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Environmental flow provision: Implications for agricultural water and land-use at the global scale

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ABSTRACT

Human activity has led to freshwater ecosystem degradation in the past and is likely to continue doing so if no appropriate protection mechanisms are implemented. One potential protection measure is the reallocation of water from human use to environmental purposes – also called environmental flows. Such reallocation may decrease the availability of irrigation water with possible adverse effects on agricultural production. In this analysis, we provide an initial quantitative estimate of how the allocation of annual volumes of water for environmental flow protection (EFP) might influence the food production system on a global scale. The application of a spatially explicit global land and water-use allocation model (MAgPIE) allows us to explore the effect of EFP on agricultural water withdrawals. We will also examine associated reactions in terms of land-use changes and agricultural intensification. Our results suggest that the implications of conserving annual volumes of water for EFP on the land-use system are moderate on an aggregate global level. Cropland expansion into unmanaged land arising from increased food demand up to 2045 is higher by a factor 5–9 than cropland expansion induced by EFP. Global forest losses associated with EFP remain below 1% of current forest area. Production reallocation and associated land-use change hotspots suggest that local effects are of more concern than aggregate cropland expansion and deforestation.

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1. Introduction

Freshwater is indispensable for sustaining life on Earth and adequate freshwater availability is essential for human well-being (Oki, 2006). Direct human water abstraction includes water extracted for irrigated crop production, energy production, industrial fabrication, and domestic purposes (Flörke et al., 2013). Additionally, humanity benefits from a variety of services provided by freshwater ecosystems. These include the provision of fish, other food and fiber, water purification, erosion protection, biodiversity conservation and cultural and recreational benefits (Poff et al., 2010; UNESCO, 2009). The third World Water Development Report by UNESCO (2009) highlights that the economic value of freshwater ecosystem services exceeds $600 million in Uganda alone and that 10% of undernourished people depend on freshwater ecosystem services across developing countries.

At the same time, it is widely recognized that human disturbance leads to degradation of freshwater ecosystems (Grafton et al., 2012; Hoff, 2009; Poff et al., 2010). It has been estimated that freshwater vertebrate populations have declined by 54% globally and that 32% of the world's amphibian species are threatened with extinction (Dudgeon et al., 2006). Increasing human water demand due to population growth and economic development is likely to put additional pressure on freshwater resources in the future (Vorosmarty et al., 2010). This has led to the call for water management strategies that explicitly recognize environmental water requirements (Falkenmark and Molden, 2008). Sustaining river ecosystems and associated livelihoods

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requires the provision of environmental flows (EFs) that ensure sufficient quantity, quality and timing of stream-flow (Poff et al., 2010). However, focusing on a single conservation goal can lead to negative feedbacks on other ecosystems (Bennett et al., 2009; Seppelt et al., 2013). Therefore, environmental flow protection (EFP) cannot be pursued in isolation but has to be put into a broader context of sustainable use of natural resources (Gerten et al., 2013).

Freshwater use for irrigation accounts for around 70% of human water withdrawals (Rost et al., 2008) and plays an important role in global food production (Naylor, 1996). Since the allocation of water resources for environmental purposes reduces available water for other uses (Falkenmark and Molden, 2008), EFP is likely to reduce water available for irrigation (Rosegrant et al., 2009; Strzepek and Boehlert, 2010). A reduction of irrigation potential may have adverse effects on food prices (De Fraiture and Wichelns, 2010) and the agricultural production required to provide sufficient food for a growing world population (Falkenmark et al., 2009; Rosegrant et al., 2009). Moreover, decreased land productivity due to irrigation water shortages may trigger cropland expansion (Lambin and Meyfroidt, 2011) at the expense of natural forests and other unmanaged land (Foley et al., 2011). Such land cover is important for a variety of ecosystem services including biodiversity conservation (Barlow et al., 2007) and carbon sequestration (Onaindia et al., 2013).

It is therefore important to assess the feedback from EFP on land-use change in order to provide the knowledge needed to design sustainable water management strategies (Pahl-Wostl et al., 2013c). While the design and implementation of EFP policies need to be tailored to local conditions (Arthington et al., 2006), it is also necessary to adopt a global point of view in order to account for non-local drivers of water and land-use such as agricultural trade, population growth and economic development (Hoekstra, 2010; Hoff, 2009). Global investigations of the effects of EFP on agriculture to date are however lacking. Strzepek and Boehlert (2010) have studied the effects of providing annual volumes of water for EFP on current agricultural water availability. However, they do not investigate, which adaptation mechanisms in the agricultural system are to be expected and what the consequences would be for global land-use change.

This article aims to provide an initial quantitative estimate of the effect on global land-use change of a reduction in water available for agriculture which would result from the allocation of water for EFP. We compare scenarios including the reservation of the annual water quantity needed for EFP to a business as usual scenario without EFP. Global land-use patterns, yield increases and agricultural water withdrawals under biophysical and socioeconomic constraints are simulated by the spatially explicit global agricultural land and water-use model MAgPIE (Model of Agricultural Production and its Impacts on the Environment) (Lotze-Campen et al., 2008; Popp et al., 2010). This setup allows us to quantify the effect of conserving annual volumes of water for EFP on agricultural water withdrawals as well as associated reactions in terms of land-use change and agricultural intensification under different future socioeconomic conditions.

2. Methods

2.1. Model description MAgPIE

2.1.1. General model description

MAgPIE is a spatially explicit global land and water-use allocation model that simulates in 10-year time steps from 1995 to 2045 using recursive dynamic optimization (Lotze-Campen et al., 2008; Popp et al., 2010). The objective function of the model is to fulfill demand for food, livestock and materials at minimum costs under biophysical and socio-economic constraints. Demand and socio-economic constraints are defined at the regional level (10 world regions, Fig. A1). Biophysical constraints enter the model at grid cell level ($0.5^\circ \times 0.5^\circ$ longitude/latitude; 59,199 grid cells). Due to computational constraints, grid-cells are aggregated to 1000 simulation units globally (Fig. A2) based on similarity of biophysical conditions (Dietrich et al., 2013). Demand scenarios are based on exogenous population, income and diet projections (Section 2.2.2). The production function takes land, water, yield information and monetary costs as inputs. MAgPIE endogenously determines cropland (rainfed and irrigated), forest and other natural vegetation patterns. Urban areas and pasture areas are assumed to be static over time and forest land is partly reserved for forestry activities and nature conservation (Section 2.2.2). Each land pool is initialized with historical patterns in 1995 (Krause et al., 2013). Crop yields (rainfed and irrigated) for 17 cropping activities, crop water demand, and water availability are provided by the global vegetation and hydrology model LPJmL (Bondeau et al., 2007; Müller and Robertson, 2014). Yields are calibrated at a regional level to meet historical FAO cropland (FAOSTAT, 2013) in 1995.

Technological improvements have helped to increase yields in the past (Fischer and Edmeades, 2010). In MAgPIE, future yield increases from technological change (TC) are modeled endogenously. Land-use intensities (τ) for each region in 1995 are derived from historical data (Dietrich et al., 2012). Yields in MAgPIE scale linearly with τ, and the model can invest in TC in order to increase τ (Dietrich et al., 2014). The investment-yield ratio (IY; investments per unit of yield growth) is determined from historical data on total agricultural research and development spending (Pardey et al., 2006), agricultural infrastructure investments (transport, energy and water distribution, telecommunication and financial services; Narayanan and Walmsley, 2008) and yield data (FAOSTAT, 2013). A regression analysis is used to estimate the elasticity of IY with respect to τ (Eq. (1)).

$$\mathrm{IY}(\tau) = (1900 \pm 400) * \tau^{2.4 \pm 0.9} \quad (1)$$

Thus, yield improvements due to TC are more costly in intensive systems with high τ values where low-cost intensification options are already implemented. Factor requirement costs (capital, labor and chemicals, e.g. fertilizer) per hectare scale linearly with τ (Dietrich et al., 2014).

Agricultural production costs comprise factor requirement costs, land conversion costs, transportation costs to the closest market, investment costs for irrigation infrastructure and investment costs for technological change. The cost minimization problem is solved through endogenous variation of rainfed and irrigated production patterns for 17 cropping activities (subject to regional trade constraints; Schmitz et al., 2012), land conversion (all at simulation unit level) and technological change (at regional level) (Lotze-Campen et al., 2010).

2.1.2. Water and irrigation representation

Water-use categories in MAgPIE include irrigation and livestock production, non-agricultural human water demand (domestic use, industrial use and use for electricity production) and environmental water requirements. Non-agricultural human water demand and environmental water requirements enter the model as exogenous scenarios (Section 2.2.2). Non-agricultural water demand is always fulfilled before agricultural water demand and thus effectively limits water availability for agriculture (similar to Elliott et al. (2013)). Livestock water demand per unit produced is derived from FAO (2005). Rainfed crop production is based on green water only (precipitation infiltrated into the soil; Rost et al. (2008)). The model can endogenously decide to apply

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