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Research Article

Livestock production and the water challenge of future food supply: Implications of agricultural management and dietary choices

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ABSTRACT

Human activities use more than half of accessible freshwater, above all for agriculture. Most approaches for reconciling water conservation with feeding a growing population focus on the cropping sector. However, livestock production is pivotal to agricultural resource use, due to its low resource-use efficiency upstream in the food supply chain. Using a global modelling approach, we quantify the current and future contribution of livestock production, under different demand- and supply-side scenarios, to the consumption of "green" precipitation water infiltrated into the soil and "blue" freshwater withdrawn from rivers, lakes and reservoirs. Currently, cropland feed production accounts for 38% of crop water consumption and grazing involves 29% of total agricultural water consumption (9990 $km^3\,yr^{-1}$). Our analysis shows that changes in diets and livestock productivity have substantial implications for future consumption of agricultural blue water (19–36% increase compared to current levels) and green water (26–69% increase), but they can, at best, slow down trends of rising water requirements for decades to come. However, moderate productivity reductions in highly intensive livestock systems are possible without aggravating water scarcity. Productivity gains in developing regions decrease total agricultural water consumption, but lead to expansion of irrigated agriculture, due to the shift from grassland/green water to cropland/blue water resources. While the magnitude of the livestock water footprint gives cause for concern, neither dietary choices nor changes in livestock productivity will solve the water challenge of future food supply, unless accompanied by dedicated water protection policies.

1. Introduction

Water is essential to all life on Earth and may be regarded as the "bloodstream of the biosphere" (Rockström et al., 1999). Current overexploitation of freshwater resources undermines biodiversity and resilience of aquatic ecosystems in many regions (Vörösmarty et al., 2010), thereby also rapidly approaching planetary boundaries for freshwater use beyond which there is a high risk for detrimental impacts on human welfare (Gerten et al., 2013; Steffen et al., 2015). Around the world, more than half of fresh and accessible runoff water is used by human enterprises (Postel et al., 1996); by far the largest share of this use (~70%) is attributable to agriculture (Rost et al., 2008). While irrigation heavily sustains global agricultural production and food security (Jägermeyr et al., 2016), 41% of current water withdrawals for irrigation tap into the environmental flow requirements needed to maintain local riverine ecosystems (Jägermeyr et al., 2017).

Human use of water is basically driven by the need to eat. In contrast to the recommended annual basic water requirements of 18 m^3 per capita for drinking, hygiene, sanitation, and food preparation (Gleick, 1996), an annual 1300 m^3 of water per capita is needed to produce a balanced diet (Rockström et al., 2007). At a closer look, the composition of diets – especially the share of animal-based products – substantially influences water requirements of food production (Jalava et al., 2014; Liu and Savenije, 2008; Rockström et al., 2007). Depending

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on the climatic conditions and production methods, 1–5 m^3 water are needed to produce 1 kg grain, whereas 5–20 times more water is required to produce 1 kg livestock products (Chapagain and Hoekstra, 2003). As in the case of humans, water for animals is primarily needed to eat rather than to drink. Water requirements for livestock drinking and servicing are very small and represent only 0.6% of global freshwater use (Herrero et al., 2009; Steinfeld et al., 2006). Therefore, how much and what kind of feed is used to produce one unit of livestock products entails important implications for livestock related water consumption.

There is substantial heterogeneity with regard to total feed efficiency (product output per feed input) and feed basket composition across different livestock production systems and levels of intensification (Herrero et al., 2013). As a consequence, shifts in production systems and improved livestock productivity are increasingly considered as an important lever to enhance resource efficiency of the livestock sector and confine the environmental burden of agriculture as a whole (Bouwman et al., 2013; Cohn et al., 2014; Havlík et al., 2014; Herrero et al., 2013; Steinfeld and Gerber, 2010; Valin et al., 2013; Weindl et al., 2015; Wirsenius et al., 2010). Changes in livestock production systems and related feed baskets do not only affect total livestock water productivity (product output per water input) (Herrero et al., 2009; Peden et al., 2007; Thornton and Herrero, 2010), but also the type of water resources involved in the production of animal feed, either "green" precipitation water infiltrated into the soil or "blue" irrigation water withdrawn from rivers, lakes and reservoirs (Hoekstra and Chapagain, 2007). Besides affecting the relative importance of blue and green water resources, production systems and feed basket composition also determine the share of water consumed on cropland and rangeland (de Fraiture et al., 2007).

While understanding livestock systems is crucial to assess the water challenge of feeding a growing and increasingly wealthy world population with changing dietary preferences towards animal-based products, several authors state that interrelations between livestock and water have widely been disregarded by both water and livestock research communities to date (Bossio, 2009; Cook et al., 2009; Herrero et al., 2009; Peden et al., 2007; Thornton and Herrero, 2010). Recently, dietary changes have climbed up the scientific agenda as an option to reduce the water requirements of food production (Gerten et al., 2011; Jalava et al., 2014; Liu and Savenije, 2008; Mekonnen and Hoekstra, 2012; Vanham et al., 2013). However, recommendations to cut down on consumption of livestock products in order to protect water resources are often based on static inventories of livestock related water consumption and resulting virtual water content of livestock products. Moreover, these studies do not account for secondary effects like shifting trade flows, altered incentives to invest in land and water productivity and reallocation of water resources between food and feed crops. To our knowledge, no study addresses implications of changes in feed efficiencies and livestock production systems on global water resources.

In the analysis presented here, we aim to take a step forward in unravelling the effects of the livestock sector on water use and obtaining a broader picture of options to meet the water challenge of future food supply. We estimate current and future levels of agricultural green and blue water consumption attributable to livestock production and assess potentials of dietary changes and shifts in livestock production systems to reduce agricultural water requirements and attenuate water scarcity. For this purpose, we apply the global land and water use model MAgPIE (Model of Agricultural Production and its Impact on the Environment) (Bodirsky et al., 2014; Popp et al., 2014; Stevanović et al., 2016) where the livestock sector is represented as a highly interconnected part of agricultural activities. Links between livestock and crop production are established through regional and product-specific feed baskets that evolve with the level of intensification, through trade-induced shifts in production, investments in research and development and competition for land and water resources between food and animal feed production.

Table 1
Socio-economic regions in MAgPIE (Model of Agricultural Production and its Impact on the Environment).

Acronyms	MAgPIE regions
AFR	Sub-Sahara Africa
CPA	Centrally Planned Asia (incl. China)
EUR	Europe (incl. Turkey)
FSU	Former Soviet Union
LAM	Latin America
MEA	Middle East and North Africa
NAM	North America
PAO	Pacific OECD (Australia, Japan and New Zealand)
PAS	Pacific Asia
SAS	South Asia (incl. India)

2. Methods and data

2.1. Modelling framework

MAgPIE is a global economic land and water use model that operates in a recursive dynamic mode and incorporates spatially explicit information on biophysical constraints into an economic decision making process (Lotze-Campen et al., 2008). It is thus well suited to analyse interactions between socio-economic processes, the natural resources required in agricultural production and related environmental impacts. By minimizing a nonlinear global cost function for each time step, the model fulfils demand for food, feed and materials for 10 world regions (Table 1).

Geographically explicit data on biophysical constraints are provided by the Lund-Potsdam-Jena managed land model (LPJmL) (Bondeau et al., 2007; Müller and Robertson, 2014; Rost et al., 2008) on 0.5° resolution and include pasture productivity, crop yields under both rainfed and irrigated conditions, related irrigation water demand per crop, water availability for irrigation as well as blue and green water consumption per crop. LPJmL is a process-based model which simulates natural vegetation at the biome level by nine plant functional types (Sitch et al., 2003) and agricultural production by 12 crop functional types (Bondeau et al., 2007; Lapola et al., 2009) as well as associated terrestrial carbon and water cycles. Although LPJmL allows for transient simulations of agriculture and natural vegetation under climate change (Müller and Robertson, 2014; Rosenzweig et al., 2013), we deliberately exclude climate change impacts and instead focus on socio-economic dynamics that drive green and blue water consumption along the food supply chain.

Spatial distribution of crops and pasture in MAgPIE is guided by geographically explicit information on vegetation growth and the balance between crop water demand and water availability, by initial cropland and pasture maps (Krause et al., 2013), area equipped for irrigation (Siebert et al., 2007), as well as by economic conditions like trade barriers, management intensity and transport costs, thus integrating information about market access into the decision process where to allocate cropping activities and livestock production. Land types explicitly represented in MAgPIE comprise cropland, pasture, forest, urban areas, and other land (e.g. non-forest natural vegetation, abandoned agricultural land, and desert). Natural vegetation or pasture can be converted to cropland if the land is at least marginally suitable for rainfed crop production with regard to climate, topography and soil type according to the Global Agro-Ecological Assessment (GAEZ) methodology on land suitability (Fischer et al., 2002; Krause et al., 2013; van Velthuizen et al., 2007). Parts of the forests are excluded from conversion into agricultural land if designated for wood production or located in protected areas (FAO, 2010).

In response to all involved costs (SI appendix, section A.1) and biophysical constraints, MAgPIE simulates major dynamics of the