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Feeding 10 billion people under climate change: How large is the production gap of current agricultural systems?

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ABSTRACT

The human population is projected to reach more than 10 billion in the year 2100. Together with changing consumption pattern, population growth will lead to increasing food demand. The question arises whether or not the Earth is capable of fulfilling this demand. In this study, we approach this question by estimating the carrying capacity of current agricultural systems (K_C), which does not measure the maximum number of people the Earth is likely to feed in the future, but rather allows for an indirect assessment of the increases in agricultural productivity required to meet demands. We project agricultural food production under progressing climate change using the state-of-the-art dynamic global vegetation model LPJmL, and input data of 3 climate models. For 1990 to 2100 the worldwide annual caloric yield of the most important 11 crop types is simulated. Model runs with and without elevated atmospheric CO_2 concentrations are performed in order to investigate CO_2 fertilization effects. Country-specific per-capita caloric demands fixed at current levels and changing demands based on future GDP projections are considered to assess the role of future dietary shifts. Our results indicate that current population projections may considerably exceed the maximum number of people that can be fed globally if climate change is not accompanied by significant changes in land use, agricultural efficiencies and/or consumption pathways. We estimate the gap between projected population size and K_C to reach 2 to 6.8 billion people by 2100. We also present possible caloric self-supply changes between 2000 and 2100 for all countries included in this study. The results show that predominantly developing countries in tropical and subtropical regions will experience vast decreases of self-supply. Therefore, this study is important for planning future large-scale agricultural management, as well as the critical assessment of population projections, which should take food-mediated climate change feedbacks into account.

1. Introduction

The Earth currently sustains about 7 billion people. Their demand for food, fiber, energy, and industrial products already now exceeds many of the provisioning and regulatory services of the planetary system (Rockström et al., 2009). According to recent estimates of the United Nations (2011), the world population is expected to increase to 9.3 billion in 2050 and to reach about 10.1 billion by 2100. The question to be answered here is: can these projected numbers be fed under climate change and changing consumer behavior without expanding cropland area or significantly improving agricultural management and technology?

We assess this crucial question by revisiting the long-standing debate on the human carrying capacity of planet Earth (K). According to the analysis of Cohen (1995a,b) the median of all estimations of K published up to 1995 ranged between 7.7 to 12 billion people. Acknowledging that K is effectively determined by many different factors ranging from biophysical boundaries (e.g., land and energy availability) to socio-economic developments (e.g., the rate of technological progress and wealth distribution), we consider caloric food supply as the sole limiting factor here (similar to Franck et al., 2010) but constrain our estimates to current (year 2000) land use patterns and management intensity, which we refer to as the carrying capacity of current land use systems, K_C. Our estimates of K_C should not be understood as direct predictions of how many people

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the Earth will be able to support in the future. Instead, they point to potential future gaps between food supply and demand, which may result from climate change, population growth and increasing per-capita consumption, if agricultural practices are not adapted accordingly.

We compute K_C for different global warming and diet shift scenarios spanning 1990–2100. We do not apply yield transfer functions (regression functions of crop yield responses on climate based on previous simulations; e.g. Parry et al., 2004), but we compute global caloric production using the dynamic global vegetation model LPJmL which includes crops and pasture (Bondeau et al., 2007; Sitch et al., 2003). Recent studies show that projections of agricultural production are sensitive to differences in climate projections of various climate models, which is often explained by distinct precipitation patterns (Gornall et al., 2010). Therefore, we use projections of 3 different climate models to estimate the importance of uncertainty in climate change projections for estimates of K_C. Furthermore, since yield projections can depend strongly on the effectiveness of CO_2 fertilization (Parry et al., 2004; Nelson et al., 2009; Gornall et al., 2010) we explore these uncertainties by calculating all scenarios with and without the direct effects of rising atmospheric CO_2 concentrations on plant growth.

To assess the role of diet shifts with increasing income (e.g. Popp et al., 2010), K_C is estimated using country-specific present-day food demands (according to FAOSTAT) as well as changing demands e.g. of animal products based on future projections of country-specific gross domestic product (GDP). Population growth, effects of economic growth on lifestyles, and impacts of climate change on yields will differ strongly around the globe, especially between developed and developing countries (e.g. Reilly et al., 2001; Darwin and Kennedy, 2000; Parry et al., 2004). To examine national and regional differences we also present possible caloric self-supply change between 2000 and 2100 for all countries included in this study.

2. Methods

2.1. Dynamic global vegetation model LPJmL

LPJmL is a process-based ecosystem model that simulates the growth, production and phenology of 9 plant functional types (PFTs representing natural vegetation at the level of biomes; Sitch et al., 2003), 11 crop functional types (CFTs) and managed grass (Bondeau et al., 2007). Plant productivity is modeled via leaf-level photosynthesis that responds to the photosynthetic pathway (C3/C4), climate conditions, atmospheric CO_2 concentrations and canopy conductance (Farquhar et al., 1980; Collatz et al., 1991, 1992; Haxeltine and Prentice, 1996), autotrophic respiration, phenology (Bondeau et al., 2007; Sitch et al., 2003) and management intensity. The phenology and management dates (sowing and harvest) of the different crop types are simulated dynamically based on crop-specific parameters and past climate experience, allowing for adaptation of varieties and growing periods to climate change (Waha et al., 2012). Technical coefficients for the representation of management intensity and production efficiency in this study are based on Fader et al. (2010). We assumed limited irrigation constrained by surface water supply (Rost et al., 2008).

2.2. LPJmL settings and runs

For all model runs land-use patterns and local specification of agricultural management levels were set to the year 2000 (Fader et al., 2010). This approach keeps agricultural area and management levels constant and implies that K_C depends on climate impacts, CO_2 fertilization and diet shifts only. Climatic parameter inputs for LPJmL were obtained from 3 general circulation models (GCMs): CCSM3 (Collins et al., 2005; National Center for Atmospheric Research), Echam5 (Roeckner et al., 2003, Max-Planck-Institute for Meteorology) and HadCM3 (Gordon et al., 2000; UK Meteorological Office), which were chosen for their ability to accurately reproduce current temperatures and precipitation. Climate scenarios corresponded to the relatively high-emission scenario SRES A2 of the IPCC (Nakicenovic et al., 2000), with global mean temperatures rising by 4.6–4.9 °C above pre-industrial levels until 2100.

To investigate a possible CO_2 fertilization effect, each LPJmL model run was performed twice: One run with rising CO_2 concentrations (according to the SRES A2 scenario) and the other with fixed CO_2 concentrations of the year 2000 (disabling additional CO_2 fertilization). LPJmL delivered an annual harvested caloric amount for each country in the study period from 1990 to 2100 by summing up the produced calories in the respective grid cells. Crop yields were converted into caloric yields as in Franck et al. (2010) after Wirsenius (2000) and FAO (2001).

2.3. Caloric demand calculations

For each country i, the per-capita caloric demand (C_i, kcal cap^{-1} d^{-1}) was calculated according to

$$C_i = (1 - a_i)S_i + \nu a_i S_i \tag{1}$$

where S_i is the country-specific total per-capita caloric consumption (kcal cap^{-1} d^{-1}), a_i is the country-specific share of animal products in per-capita caloric consumption, and ν is the conversion factor of transforming vegetal into animal calories. C_i is expressed as vegetal calories (as derived from crops and pasture; see Section 2.4), accounting for the vegetal calories consumed both directly, and indirectly as meat and/or other animal products. C_i is always larger than S_i due to the conversion losses related to meat production. The conversion factor ν was fixed at 5, which is a rough average from a variety of conversion factors for pork, cattle and poultry under different feeding treatments (Smil, 2000), weighted by the respective global meat production in 2000 (FAOSTAT, 2011b).

When food demand was fixed at present-day levels, C_i was set to the value of the year 2000. When food demand was assumed to change, projections of S_i and a_i were derived from projections of country-specific per-capita GDP (G_i) for 1990 to 2100 using the following log–linear relationships:

$$S_i = 729.2 + 587.8 \log_{10}(G_i) \tag{2}$$

$$a_i = -0.255 + 0.132 \log_{10}(G_i) \tag{3}$$

These relationships were established by fitting pooled country-specific data for 1961–2007, and explain approximately 58% and 60% of the observed variability in globally pooled S_i and a_i, respectively (Fig. 1). Data of per-capita GDP expressed as current US$ was taken from the World Bank data base (World Bank Indicators, 2011) and converted into 1990 US$ to match with GDP projections. Food consumption data was taken from FAOSTAT (2011a). It represents the calories available at the retail level, thus potentially including calories wasted by the consumer. Projections of per-capita GDP for 1990–2100 corresponded to the SRES B2 scenario downscaled and aggregated at country-level by Columbia Earth Institute (Center for International Earth Science Information Network, 2002). SRES B2 was chosen because its underlying assumption on population growth (with around 10 billion people in 2100) corresponded well with the most recent UN population projections (United Nations, 2011) also used in this study. Projections of S_i, a_i, and C_i are shown in Figs. 2 and 3.