



Uncertainty in crop production and its role in mitigation planning

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

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efficiency shifts the distribution right as less CO₂ 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 CO₂ 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?

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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 CO₂-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 CO₂ 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

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 CO₂ 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 CO₂ 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

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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 $+7\% \text{ } ^\circ\text{C}^{-1}$ for wheat, -8 to $+6\% \text{ } ^\circ\text{C}^{-1}$ for maize, -4 to $+19\% \text{ } ^\circ\text{C}^{-1}$ for rice and -8 to $+12\% \text{ } ^\circ\text{C}^{-1}$ 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

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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

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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 ΔC_{veg} [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

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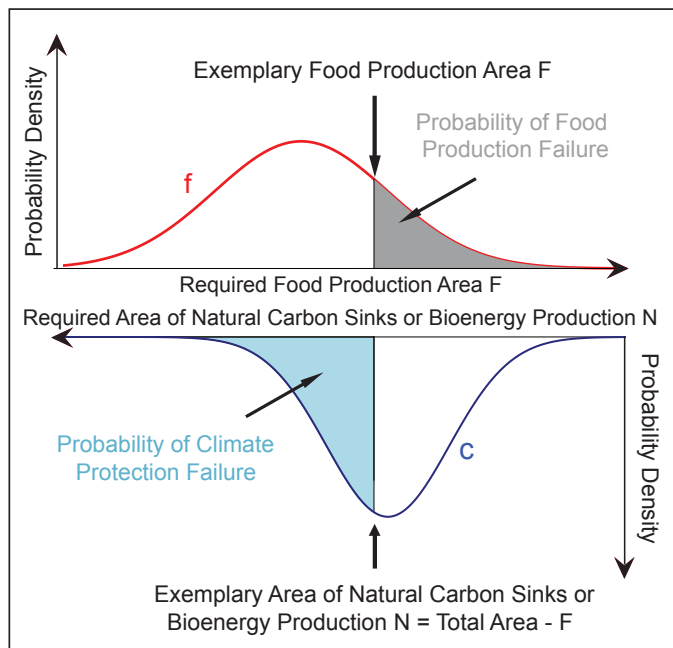
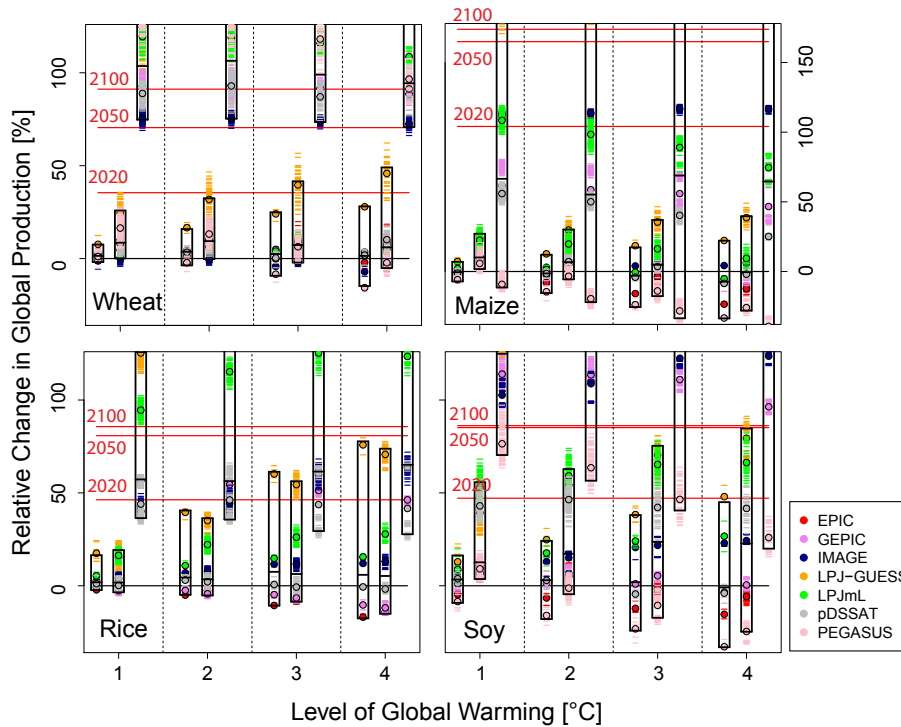


Figure 1. Land use changes in a risk assessment framework. Red pdf: uncertainty associated with the area of crop land required to fulfill future food demand. Blue pdf: uncertainty associated with the (natural) carbon sinks and stocks required to ensure climate protection.

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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.

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