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The relevance of uncertainty in future crop production for mitigation strategy planning

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Abstract

In order to achieve climate change mitigation, long-term decisions are required that must be reconciled with other societal goals that draw on the same resources. For example, ensuring food security for a growing population may require an expansion of crop land, thereby reducing natural carbon sinks or the area available for bio-energy production. Here, we show that current impact-model uncertainties pose an important challenge to long-term mitigation planning and propose a new risk-assessment and decision framework that accounts for competing interests.

Based on cross-sectorally consistent simulations generated within the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) we discuss potential gains and limitations of additional irrigation and trade-offs of the expansion of agricultural land as two possible response measures to climate change and growing food demand. We describe an illustrative example in which the combination of both measures may close the supply demand gap while leading to a loss of approximately half of all natural carbon sinks.

We highlight current limitations of available simulations and additional steps required for a comprehensive risk assessment.

1 Introduction

Climate change and rising food demand motivate competing responses (Falloon and Betts, 2010; Warren, 2011) resulting in, for example, competition for land between food and bio-energy production (Godfray et al., 2010a; Searchinger et al., 2008; Tilman et al., 2009). Mitigation, in particular, requires long-term planning, which is inevitably done under considerable uncertainty of e.g. future land required for food production.

Models already exist that couple surface hydrology, ecosystem dynamics, crop production (Bondeau et al., 2007; Rost et al., 2008) and agro-economic choices (Havlik et al., 2011; Lotze-Campen et al., 2008a; Stehfest et al., 2013) to address, for example, carbon-cycle implications of LU changes and irrigation constraints. However, modeling such complicated systems requires a series of assumptions, in particular with respect to process representation and parameter values.

In addition to individual coupled analyses there is a large number of detailed sector-specific studies covering a wide range of process representations and parameter settings not represented by single, integrative studies (Haddeland et al., 2011; Sitch et al., 2008). A comprehensive assessment as requested by the Intergovernmental Panel on Climate Change (IPCC) must cover the full uncertainty range spanned by these models by quantifying the inter-impact-model spread.

Owing to its cross-sectoral design (Warszawski et al., 2013a) the recently launched Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, http://www.isi-mip.org) provides an opportunity to bring this multi-impact-model dimension to the available integrative analyses of climate change impacts and response options, and allows for a cross-sectoral quantification of uncertainties cascading through the model chain.

An associated risk-assessment framework may be described by two probability density functions (pdfs, see Fig. 1): the red pdf (f) in the upper panel of Fig. 1 describes our knowledge of the required food-production area given certain management decisions (i.e. fertilizer use, irrigation fractions and selection of crop varieties) and a prescribed global-warming level. The width of the distribution is determined by uncertainties in food demand, regional climate change, and crop-model projections describing the effect of climate change and CO_2 fertilization on crop yields. Intensification of production, for example by increasing irrigation or fertilizer use, shifts the pdf to the left, since less land would be required to meet demand.

The blue pdf (c) illustrates our knowledge of the area of land required to be maintained as natural carbon sinks or used for bio-energy production in order to limit global warming, for example to 2 °C. We assume that other factors, such as the degree of decarbonisation of the industry, remain fixed. In this case the width of the distribution depends e.g. on uncertainties regarding climate sensitivity and the capacity of the natural carbon sinks as projected by biogeochemical models. Assuming higher energy efficiency shifts the distribution right as less CO_2 has to be extracted from the atmosphere.

Mitigation strategies must compare the area of land required for food production (F) with the associated reduction of the area available for retention of natural carbon sinks and stocks or bio-energy production (N), such that $N = T - F$, where T = total available area. Assuming food demand will always be met, even at the expense of climate protection, the probability of climate protection failure (exceedance of a given global-warming target) is given by

$$P = \int_{0}^{\infty} \int_{T-F}^{\infty} c(N)\, dN\, f(F)\, dF$$

where the inner integral describes the probability of climate protection failure for a fixed agricultural area F (blue area in Fig. 1). P cannot be determined without knowledge of the uncertainty associated with the required food-production area.

To date, the required pdfs have not yet been quantified except for a first attempt to quantify f based on multiple crop and economic models (Nelson et al., 2013). In this case the economic models evaluate different intensification options or the expansion of agricultural land to translate crop yields and demand into land-use patterns. Here we restrict our analysis to purely biophysical questions and do not provide a full quantification of the different pdfs. We use simulations from 7 Global Gridded Crop Models (GGCMs; Rosenzweig et al., 2013b), 11 global hydrological models (Schewe et al., 2013), and 7 terrestrial bio-geochemical models (Friend et al., 2013; Warszawski et al., 2013b) generated within ISI-MIP to address the following questions in the context of the described risk-assessment framework: (1) how large is the expected future supply-demand gap under climate change and CO_2 fertilization assuming present-day land-use (LU) patterns and fixed management (see Table S1 in the Supplement)?; (2) how much can be gained from additional water-availability-limited irrigation without land expansion?; and (3) what are the costs in terms of natural carbon sinks and stocks of an illustrative LU pattern that provides a chance to meet future demand?

Not all of the crop models provide yield projections starting at present day levels (Rosenzweig et al., 2013a). In particular, EPIC provides potential yields assuming high fertilizer input, and LPJ-GUESS does not account for nutrient constraints. Therefore, we only compare relative changes in global production to relative changes in demand. Whilst the assumption that the effects of climate change are relatively independent from the starting conditions is not necessarily valid, we focus on *illustrating* how such a comprehensive risk assessment could be conducted.

2 Data and methods

2.1 Input data for impact model simulations

All impact projections used within this study are forced by the same climate input data (Warszawski et al., 2013a). For ISI-MIP daily climate data of five General Circulation Models (GCMs) derived from the CMIP5 archive (Taylor et al., 2012) were bias-corrected to match historical reference levels (Hempel et al., 2013). Here, we only use data from HadGEM2-ES, IPSL-CM5A-LR and MIROC-ESM-CHEM (see Table S6 in the Supplement) as these models reach a global mean warming of at least 4° w.r.t. 1980–2010 levels under the Representative Concentration Pathway RCP8.5 – the highest of the four RCPs (Moss et al., 2010). All model runs accounting for changes in CO_2 concentrations are based on the relevant RCP-CO_2 input.

2.2 LU patterns and demand

The illustrative LU patterns applied to answer question three are based on projections of the agro-economic LU model MAgPIE (Lotze-Campen et al., 2008b; Schmitz et al., 2012) generated within the ISI-MIP-AgMIP cooperation and published in Nelson et al. (2013). The model computes land-use patterns necessary to fulfill the future demand (Bodirsky et al., 2014). The associated land use projections are based on the historical and RCP8.5 simulations by HadGEM2-ES and associated yields provided by LPJmL (Nelson et al., 2013). The pattern is based on fixed CO_2-concentration (370 ppm) crop-model simulations. MAgPIE accounts for technological change increasing crop yields (applied growth rates are listed in Table S4 in the Supplement), while our analysis is based on crop-model simulations accounting for increasing levels of atmospheric CO_2 concentrations but no technological change.

2.3 Impact model simulations

Our considered crop model ensemble represents the majority of GGCMs currently available to the scientific community (run in partnership with the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2012)). In their complementarity, the models cover a broad range of crop growth mechanisms and assumptions. The quantity projected differs from model to model, ranging from yields constrained by current management deficiencies to potential yields under effectively unconstrained nutrient supply (Table S1 in the Supplement and Rosenzweig et al., 2013b). The default configuration of most models includes an adjustment of the sowing dates in response to climate change, while total heat units to reach maturity are held constant except for PEGASUS and LPJ-GUESS. Three models include an automatic adjustment of cultivars. The applied hydrological and biomes models and their basic characteristics are listed in Tables S3 and S5 in the Supplement, respectively.

2.4 Partitioning of the uncertainty budget associated with crop production changes

To separate the climate model induced uncertainty from the impact model uncertainty the GGCM-specific spread of the relative crop production changes at different levels of global warming is estimated by the standard deviation of the GGCM-specific mean values calculated over all climate model- (and RCP-) specific individual values (e.g. colored dots in Fig. 2) or all water-model-specific individual values in case of

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the production under maximum irrigation. The climate model or water-model-induced spread is estimated as the standard deviation over the individual deviation from these GGCM means.

3 Results

3.1 Adaptive pressure on future food production

Crop models project a wide range of relative changes in global wheat, maize, rice and soy production at different levels of global warming and associated CO_2 concentrations (first column of each global mean warming box in Fig. 2). At 4 °C the GGCM spread is more than a factor 5 larger than the spread due to the different climate models (estimated as described in Sect. 2.4) (wheat: 13 % vs. 2 %, maize: 18 % vs. 2 %, rice: 33 % vs. 2 %, and soy: 28 % vs. 4 %). This is partly due to the bias correction of the climate projections, which includes a correction of the historical mean temperature to a common observational data set (Hempel et al., 2013), and may depend on the selection of the three GCMs. However, the results suggest that the inter-crop-model spread will also be a major component of the uncertainty distribution associated with the area of crop land required to meet future food demand.

Production changes are evaluated in the context of potential demand changes based on population and GDP projections. We consider the “middle of the road” Shared Socioeconomic Pathway (SSP2) (Kriegler et al., 2010) (red lines in Fig. 2). Despite considerable uncertainty, it is evident that even if global production increases based on optimistic assumptions about CO_2 fertilization, this effect alone is unlikely to balance demand increases driven by population growth and economic development (assuming that the observed relationship between per capita consumption patterns and incomes holds in the future and ignoring demand-side measures; Foley et al., 2011; Parfitt et al., 2010). In terms of the risk-assessment framework, the projections mean that there is a probability of 100 % that the considered present-day LU and default management as implemented in the models is not sufficient to meet the estimated food demand in 2050.

All GGCMs show a quasi-linear dependence on global mean temperature across the three different climate models, considered scenarios and range of global mean temperature changes (Figs. S5–S6 in the Supplement). Values range from −3 to +7 % °C^{-1} for wheat, −8 to +6 % °C^{-1} for maize, −4 to +19 % °C^{-1} for rice and −8 to +12 % °C^{-1} for soy (Table S2 in the Supplement, cf. Rosenzweig et al., 2014 for an update of the IPCC-AR4 Table 5.2 (Easterling et al., 2007)). It is not necessarily clear that crop-production changes can be expressed in a path-independent way as a function of global mean temperature change. In particular, CO_2 concentrations are expected to modify the relationship with global mean temperature. However, for the 7 GGCMs and the RCP scenarios considered here the path dependence is weak (Figs. S1-S4 in the Supplement). This suggests that the red pdfs shown in Fig. 1 could also be determined for specific global warming (and CO_2) levels, but relatively independent of the specific pathway.

The disagreement in the sign of the change in crop production in Fig. 2 arises predominantly from differences in the strength of the CO_2 fertilization effect. Projections based on fixed CO_2 levels show a smaller spread and a general decrease in global production with increasing global warming (Table S2 and Fig. S6 in the Supplement). Given the ongoing debate about the efficiency of CO_2 fertilization, in particular under field conditions (Leakey et al., 2009; Long et al., 2006; Tubiello et al., 2007), and the fact that most models do not account for nutrient constraints of this effect, projections are likely to be optimistic about the growth-promoting effects of increased atmospheric CO_2 concentrations.

3.2 Irrigation potential

Using different means of intensifying crop production on existing crop land, the red uncertainty distributions in Fig. 1 can be shifted to the left. For example, we discuss the potential production increase due to expansion of irrigated areas based on water availability, using only present-day agricultural land. The effect is constrained by

(1) biophysical limits of yield response to irrigation, and (2) water availability. For illustrative purposes we assume that irrigation water (plus a minor component of water for industrial and household uses) is limited to 40 % (Gerten et al., 2011) of the annual runoff integrated over the area of one Food Production Unit (FPU; Kummu et al., 2010). In addition, we assume a project efficiency of 60 %, where 60 % of the irrigation water is ultimately available for the plant. Runoff projections are based on 11 hydrological models participating in ISI-MIP (Table S3 in the Supplement). The available water is distributed according to where it leads to the highest yield increases per applied amount of water, as calculated annually. The approach only accounts for renewable surface and groundwater (for details of the method see Supplement).

While potential expansion of irrigation (or reduction, in the case of insufficient water availability for full irrigation of currently-irrigated areas) could compensate for the climate-induced adaptive pressure projected by some GGCMs (second column of each global mean warming level in Fig. 2), the feasible increase in global production is insufficient to balance the relative increase in demand by the end of the century. For example, the production gap that needs to be overcome through additional technological progress or land-use changes amounts to 60 % (40–70 %) (median, min and max based on the GGCM-specific dots in Fig. 2) at 2 °C in 2050 for wheat w.r.t. average 1980–2010 production. In the case of rice, which is to a large extent already irrigated (Fig. S3 in the Supplement), the imposed water limitation reduces production in comparison to full irrigation on currently irrigated areas for some of the GGCMs (see Elliott et al., 2013 for a more detailed discussion of limits of irrigation on currently irrigated land).

In terms of Fig. 1, additional irrigation shifts the red uncertainty distributions to the left. However, even with this shift, it remains unlikely that the currently cultivated land will be sufficient to fulfill future food demand.

The spread of projections of global crop production under additional irrigation is dominated by the differences between GGCMs rather than the projections of available water (the partitioning of uncertainty is described in Sect. 2.4). Based on the HadGEM2-ES, RCP8.5 climate projections, the GGCM-induced (5 models provide the necessary information) spread at 4 °C is at least a factor of 4 larger than the spread induced by the hydrological models (wheat: wheat: 17 % vs. 4 %, maize: 21 % vs. 3 %, rice: 36 % vs. 2 %, soy: 41 % vs. 3 %).

The production levels shown in Fig. 2 do not reveal whether the increase is mainly biophysically limited by potential yields under full irrigation, or by water availability. Further analysis (Fig. S7 in the Supplement) shows that production under the highly optimistic assumptions regarding water distribution is relatively close to production under unlimited irrigation on present day crop areas with the exception of wheat. In addition, we calculated the distance from rainfed production and production under full irrigation for different project efficiencies (see Fig. S8 in the Supplement), respectively.

3.3 Effect of LU changes on global crop production

Intensification options are certainly not exhausted by additional irrigation. For example, other possibilities include improved fertilizer application, switching to higher yielding varieties, or implementing systems of multiple cropping per year. Historically, most of the long-term increase in crop demand was met by a variety of intensification options (Godfray et al., 2010b; Tilman et al., 2011). However, the expansion of arable land may become more important in light of further increasing demand and possibly saturating increases in crop yields (Alston et al., 2009; Lin and Huybers, 2012). A recent study (Ray et al., 2013) suggests that observed increases in yields will not be sufficient to meet future demand.

To illustrate the potential to increase yields via land-use change, we apply a LU pattern generated by the agro-economic LU model MAgPIE for the year 2085 (Sect. 2.2) in combination with the water distribution scheme discussed above (see third column of each global mean warming bin in Fig. 2). There is a very large spread in the relative changes in crop production w.r.t. 1980–2010 reference values, reaching standard deviations of 31 % for wheat, 84 % for maize, 80 % for rice, and 79 % for soy at 4 °C, and in one case even leading to a reduction in production. That may be due to the fact that MAgPIE's optimization scheme results in highly concentrated agricultural patterns by 2085, exaggerating regional features of the GGCM simulations (Figs. S9–S12 in the Supplement). The relative increase in production by some crop models exceeds the projected demand increase. However, in spite of the strong expansion of cultivated land, with particularly high losses in the Amazon rainforest (see Fig. S14 in the Supplement), the lower ends of the samples still do not balance the projected demand increase in 2050 (except for wheat). In terms of Fig. 1 these results indicate a very wide uncertainty distribution associated with the area required for food production. The level of expansion given by the MAgPIE pattern does not seem to be sufficient to fulfill the future demand with high confidence.

3.4 Effect of LU changes on natural carbon sinks and stocks

The increase in production by LU changes comes at the cost of natural vegetation. The considered illustrative reduction of the area of natural vegetation reaches 480 Mha in 2085 compare to 1995 levels. To estimate the associated potential loss of carbon sinks, the ecosystem-atmosphere carbon flux is spatially integrated over, (1) the 1995 area of natural vegetation provided by MAgPIE in each year; and (2) the shrinking area of natural vegetation. Biophysical simulations are based on HadGEM2-ES and RCP8.5. For all but one vegetation model (Hybrid) the reduction of the area of natural vegetation (Fig. 3) means a loss of carbon sinks. There is a wide spread in losses, in some cases reaching 50 % compared to the reference period (see Table 1). For the Hybrid model natural vegetation turns into a carbon source over the fixed 1995 area of natural vegetation by mid-century (cf. Friend et al., 2013) (Fig. S15 in the Supplement), which means that a reduction in natural vegetation leads to an increase in the global carbon sink. Our approach does not account for the carbon released from soil after LU changes (Smith, 2008). While agricultural land can be considered as carbon neutral to first order (cultivated plants are harvested and consumed), the conversion process emits carbon to the atmosphere as soil carbon stocks typically degrade after deforestation (Müller et al., 2007). The direct reduction of the vegetation carbon stock reaches a multi-model median of about 85 Pg (about 8.5 years of current CO_2 emissions) by the end of the century. Results for the experiments with fixed present-day CO_2 are shown in Fig. S16 in the Supplement.

4 Discussion and conclusion

The competition between food security for a growing population and the protection of ecosystems and climate poses a dilemma. This dilemma is fundamentally cross sectoral, and its analysis requires an unprecedented cross-sectoral, multi-impact-model-analysis of the adaptive pressures on global food production and possible response strategies. To date, a full quantification of the probability distributions necessary to address the issue in a risk-assessment framework has been inhibited by the lack of cross-sectorally consistent multi-impact-model projections. Here, simulations generated within ISI-MIP were applied to achieve the first steps to address the gap.

The spread across different impact models is shown to be a major component of the uncertainty of climate impact projections. In the case of multiple interests and conflicting response measures this uncertainty means a dilemma as ensuring one target with high certainty means putting another one at particularly high risk.

For a full quantification of the probability distributions illustrated in Fig. 1 multiple crop models, simulations and projections of socio-economic development have to be translated into a pdf of the "required food production area" accounting, for example, for changing trade patterns (Nelson et al., 2013). This integration has already started within the AgMIP-ISI-MIP cooperation and will enable the generation of a probability distribution of the required food production area. However, current estimates (Nelson et al., 2013) are based on crop model runs that do not account for the CO_2-fertilization effect and only a limited number of models provide explicit LU patterns in addition to the aggregated area.

To estimate the associated risk for climate protection, carbon emissions due to the loss of natural carbon sinks and stocks, particularly including effects of soil degradation, must be quantified. Therefore, the set of demand-fullfilling LU-patterns has to be provided as input for multi-model biomes simulations. ISI-MIP is designed to facilitate this kind of cross-sectoral integration, which can then be employed to fulfil the urgent demand for a comprehensive assessment of the impacts of climate change, and our options to respond to these impacts and socio-economic developments, along with the corresponding trade-offs.

Our illustration of the uncertainty dilemma is by no means complete. In addition to the irrigation scheme considered here, a more comprehensive consideration of management options for increasing crop yields on a given land area is required. To this end, the representation of management within the crop model simulations needs to be harmonized to quantify the effect of different management assumptions on crop-model projections. These effects of these assumptions should be considered separately to the crop-model spread due to uncertain representation of biophysical processes.

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Table 1. Maximal loss of carbon sinks and the vegetation carbon stock as estimated for the illustrative LU change scenario (based on colored lines in panel a and b of Fig. 3). The maximum of the transient changes (column 2 and 4) is compared to mean values of the C-fluxes and the C-stock averaged over the reference period 1980–2010 (column 3 and 5).

Model	Max ΔC sink [Pg yr^{-1}]	Ref [Pg yr^{-1}]	Max ΔCveg [Pg]	Ref [Pg]
LPJmL	0.5	−1.4	86	201
JULES	0.1	−0.6	67	148
JeDI	0.4	−0.7	89	141
SDGVM	0.3	−0.6	89	161
VISIT	0.3	−0.7	57	126
ORCHIDEE	0.5	−0.7	121	224
Hybrid	0.0	−0.6	32	137

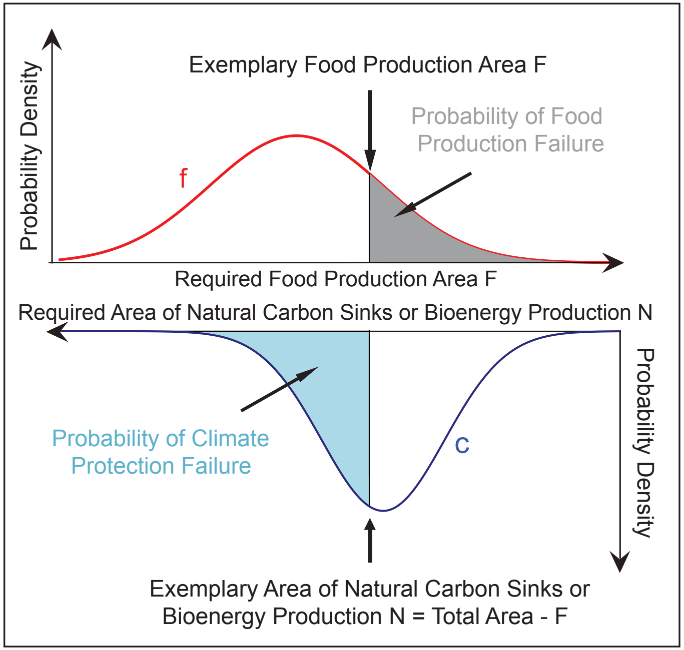

Figure 1. Land use changes in a risk assessment framework. Red pdf: uncertainty associated with the area of crop land required to fulfill future food demand. Blue pdf: uncertainty associated with the (natural) carbon sinks and stocks required to ensure climate protection.

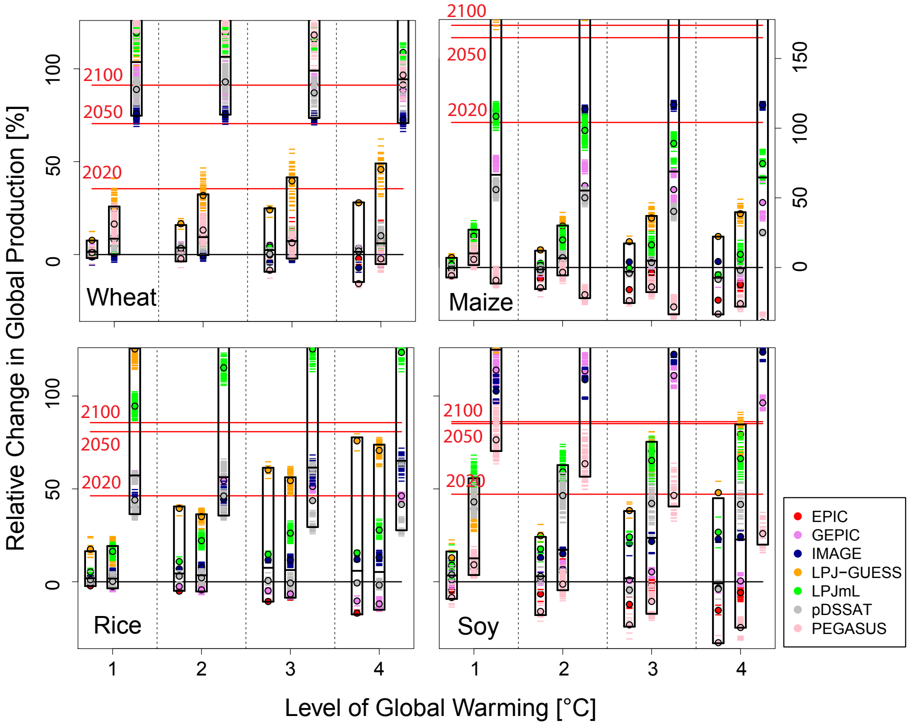

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Figure 2. Adaptive pressure on global crop production and effects of irrigation and LU adaptation. Relative changes in crop global production (wheat, maize, rice, soy) at different levels of global warming with respect to the reference data (global production under unlimited irrigation on currently-irrigated land; averaged over the 1980–2010 reference period). Horizontal red lines indicate the relative change in demand projections for the years 2020, 2050, and 2100 due to changes in population and GDP under SSP2. First column of each global mean warming block: change in global production under fixed current LU patterns assuming unlimited irrigation restricted to present-day irrigated land. Second block: relative change (w.r.t. reference data) in global production assuming potential expansion of irrigated land accounting for irrigation water constraints as projected by 11 water models (for details see Supplement). Third column: based on the same water distribution scheme as column 2 but applied to the 2085 LU pattern provided by MAgPIE. EPIC is excluded from the LU experiment as simulations are restricted to present-day agricultural land. Color coding indicates the GGCM. Horizontal bars represent results for individual climate models, RCPs, GGCMs, and hydrological models (for column 2 and 3). Colored dots represent the GGCM-specific means over all GCMs and RCPs (and hydrological models). Black boxes mark the inner 90 % range of all individual model runs. The central black bar of each box represents the median over all individual results.

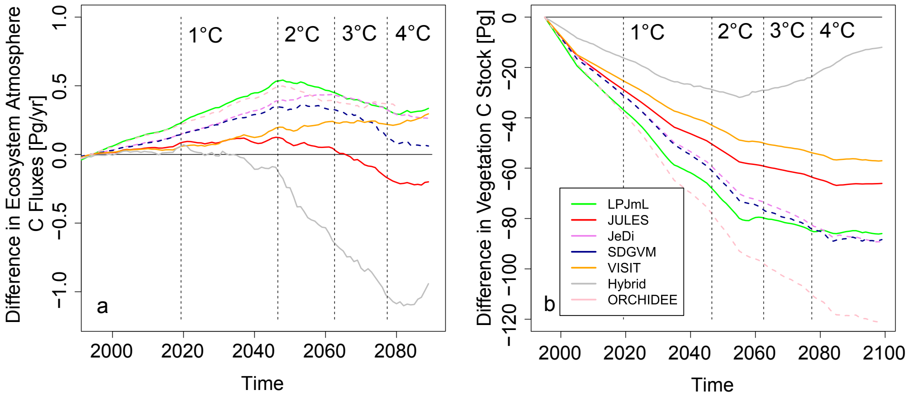

Figure 3. (a) Loss of carbon sinks (ecosystem-atmosphere C flux) due to reduction of natural vegetation and **(b)** associated changes in the vegetation C stock (Cveg). Colored lines represent 20 year running means of the differences of these variables between the LU change scenario and the reference scenario (fixed 1995 area of natural vegetation). Positive values indicate higher ecosystem-atmosphere C fluxes and a reduction in Cveg under LU change, respectively. Color coding indicates the different bio-geochemical models. Solid (dashed) lines represent simulations based on dynamic (static) vegetation patterns. Results are based on the historical and RCP8.5 simulations by HadGEM2-ES. Dashed vertical lines: years where the global mean temperature change with respect to 1980–2010 reaches 1, 2, 3, and 4 °C.