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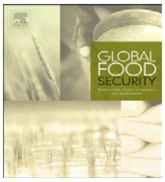

Integrating the complexity of global change pressures on land and water

Christoph Müller*, Hermann Lotze-Campen

Potsdam Institute for Climate Impact Research, Telegraphenberg A51, D-14473 Potsdam, Germany

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Global agriculture is facing multi-faceted challenges, interacting with changing societies and changing environmental conditions. Major transitions in current agricultural systems are required to meet these challenges. Transition pathways need to be analyzed and facilitated in a much broader perspective, including the interaction with societal structures, non-food markets, and the Earth system. Especially the globalization of agricultural production offers potentials to increase productivity but can also endanger food security through volatile food prices or dispossession of rural poor. It thus requires better regulation and suitable institutional settings. Integrated assessment models are helpful tools for analyzing the complex interactions and for deriving multi-targeted development pathways.

1. Introduction

Land and water, the most basic resources in food production have attracted much attention in the global change debate for various reasons. Most obviously, there is the question of how we will be able to feed a growing population (Lutz and Samir, 2010) that is increasingly demanding higher quality food and higher shares of livestock products (Kearney, 2010; Rask and Rask, 2010). Availability of freshwater and land is limited, and not only food production is claiming its share, the demand for forest and wood products is still increasing, although at low rates (Ajani, 2011). Land is also needed to conserve the natural treasures of wilderness, biodiversity, and to provide other ecosystem services (Millennium Ecosystem Assessment, 2005). We use increasing shares of land for expanding settlements and infrastructure (Seto et al., 2011). The scarce resources of fertile land and freshwater are also diminished by non-sustainable use. About 2 billion hectares of the global land surface, more than the world's total cropland have been degraded already by overgrazing, deforestation, over-exploitation, and non-sustainable agricultural practices (Oldeman, 1994).

Climate change will lead to changes in the patterns of land productivity (Müller et al., 2009) and freshwater availability (Gerten et al., 2011). There may be regions in which land will become more productive, especially in those areas where plant growth is currently constrained by cold temperatures, while in others there is considerable risk that productivity will go down significantly or that the land will become unsuitable for agricultural production (Müller et al., 2011 and references therein). Besides these direct impacts of climate change on land and water resources, there is also an indirect but yet very important mechanism, through which climate change puts pressure on these precious resources: energy from biomass, often referred to as *bioenergy*.

Plants are cheap and effective means to harvest and store energy from the sun. They extract carbon dioxide (CO_2) from the atmosphere during growth and store it in form of sugars and other carbohydrates (cellulose, lignin, etc.). When biomass or its derivatives such as ethanol are burnt, the previously absorbed CO_2 is emitted to the atmosphere again. Such usage of biomass constitutes in theory a carbon-neutral source of energy. There are, however, multiple mechanisms that undermine the carbon neutrality (Searchinger et al., 2008), e.g., if the cultivation of biomass causes a net carbon flux from the soil carbon stocks to the atmosphere (Carlson et al., 2012; Page et al., 2002; van der Werf et al., 2009) or a reduction of the carbon sequestration capacity (Gitz and Ciais, 2004). Moreover, nutrients are removed at harvest and need to be replaced at high energy costs (Bouwman et al., 2009), and the former use of land may be driven into pristine ecosystems (so-called *indirect land-use change*, such as in the Amazon (Barona et al., 2010; Lambin and Meyfroidt, 2011)). Bioenergy production may lead to increasing intensity in overall agricultural production which causes additional net emissions due to nitrogen fertilization (Popp et al., 2011a).

The likelihood of limiting global warming to no more than 2 degrees centigrade above preindustrial levels, in order to avoid dangerous climate change (Smith et al., 2009), decreases with growing total greenhouse gas (GHG) emissions (Meinshausen

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* Corresponding author.
E-mail address: Christoph.Mueller@pik-potsdam.de (C. Müller).

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et al., 2009). Without effective measures to reduce GHG emissions, humanity is set to exceed the total emission budget for the 21st century, allowable under the 2°-target, already within a few decades (Meinshausen et al., 2009). If harmful climate change impacts are to be avoided, there is a growing need for ''negative emissions'', that is, to extract CO_2 directly from the atmosphere. Bioenergy, even if not as carbon-neutral as in theory (e.g., Havlík et al., 2011; Melillo et al., 2009; Wise et al., 2009), can actively pump CO_2 from the atmosphere if combined with carbon capture and storage (CCS) technologies. In principle, CO_2 exhaust from burnt biomass can be extracted and stored in geological formations such as depleted reserves of oil or gas. However, CCS has not been proven at a commercial scale and is still being debated (Rubin et al., 2005). Projections of energy supply and mitigation options show that there is high demand for vast quantities of biomass in combination with CCS, especially for ambitious emission reduction targets (Knopf et al., 2011).

Given these pressures on land and water resources, we here discuss general options to increase agricultural productivity and modeling tools that can help in understanding and analyzing the complex dynamics of land-use change. Future development needs become evident from current modeling capabilities and identified drivers.

2. Options for improving global agricultural productivity

People have repeatedly discussed the *carrying capacity* of the planet Earth, following up on the work of Antonie van Leeuwenhoek in the 17th century. The carrying capacity debate aims at quantifying the maximum human population that can be sustained by the planet indefinitely without permanently damaging the ecosystems on which they depend. This debate is of academic nature with little practical meaning as many assumptions are needed that strongly determine the results (e.g. availability of capital, energy, and technologies) (Müller et al., 2010) so that estimates are extremely broad (Cohen, 1995; Franck et al., 2011). However, the inverse of the carrying capacity question is of significant and political relevance (Wirsenius et al., 2010). How much land, water, capital, and technological progress do we need to sustain current and projected future populations in a sustainable way? To some extent, these four factors can substitute each other: if lack of irrigation water reduces crop yields, production can still be increased if more land is cultivated, money can buy more labor or mechanization to increase productivity and thus decrease requirements in land and water.

As production needs to be increased but land and water are in limited supply, there is a strong demand to increase land and water productivity, if agriculture is not to be extended to highly artificial environments (Germer et al., 2011). Land productivity is determined by the crop yield (measured in biomass, energy, or monetary units per unit of area) and the frequency of cultivation (also referred to as land-use intensity, measured in harvests per unit of time), which accounts for fallow periods within the crop rotation and multiple cropping cycles within one year. Consequently, an increase in land and water productivity can be achieved either by supplying additional inputs (such as fertilizers or pesticides) or by increasing total factor productivity, e.g. by improved management of the given set of inputs, such as timing of fertilizer or irrigation water applications (e.g., Zaks and Kucharik, 2011), targeted breeding or other types of agricultural research (Dietrich et al., 2012), such as during the *green revolution* (Evenson and Gollin, 2003), and the reduction of fallow periods (e.g., Li et al., 2012). The challenge to increase productivity of current agricultural land is, however, substantial: within 50 years, land productivity needs to increase by $\sim$70% globally (Lotze-Campen et al., 2010). Compared to the historic development of 1.4% per year (i.e. doubling in 50 years) from 1970 to 2005 (FAOSTAT data, 2011), this may not seem too dramatic, but increases in productivity have stalled for many major crops and production areas over the last decade (FAOSTAT data, 2011; Lin and Huybers, 2012) and investment in agricultural research has stagnated (Alston et al., 2009; Beintema and Stads, 2010). In the future, pressures on agriculture and the competition for land and freshwater may accumulate, as a consequence of the combined effects of increased demand for food and other land-based products, unfavorable climate impacts, and limited availability of land (Lotze-Campen et al., 2009). These challenges can only be met by strongly and continuously investing in agricultural research and development (R&D), rural education, and extension services. While in most developing countries the largest share of the required investments will have to come from public sources, the contribution of the private sector is increasing over time and with the level of development (Pardey et al., 2006). Foreign direct investment in agriculture could also play a role (see below).

In a globalized world, higher input use efficiencies (fertilizers, pesticides, etc.) can be complimented by improved spatial allocation. As environmental conditions (soils and climate) are variable around the globe, one option to increase land productivity at the global scale would be to optimize and re-allocate spatial agricultural production patterns. Such spatial concentration of agricultural production has also been proposed to supply additional land for nature conservation (Goklany, 1998; Green et al., 2005). As demonstrated in an academic exercise (Müller et al., 2006), this would theoretically yield much potential to reduce the land requirements of agriculture. However, an implementation of such improved spatial allocation of land use through, e.g., reduced trade barriers could also lead to unwanted side-effects, such as large-scale deforestation (Schmitz et al., 2012).

A global land-use transition with the aim to reduce inefficient production patterns is, however, also quite challenging: as far as benefits of diversified land-use patterns (pest control, nutrient cycles, risk minimization, prevention of erosion, etc.) can be compensated by technological solutions, these typically have unwanted side-effects. These include negative externalities to other ecosystems or spheres of the Earth System, such as the eutrophication of water bodies (Monteagudo et al., 2012) or greenhouse gas emissions to the atmosphere (Smith et al., 2008), but also environmental impacts on the agro-ecosystem. These reflect the lack of sustainable management practices and include soil erosion (Van Oost et al., 2006), salinization in irrigated areas (Singh, 2009), nutrient depletion (Flora, 2010; MacDonald et al., 2011) and compaction of soils (Batey, 2009), accumulation of pesticides (Pretty et al., 2010) and loss of biodiversity (e.g. Underwood et al., 2009).

Increasing land productivity at the global scale is not only a question of improved management options. There are many more open questions that have not been addressed in sufficient detail in recent literature (Foley et al., 2011; Tilman et al., 2011): How strongly is a transition of land-use systems inhibited by existing societal systems that may need to be changed even though only loosely connected to the land sector? Analogous to the history of the development of typewriter and computer keyboards (*QWERTY phenomenon*), current land-use systems represent to some extent locked-in systems. They have developed under constraints of which some are no longer binding (e.g. very inter-regional exchange), but cannot easily transform as transition costs (e.g. investment costs, cultural habits, knowledge) are much higher than the short-term benefits. As such, it may prove difficult to transform agricultural production systems if the focus is only on agriculture. The agricultural transition in developed countries has not been sufficiently analyzed with respect to the societal