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

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scenarios, to the consumption of "green" precipitation water infiltrated into the soil and "blue" freshwater withdrawn from rivers, lakes and reservoirs.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^3yr^{-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.

Keywords

livestock; productivity; dietary changes; consumptive water use; water scarcity; water resources

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 on the climatic conditions and production methods, 1 to 5 m^3 of water are needed to produce 1 kg of grain, whereas 5 to 20 times more water is required to produce 1kg of 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.

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).

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)

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 degree 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 agricultural sector like investments in research and development (*R&D*) (Dietrich et al., 2012, 2014) and associated increases in both crop yields and biomass removal through grazing on pastures, land use change (including deforestation, abandonment of agricultural land and conversion between cropland and pastures), interregional trade flows, and irrigation (see section 2.3). More information on the model version underlying this study can be found in the SI appendix.

2.2. Livestock sector

Livestock products (ruminant meat, whole-milk, pork, poultry meat and eggs) are supplied by five animal food systems (beef cattle, dairy cattle, pigs, broilers and laying hens) that further account for different animal functions (reproducers, producers and replacement animals). The parameterization of the livestock sector in the initial year 1995 is consistent with FAO statistics (FAOSTAT, 2013) regarding livestock production, livestock productivity and concentrate feed use. Following the methodology of Wirsenius (2000), feed conversion F_C (total feed input per product output in dry matter) and feed baskets F_B (demand for different feed types per product output in dry matter) are derived by compiling system-specific feed energy balances (SI appendix, section A.2). For the establishment of these balances, we apply feed energy requirements per output, as estimated by Wirsenius (2000) for each animal function and animal food system. These estimates are based on standardized bio-energetic equations and include the minimum energy requirements for maintenance, growth, lactation, reproduction and other basic biological functions of the animals. Moreover, they comprise a general allowance for basic activity and temperature effects.

Establishing feed energy balances also requires information on feed energy supply. Feed use data from the CBS for food crops and food industry by-products are supplemented by production data on forage crops (FAOSTAT, 2013) and by estimates on feed use covering other categories like crop residues, food waste and grazed biomass (Bodirsky et al., 2012; Eggleston et al., 2006; Krausmann et al., 2008; Lal, 2005; Wirsenius, 2000). Understanding dynamics of F_C and F_B composition over time is crucial to assess future pathways of the livestock sector. To facilitate projections, we create regression models with livestock productivity (annual production per animal [ton/animal/year]) as predictor, which permit the construction of productivity dependent feed baskets (SI appendix, section A.3).

2.3. Agricultural water use

Both rainfed and irrigated agriculture rely on the availability of water resources, originating from liquid water in rivers, lakes and reservoirs in the case of blue water or from naturally infiltrated soil water formed by precipitation in the case of green water. LPJmL partitions green and blue water flows into transpiration, interception loss, evaporation from soils and canals, soil moisture, deep percolation, and runoff (Rost et al., 2008; Schaphoff et al., 2013). For each crop and plant functional type, LPJmL calculates productive (i.e. transpiration) and unproductive (i.e. interception and evaporation from soils and water surfaces) consumption, thereby distinguishing the contributions of green (G) and blue water consumption (B).

Water consumption on irrigated cropland comprises blue as well as green components, while rainfed agriculture exclusively involves productive and unproductive evapotranspiration (ET) of green water. On pastures, we only consider G, due to the exclusion of irrigation as a pasture management option in our study, and differentiate between G on total area and G related to the fraction of biomass actually grazed by animals compared to the potential biomass harvest simulated by LPJmL. The difference can be interpreted as green water flows sustaining ecosystem functioning and services on pastures. Increases in biomass removal on existing pastures shift the balance from green water flows maintaining ecosystem functioning to G associated with biomass appropriation through grazing or moving, reflecting intensification of pasture management.

Net irrigation water demand is derived from the soil water deficit below optimal plant growth for simulated crop functional types by LPJmL (Rost et al., 2008) and corrected for losses from source to plant (Bonsch et al., 2015; Rohwer et al., 2007) to estimate gross irrigation water demand per crop and resulting total blue water withdrawals for irrigation (BW_{ir}). Irrigation water productivity (crop production per withdrawn irrigation water [ton m^{-3}]) can be enhanced by minimizing losses in water transport from source to field and in across-field distribution and by improving plant water use efficiency by breeding and better management (Bonsch et al., 2015; Jägermeyr et al., 2015). Therefore, we assume in the default model setting that $R\&D$ investments improving crop yields simultaneously improve irrigation water productivity (Bonsch et al., 2014), thus leaving gross irrigation water demand per area (m^3 ha^{-1}) constant. To test implications of this assumption, we conduct a sensitivity analysis where gross irrigation water demand per area linearly increases with crop yields.

Blue water available for irrigation in MAgPIE only accounts for accessible and renewable freshwater resources (BRR), which are defined by total runoff as simulated by LPJmL during the growing season (Bonsch et al., 2014). Simulation units with water storage infrastructure (Biemans et al., 2011) contribute total annual runoff to basin water availability. Blue water withdrawals (BW_{os}) for other sectors (industry, electricity and domestic use) are obtained from WaterGAP (Alcamo et al., 2003; Flörke et al., 2013) and enter the model as exogenous pathways, thus reducing the de-facto blue water availability for agriculture. Based on yield differences between rainfed and irrigated crops, crop-specific gross irrigation water demand, the availability of blue water and presence of irrigation infrastructure, the model can endogenously decide to apply irrigation and expand the area equipped for irrigation at additional costs (Bonsch et al., 2014, 2015). Irrigation costs include investment costs for establishing new irrigation infrastructure, which are based on Worldbank data (Jones, 1995), and annual costs for operating irrigation systems (Bonsch et al., 2014). More information on agricultural water use can be found in the SI appendix, section A.4.

We contextualize estimates of water consumption by two complementary water scarcity indicators to capture the environmental and agro-economic relevance of agricultural water use: the model internal water shadow price *(WSP_B)* for agro-economic and the water withdrawal-to-availability ratio (WTA_B) for biophysical evaluation of pressures on blue water resources, where WTA_B is defined as the quotient of blue water withdrawals from all sectors (including agriculture) and renewable freshwater resources (*BRR*). The WSP_B is calculated as the Lagrange multiplier of the blue water-balance constraints and indicates the value of an additional unit of irrigation water in the context of all constraints and costs that guide the economic decision process, thereby reflecting availability and suitability of natural resources for agriculture including geographically explicit limitations for rainfed agriculture, as well as the socio-economic setting, e.g. regional comparative advantages and the configuration of interregional trade (Biewald et al., 2014; Schmitz et al., 2013).

2.4. Scenarios

Socio-economic drivers are parametrized according to the Shared Socioeconomic Pathways (SSPs) for climate change research (Kriegler et al., 2017; O'Neill et al., 2014; Popp et al., 2017). This study follows the narrative of **SSP2**, a "Middle of the Road" scenario characterized by a continuation of current social, economic and technological developments. World population reaches ~9.1 million people in 2050 and growing incomes facilitate the transition towards more affluent diets with a higher share of animal-based calories which increases from 19% in 2010 to 24% around mid-century. However, as many fish populations are already over-exploited, regional consumption of fish is assumed to be limited to current levels (FAO, 2005). Until 2050, food demand rises to 3051 kcal capita^{-1} d^{-1} which corresponds to 89 g protein capita^{-1} d^{-1}. Resulting regional contribution of proteins to daily food energy demand in 2050 (10-14%) is in line with the recommendations of the World Health Organization (WHO) for macronutrient intake (WHO, 2003).

In order to assess demand- and supply-side potentials in the livestock sector to reduce agricultural water requirements, we construct eight scenarios (Table 2) along the dimensions of *dietary choices* and *livestock productivity* (annual production per animal).

Starting from the SSP2 diet scenario (**SSP2**), which serves as the baseline for the analysis, we construct the second diet scenario by reducing the contribution of animal-based calories in diets until mid-century to 15%. As the scenario target for animal-based calories represents half the currently observed level in OECD countries, this diet scenario (**DEMI**) is frequently referred to as "demitarian" Western diet (Bodirsky et al., 2014; Sutton and Ayyappan, 2013). The 15% target usually includes the contribution of calories from fish which reduces the possible contribution of calories from livestock products such as meat, milk and eggs (SI appendix, Fig. S7 and Table S8). Because fish is not explicitly modelled in MAgPIE, regional fish consumption is, also in the DEMI scenario, fixed to current levels. Although the transition to more plant-based diets is designed without replacing animal-based food with dedicated high-protein crops to preserve as close as possible observed dietary patterns, the resulting regional contribution of proteins to daily food energy demand in 2050 (10-13%) still fulfills the dietary guidelines by the WHO, because reductions in animal-based calories mainly pertain to regions with affluent diets.

Table 2. Overview of the scenario design, based on the narrative of SSP2, the "Middle of the Road" scenario of the Shared Socioeconomic Pathways (SSPs). Scenarios are constructed along the dimensions of *dietary choices* and *livestock productivity* (annual production per animal) as combinations of two variants of the share of animal-based calories in future food demand and four variants of livestock productivity trajectories.

Scenario		Description
Dietary choices	SSP2	Regional food demand and dietary preferences converge slowly towards more affluent diets, resulting in a global average per capita food demand of 3051 kcal capita^{-1} d^{-1} and 24% animal-based calories in diets in 2050.
	DEMI	The transition towards a demitarian Western diet reduces the share of animal-based calories to 15% in 2050. Countries which stay below the scenario target are not affected.
Livestock productivity	BASELINE	Livestock productivity trajectories develop according to the SSP2 narrative with medium pace in productivity increases and a slight catch-up of low productive systems.
	DIVERGENCE	The historically observed divergence of livestock productivity trends continues until mid-century. While productive regions can extend the lead, only small productivity gains are achieved in low productive livestock systems.
	CATCH-UP	Regions with low productive systems achieve substantial productivity gains and can catch up to a certain extent. In ruminant systems, 45% of the productivity gap to intensive systems can be closed, in monogastric systems 60%.
	MODERATION	Highly intensive systems experience productivity reductions until mid-century to moderated productivity levels equalling 75% of the current productivity frontier.

The diet scenarios are combined with four livestock productivity scenarios (see Fig. 1 for global and SI appendix, Fig. S8 for regional developments). The **BASELINE** scenario (livestock sector parametrisation according to SSP2 storyline) is characterized by a medium pace in productivity improvements, but low-productive regions catch up to a certain extent (Popp et al., 2017). The **DIVERGENCE** scenario represents the continuation of historically observed very divergent productivity developments with little improvements in some regions' low productive systems and is constructed by following the extrapolation of historical trends between 1970 and 2010, if these extrapolated trends are lower than SSP2 projections. In contrast to the DIVERGENCE scenario, where low livestock productivities are assumed to prevail, the ambitious **CATCH-UP** scenario prescribes a further closure of the productivity gap, defined by top-performing countries in 2010, by 45% for ruminant systems and by 60% for monogastric systems until 2050. We assume a stronger intensification trend for non-ruminant systems, because the majority of future increases in poultry and pork production is expected to occur in industrial systems (Herrero et al., 2009; Steinfeld et al., 2006). The **MODERATION** scenario explores a variation of SSP2 livestock productivity trends at the opposite end of the range, the highly intensive systems. Until 2050, these systems are assumed to experience a reduction in livestock productivity to the level of 75% relative to the productivity frontier defined by top-performing countries in 2010. The MODERATION scenario is designed to explore the room to maneuver for measures to tackle challenges related to livestock production that might impede productivity, such as improvements in animal health and welfare.

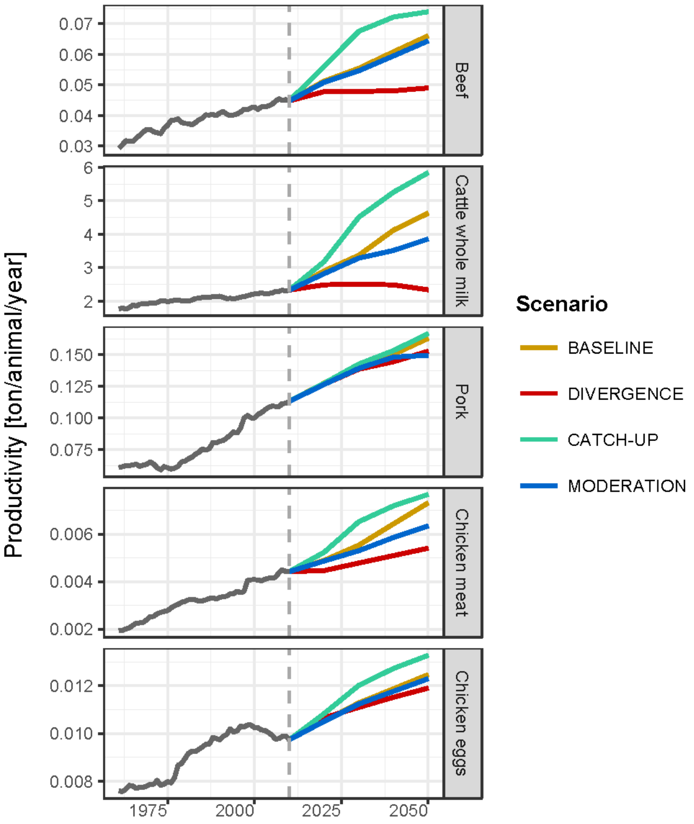

Fig. 1. Global past and future livestock productivity (annual production per animal [ton/animal/year]) for all livestock commodities. Historical developments (left of the vertical dashed line) according to FAOSTAT (2013) and future developments (right of the vertical dashed line) for the four productivity scenarios. Global aggregates are determined by regional productivity trends (see SI appendix, Fig. S8) and regional production volumes of livestock commodities.

3. Results

3.1. Contemporary water withdrawals and consumption

The pivotal role of green water resources for agricultural production is apparent in our results for the year 2010, estimating 6040 km^{3}yr^{-1} for green (G) and 1020 km^{3}yr^{-1} for blue (B) water consumed by crops, of which 2290 km^{3}yr^{-1} G and 370 km^{3}yr^{-1} B can be attributed to feed production on cropland (Table 3). Accordingly, the livestock sector is responsible for 38% of global crop water consumption. Considering also evapotranspiration (ET) on pastures, the prominence of green water for agriculture becomes even more distinct. G related to grazed biomass alone contributes 29% to the resulting 9990 km^{3}yr^{-1} water consumption associated with total agricultural biomass appropriation (cropland harvest and grazed biomass), hereafter referred to as agricultural water consumption. The contribution of livestock related water consumption thereby represents 56% of water consumed by agriculture. Although only 10% of agricultural water consumption originates from blue resources, withdrawn irrigation water (BW_{ir}) accounts for 77% of all anthropogenic water withdrawals (3390 km^{3}yr^{-1}). The resulting severe limitation of freshwater availability is a prevailing phenomenon in much of the populated regions of the world (Fig. 2).

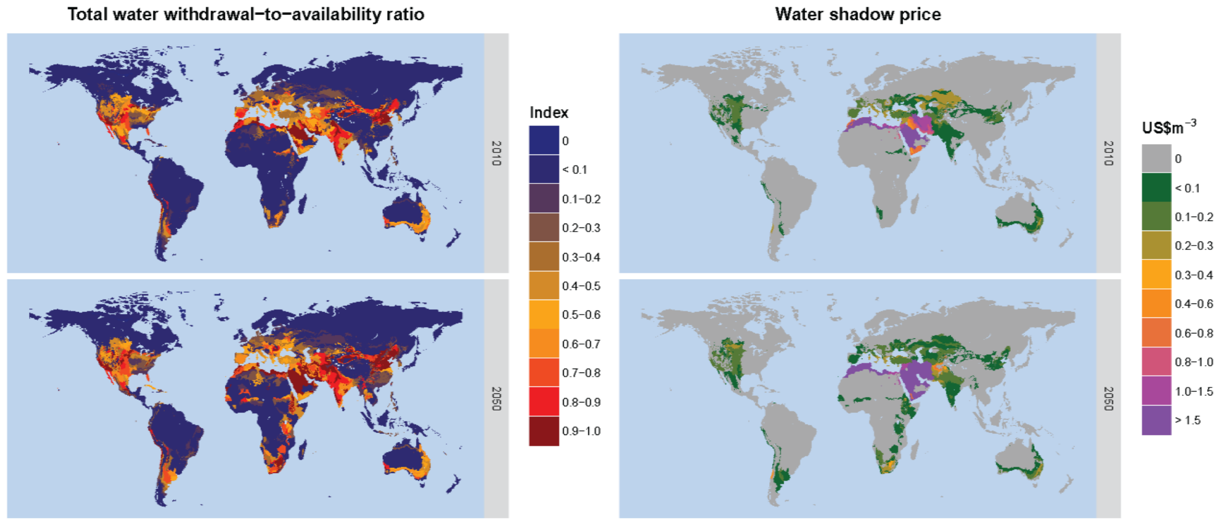

Fig. 2. Global distribution of the water withdrawal-to-availability ratio (WTA_B - left panel) and the water shadow price (WSP_B - right panel) for the SSP2 BASELINE scenario and the years 2010 and 2050. The WTA_B ratio is calculated as $WTA_B = BW_{total}/BRR$, where BW_{total} represents water withdrawals from all sectors and *BRR* denotes accessible and renewable freshwater resources. The WSP_B (in US\$$m^{-3}$) is calculated as the Lagrange multiplier of the water-balance constraints (see section 2.3).

3.2. Livestock futures and global water resources

For the SSP2 BASELINE scenario, we estimate an increase in B by 310 km^3yr^{-1} (+30%) and in G on cropland by 3400 km^3yr^{-1} (+56%) between 2010 and 2050 (Fig. 3, Table 3). Water consumption of feed crops (Fig. 4) accounts for 560 km^3yr^{-1} B (+51%) and 3980 km^3yr^{-1} G (+74%) in 2050. Driven by the expansion of irrigated cropping, additional 690 km^3yr^{-1} (+26%) blue water is withdrawn from *BRR*. Due to more intensive pasture management, pasture area as well as related *ET* decline, whereas G attributable to grazed biomass slightly increases by 150 km^3yr^{-1} (+5%). Global water resources are strongly affected by future demand- and supply-side changes of livestock production, where the type of resource use (green or blue water on cropland or pasture) is essentially influenced by assumptions on livestock productivity.

For BASELINE productivity trends, we estimate under different diet scenarios that 40-41% of livestock related water consumption in 2050 is attributable to grazed biomass, 7-8% to B and the remaining 51-52% to G related to cropland feed. Compared to 2010, this represents a shift from green water resources on grasslands to those on cropland. A further catch-up of less productive systems (CATCH-UP) strengthens this trend, with only 33-35% of livestock water consumption related to grazing and 58-59% to G on cropland, a consequence of substantial pasture-to-cropland conversion processes. In absolute values, CATCH-UP scenarios involve lowest estimates of total water consumption attributable to livestock production, together with highest levels of water consumed by cropland feed (Fig. 4) and agricultural BW_{ir}. (Fig. 3). High demand for concentrates from cropland drives expansion of both rainfed and irrigated cropland and increases water scarcity on arable land (e.g. South Asia and Sub-Saharan Africa) (see Fig. 5 for global and SI appendix, Fig. S15 for regional results).

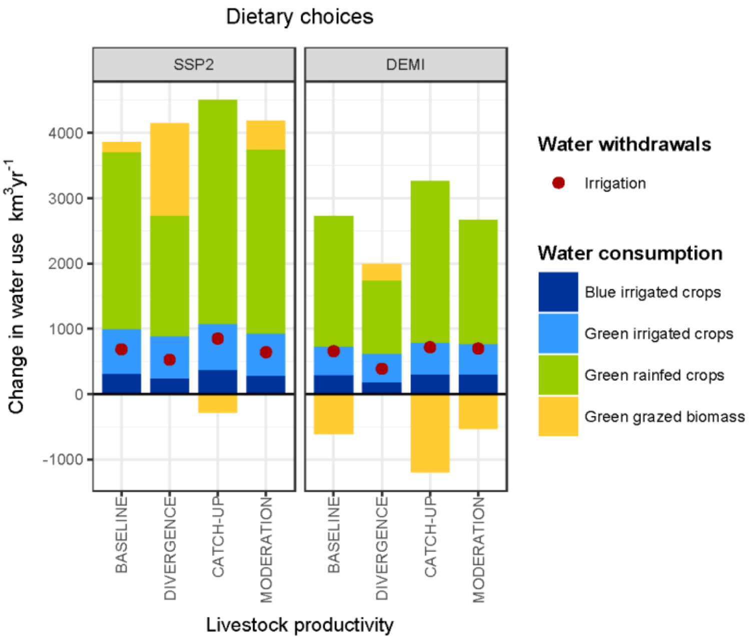

Fig. 3. Changes in global agricultural green and blue water consumption between 2010 and 2050 in km^{3}yr^{-1}. Red points indicate changes in global water withdrawals for irrigation between 2010 and 2050 in km^{3}yr^{-1} that include non-consumptive components and losses from source to plant. Note that water consumption on irrigated cropland also comprises green components.

On the contrary, a continuation of divergent productivity trajectories (DIVERGENCE scenarios) involves lowest crop water consumption, total cropland area as well as cropland prone to water stress, but at the expense of a rising contribution of *ET* from pastures to agricultural *G.* This is partly facilitated by the exploitation of *ET* on newly converted pasture (+16% and +5% increase of *G* on total pasture area for SSP2 and DEMI diet scenarios), implying a loss of natural vegetation. For all other diet and productivity scenarios, *ET* from pastures decreases over time by 5-13% (Table 3). Productivity reductions in highly productive systems (MODERATION) have minor and ambiguous effects on type and magnitude of livestock related water consumption and water scarcity.

Fig. 4. Global agricultural green and blue water consumption in 2050 attributable to livestock feed production in km^{3}yr^{-1}. Vertical stacked lines indicate water consumption related to feed production in 2010 in km^{3}yr^{-1}. Note that water consumption on irrigated cropland also comprises green components.

For all productivity scenarios, lower intake of livestock products (DEMI) entails a reduction of water consumption related to cropland feed and grazed biomass (Fig. 4). As a consequence, we also observe a general decline in total agricultural water consumption (both *G* and *B* on cropland and pasture) and similar patterns with respect to productivity scenarios, with the exception of *B* for the MODERATION scenarios. Reductions in demand for livestock products also attenuate cropland requirements and levels of water stress (Fig. 5). Whereas *G* attributable to cropping and grazing is sensitive to dietary changes (25-35% and 10-12% reduction compared to SSP2 diets), *B* and BW_{ir} are less responsive. In contrast to *G* on cropland, which beside spatial relocation of crop production is principally driven by cropping area and yield growth, *B* is additionally influenced by water availability and economic competitiveness of irrigation activities and establishment of irrigation infrastructure compared to cropland expansion and *R&D* investments.

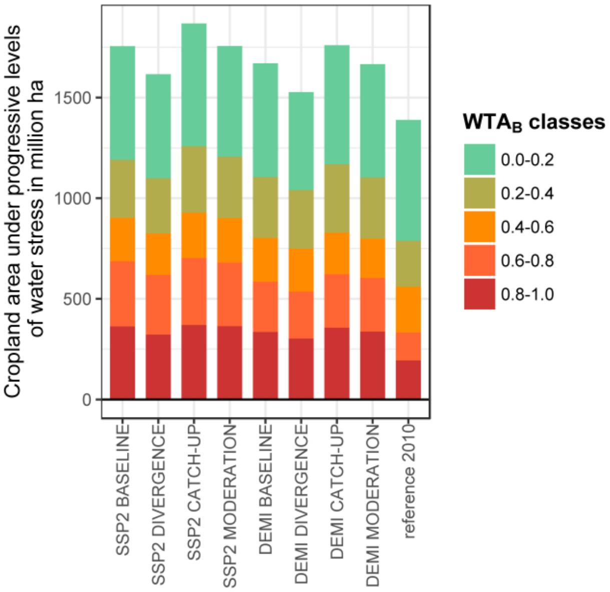

Fig. 5. Global cropland under progressive levels of water stress in million ha. Scenario results are given for 2050. The last bar (*reference 2010*) indicates values for the year 2010. Water stress is defined by the water withdrawal-to-availability ratio ($WTA_B = BW_{total}/BRR$), where BW_{total} represents water withdrawals from all sectors and *BRR* denotes accessible and renewable freshwater resources. Global estimates of cropland under progressive levels of water stress are derived by aggregating cropland area of concordant WTA_B classes from simulation units to global values. The length of each bar represents total global cropland.

Table 3. Global green (*G*) and blue (*B*) water consumption attributable to total biomass and feed production on cropland, pasture and agricultural land in 2010 in km^3yr^{-1} and percentage changes between 2010 and 2050 for all scenarios. *G* on cropland is differentiated between rainfed and irrigated cropland. For pasture, estimates of *G* are presented for total area and for the fraction of biomass actually harvested by grazing compared to the potential pasture biomass harvest simulated by LPJmL. The difference is attributable to non-harvested pasture biomass and can be interpreted as green water flows sustaining ecosystem functioning and services.

			SSP2 (2050)				DEMI (2050)			
		2010	BASELINE	DIVERGENCE	CATCH-UP	MODERATION	BASELINE	DIVERGENCE	CATCH-UP	MODERATION
Cropland										
B	irrigated	1020	+30%	+24%	+36%	+28%	+28%	+19%	+30%	+30%
G	irrigated	790	+89%	+82%	+90%	+82%	+56%	+56%	+62%	+59%
G	rainfed	5250	+52%	+35%	+65%	+54%	+38%	+21%	+47%	+36%
G	total	6040	+56%	+41%	+69%	+57%	+41%	+26%	+49%	+39%
G+ B	total	7070	+52%	+39%	+64%	+53%	+39%	+25%	+46%	+38%
Pasture										
G	harvested	2930	+5%	+48%	-10%	+15%	-21%	+8%	-41%	-19%
G	non-harvested	13500	-8%	+9%	-13%	-9%	-6%	+1%	-6%	-6%
G	total	16430	-6%	+16%	-12%	-5%	-9%	+2%	-13%	-9%
Agricultural land										
G + B	harvested[a]	9990	+39%	+42%	+42%	+42%	+21%	+20%	+21%	+21%
G+ B	total	23500	+12%	+23%	+11%	+13%	+5%	+9%	+5%	+5%
Cropland used for feed production										
B	irrigated	370	+51%	+43%	+51%	+49%	+22%	+11%	+19%	+24%
G	irrigated	330	+94%	+100%	+91%	+85%	+21%	+30%	+27%	+24%
G	rainfed	1960	+70%	+47%	+90%	+74%	+24%	+1%	+36%	+20%
G	total	2290	+74%	+55%	+90%	+76%	+24%	+5%	+34%	+21%
G + B	total	2670	+70%	+52%	+85%	+71%	+23%	+6%	+32%	+21%
Agricultural land used for feed production										
G + B	harvested[b]	5590	+36%	+50%	+35%	+42%	0%	7%	-6%	+1%
G+ B	total	19100	+5%	+21%	+1%	+6%	-5%	3%	-6%	-5%

a: Water consumption attributable to harvested biomass on agricultural land includes total crop water consumption and *G* related to the fraction of biomass harvested on pastures via grazing.

b: Water consumption on agricultural land attributable to harvested feed biomass includes crop water consumption related to cropland feed production and *G* related to the fraction of grazed biomass on pastures.

3.3. Regional relevance of water withdrawals and consumption

Global values of water withdrawals and consumption are the aggregate of diverse dynamics on the regional scale (Fig. 6). Reduced demand for livestock commodities generally lowers total agricultural water consumption in all regions. However, regional BW_{ir} and B are not very responsive to dietary changes – with the exception of Northern America. In Sub-Saharan Africa, water consumption and withdrawals in 2050 are projected to substantially surpass contemporary levels, reflecting the strong increase in population as well as per-capita food and livestock demand in all scenarios. The sensitivity of the interplay between pasture and cropping activities to livestock productivity gains (BASELINE and CATCH-UP scenarios relative to DIVERGENCE) is mirrored by the considerable shift from G attributable to grazing to G on cropland. Management of remaining pastures is intensified and ET related to the non-appropriated fraction of pasture biomass is strongly reduced (SI appendix, Fig. S13).

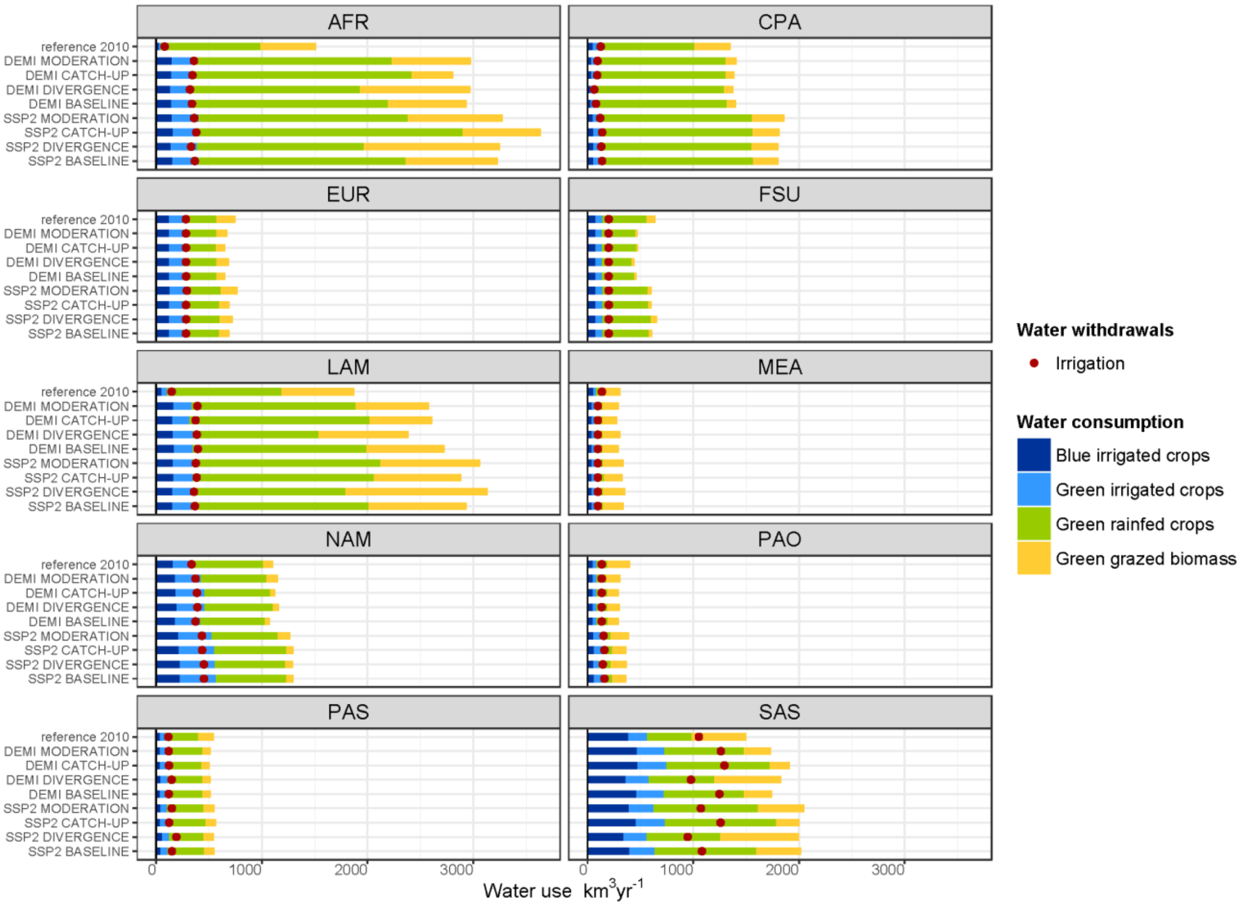

Fig. 6. Regional agricultural green and blue water consumption in km^{3}yr^{-1}. Scenario results are given for 2050. The first bar in each panel (*reference 2010*) indicates values for the year 2010. Red points represent changes in regional water withdrawals for irrigation between 2010 and 2050 in km^{3}yr^{-1} that include non-consumptive components and losses from source to plant. Note that water consumption on irrigated cropland also comprises green components.

While expansion of cropland and irrigation in Sub-Saharan Africa goes along with a rise in area affected by water scarcity, extended cropping activities in Latin America pertain to areas more abounding in water. Moreover, growth in G attributable to grazing can be realized by higher grazing intensities in all scenarios except SSP2 DIVERGENCE, where a combination of higher demand for livestock products and lower livestock productivities involves an expansion of pastures. In South Asia, *G* and *B* strongly respond to the additional feed demand for crops induced by increasing livestock productivity. In the Middle East and North Africa, *B* and BW_{ir} are not responsive to scenario assumptions and even decrease compared to 2010, due to severe scarcity of *BRR* and a growing water demand from other sectors. In North America, the SSP2 baseline scenario entails an expansion of irrigated crop production compared to 2010. Yet, with decreasing consumption of animal-based products, this trend may partly be reversed.

3.4. Uncertainties in projected blue water consumption

To better elucidate constituents of *B* dynamics, we conduct a sensitivity analysis defining three additional scenario settings: a) *Unlimited water supply* to analyse the influence of resource scarcity; b) *Static irrigation water productivity* where, in contrast to our default setting, *R&D* investments improve land productivity but leave irrigation water per ton output ($m^3 ton^{-1}$) constant, thereby increasing irrigation water demand per area ($m^3 ha^{-1}$) linearly with yields; and c) *Exogenous yield trajectories* where all standard productivity and diet scenarios are calculated with identical regional yield growth trajectories, based on the endogenous crop yield trajectories from the SSP2 BASELINE scenario.

The assumption of *unlimited water availability* entails a substantial increase in irrigated area and *B* (Fig. 7a) due to the comparative advantage of expanding irrigation activities relative to cropland expansion and investments into other yield increasing innovations and management strategies (Fig. 7b). Although average annual rates of technological change further decline in the wake of reduced consumption of livestock products, both area equipped for irrigation and *B* are very sensitive to dietary changes (11-15% reduction of *B*, see Table 4).

Compared to the default setting, the assumption of *static irrigation water productivity* decreases potentials and therefore leads to low estimates of irrigated area. As irrigation water is less productive to generate a high production volume, expansion of cropland together with *R&D* investments supersede irrigation in delivering growth in crop production, implying strongest increases in cropland across all sensitivity settings. In the case of static irrigation water productivity, both irrigation water demand and *B* are assumed to increase linearly with yield, therefore leading to higher estimates of *B* than in the default setting. Dietary changes lead to a reduction in *B* by 4-8%.

Table 4. Impacts of lower demand for livestock products along a demitarian diet (DEMI) on global blue water consumption (*B*) for all productivity scenarios under the default and additional model settings of the sensitivity analysis (changes in *B* [%] for the DEMI diet scenario relative to the "Middle of the Road" diet scenario in 2050).

Model settings	BASELINE	DIVERGENCE	CATCH-UP	MODERATION
Default	-1%	-4%	-5%	2%
Unlimited water supply	-15%	-11%	-11%	-15%
Static irrigation water productivity	-8%	-4%	-8%	-4%
Exogenous yield trajectories	-10%	-12%	-9%	-8%

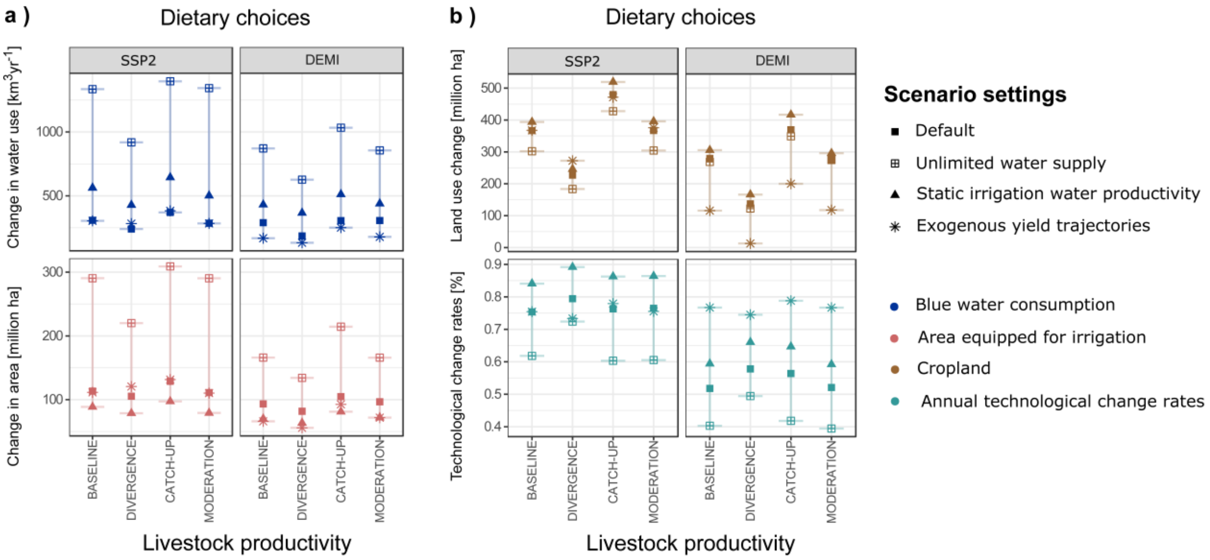

Fig. 7. Sensitivity analysis. Panel a) illustrates changes in global agricultural blue water consumption in km^3yr^{-1} and in global area equipped for irrigation in million ha between 2010 and 2050. Panel b) shows changes in global cropland in million ha and annual technological change rates (%) between 2010 and 2050.

Results of all diet and productivity scenarios assuming *Exogenous yield trajectories* accentuate the importance of technological innovation as a buffer in the whole food system, dampening the translation of demand-side signals into resource use. Under the *default* setting, a reduction of livestock products in diets attenuates the pressure in the food system, involving not only a general decline in the exploitation of natural resources (both land and water) but also lowering efforts to increase agricultural productivity. If technological innovation and improved management are presumed to be persistent under a dietary transformation towards less livestock products, we observe larger positive impacts in terms of mitigated land conversion and blue water use (reduction in *B* by 8-12%).

4. Discussion

4.1. Current blue and green water consumption

It has been noted earlier that an analysis of livestock systems offers substantial scope to understand and increase total agricultural water productivity (Cook et al., 2009; Herrero et al., 2009; Peden et al., 2007; Steinfeld et al., 2006). However, many approaches to reconcile water conservation with the challenge to feed a growing population exclusively target the crop sector (Jägermeyr et al., 2016, 2017; Rockström et al., 2007; Wada et al., 2014). Our findings underline the relevance of exploring links between livestock and water, with one-third of crop water consumption being attributable to feed production. We adopt a combined blue-green approach to assess agricultural water use under different livestock futures that facilitates the identification of land-water related trade-offs and other than blue-only strategies to meet the water requirements of future food production, like expansion, relocation and intensification of rainfed cropping (Rockström et al., 2007, 2009) and optimized use of *in situ* precipitation water like alleviated soil evaporation (Jägermeyr et al., 2016; Rockström, 2003).

Our estimate of 2170 km^{3}yr^{-1} water consumed by cropland feed in 2000 is higher than previously suggested (Table 5), due to a high contribution of cultivated forage (e.g. alfalfa, rye grass and forage maize), inclusion of all major feed categories (including food industry by-products like soy meal) and full feed energy balances. Mekonnen and Hoekstra (2010) estimate that consumptive water use of feed crops accounts for 1463 km^{3}yr^{-1} (1996-2005) and that 6.2% of livestock related water consumption is of blue origin, based on virtual water calculations. As also our estimates for G attributable to cropland feed production and grazing are higher, our calculations lead to a similar contribution of 7% blue water to the livestock water footprint. Our estimate for G on cropland (5100 km^{3}yr^{-1}) is at the lower end of earlier estimates, owing to optimality of land allocation patterns regarding cost-effectiveness and resource constraints inherent in our modelling approach, whereas estimated B (1010 km^{3}yr^{-1}) is well within the range of 600-1570 km^{3}yr^{-1} of previous studies.

Combining water consumed on cropland for animal feed production with G attributable to grazing, consumptive water use of livestock amounts to 56% of total agricultural water consumption, which is higher than the 45% estimated by Zimmer and Renault (2003). Thus, grazing land is not only from the land but also from the water perspective an important resource. Because impacts of grazing on the hydrological cycle are small compared to irrigated agriculture (Peden et al., 2007; Steinfeld et al., 2006), the relevance of water consumption on grazing land is better described by the opportunity costs of involved green precipitation water (and land) as by the environmental impact of its use. Differentiation between the type of land (cropland or pasture) and water use (green or blue) may shed some light on the implications of involved resource use, because the opportunity costs and environmental impacts of cropland and blue water are typically higher.

Table 5. Estimates of global green (G) and blue (B) water consumption and water withdrawals for irrigation (BW_{ir}) in km^{3}yr^{-1}. G on cropland is differentiated between rainfed and irrigated cropland. For pasture, estimates of G are presented for total area and for the fraction of biomass actually harvested by grazing compared to the potential pasture biomass harvest simulated by LPJmL.

		Our estimates 2000	Our estimates 2010	Rost et al. (2008) 1971-2000	Hanasaki et al. (2010) 1985-1999	Molden (2007) 2000	Other estimates Not specified
Cropland							
BW_{ir}	irrigated	2570	2610	1161-2555		2630	2200-3800[c]
B	irrigated	1010	1020	600 - 1258	1530[a]	1570[a]	1257[d]
G	irrigated	720	790	307 - 325[a]	850[a] -1720[b]	650[a]	
G	rainfed	4380	5250	6936 - 6949[b]	4700[a] - 7820[b]	4910[b]	
G	total	5100	6040	7242 -7273	5550[a]-9540[b]	5560	
$G + B$	total	6100	7070	7874 - 8501	7080[a]-11070[b]	7130	6390[e]
Pasture							
G	harvested	2590	2930			840	913[f]
G	total	16520	16430	8191 - 8258	12960		5800[e]-20400[g]
Cropland used for feed production							
$G + B$	total	2170	2670			1312	1463[h]

a: Cropping period.
b: Throughout the year.
c: Wisser et al. (2008).
d: Jägermeyr et al. (2015), estimate for 2004-2009.
e: Chapagain (2006).
f: Mekonnen and Hoekstra (2010), estimate for 1996-2005.
g: Postel (1998), estimate for 1995.
h: Falkenmark and Rockström (2004), estimate for 1999.

4.2. Livestock futures and the water challenge of agricultural production

Dietary changes are a frequently discussed option to meet the water challenge of future food supply and alleviate water scarcity (Gerten et al., 2011; Jalava et al., 2014; Liu and Savenije, 2008; Marlow et al., 2009; Mekonnen and Hoekstra, 2010; Schmitz et al., 2013; Steinfeld et al., 2006). However, recommendations to reduce meat consumption in order to preserve water resources are often based on static inventories of current livestock related water consumption and resulting virtual water content of livestock products (Jalava et al., 2014; Mekonnen and Hoekstra, 2010; Steinfeld et al., 2006), or informed by simplified assumptions on livestock feeding and related water use (Gerten et al., 2011; Zimmer and Renault, 2003). Adding to the existing literature, our assessment of the green and blue water-saving potential of dietary changes does not only consider alternative assumptions on future livestock productivity, thereby altering feed and water use per product over time, but also comprises secondary effects like changes in *R&D* investments, land-use dynamics and adjustments in trade flows (SI appendix B). Our results emphasize the outstanding importance of economic processes for evaluating sustainability issues and reveal the non-linearity of systems' responses to demand- and supply side changes.

The potential of a demitarian diet to lower pressures on blue freshwater resources is indeed influenced by productivity trajectories, but, as the sensitivity analysis highlights, even more by other factors that indirectly influence dynamics within the food system. Especially assumptions on the availability of blue water, dependence of *R&D* investments from demand-side pressures and economic competitiveness of irrigation determine the freshwater-saving potential of dietary changes. Assuming limited blue water supply (*BRR* only), improved irrigation water productivity and feedbacks between *R&D* investments and biomass demand in our default model setting, B is less responsive to reduced consumption of livestock products than G. The latter observation also confirms findings by Jalava et al. (2014) that lower protein supply from livestock products (at most 50% and 12.5% respectively of total protein supply) has a larger effect on G (-6% to -15%) than on B (-4% to -9%).

Consequently, irrigated agriculture will continue to play an important role, even if demand for crops strongly declines, because in many locations deployment of irrigation is constrained by water availability and below optimum regarding economic and agronomic considerations. This is in line with findings that more efficient irrigation systems tend to boost profitability of irrigation, trigger expansion of irrigated cropland and even increase the depletion of blue water resources (Perry and Hellegers, 2012; Pfeiffer and Lin, 2014; Ward and Pulido-Velazquez, 2008). As long as there are no opportunity costs (e.g. use from other sectors) or water protection policies such as pricing, the model is inclined to use accessible water wherever the soil water deficit below optimal plant growth is large enough to make irrigation economically competitive to other yield increasing management options. The higher sensitivity of rainfed agriculture to dietary changes indicates that it is primarily land that is spared and only secondarily freshwater.

The balance between water consumption attributable to cropland and grassland, as well as between green and blue flows, is strongly influenced by livestock productivity via changes in feed efficiency and composition. Assuming the continuation of low historical productivity trajectories in some regions, we observe an increase of water consumption attributable to grazing to fulfil food water requirements, which goes along with expansion of pasture into pristine areas, entailing loss of natural vegetation and carbon emissions. Intensification of low productive systems involves a shift from grassland/green water resources to cropland/blue water resources. Analogously to land use change, where conversion from pastures to cropland might reduce pressures on natural ecosystems, a shift from green water consumption from grazing to cropping may unlock additional water resources other than irrigation. From the perspective of maintaining ecosystem services, biodiversity (Alkemade et al., 2013) and carbon sequestration (Conant et al., 2001; Don et al., 2011; Popp et al., 2014) on agricultural land, pasture-to-cropland conversion may also be seen critical and is likely to affect hydrological processes through e.g. higher run-off from cropland (Peden et al., 2007).

Although increases in livestock productivity are beneficial with regard to feed conversion efficiencies, resulting decrease in feed demand is less than proportionate, due to higher competitiveness of some regions' livestock sectors and interregional reallocation of production. Especially in Latin America, efficiency gains lead to a growth in production and export volume. Owing to higher feed demand from cropland, intensification of livestock systems increases blue water use which may jeopardize human water security and aquatic ecosystems, e.g. in India, where water withdrawals substantially undermine environmental flow requirements (Jägermeyr et al., 2017), and East Africa, where already current pressures from feed production on water resources are high (Herrero et al., 2010). However, pressures on global land resources are diminished, because cropland can expand into pastures, thereby sparing natural vegetation and avoiding carbon emission from deforestation. Trade-offs between water and land inherent in livestock system intensification could be alleviated by water protection policies such as pricing mechanisms or water rights cap-and-trade schemes that entail only minor additional land requirements (Bonsch et al., 2015).

Improving low productivity levels is often considered beneficial both regarding environmental and social impacts like improved food security and livelihoods (Herrero et al., 2009, 2010; Steinfeld et al., 2006; Weindl et al., 2015). In contrast, there is an increasingly critical debate about intensification at high productivity levels, because large-scale industrial livestock operations are associated with heavy nutrient loadings, pollution of terrestrial and aquatic ecosystems through excessive use of nitrogen and pesticides as well as pathogens, conflicts with animal welfare, and loss of biodiversity (Franzluebbers, 2007; Lemaire et al., 2014; Russelle et al., 2007; Tilman et al., 2002). As productivity reductions in the MODERATION scenarios have only minor effects on type and magnitude of agricultural water consumption, measures aimed at abating side-effects of industrial livestock operations that might impede productivity could be successful without substantially increasing water requirements to produce food.

4.3. Assumptions and limitations

Vörösmarty et al. (2005) and Rost et al. (2008) suggest that a substantial share (16-33% and 55%) of BW_{ir} (400-800 km^{3}yr^{-1} and 1400 km^{3}yr^{-1}) exceeds locally accessible and renewable freshwater supplies and stems e.g. from groundwater abstraction, depleting global groundwater reserves by 283 km^{3}yr^{-1} (Wada et al., 2010). Accounting only for renewable freshwater resources we may underestimate B and BW_{ir}, especially in major irrigation countries like India, China and the Unites States. Moreover, water withdrawn especially by non-agricultural sectors partially re-enters rivers and is, after wastewater treatment, available for downstream use (Flörke et al., 2013). We assume inelastic water demand from non-agricultural sectors which limits the de-facto water availability for agriculture. On the other hand, we may overestimate accessibility of freshwater, because the balance between water supply and demand is established on the level of 1000 simulation units, thus assuming that water can freely be allocated within rather large areas. Moreover, in this analysis we do not consider climate change impacts on the hydrological cycle and on crop yields.

Although our analysis tries to cover several aspects of water scarcity, there is a multitude of relevant aspects of the livestock-water-nexus that are not considered. It is widely acknowledged that freshwater ecosystems and river biodiversity are in a state of crisis (Falkenmark and Molden, 2008; Vörösmarty et al., 2010). Knowledge of relative water demand alone is not sufficient to assess how human water use may threaten freshwater ecosystems. Environmental flow requirements sustaining river ecosystems vary by location (Bonsch et al., 2015; Hanasaki et al., 2008; Smakhtin et al., 2004), stressors are very diverse (watershed disturbance, water resource development, pollution) and may partially be abated by considerable investments in water technologies, as it has been successfully done by affluent nations to alleviate threats to human water security (Vörösmarty et al., 2010). Agricultural activities do not only disturb hydrological processes by water withdrawals, but also by water contamination, deforestation and inappropriate land use (Peden et al., 2007). Our focus on water consumption linked to feed production neglects the implications of livestock for water pollution, being especially relevant in the context of highly intensive livestock production systems (Carvalho et al., 2010; Russelle and Franzluebbers, 2007). Especially nitrogen and phosphorus surpluses represent a major threat to water quality and aquatic ecosystems leading to eutrophication with severe impacts on the mix of aquatic plants, habitat characteristics as well as aquaculture and fisheries (Grizzetti et al., 2011; Steinfeld et al., 2006).

5. Conclusion

Both human and animal diets matter for limiting further disruption of hydrological processes. We show that intensification of currently low-productive livestock systems will substantially alter both magnitude of water consumption and the balance between different types of water and land use. Although effects on total livestock-related water consumption are beneficial, an increase in blue water use could negatively affect human water security and environmental flow requirements. Furthermore, results indicate that moderate productivity reductions in intensive systems are possible without increasing total crop water consumption, thereby opening up leeway to abate impacts from large-scale industrial enterprises, such as pollution of aquatic ecosystems through heavy nutrient loadings, pesticides and pathogens. A continuation of low productivity trends heavily relies on green water consumption related to expanding pastures, involving further land conversion at the expense of natural ecosystems.

The magnitude of the total livestock water footprint gives cause for serious concern regarding the water implications of our food choices. Dietary changes have considerable beneficial impacts on agricultural water consumption, but mainly of green origin, thereby also relaxing pressures on land. Direct positive effects on blue water are prone to high uncertainties and depend on the interplay of biophysical and socio-economic conditions. Neither dietary changes nor a transition of livestock production systems along the investigated productivity trajectories will solve the water challenge of future food supply if not accompanied by water protection policies, such as water pricing or water rights cap-and-trade schemes. Even the lowest estimate of future agricultural blue water consumption still represents an increase by 19% compared to current levels. As a consequence, it is important to combine demand-side policies aiming at a transformation of consumption patterns with supply-side interventions, capacity building, dedicated water policies and agricultural *R&D* to protect aquatic ecosystems and mitigate unsustainable water use that might compromise livelihoods of future generations.

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., Siebert, S., 2003. Global estimates of water withdrawals and availability under current and future “business-as-usual” conditions. Hydrol. Sci. J. 48, 339–348. doi:10.1623/hysj.48.3.339.45278

Alkemade, R., Reid, R.S., Berg, M. van den, Leeuw, J. de, Jeuken, M., 2013. Assessing the impacts of livestock production on biodiversity in rangeland ecosystems. Proc. Natl. Acad. Sci. 110, 20900–20905. doi:10.1073/pnas.1011013108

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R.W.A., Heinke, J., von Bloh, W., Gerten, D., 2011. Impact of reservoirs on river discharge and irrigation water supply during the 20th century. Water Resour. Res. 47, W03509. doi:10.1029/2009WR008929

Biewald, A., Rolinski, S., Lotze-Campen, H., Schmitz, C., Dietrich, J.P., 2014. Valuing the impact of trade on local blue water. Ecol. Econ. 101, 43–53. doi:10.1016/j.ecolecon.2014.02.003

Bodirsky, B.L., Popp, A., Lotze-Campen, H., Dietrich, J.P., Rolinski, S., Weindl, I., Schmitz, C., Müller, C., Bonsch, M., Humpenöder, F., Biewald, A., Stevanovic, M., 2014. Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. Nat. Commun. 5. doi:10.1038/ncomms4858

Bodirsky, B.L., Popp, A., Weindl, I., Dietrich, J.P., Rolinski, S., Scheiffele, L., Schmitz, C., Lotze-Campen, H., 2012. N2O emissions from the global agricultural nitrogen cycle – current state and future scenarios. Biogeosciences 9, 4169–4197. doi:10.5194/bg-9-4169-2012

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Change Biol. 13, 679–706. doi:10.1111/j.1365-2486.2006.01305.x

Bonsch, M., Humpenöder, F., Popp, A., Bodirsky, B., Dietrich, J.P., Rolinski, S., Biewald, A., Lotze-Campen, H., Weindl, I., Gerten, D., Stevanovic, M., 2014. Trade-offs between land and water requirements for large-scale bioenergy production. GCB Bioenergy. doi:10.1111/gcbb.12226

Bonsch, M., Popp, A., Biewald, A., Rolinski, S., Schmitz, C., Weindl, I., Stevanovic, M., Högner, K., Heinke, J., Ostberg, S., Dietrich, J.P., Bodirsky, B., Lotze-Campen, H., Humpenöder, F., 2015. Environmental flow provision: Implications for agricultural water and land-use at the global scale. Glob. Environ. Change 30, 113–132. doi:10.1016/j.gloenvcha.2014.10.015

Bossio, D., 2009. Livestock and water: understanding the context based on the “Comprehensive Assessment of Water Management in Agriculture.” Rangel. J. 31, 179–186.

Bouwman, L., Goldewijk, K.K., Hoek, K.W.V.D., Beusen, A.H.W., Vuuren, D.P.V., Willems, J., Rufino, M.C., Stehfest, E., 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proc. Natl. Acad. Sci. 110, 20882–20887. doi:10.1073/pnas.1012878108

Carvalho, P.C. de F., Anghinoni, I., Moraes, A. de, Souza, E.D. de, Sulc, R.M., Lang, C.R., Flores, J.P.C., Lopes, M.L.T., Silva, J.L.S. da, Conte, O., Wesp, C. de L., Levien, R., Fontaneli, R.S., Bayer, C., 2010. Managing grazing animals to achieve nutrient cycling and soil improvement in no-till integrated systems. Nutr. Cycl. Agroecosystems 88, 259–273. doi:10.1007/s10705-010-9360-x

Chapagain, A.K., Hoekstra, A.Y., 2003. Virtual water flows between nations in relation to trade in livestock and livestock products. UNESCO-IHE Delft, The Netherlands.

Chapagain, A.K., UNESCO-IHE, Institute for Water Education, 2006. Globalisation of water: opportunities and threats of virtual water trade. Balkema, Taylor & Francis Group; http://www.taylorandfrancis.co.uk.

Cohn, A.S., Mosnier, A., Havlík, P., Valin, H., Herrero, M., Schmid, E., O'Hare, M., Obersteiner, M., 2014. Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. Proc. Natl. Acad. Sci. 111, 7236–7241. doi:10.1073/pnas.1307163111

Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland Management and Conversion into Grassland: Effects on Soil Carbon. Ecol. Appl. 11, 343–355. doi:10.1890/1051-0761(2001)011[0343:GMACIG]2.0.CO;2

Cook, S.E., Andersson, M.S., Fisher, M.J., 2009. Assessing the importance of livestock water use in basins. Rangel. J. 31, 195–205.

de Fraiture, C., Wichelns, D., Rockstrom, J., Kemp-Benedict, E., Eriyagama, N., Gordon, L.J., Hanjra, M.A., Hoogeveen, J., Huber-Lee, A., Karlberg, L., 2007. Looking ahead to 2050: scenarios of alternative investment approaches.

Dietrich, J.P., Schmitz, C., Lotze-Campen, H., Popp, A., Müller, C., 2014. Forecasting technological change in agriculture—An endogenous implementation in a global land use model. Technol. Forecast. Soc. Change 81, 236–249. doi:10.1016/j.techfore.2013.02.003

Dietrich, J.P., Schmitz, C., Müller, C., Fader, M., Lotze-Campen, H., Popp, A., 2012. Measuring agricultural land-use intensity – A global analysis using a model-assisted approach. Ecol. Model. 232, 109–118. doi:10.1016/j.ecolmodel.2012.03.002

Don, A., Schumacher, J., Freibauer, A., 2011. Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. Glob. Change Biol. 17, 1658–1670. doi:10.1111/j.1365-2486.2010.02336.x

Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., 2006. IPCC guidelines for national greenhouse gas inventories. Inst. Glob. Environ. Strateg. Hayama Jpn.

Falkenmark, M., Molden, D., 2008. Wake Up to Realities of River Basin Closure. Int. J. Water Resour. Dev. 24, 201–215. doi:10.1080/07900620701723570

Falkenmark, M., Rockström, J., 2004. Balancing Water for Humans and Nature: The New Approach in Ecohydrology. Earthscan.

FAO, 2010. Global Forest Resources Assessment 2010: Main Report. Food and Agriculture Organization of the United Nations.

FAO, 2005. Review of the state of world marine fishery resources (No. 457), FAO Fisheries Technical Paper. Marine Resources Service, Fishery Resources Division of the Food and Agricultural Organization of the United Nations, Rome, Italy.

FAOSTAT, 2013. Database collection of the Food and Agriculture Organization of the United Nations.

Fischer, G., Velthuizen, H.V., Shah, M., Nachtergaele, F., 2002. Global Agro-Ecological Assessment for Agriculture in the 21st Century: Methodology and Results. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., Alcamo, J., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. Glob. Environ. Change 23, 144–156. doi:10.1016/j.gloenvcha.2012.10.018

Franzluebbers, A.J., 2007. Integrated Crop–Livestock Systems in the Southeastern USA. Agron. J. 99, 361. doi:10.2134/agronj2006.0076

Gerten, D., Heinke, J., Hoff, H., Biemans, H., Fader, M., Waha, K., 2011. Global Water Availability and Requirements for Future Food Production. J. Hydrometeorol. 12, 885–899. doi:10.1175/2011JHM1328.1

Gerten, D., Hoff, H., Rockström, J., Jägermeyr, J., Kummu, M., Pastor, A.V., 2013. Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Curr. Opin. Environ. Sustain. 5, 551–558. doi:10.1016/j.cosust.2013.11.001

Gleick, P.H., 1996. Basic Water Requirements for Human Activities: Meeting Basic Needs. Water Int. 21, 83–92. doi:10.1080/02508069608686494

Grizzetti, B., Bouraoui, F., Billen, G., van Grinsven, H., Cardoso, A.C., Thieu, V., Garnier, J., Curtis, C., Howarth, R., Johnes, P., 2011. Nitrogen as a threat to European water quality, in: The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge University Press, pp. 379–404.

Hanasaki, N., Inuzuka, T., Kanae, S., Oki, T., 2010. An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model. J. Hydrol., Green-Blue Water Initiative (GBI) 384, 232–244. doi:10.1016/j.jhydrol.2009.09.028

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., Tanaka, K., 2008. An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing. Hydrol Earth Syst Sci 12, 1007–1025. doi:10.5194/hess-12-1007-2008

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M.C., Mosnier, A., Thornton, P.K., Böttcher, H., Conant, R.T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., Notenbaert, A., 2014. Climate change mitigation through livestock system transitions. Proc. Natl. Acad. Sci. 111, 3709–3714. doi:10.1073/pnas.1308044111

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. 110, 20888–20893. doi:10.1073/pnas.1308149110

Herrero, M., Thornton, P.K., Gerber, P., Reid, R.S., 2009. Livestock, livelihoods and the environment: understanding the trade-offs. Curr. Opin. Environ. Sustain. 1, 111–120. doi:10.1016/j.cosust.2009.10.003

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., Steeg, J. van de, Lynam, J., Rao, P.P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart Investments in Sustainable Food Production: Revisiting Mixed Crop-Livestock Systems. Science 327, 822–825. doi:10.1126/science.1183725

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: Water use by people as a function of their consumption pattern. Water Resour. Manag. 21, 35–48. doi:10.1007/s11269-006-9039-x

Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., Lucht, W., 2015. Water savings potentials of irrigation systems: global simulation of processes and linkages. Hydrol Earth Syst Sci 19, 3073–3091. doi:10.5194/hess-19-3073-2015

Jägermeyr, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W., Rockström, J., 2016. Integrated crop water management might sustainably halve the global food gap. Environ. Res. Lett. 11, 025002. doi:10.1088/1748-9326/11/2/025002

Jägermeyr, J., Pastor, A., Biemans, H., Gerten, D., 2017. Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. Nat. Commun. 8, ncomms15900. doi:10.1038/ncomms15900

Jalava, M., Kummu, M., Porkka, M., Siebert, S., Varis, O., 2014. Diet change—a solution to reduce water use? Environ. Res. Lett. 9, 074016. doi:10.1088/1748-9326/9/7/074016

Jones, W.I., 1995. The World Bank and Irrigation. World Bank Publications.

Krause, M., Lotze-Campen, H., Popp, A., Dietrich, J.P., Bonsch, M., 2013. Conservation of undisturbed natural forests and economic impacts on agriculture. Land Use Policy 30, 344–354. doi:10.1016/j.landusepol.2012.03.020

Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., Haberl, H., 2008. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. Ecol. Econ. 65, 471–487. doi:10.1016/j.ecolecon.2007.07.012

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B.L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., Biewald, A., Bonsch, M., Giannousakis, A., Kreidenweis, U., Müller, C., Rolinski, S., Schultes, A., Schwanitz, J., Stevanovic, M., Calvin, K., Emmerling, J., Fujimori, S., Edenhofer, O., 2017. Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. Glob. Environ. Change 42, 297–315. doi:10.1016/j.gloenvcha.2016.05.015

Lal, R., 2005. World crop residues production and implications of its use as a biofuel. Environ. Int. 31, 575–584. doi:10.1016/j.envint.2004.09.005

Lapola, D.M., Priess, J.A., Bondeau, A., 2009. Modeling the land requirements and potential productivity of sugarcane and jatropha in Brazil and India using the LPJmL dynamic global vegetation model. Biomass Bioenergy 33, 1087–1095. doi:10.1016/j.biombioe.2009.04.005

Lemaire, G., Franzluebbers, A., Carvalho, P.C. de F., Dedieu, B., 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. Agric. Ecosyst. Environ., Integrated Crop-Livestock System Impacts on Environmental Processes 190, 4–8. doi:10.1016/j.agee.2013.08.009

Liu, J., Savenije, H.H.G., 2008. Food consumption patterns and their effect on water requirement in China. Hydrol Earth Syst Sci 12, 887–898. doi:10.5194/hess-12-887-2008

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., Lucht, W., 2008. Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. Agric. Econ. 39, 325–338. doi:10.1111/j.1574-0862.2008.00336.x

Marlow, H.J., Hayes, W.K., Soret, S., Carter, R.L., Schwab, E.R., Sabaté, J., 2009. Diet and the environment: does what you eat matter? Am. J. Clin. Nutr. 89, 1699S–1703S. doi:10.3945/ajcn.2009.26736Z

Mekonnen, M.M., Hoekstra, A.Y., 2012. A Global Assessment of the Water Footprint of Farm Animal Products. Ecosystems 15, 401–415. doi:10.1007/s10021-011-9517-8

Mekonnen, M.M., Hoekstra, A.Y., 2010. The green, blue and grey water footprint of farm animals and animal products.

Molden, D., 2007. Water for food, water for life: a comprehensive assessment of water management in agriculture.

Müller, C., Robertson, R.D., 2014. Projecting future crop productivity for global economic modeling. Agric. Econ. 45, 37–50. doi:10.1111/agec.12088

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., Vuuren, D.P. van, 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change 122, 387–400. doi:10.1007/s10584-013-0905-2

Peden, D., Tadesse, G., Misra, A.K., Awad Amed, F., Astatke, A., Ayalneh, W., Herrero, M., Kiwuwa, G., Kumsa, T., Mati, B., Mpairwe, D., Wassenaar, T., Yimegnuhal, A., 2007. Water and livestock for human development. Oxford University Press.

Perry, C.J., Hellegers, P.J.G.J., 2012. To what extent do improved irrigation technologies extend aquifer life? Hydrogeol. J. 20, 907–913. doi:10.1007/s10040-012-0872-0

Pfeiffer, L., Lin, C.-Y.C., 2014. Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. J. Environ. Econ. Manag. 67, 189–208. doi:10.1016/j.jeem.2013.12.002

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., Vuuren, D.P. van, 2017. Land-use futures in the shared socio-economic pathways. Glob. Environ. Change 42, 331–345. doi:10.1016/j.gloenvcha.2016.10.002

Popp, A., Humpenöder, F., Weindl, I., Bodirsky, B.L., Bonsch, M., Lotze-Campen, H., Müller, C., Biewald, A., Rolinski, S., Stevanovic, M., Dietrich, J.P., 2014. Land-use protection for climate change mitigation. Nat. Clim. Change 4, 1095–1098. doi:10.1038/nclimate2444

Postel, S.L., 1998. Water for Food Production: Will There Be Enough in 2025? BioScience 48, 629–637. doi:10.2307/1313422

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human Appropriation of Renewable Fresh Water. Science 271, 785–788. doi:10.1126/science.271.5250.785

Rockström, J., 2003. Water for food and nature in drought–prone tropics: vapour shift in rain–fed agriculture. Philos. Trans. R. Soc. Lond. B Biol. Sci. 358, 1997–2009. doi:10.1098/rstb.2003.1400

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., Gerten, D., 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change. Water Resour. Res. 45, W00A12. doi:10.1029/2007WR006767

Rockström, J., Gordon, L., Folke, C., Falkenmark, M., Engwall, M., 1999. Linkages Among Water Vapor Flows, Food Production, and Terrestrial Ecosystem Services.

Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. Proc. Natl. Acad. Sci. 104, 6253–6260. doi:10.1073/pnas.0605739104

Rohwer, J., Gerten, D., Lucht, W., 2007. Development of functional types of irrigation for improved global crop modelling, in: PIK Report. Potsdam Institute for Climate Impact Research, Potsdam.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., 2013. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. 111, 3268–3273. doi:10.1073/pnas.1222463110

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. 44, W09405. doi:10.1029/2007WR006331

Russelle, M.P., Entz, M.H., Franzluebbers, A.J., 2007. Reconsidering Integrated Crop–Livestock Systems in North America. Agron. J. 99, 325. doi:10.2134/agronj2006.0139

Russelle, M.P., Franzluebbers, A.J., 2007. Introduction to "'Symposium: integrated crop-livestock systems for profit and sustainability.'" Agron. J. 99, 323–324.

Schaphoff, S., Heyder, U., Ostberg, S., Gerten, D., Heinke, J., Lucht, W., 2013. Contribution of permafrost soils to the global carbon budget. Environ. Res. Lett. 8, 014026. doi:10.1088/1748-9326/8/1/014026

Schmitz, C., Lotze-Campen, H., Gerten, D., Dietrich, J.P., Bodirsky, B., Biewald, A., Popp, A., 2013. Blue water scarcity and the economic impacts of future agricultural trade and demand. Water Resour. Res. 49, 3601–3617. doi:10.1002/wrcr.20188

Siebert, S., Döll, P., Feick, S., Hoogeveen, J., Frenken, K., 2007. Global map of irrigation areas version 4.0. 1. Johann Wolfgang Goethe University, Food and Agriculture Organization of the United Nations.

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob. Change Biol. 9, 161–185. doi:10.1046/j.1365-2486.2003.00569.x

Smakhtin, V., Revenga, C., Döll, P., 2004. A pilot global assessment of environmental water requirements and scarcity. Water Int. 29, 307–317.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., others, 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855.

Steinfeld, H., Gerber, P., 2010. Livestock production and the global environment: Consume less or produce better? Proc. Natl. Acad. Sci. 107, 18237–18238. doi:10.1073/pnas.1012541107

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., Haan, C. de, 2006. Livestock's long shadow: environmental issues and options. xxiv + 390 pp.

Stevanović, M., Popp, A., Lotze-Campen, H., Dietrich, J.P., Müller, C., Bonsch, M., Schmitz, C., Bodirsky, B.L., Humpenöder, F., Weindl, I., 2016. The impact of high-end climate change on agricultural welfare. Sci. Adv. 2, e1501452. doi:10.1126/sciadv.1501452

Sutton, M.A., Ayyappan, S., 2013. Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution. Centre for Ecology & Hydrology.

Thornton, P.K., Herrero, M., 2010. The inter-linkages between rapid growth in livestock production, climate change, and the impacts on water resources, land use, and deforestation (No. WPS5178). The World Bank.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677. doi:10.1038/nature01014

Valin, H., Havlík, P., Mosnier, A., Herrero, M., Schmid, E., Obersteiner, M., 2013. Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? Environ. Res. Lett. 8, 035019. doi:10.1088/1748-9326/8/3/035019

van Velthuizen, H., Huddleston, B., Fischer, G., Salvatore, M., Ataman, E., Nachtergaele, F.O., Zanetti, M., Bloise, M., Antonicelli, A., Bel, J., others, 2007. Mapping biophysical factors that influence agricultural production and rural vulnerability, Environment and Natural Resources Series. FAO, Rome, Italy.

Vanham, D., Hoekstra, A.Y., Bidoglio, G., 2013. Potential water saving through changes in European diets. Environ. Int. 61, 45–56. doi:10.1016/j.envint.2013.09.011

Vörösmarty, C.J., Lévêque, C., Revenga, C., 2005. Fresh Water, in: Ecosystems and Human Well-Being: Current State and Trends. Millenium Ecosystem Assessment Report. Island Press, Washington, DC, pp. 165 – 207.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561. doi:10.1038/nature09440

Wada, Y., Gleeson, T., Esnault, L., 2014. Wedge approach to water stress. Nat. Geosci. 7, 615–617. doi:10.1038/ngeo2241

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., Bierkens, M.F.P., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37, L20402. doi:10.1029/2010GL044571

Ward, F.A., Pulido-Velazquez, M., 2008. Water conservation in irrigation can increase water use. Proc. Natl. Acad. Sci. 105, 18215–18220. doi:10.1073/pnas.0805554105

Weindl, I., Lotze-Campen, H., Popp, A., Müller, C., Havlík, P., Mario Herrero, Schmitz, C., Rolinski, S., 2015. Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. Environ. Res. Lett. 10, 094021. doi:10.1088/1748-9326/10/9/094021

WHO, 2003. Diet, nutrition and the prevention of chronic diseases (Report of a joint WHO/FAO expert consultation No. 916), WHO technical report series. World Health Organization (WHO), Geneva.

Wirsenius, S., 2000. Human Use of Land and Organic Materials: Modeling the Turnover of Biomass in the Global Food System (Doctoral thesis). Chalmers University of Technology.

Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric. Syst. 103, 621–638. doi:10.1016/j.agsy.2010.07.005

Wisser, D., Frolking, S., Douglas, E.M., Fekete, B.M., Vörösmarty, C.J., Schumann, A.H., 2008. Global irrigation water demand: Variability and uncertainties arising from agricultural and climate data sets. Geophys. Res. Lett. 35, L24408. doi:10.1029/2008GL035296

Zimmer, D., Renault, D., 2003. Virtual water in food production and global trade: Review of methodological issues and preliminary results, in: Proceedings of the International Expert Meeting on Virtual Water Trade, Value of Water-Research Rapport Series. pp. 93–109.