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Article

The Positive Feedback Loop between the Impacts of Climate Change and Agricultural Expansion and Relocation

Bojana Bajželj [1,]* and Keith S. Richards [2]

[1] Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ, UK

[2] Department of Geography, University of Cambridge, Cambridge, CB2 3EN, UK; E-Mail: ksr10@cam.ac.uk

* Author to whom correspondence should be addressed; E-Mail: bb415@cam.ac.uk; Tel.: +44-1223-332-682.

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Abstract: Climate change and agriculture influence each other. The effects of climate change on agriculture seem to be predominantly negative, although studies show a large variation in impacts between crops and regions. To compensate for these effects, agriculture can either intensify or expand in area; both of these options increase greenhouse gas emissions. It is therefore likely that such negative effects will increase agriculture's contribution to climate change, making this feedback a positive, self-reinforcing one. We have previously used a data-driven model to examine greenhouse gas emissions in 2050 related to agricultural scenarios of increasing demand for food. Here, we extend this approach by introducing the impacts of climate change on agricultural yields. We estimate the additional losses of natural habitats and increases in greenhouse gas emissions resulting from agricultural expansion and relocation induced by the negative effects of climate change. We studied two climate change scenarios and different assumptions about trade. These additional impacts caused by climate change are found to be relatively moderate compared to demand-driven impact, but still significant. They increase greenhouse gas emissions from land use change by an additional 8%–13%. Climate change tends to aggravate the effects of demand drivers in critical regions. Current emission scenarios are underestimates in that they do not include these feedback effects.

Keywords: agriculture; climate change; greenhouse gas emissions; deforestation; feedback

1. Introduction

Climate and agricultural change form a two-way feedback loop. Agriculture affects the climate through the emissions of greenhouse gases (GHGs) associated with agricultural productivity (e.g., from livestock and nitrogen fertiliser) and also through agricultural expansion into areas of natural vegetation. Land-cover changes also influence climate through changes in other physical properties, such as evapotranspiration and surface albedo. In the opposite direction, climate change affects crop growth both directly as temperature and precipitation patterns change and also through many indirect effects: for example, by affecting weed competitiveness and pest outbreaks.

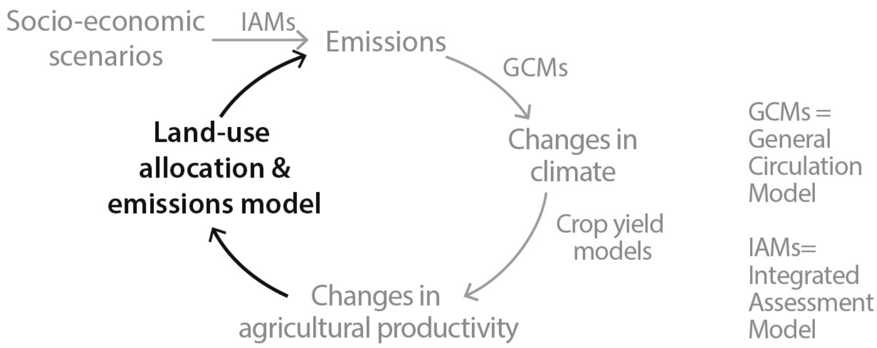
Agriculture is a major influence on the global carbon cycle. When the global carbon cycle was in natural balance, roughly the same amount of carbon was sequestered via photosynthesis by terrestrial plants as was returned to the atmosphere by respiration. However, land conversion from non-agricultural to agricultural land has caused a decrease in the ability of the land to store carbon, resulting in ongoing releases of carbon to the atmosphere. The rate of conversion has been slowing down, but it still contributes about 5.1 (±1.9) Pg·CO_2e/yr [1]. Anthropogenic changes in the carbon storage capacity of land can also occur in the absence of land conversion. For example, soil organic carbon is lost over time through many agricultural practices [2]. In addition to land use change emissions, agriculture also contributes to climate change through its ongoing activities: the large number of domesticated ruminants has increased CH_4 emissions and, likewise, the application of fertiliser results in N_2O emissions; both are strong GHGs.

The magnitude of agriculture-related emissions in the coming decades is uncertain. However given that the demand for food is rising, they are likely to increase [3]. In previous work [4] we have examined the future of agriculture and agriculture-related GHG emissions in relation to increases in global food demand. We explored a series of scenarios in the light of different options for demand reduction, trends in yields and agricultural expansion into natural ecosystems to 2050, but without including climate change feedback effects. This study has shown that closing the current yield gap is unlikely to result in sufficient food production for the 2050 population without significant expansion of agricultural land and, therefore, increased GHG emissions, unless there are significant reductions in waste and changes in diet. Without such demand-side measures, cropland will need to increase by 5%–42%, and agriculture-related GHG emissions could therefore increase by over 40% [4]. However, these conclusions did not consider the effects of climate change on crop yields, such as have recently been highlighted by the International Panel on Climate Change [5].

A vast amount of research is currently dedicated to understanding future climate change. The main research topics include: (i) different possible emission pathways related to human activities; (ii) the magnitude and patterns of their resulting climate change; and (iii) their effects on the environment and human society, including on food production. Different possible scenarios of global population, affluence and the level of global convergence are inputs into the integrated assessment models (IAM), which predict future emissions associated with these economic and technological developments. Some IAMs include agricultural and land use change considerations (e.g., the IMAGE model [6]); however, the focus has predominantly been on energy systems [7]. General circulation models (GCMs), representing the physical climate system, then use these emission predictions to estimate the spatially-explicit changes in temperatures and precipitation. Based on these, crop yield models (described in more detail later) estimate the resulting changes in crop production.

In this paper, we consider the "missing link" of how climatic impacts alter agricultural contributions to GHG emissions, an important building block in understanding the whole feedback loop between climate change and agriculture (Figure 1).

Figure 1. Schematic overview of the feedback loop between climate change and agriculture. Previous studies have started from emission scenarios based on socio-economic assumptions and stop at the modelling of climate change impacts on agricultural yields. We take a further step by estimating deforestation emissions caused by climatic impacts on agriculture, therefore closing the loop. The aspect to which this paper contributes is highlighted in bold.



Some aspects of the impacts of climate change on agriculture have been well studied in the literature (although, as with all studies of future scenarios, the results retain a degree of uncertainty). In particular, the impact of climate change on agricultural yield has received much attention. Four main approaches are used to assess possible future impacts on yields at the global scale: (i) process-based crop yield models; (ii) statistical crop yield models; (iii) Ricardian models of land value; and (iv) zoning studies.

Process-based crop models have the strongest tradition. These consist of agronomic crop yield models, applied at the global scale, and verified and parameterised for current conditions with agricultural statistics. The climatic conditions are then changed based on the predictions of one or more GCMs, returning different yields from those at currently prevailing conditions. The differences between the two sets of yields are therefore the predicted impacts of climate change. Atmospheric CO_2 concentration, as a benefactor for plant growth, can also be included in these process-based models, some of which (for example, that used by Rosenzweig *et al.* [8–10]) have a rich history of publication and validation and are being continuously improved [11]. Statistical crop yield models examine current relationships between observed weather and crop yields and extrapolate them based on future climate scenarios (for example, a study by Tebaldi and Lobell [12]). Ricardian models use a simpler approach, where land value is a function of temperature and precipitation, which need to be in a certain ratio, or else the crop productivity (and, therefore, the land value) is compromised [13]. Zoning studies use a similar approach; however, the value of land (in this case, called suitability) is derived through a much more complex modelling approach, which also includes the role of soil, terrain, CO_2 concentration and crop calendars. The best example on a global scales is the Global Agro-Ecosystem Zones model

(GAEZ) [14]. An overview of the main studies that have considered impacts of climate change on global crop yields is presented in Table 1 [9,10,12,13,15–17].

Although some crops and regions will apparently benefit from climate change, the studies reviewed converge on agreement that the overall global impact on yields will be slightly negative by 2050 and severely negative towards the end of the century. In some regions and locations, much more dramatic changes are predicted. The tropics will see a significant worsening of climatic conditions for agriculture, while boreal regions (Canada and Russia) will possibly see an improvement. There is agreement that low-income countries will be worse hit than high-income countries. Changes in precipitation and temperature can have both positive and negative effects. The elevated CO_2 concentration is expected to contribute positively, although it is unclear how the increased competitiveness of weeds, which is not yet included in the models, will decrease such benefits [2]. Maize and other C4 crops generally fare the worst, as they do not benefit as much from increased CO_2 levels [18]. An increase in the magnitude and frequency of extreme weather events will also certainly affect agriculture negatively. This is, however, much more difficult to include fully in crop models. Because of the complexity and antagonistic effects of these different drivers, the impacts of climate change on agriculture remain highly uncertain, and crop models vary considerably in their predictions. Rosenzweig *et al.* [11] observe that the choice of the crop model is more influential on crop yield projections than the selection of the GCM or even emission scenario.

On reviewing the literature, we have concluded that since climate change will likely affect agricultural yields negatively (with great regional variations), more land will have to be brought into agricultural production to supply crop demands, compared to a hypothetical future with no climate change and the same levels of agricultural intensification and yield improvement. Land conversion from non-agricultural land to agricultural land will likely be required in addition to other adaptations, the more so due to the overall negative effects of climate change. The expansion or relocation of cropping and grazing areas cause deforestation-related GHG emissions, in turn exacerbating climate change and consequently creating a positive feedback loop. We have identified three main pathways through which climate change affects agriculture in ways that could ultimately result in an agricultural impact back to climate:

1. Change in yields, followed by a change in the area needed to supply the same amount of food. As discussed above, yields are projected to be affected from mildly positively to severely negatively, meaning that overall cropland will have to expand further into natural vegetation to compensate for somewhat lower average yields.
2. Shifts in agricultural suitability, followed by relocation of agriculture. Cropping will follow agricultural suitability into higher latitudes, sometimes higher altitudes, causing deforestation of previously uncultivated areas and some reforestation on abandoned land.
3. Changes in water demand for irrigated agriculture. In crop yield models, areas equipped with irrigation are "protected" from any changes in precipitation and optimal evapotranspiration. That is, the models assume that enough water will be available for optimum irrigation. In reality, yields of irrigated agriculture can be affected if climate change alters the balance between the water available for irrigation and irrigation water demand (it can influence both the supply and demand sides). This again would result in cropland expansion as compensation for

lower yields. Because of the problem of a lack of reliable data on the availability of irrigation water, this pathway is not included in the present paper.

Table 1. Studies of climate change impacts on global crop yields in 2050. Studies are listed by the method used, their scope, climate change models and the underpinning socio-economic emission scenarios. SRES, Special Report on Emission Scenarios; GCM, general circulation models; IFPRI, International Food Policy Research Institute.

	Method/Model	**Crops**	**No of GCMs**	**SRES Scenarios**	**Adaptation**	**C Fertilisation**	**Global Impact on Yields**
Rosenzweig *et al.* [8], Iglesias *et al.* [10]	Process-based crop yield models (CERES, SOYGRO)	W R M	1 (HadCM3)	A1Fl, A1B, A2, B1, B2	Yes	Yes	−1% to −16%
Cline [13]	Merges Ricardian approach with the results from Parry *et al.* [9]	W R M	6	A2	Yes	Yes	−3% to −6%
Tebaldi *et al.* [12] (For 2030)	Regression analysis of y = f(T,p) + pdfs from GCMs	W M B	25	A1B	No	Yes	W +1.6% M −14.1% B −1.8%
IFPRI [15]	Process-based crop yield model (DSSAT) + IMPACT (PE model)	M, R, W, Potato, Cassava, Sorghum	2 (CSIRO, MIROC)	A1B, B1	Yes (economic)	Yes	LIC HIC M −0.3% to −2.6% R −16.5% to −4.5% W −1.3% to +2.8%
Jaggard *et al.* [16]	Compilation of several models	W M R S Sugar Cane	1	A1B	Yes	Yes	W −2.5% to +2.8% M −2.5% to −0.3% R −16.5% to −4.5% S −6% to −3.2%
Osborne *et al.* [17]	Process-based crop yield model (GLAM)	W S	14	A1B	Yes, 3 levels	Yes	0% to −50%

Abbreviations: Crops: W, wheat; R, rice; M, maize; S, soybean; B, barley; pdf = probability distribution function; PE = partial equilibrium; A1Fl, A1B, A2, B1, B2, the names of SRES IPCC scenarios for future emission pathways; LIC, Low Income Countries; HIC, High Income Countries; other abbreviations = model names.

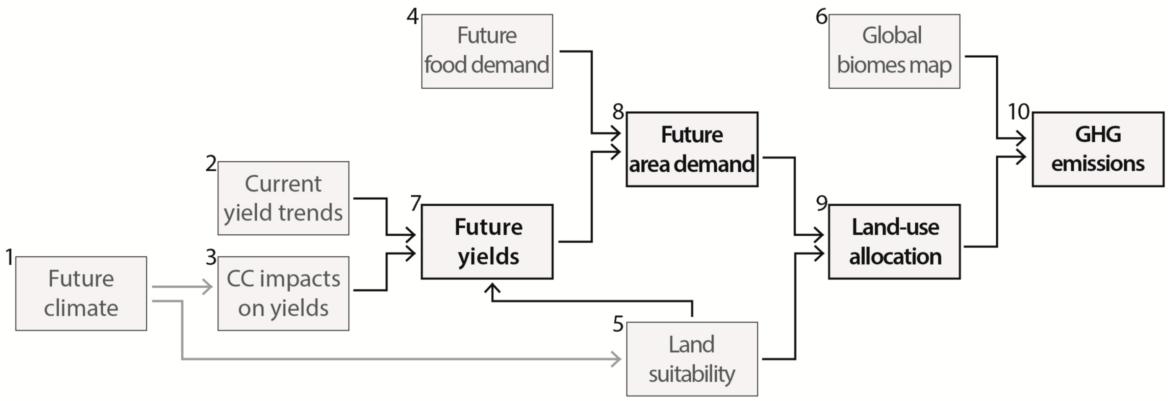
Despite the increasing wealth of knowledge on the topic, it has been impossible to include all aspects of agriculture and climate change feedbacks at a global scale. For example, impacts related to changes in albedo or evapotranspiration patterns have not been included. In terms of climate change impacts of agriculture, assessments of the possible changes to pest outbreaks, food storage, livestock health and weed competitiveness are missing [5]. Furthermore, although our study aims to make a further step towards closing the feedback loop by estimating deforestation emissions caused by negative climatic impacts on agricultural yields (Figure 1), we are unable to evaluate a fully coupled climate-agriculture system. That would necessitate re-runs of the GCMs to obtain new temperature and precipitation patterns based on revised emissions that include our estimates of the effects of increased land use change and so on. In the Discussion section, we do, however, offer some observations on what our findings mean for the entire feedback loop.

2. Methodology

Our methodology builds on several previous studies that together provide inputs to our own model (highlighted in bold in Figure 2). Our model is a slightly adapted version of one we have used previously to test the effects of sustainable intensification and food demand-reduction scenarios and their consequences for agriculture-related GHG emissions in 2050 [4].

The model we use in this paper is based on the methodology involving 10 steps, as described below and illustrated in Figure 2 [10,14,19–21]. Steps 1–6 describe the incorporation of the evidence from previous studies as external inputs. Steps 7–10 define the inner components of our own model, which is described in more detail in Bajželj *et al.* [4].

Figure 2. Work flow for the study. Grey boxes represent previously existing data: 1, future climate predictions from GCMs (most notably, HADCM3); 2, Ray *et al.* [19]; 3, Iglesias and Rosenzweig [10]; 4, FAO [20]; 5, Global Agro-Ecosystem Zones (GAEZ) [14]; 6, Ramankutty and Foley [21]. Black boxes and arrows represent internal steps in our model. CC, climate change.



Step 1, future climate: We used the scenarios from the IPCC Special Report on Emission Scenarios (SRES) A1 and B1 to represent two possible outcomes for the future climate [7]. These scenarios were published in 2000 and are gradually being outdated. The climate science community has prepared newer versions, the Representative Concentration Pathways [22]. However, these have not yet been taken up widely in further studies of agricultural impacts (which we require for our analysis). We chose A1 and B1 as the highest and lowest of the four SRES families and were able to obtain data specific to these two scenarios for Steps 3 and 5. In our study, A1 and B1 are used only to represent high and low climate change scenarios, but not the underlying socio-economic parameters. Food demand and the intrinsic yield improvements are independent of SRES in our study, because we use alternative sources to quantify them [13,14]. Both data sources for Steps 3 and 5 used the results from HadCM3 GCM for temperature and precipitation inputs.

Steps 2 and 3, future yields: To obtain future yields in a transparent manner, we required two pieces of information (see Equation (1)). The first is what Nelson *et al.* [15] call the intrinsic productivity growth rates (IPR). These represent the increases in yields that happen due to the advances in agronomy and dissemination of technology (e.g., increased fertiliser use and efficiency, new crop breeds). The second is the impact of climate change on yields, normally expressed in % reduction or increase of future yields. The negative climate change impacts on yields, for example those reported in the recent IPCC report [5,23,24], do not necessarily mean that future yields will be lower than yields today. As Equation (1) shows, that depends on the interplay between the IPR and climate change impacts.

$$y_{2050} = y_{2009} \times (1 + IPR + CCI) \tag{1}$$

where y_{2050} = yield in 2050; y_{2009} = current yield; IPR = intrinsic productivity growth rate; CCI = climate change impacts on yields.

To obtain the yields as a result of the IPR, we used the current yield trends for the main crops in each region [19] and extrapolated them linearly to 2050. We used results from a process-based model by Iglesias and Rosenzweig [10] to obtain the climate change impacts (CCIs). This source was chosen because of its good validation and its compatibility with our approach. We cross-checked their figures where possible with the most appropriate estimates extracted from the IPCC fifth assessment report [5]. Compared to these, Iglesias and Rosenzweig's figures appear conservative however, other studies did not offer sufficient coverage of crops and SRES scenarios. Both IPR and CCI are only available in the literature for main crops, such as wheat, maize, soybean and rice. These were taken as proxies for changes in yields of other crops (maize is a proxy for other C4 crops, soybean for oil crops and pulses, wheat for other grains and roots). See Tables S1–14 in the Supplementary Information for IPRs and CCIs and resulting yields by each crop, region and scenario.

Step 4, future food demand: Globally, the demand for food is predicted to increase by 60%–100% by 2050 [20,25]. We used the recent UN middle projection for population in each region, summing to 9.6 billion globally [26]; and per capita demand by food commodity as supplied by UN FAO [20].

Step 5, land suitability: We used a pre-existing study of land suitability under different climate scenarios—the GAEZ [14]. Land suitability in GAEZ is modelled from climatic conditions, terrain and soil properties individually for each crop. GAEZ publishes suitability indices for over 30 individual crops under three artificial input scenarios. We compiled and simplified these data sets to derive a general suitability map of the highest suitability indices across crops, assuming that high artificial inputs are possible (therefore reducing the importance of natural soil nutrient availability). We then reclassified suitability indices into three categories: high, medium and low suitability).

Step 6, global biomes: The spatial distribution of global biomes was taken from the global potential natural vegetation GIS dataset (half-degree resolution) [21]. We have not included any changes in biome distribution due to climate change. The most suitable data for the location and spatial distribution of cropland and grazing land were deemed to be those by Ramankutty *et al.* [27], who employed a critical analysis to combine several satellite-based maps.

Step 7: future yields were obtained by combining the IPR and climate change impacts on yield as described under Steps 2 and 3 and defined in Equation 1.

Step 8, future land demand: Our model uses current agricultural statistics [28] and additional data from many sources [29–35] to construct a snapshot of agricultural biomass flows by means of material flow analysis [4]. Based on assumed yields, it calculates plant growth and then allocates it to various purposes and losses along the chain (food, animal feed, fibre, fuel, soil recycling, *etc.*). With those allocations established, future demand for food commodities can be translated into a demand for crop and grazing land in each region. In addition to changes in demand, the agricultural supply chain can also change in terms of efficiencies, livestock management systems, feed-mixes and other allocations. Here, we assume that livestock production continues to intensify and industrialise, consistent with recent rates [36–38], which means using more cropland-based feed in comparison to pasture and achieving somewhat higher efficiencies. No other changes in the system are included. We have not included the impacts of climate change on grass yields for livestock systems. For a detailed examination of changes in wastage rates and dietary preferences, see Bajželj *et al.* [4].

Step 9, land allocation: If the demand for crop and grazing land calculated in Step 8 exceeds the current extents, cropland is assumed to expand on the remaining land in the high-suitability category. If such suitable land is found in several biomes (e.g., both temperate forests and grasslands), new cropland expands on those biomes in the same proportions as the current distribution. The template for pasture expansion is the historical distribution over suitability and biome categories only; however, we have not relocated existing pasture even if the suitability of land it currently occupies has changed. If future demand for agricultural land is less than the current land use, the area of the least suitable agricultural land is assumed to return to natural vegetation. Agricultural yields are then readjusted, depending on the new distribution of cropland over suitability classes, and the whole process is repeated until the demand for area converges. The final output is a new distribution of agricultural land over biomes and quantified changes from one land cover class to another, which are also a baseline for calculating GHG emissions.

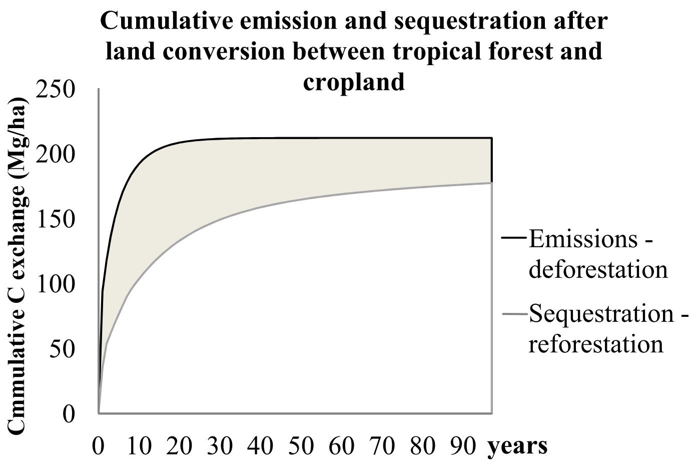
Step 10, GHG emissions: GHG emissions from land use change are notoriously difficult to assess, and in the expert view, current estimates carry about 70% uncertainty [1,39]. The difficulties arise from estimating the areas converted and from estimating carbon density before and after the conversion [1]. IPCC offers some guidance in calculations of land use change emissions [39], but we have instead used a newer, more detailed methodology of the GHG values of ecosystems [40]. We also use the literature-based assessments of carbon density parameters (in vegetation, litter and soil; and their decay constants) from the same study [40].

Deforestation generally results in rapid emissions of the larger part of organic carbon stored in plant biomass and a slower carbon release following the decomposition of the remaining vegetation carbon and soil organic carbon, until carbon capacities of the new land cover are reached [40]. Due to lack of information on the fate of wood after deforestation, we assumed that when land is cleared for cropping, biomass is burned (rather than used for wood products). Reforestation is a slower process than deforestation and often does not achieve the same carbon storage as primary vegetation [41]. We assumed biomass starts accumulating at a decreasing rate as a function of its net primary productivity, until it reaches the maximum carbon storage in the above and below-ground biomass. If one unit of land is deforested and the same amount of land is reforested, there will still be a considerable net global warming effect, although the net area of forest and agriculture remain the same (Figure 3). Therefore, even if climate change only affects the location of crop production (rather than the total area), it can still result in net GHG emissions.

In addition to GHG emission from land use change, we also calculated emissions associated with other agricultural sources (namely livestock, fertiliser, rice paddies and energy use), based on the current emissions from these sources [42–44]. Although there are numerous options to mitigate emissions from agricultural land use [45], GHG emissions are thought likely to scale up with agricultural production in the absence of decisive policy interventions.

This study draws from a number of previous studies (Figure 2), which are not necessarily consistent in their spatial and temporal resolutions or internal assumptions. For example, the climate change predictions we use are based on SRES scenarios, which are underpinned by specific socio-economic assumptions about the population and its affluence. Our assumed food demand, IPR and trade also reflect the same socio-economic drivers, but these do not necessarily match those in SRES (SRES are only used to characterise the magnitude of climate change). The differences between the scenarios are therefore a consequence of different levels of climate change alone.

Figure 3. The differences between emissions from deforestation and sequestration from reforestation in years after a land use change event. The grey area shows the net emissions resulting from relocation of a unit of cropland within tropical forest.



Using the workflow outlined in Steps 1–10, we were able to assess different aspects of the climate change interactions with agriculture. Firstly, we ran a hypothetical, business-as-usual, baseline scenario with no climate change impacts. Secondly, we changed yields according to two climate change scenarios (A1 and B1). Thirdly, we estimated the emissions associated with relocation. We compared agricultural suitability distribution with and without climate change using GIS. From these data, we calculated how much high- and medium-suitability agricultural land could change to the low-suitability category under the A1 and B1 scenarios. Each unit of apparent net loss of highly suitable cropland is replaced by the conversion of the same area of highly suitable land under natural vegetation. Each unit of apparent net loss of medium suitability land is replaced by the conversion of 0.62 units of highly suitable land under natural vegetation (to compensate for different nominal yields between high and medium suitability land). In previous work, we also examined demand reduction (decrease in food waste and dietary change), which showed the benefits of reducing conversion to cropland; however, scenarios explored in the previous study did not take climate change feedback into account. Here, we focus on "business-as-usual" to show what the additional consequences of climate change feedback without any socio-economic adjustments.

3. Results and Discussion

The main results from the study are estimates of additional GHG emissions arising from climate change impacts on agriculture. They are calculated in two stages, corresponding to the two causes.

The first of these are associated with climate change lowering yields and, therefore, increasing the need for cropland expansion into natural vegetation. The second are those associated with the relocation of cropland due to changes in land suitability patterns. We then present the combined effect of these two pathways. Finally, we present the interactions between climate change impacts, demand increases and trade.

3.1. Emissions Associated with the Climate Change Impacts on Yields

The tendency of climate change to have negative effects on agriculture yields will result in additional emissions. Table 2 shows how much the yields are affected under climate change scenarios in 2050, compared to the intrinsic productivity growth rates (IPR). We assume that climate change impacts (after adaptation) result in changes in agricultural expansion, as all available intensification options are already employed to meet the increasing demand.

Table 2. Comparison of climate change impacts on yields in the A1 and B1 scenarios to intrinsic productivity growth rates and the resulting GHG emissions from land use change. CCI, climate change impacts.

	IPR Average Yield Improvement between 2009 and 2050	Climate Change Scenario: A1		Climate Change Scenario: B1	
		CCI	Net GHG Emissions ($Gt{\cdot}CO_2e/yr$)	CCI	Net GHG Emissions ($Gt{\cdot}CO_2e/yr$)
Boreal N America	+36%	+5%	−0.007	+6%	−0.008
Central Asia	+73%	−1%	0.001	−2%	0.002
East Asia	+52%	+2%	−0.018	+1%	−0.014
Eastern Europe	+3%	−9%	0.142	−5%	0.067
Tropical Latin America	+64%	−5%	0.072	−5%	0.059
North Africa	+55%	−4%	0.002	−2%	−0.002
Temp N America	+51%	−3%	0.011	−2%	0.013
Oceania	+13%	+1%	−0.019	+1%	−0.021
SE Asia	+79%	+3%	−0.061	+3%	−0.054
Southern Asia	+63%	−4%	0.068	−3%	0.051
Temp Latin America	+66%	+7%	−0.014	+7%	−0.013
Western Europe	+25%	+3%	−0.004	+4%	−0.026
Western Asia	+40%	−1%	0.004	−1%	0.005
Sub-Saharan Africa	+62%	−5%	0.118	−3%	0.060
WORLD			0.297		0.119

Table 2 also shows the amount of additional emissions (or savings) that these impacts cause through increasing or reducing the demand for cropland expansion. Climate change impacts on yield are estimated to cause an additional 0.3 $PgCO_2e$ per year for the A1 climate change scenario and 0.1 $PgCO_2e$ for the B1 scenario. The largest increases in GHG emissions due to lowered yields are predicted in Eastern Europe, Sub-Saharan Africa and South Asia. The positive impacts of climate change on agriculture result in “negative GHG emissions”, an outcome of two different processes depending on the region. In most regions, these are savings of emissions compared to the baseline scenario, as less land is required to fulfil the same food demand, and therefore, less needs to be converted from natural vegetation. In Western Europe, they represent carbon sequestration, as they reduce the need for cropland and permit some re-naturalisation.

3.2. Emissions Resulting from Cropland Relocation

Previously suitable cropland will become unsuitable, prompting the relocation of cropping areas. This will lead to additional net GHG emissions, as well as the loss of pristine habitats. Table 3 shows how much suitable (high and medium suitability) existing cropland each major region could lose due to climate change, under the A1 and B1 emissions scenarios. Climate change directly reduces suitability, where the temperature and precipitation regimes change, so that they no longer support optimum or near-optimum plant growth. As a result, we assume cropping would need to relocate into other, previously uncultivated areas. Oceania, East Asia, North Africa and Middle East, Tropical Latin America and Temperate North America would need to reallocate substantial areas (Table 3). Relocation of cropland results in net GHG emissions.

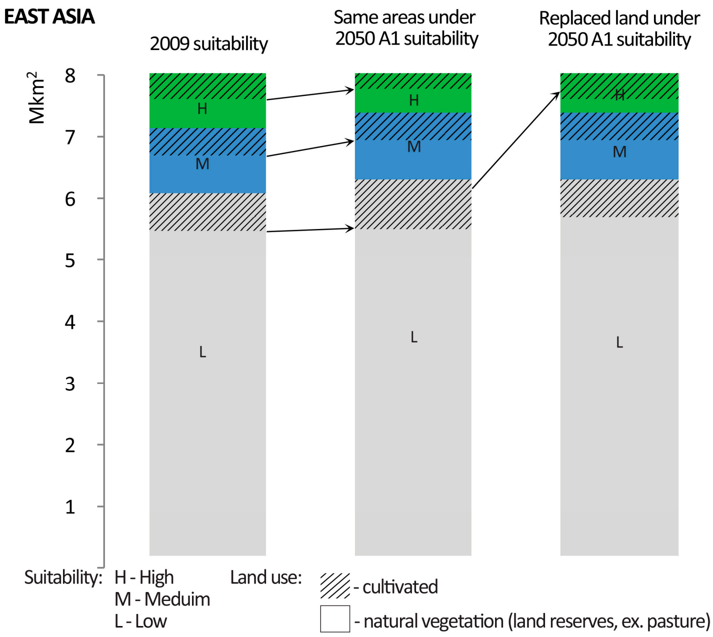
Table 3. Shifts in suitability of current cropland. This shows the total area of current high- and medium-suitability cropland, whose suitability changes to low under the A1 and B1 scenarios. This is also shown as a percentage of the total cropland in the region. Each scenario has emissions associated with the necessary cropland replacement on high-suitability land, previously covered by natural vegetation.

	Climate Change Scenario: A1			**Climate Change Scenario: B1**		
	(km^2)	**% of Total Cropland Becoming Unsuitable**	**Net GHG Emissions ($Gt{\cdot}CO_2e/yr$)**	**(km^2)**	**% of Total Cropland Becoming Unsuitable**	**Net GHG Emissions ($Gt{\cdot}CO_2e/yr$)**
Boreal N America	315	0%	0.0	1955	0%	0.0
Central Asia	4862	2%	0.0	7051	3%	0.0
East Asia	178,749	20%	0.014	92,726	10%	0.006
Eastern Europe	8409	0%	0.003	11,853	1%	0.0
Tropical Latin America	81,476	9%	0.059	65,534	8%	0.047
North Africa	35,777	14%	0.005	22,241	9%	0.003
Temp Northern America	111,772	7%	0.157	65,461	4%	0.091
Oceania	74,387	42%	0.029	63,899	36%	0.025
SE Asia	45,694	6%	0.021	32,393	4%	0.015
South Asia	44,086	3%	0.0	51,476	3%	0.0
Temp Latin America	1189	0%	0.0	893	0%	0.0
Western Europe	46,844	7%	0.011	35,796	5%	0.009
Western Asia	18,551	8%	0.005	11,861	5%	0.003
Sub-Saharan Africa	75,629	6%	0.043	76,281	6%	0.043
WORLD	652,112	4.2%	0.395	463,140	3.0%	0.244

Figure 4 shows an example of the land suitability shift taking place in the East Asian region and illustrates how the replacement land is determined. The net GHG emissions resulting from cropland relocation depend on the predicted location of the natural vegetation of the abandoned and newly-converted cropland. For this reason, the ratio between the total relocated area and resulting GHG emissions varies considerably between the regions. In total, under the A1 scenario results, about

0.65 Mkm^2 of previously high and medium suitability land becomes unsuitable, prompting a relocation of cropping and, therefore, causing 0.4 Pg·CO_2e per year. Under the B1 scenario, these impacts are smaller, but nonetheless substantial: 0.46 Mkm^2 of cropping would need relocation, causing 0.24 Pg·CO_2e. This source of emissions is therefore similar in magnitude to lowered crop yields.

Figure 4. A diagram showing shifts in suitability on current cropland and natural vegetation in East Asia. The first bar shows that about a sixth of the total area has a high suitability and another sixth medium-suitability, and the rest is low. Hashed areas show land already in cultivation, for example more than half of current high-suitability land. If cropland does not move, while the suitability of land changes due to climate change, the area of high-suitability land in cultivation would decrease substantially (second bar). We assume that cropland whose suitability decreases to "low" is replaced by cultivating more of the high-suitability land previously under natural vegetation (third bar).



3.3. Combined Effects

Table 4 shows the resulting agricultural impacts in 2050, with and without climate change. Regional results are shown in the Supplementary Information. The table shows the predicted areas of cropland, grazing land and forests (separately for pristine forest cover) in 2050. It also shows the GHG emissions associated with land use change and total GHG emissions from all agricultural sources, including, in addition to land use change, livestock, fertiliser use and production, rice paddies and agricultural energy use. The baseline 2050 scenario (a hypothetical scenario not including any climate change impacts) shows a large increase in necessary agricultural areas and agriculture-related GHG emissions, compared to current levels. This is due to an increase in demand for food commodities. Introducing climate change impacts further magnifies these results, although compared to the demand drivers related to population and dietary change, the climatic drivers appear moderate.

Our model shows 8%–13% increases in GHG emissions from land use change as a result of climate change impacts on agriculture. This corresponds to an additional 0.5 and 0.7 Pg·CO_2e/yr for the B1 and A1 scenarios, respectively. Apart from increasing emissions from land use change, our model also predicts a slight increase in emissions from fertiliser use, associated with generally larger cropping areas needed under climate change scenarios. When comparing the total GHG emissions from agriculture (including livestock emissions and fertiliser), the differences in GHG emission between the "no climate change" scenario and the A1 scenario add to about 5%.

Table 4. The overall results of modelling agricultural impacts in 2050 under two climate change scenarios.

		2009	**No CC Scenario**	**Climate Change (A1)**		**Climate Change (B1)**	
Cropland	Mkm^2	15.6	21.1	21.7	+3%	21.5	+2%
Pasture	Mkm^2	34.3	36.1	36.4	+1%	36.4	+1%
Net Forest cover	Mkm^2	40.2	37.2	35.6	−4%	35.7	−4%
Tropical Pristine Forest cover	Mkm^2	7.9	7.2	6.8	−6%	6.8	−5%
Land use change GHG emissions	$Pg{\cdot}CO_2/yr$	4.0	5.8	6.6	+13%	6.3	+8%
Total GHG emissions	$Pg{\cdot}CO_2/yr$	11.4	18.2	19.0	+5%	18.7	+3%

3.4. The Regional Interplay between Demand Increases and Climate Change Impacts

Negative impacts of climate change on agriculture and the biggest demand increases coincide regionally. Table 5 shows the predicted increases in demand for food commodities (as a result of the combined effects of increasing population and dietary changes) and compares them to the impacts of climate change on agriculture. In Sub-Saharan Africa, North Africa, Middle-East, South Asia, Central Asia and Latin America, food demand will more than double, and at the same time, climate change will impede agricultural productivity increases. These regions will therefore face a squeeze from both the demand and the supply sides. Climate change will impede agriculture in poor, tropical regions more than in richer, temperate regions; and unfortunately, as shown here, these coincide with the biggest increases in demands from growing populations. Furthermore, geographically, these also coincide with tropical forests, which are large stores of carbon and valuable ecosystems, which are at risk of conversion to agricultural land.

It is worth noting that the two main studies we have used for climate change impacts on agriculture (Iglesias and Rosensweig, 2009, for impacts on crop yields and GAEZ for suitability) do not always agree. For example, the GAEZ [14] model predicts the overall suitability of land in SE Asia will decrease with climate change; however, the crop yield simulations predict that climate change will boost its yields (with adaptation). It is possible that the suitability of land generally decreases, but the yield on cropland increases with the higher temperature (as we are assuming that sufficient irrigation water is available). The differences between the model results may also be due to structural differences between the methodological formulations of the models (structural uncertainty).

By increasing trade from high yielding to low yielding countries, emissions and the total area required for cultivation decline. We tested two scenarios of increased trade from those high-yielding regions that benefit from climate change to low yielding regions where climate change reduces yield. Higher trade scenarios reduce emissions, but not overwhelmingly so. For example, by more than doubling trade flows, the total area needed for cultivation decreases by 4% and total land use change-related emissions by 7%. (We have not included changes in GHG emissions associated with increased transportation associated with trade. These would decrease the emission savings of high trade scenarios). In our higher trade scenarios, the dynamics between different regions and their roles in global food markets change. For example, Western Europe would change from one of the biggest importers to one of the biggest exporters. Boreal Northern America and Temperate Latin America would become important exporters, while imports would increase, particularly in South Asia and Sub-Saharan Africa, and would have to decrease in East Asia (Table 6).

Table 5. A comparison of demand increases and negative climatic effects on agriculture. Countries where both factors will be significant are highlighted in red.

	Changes in Demand	Climate Change Impacts on Yields		Changes in Overall Land Suitability	
		A1	B1	A1	B1
Boreal N America	+38%	+5%	+6%	+12%	+6%
Central Asia	**+115%**	**−1%**	**−2%**	**−6%**	**−9%**
East Asia	+47%	+2%	+1%	−3%	−1%
Eastern Europe	+19%	−9%	−5%	+15%	+13%
Tropical Latin America	+92%	−5%	−5%	−10%	−7%
North Africa	**+150%**	**−4%**	**−2%**	**-%**	**-%**
Temp N America	+38%	−3%	−2%	+5%	+6%
Oceania	+89%	+1%	+1%	−6%	−10%
South-Eastern Asia	+119%	+3%	+3%	−3%	−2%
Southern Asia	**+103%**	**−4%**	**−3%**	**+3%**	**+1%**
Temp Latin America	+92%	+7%	+7%	+8%	+7%
West Europe	+10%	+3%	+4%	−4%	−4%
Western Asia	**+139%**	**−1%**	**−1%**	**−4%**	**−3%**
Sub-Saharan Africa	**+228%**	**−5%**	**−3%**	**−1%**	**−2%**

Table 6. A comparison between different trade scenarios, under the A1 climate change impacts in 2050. With increases in trade, agricultural impacts decline. The lower part of the table shows changes in export and imports of the main exporting and importing regions, with the arrows showing increases and decreases in the respective categories.

Trade Scenario	Units	Trade Fixed to 2009 Levels	Proportional Trade Increase		Enhanced Trade	
Total food exported	Tg·C	157,552	225,272	(+43%)	382,522	(+143%)
Land area	Mkm^2	21.6	21.4	(−1%)	20.8	(−4%)
LUC Emissions	$Pg{\cdot}CO_2e$	6.5	6.3	(−2%)	6.0	(−7%)
Exporting regions		1. N America	1. N America	↓	1. W Europe	↑
		2. E Europe	2. Temp Latin America	↑	2. BN America	↑
		3. BN America	3. BN America	↑	3. N America	↓
		4. Temp Latin America	4. W Europe	↑	4. Temp Latin America	↑

Table 6. *Cont.*

Trade Scenario	Units	Trade Fixed to 2009 Levels	Proportional Trade Increase	Enhanced Trade	Trade Scenario	Units
Importing regions		1. E Asia	1. E Asia	↓	1. S Asia	↑
		2. W Asia	2. S Asia	↑	2. SubS. Africa	↑
		3. W Europe	3. SubS. Africa	↑	3. W Asia	↑
		4. SubS. Africa	4. W Asia	↑	4. N Africa	↑
		5. N Africa	5. N Africa	↑	5. E Asia	↓

4. Conclusions

This paper deals with the existence of a positive feedback loop that has not yet been included in climate projections. The SRES scenarios (which are used here as inputs) used several models to calculate emissions from agriculture and land use change, most notably the IMAGE model [6]. These models appear to be, in general, more optimistic than our own model, which predicts strong increases in emissions from agriculture and land use change due to increases in demand for food commodities [4]. Furthermore, this current paper shows a further slight increase in emissions due to climate change impacts on agriculture, which, to the best of our knowledge, have not been included in emissions scenarios to date. Our results suggest that increases of about 3%–5% will occur in agricultural emissions in the 2050 scenarios, due to climate change effects, compared to emissions in the baseline scenarios without climate change (which include agricultural emissions associated with increased demand). In the cases of the B1 and A1 scenarios, where total global emissions were estimated at about 53 Pg·CO_2e/yr and 74 Pg·CO_2e/yr in 2050, we should add 0.7–1.0 Pg·CO_2e (1.4%) to account for the climate change and agriculture feedbacks. We might expect the positive feedback loop to cause the system to arrive at a state with higher emissions than a simple sum of the baseline and estimated feedback effect. However, because the additional emissions represent a relatively small proportion of the total, the system should converge at only a slightly higher emissions level.

These additional feedback emissions become more prominent when compared to the total 2050 emissions budget, allowed to achieve a likely climate change limitation of 2° (about 21 Pg·CO_2e [46]). If the climate change due to past emissions proves to be similar to that of the B1 scenario, the climate change-agricultural feedback emissions calculated here would represent about 3% of that total emissions budget.

Although the estimated additional emissions from the climate change-agricultural feedback do not appear large, especially in light of the large uncertainties, one should keep in mind that in timelines after 2050 (2080s, 2100s), these effects will be much more serious. We were unable to test this quantitatively, as most data are available for 2050 only. However, numerous studies [5,10,17] warn that climate change impacts on agriculture will intensify significantly later.

Efficient global food distribution arrangements will become even more important, as climate change affects agriculture and its emissions divergently across the globe. Already today, global food distribution is problematic. One billion people are undernourished, while an even larger number of people are overweight due to excess food consumption and poor diets. The biggest demand increases, climate change impacts and poverty, all seem to coincide and will hit the same areas simultaneously (Sub-Saharan Africa, South Asia). This could mean deforestation further expanding, especially in these regions where tropical forests constitute the largest suitable land "reserves". To avoid this, these regions would have to import much more food. However, given that agriculture plays a large role in their economies, the question remains how they would be able to afford such increased imports. If food continues to be mostly produced where people live (which it most probably will), the production in the tropics will need to increase in spite of negative climatic effects. This could start a vicious circle of more environmental degradation as a result of the preceding environmental stress and agricultural intensification. This is a further feedback that also needs to be assessed; if soil erosion and soil salinity are enhanced, it will force the need to expand agricultural area to compensate for erosion-related yield decline. This will be a subject of our continuing research.

Our research adds to thinking about future agriculture by exploring an evolving feedback relationship with climate. The uncertainties (about future climate, its impacts on agriculture and agricultural productivity rates) remain large, and many potentially significant climatic effects on agriculture have not been included (for example, the full impacts of extreme weather events, weeds, pests and diseases; changes in grassland productivity; land loss to sea level rise). Bearing these caveats in mind, it appears that the additional feedback effects due to climate change in 2050 are relatively moderate compared to the demand-driven stresses to agricultural systems. The increase in food demand from the growth in population and affluence is a critical driver for increased impacts. Therefore, mitigation efforts should also be focused on food demand as the first priority. Climate change and agriculture feedback effects should nonetheless be considered seriously, especially when we consider the Earth system in the second half of this century. Demand and climate feedback drivers coincide and exacerbate GHG emissions from land cover change for agriculture, feeding back into further climate change.

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Author Contributions

Bojana Bajželj and Keith S. Richards designed the study. Bojana Bajželj collected the data and conducted calculations. Bojana Bajželj and Keith S. Richards wrote the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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