidenweis U, Rolinski S, Biewald A and Wang X 2017 Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices *Environ. Sci. Technol.* **51** 365–74
- Tilman D, Clark M, Williams D R, Kimmel K, Polasky S and Packer C 2017 Future threats to biodiversity and pathways to their prevention *Nature* **546** 73–81
- Tubiello F N, Salvatore M, Ferrara A F, House J, Federici S, Rossi S, Biancalani R, Golec R D C, Jacobs H, Flammini A, Prosperi P, Cardenas-Galindo P, Schmidhuber J, Sanchez M J S, Srivastava N and Smith P 2015 The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990–2012 *Global Change Biology* **21** 2655–60
- Visconti P, Bakkenes M, Baisero D, Brooks T, Butchart S H, Joppa L, Alkemade R, Di Marco M, Santini L and Hoffmann M 2016 Projecting global biodiversity indicators under future development scenarios *Conservation Letters* **9** 5–13
- Vuuren D P van, Stehfest E, Elzen M G J den, Kram T, Vliet J van, Deetman S, Isaac M, Goldewijk K K, Hof A, Beltran A M, Oostenrijk R and Ruijven B van 2011 RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C *Climatic Change* **109** 95
- Waisman H, Guivarch C, Grazi F and Hourcade J C 2012 The Imacim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight *Climatic Change* **114** 101–20
- Watson J E M, Evans T, Venter O, Williams B, Tulloch A, Stewart C, Thompson I, Ray J C, Murray K, Salazar A, McAlpine C, Potapov P, Walston J, Robinson J G, Painter M, Wilkie D, Filardi C, Laurance W F, Houghton R A, Maxwell S, Grantham H, Samper C, Wang S, Laestadius L, Runting R K, Silva-Chávez G A, Ervin J and Lindenmayer D 2018 The exceptional value of intact forest ecosystems *Nature Ecology & Evolution* **2** 599–610
- Wollenberg E, Richards M, Smith P, Havlík P, Obersteiner M, Tubiello F N, Herold M, Gerber P, Carter S, Reisinger A, Vuuren D P van, Dickie A, Neufeldt H, Sander B O, Wassmann R, Sommer R, Amonette J E, Falcucci A, Herrero M, Opio C, Roman-Cuesta R M, Stehfest E, Westhoek H, Ortiz-Monasterio I, Sapkota T, Rufino M C, Thornton P K, Verchot L, West P C, Soussana J-F, Baedeker T, Sadler M, Vermeulen S and Campbell B M 2016 Reducing emissions from agriculture to meet the 2 °C target *Global Change Biology* **22** 3859–64
- Zhang X, Davidson E A, Mauzerall D L, Searchinger T D, Dumas P and Shen Y 2015 Managing nitrogen for sustainable development *Nature* **528** 51–9

Figure list:

Fig.1:

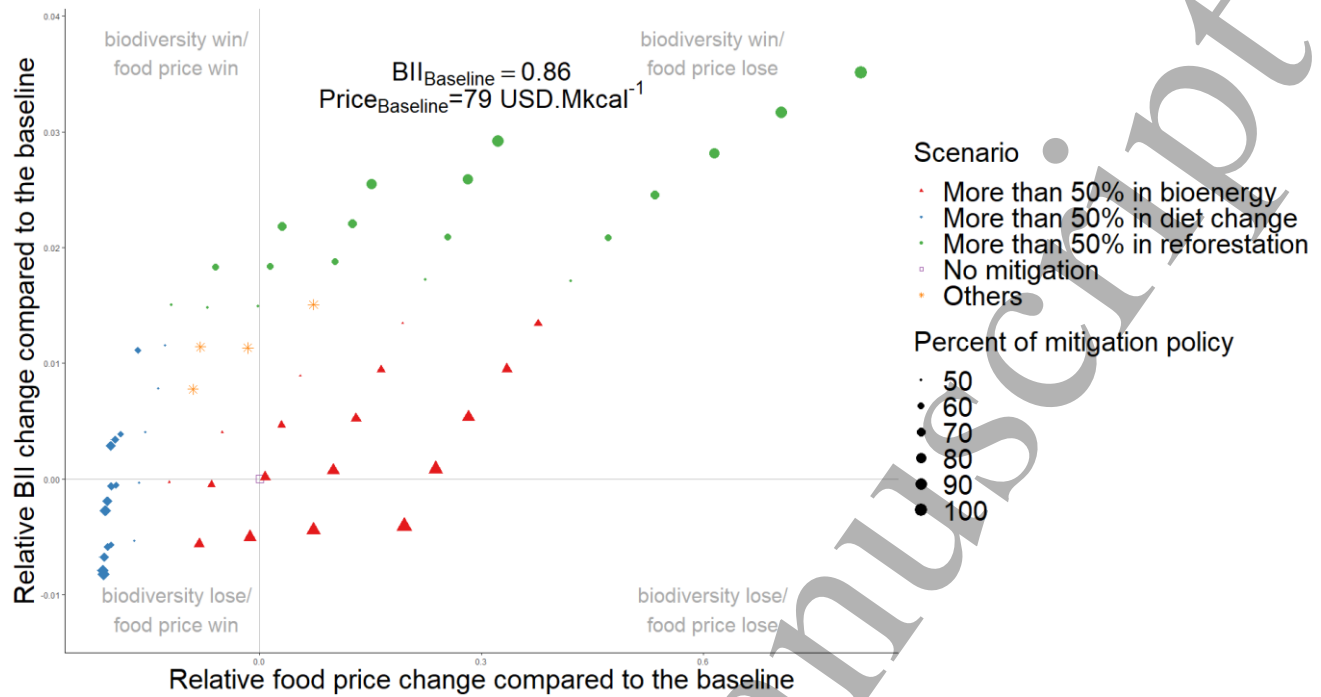


Fig. 2:

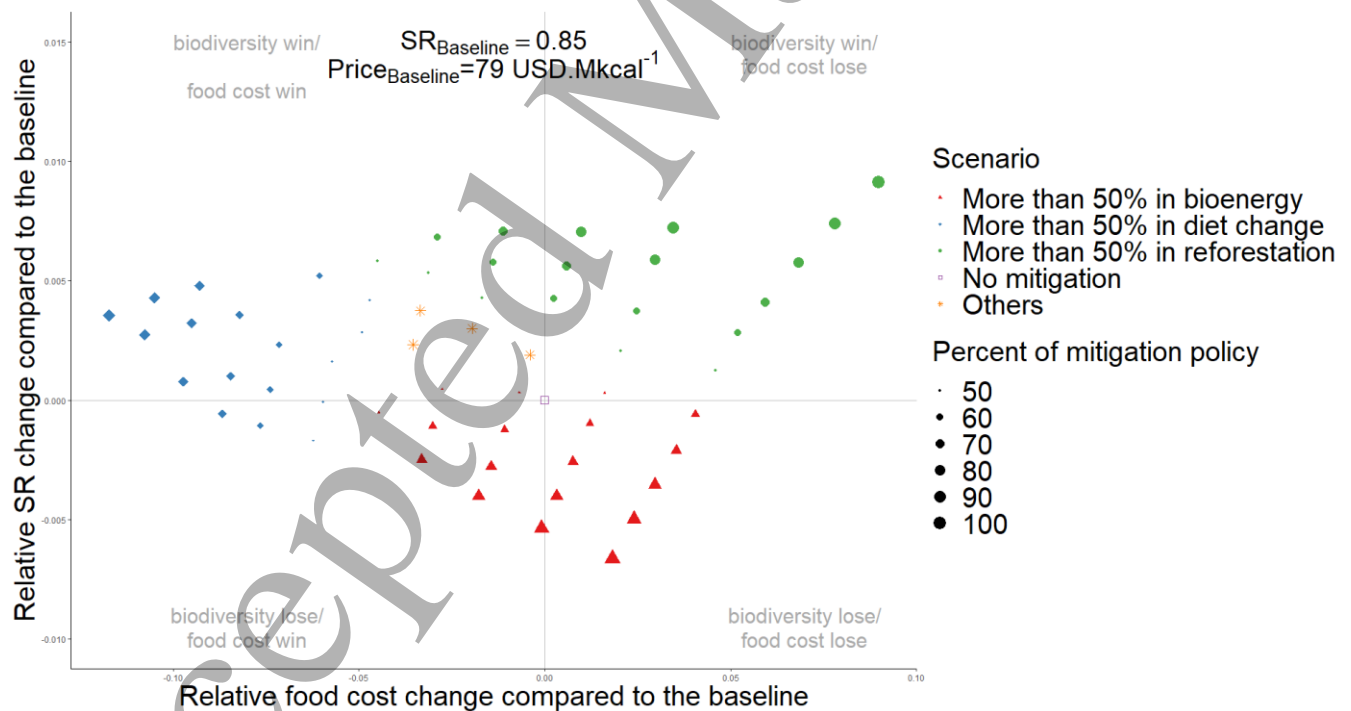


Fig. 3:

