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Water saving potentials and possible trade-offs for future food and energy supply

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ABSTRACT

The sufficient supply of food and energy requires large amounts of fresh water. Mainly required for irrigation, but also processing and cooling purposes, water is one of the essential resources in both sectors. Rising global population numbers and economic development could likely cause an increase in natural resource demand over the coming decades, while at the same time climate change might lead to lower overall water availability. The result could be an increased competition for water resources mainly in water-stressed regions of the world in the future. In this study we explore a set of possible changes in consumption patterns in the agricultural and energy sector that could be primarily motivated by other goals than water conservation measures—for example personal health and climate change mitigation targets, and estimate the indirect effect such trends would have on global water requirements until 2050. Looking at five world regions, we investigated three possible changes regarding future food preferences, and two possible changes in future resource preferences for electricity and transport fuels. We find that while an increase in food supply as a result of higher protein demand would lead to an increase in water demand as well, this trend could be counteracted by other potential dietary shifts such as a reduction in grains and sugars. In the energy sector we find that an increasing water demand can be limited through specific resource and technology choices, while a significant growth of first-generation biofuels would lead to a drastic rise in water demand, potentially exceeding the water requirements for food supply. Looking at the two sectors together, we conclude that an overall increase in water demand for both food and energy is not inevitable and that changes in food and energy preferences could indeed lead to an alleviation of water resource use despite rising population numbers.

1. Introduction

The types of foods and energy we consume have considerable direct and indirect effects on global freshwater use. By far most water resources get used for irrigation purposes in the agricultural sector, mainly for food production. In another sector, energy, electricity and fuel production requires increasing amounts of water, mainly for resource extraction and cooling (Macknick et al., 2012; Mielke and Anadon, 2010). In some regions this trend has already led to a competition between different water users (The World Bank, 2014). Rising global population numbers and socio-economic development could lead to a further increase in water demand in both sectors over the coming three to four decades. At the same time environmental changes like climate change might decrease the water availability and quality in many parts of the world (Jiménez Cisneros et al., 2014). Hence, the source and type of food, electricity, and transport fuel we choose in the future can either accelerate a rising water demand or offset increasing resource needs, depending on the effects of consumer preferences and policy initiatives on consumption patterns in both sectors. Water is one of the most important natural resources and the interactions between water use, energy demand and food production are complex, as changes in the demand of one resource in one sector can change its availability and that of another resource in another sector and vice versa. Water is used and re-used for food, electricity, and fuel production, while energy is required for agriculture and water supply, creating positive feedback loops that can aggravate already existing water shortages or generate new ones.

Over the last decade a number of scientific papers and policy reports have examined the interactions between the agriculture and energy sector from a natural resource perspective. Resources

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that received highest attention with regard to their regionally interrelated availability are water, energy, and to some extent land. A term that is often used to describe this interconnection is the so-called water-energy-(land)-food (WE(L)F) nexus, i.e. the interaction regarding water that is required for food and energy, energy required for water and food, and land required for food and energy supply. There are qualitative and quantitative approaches, as well as global and regional studies covering either specific parts of the WE(L)F nexus or trying to integrate several resource interdependencies at the same time, searching for trade-offs and potential conflicts. Existing studies on this topic discuss a growing scarcity of natural resources due to rising population numbers and economic development, and their potential social implications, while most of them focus on the water-food or water-energy nexus.

Within this context, an important issue that has not yet been examined in the scientific literature are the effects that potential changes in consumer preferences could have on natural resource use. The amounts of water that get consumed for supplying food, electricity, and transport fuel can vary vastly depending on type of food and energy source chosen. In this study, we address this very question: how an increasing global per capita and overall demand for food and energy would potentially be influenced through a set of different consumption trends regarding changes in dietary and energy source preferences. In the form of a global high-level quantification for water consumption in the agricultural and energy sector, we model the water use for irrigation, cooling and processing purposes in five world regions as defined for the shared socio-economic pathways (SSPs) used for the latest IPCC assessment report (Field et al., 2014). Our aim is to compare and evaluate the water consumption shares for food, electricity, and transport fuels until 2050 and detect global and regional patterns in water demand across these two sectors. Through this integrated analysis we will be able to identify a set of relative and combined effects of resource preference changes on the presumably steadily rising water demand in both sectors.

2. Background

A number of recent qualitative and quantitative papers have discussed the WE(L)F nexus in general and particular resource interactions, often focusing on specific parts of the world which are characterized by significant natural resource scarcity and competition. A first set of studies has looked at (aspects of) the WE(L)F nexus on a qualitative basis. Ringler et al. (2013) discussed the linkages of water and food, energy and water, energy-food, land-energy, and energy-land, and underlined the importance of an integrated management approach. Halstead et al. (2014) reviewed the current literature on the WEF nexus, though did not relate water use shares of both sectors to each other. FAO (2014) examined the WEF nexus as a new approach to support food security and sustainable agriculture. Bogardi et al. (2012) analyzed the interconnected challenges for water security for a planet facing increasing regional water stress due to rising population, climate change, urbanization and development, calling for an integrated management framework in order to address all of these challenges simultaneously. De Fraiture et al. (2010) discussed comprehensive assessment methods for water management in agriculture. Also Rosegrant et al. (2009) focused on the water use intensity of the agricultural sector and how to maintain food security while water stress increases with an emphasis on improving efficiencies. Hellegers et al. (2008) presented a debate on the interactions between water, energy, food and environment with a focus on water-related policy issues. Allouche (2011) looked at water and food security predominantly from a social and political perspective, doing so on a global, regional and national scale. Harvey and Pilgrim (2011) explored the “new competition for land”, integrating food, energy and climate change into their discussion. All of these studies have envisioned a drastic rise in natural resource demand based on an extrapolation of current requirements to future population numbers and ongoing socio-economic development trends, and hence have called for an integrated policy and management framework.

Another set of studies has tried to quantify natural resource interconnections on a global level. Hanjra and Qureshi (2010) analyzed expected reduced global water availability and future food security, reviewing quantitative results from previous studies to underline the severity of limited water resources for agriculture over the coming decades. Chartres and Sood (2013) undertook a global quantitative analysis for the water demand for food production until 2050. Using the WATERSIM model they developed three scenarios with differing assumptions on population and GDP growth rates where they extrapolated current dietary patterns, but did not integrate a discussion on potential changes in future consumer preferences. All scenarios show an increase in global water demand for agriculture from 2400 km^3/yr in 2010 to between 3820 and 7230 km^3/yr in 2050. Sulser et al. (2010) used IFPRI’s IMPACT model for their analysis of the Nile and Ganges river basins, including a set of global scenarios that illustrate the potential growth rates of consumptive water use in the agricultural sector until the mid-century depending on global per capita income growth. They projected an increase from 1425 km^3/yr irrigation (blue) water demand for crop production in 2000 to 1785 km^3/yr in 2050 in their baseline scenario.

A third set of studies followed a regional approach to the WE(L)F nexus. Lele et al. (2013) debated governance issues when integrating food, water and energy security, including a case study for water management in China and India. Gulati et al. (2013) presented a national WEF study for South Africa, exploring the interdependencies of these three resources, including an economic analysis. Hardy et al. (2012) undertook a quantitative analysis of the water-energy nexus for Spain, calculating a potentially increasing water demand for energy supply. Scott et al. (2011) looked at the policy and institutional dimension of the water-energy nexus including cases studies from the United States, highlighting the role of integrated local water management. Khan et al. (2009) presented ways to reduce water and energy demand for grain production in Australia. Larson (2013) analyzed the water demand for alternative food security policies in the Middle East and North Africa, focusing on wheat production and trade. Rasul (2014) studied food, water and energy security in South Asia. Lawford et al. (2013) gave a basin perspective on the WEF security nexus, using results from case studies from different large river basins. Perrone et al. (2011) presented an integrated qualitative analysis framework for the water-energy nexus on the community level. In all of these regional analyses natural resource availability is expected to decline due to rising demands and simultaneous adverse ecological changes.

There have also been several regional and global studies looking particularly at the water (and land) demand of energy in the form of biofuels, and their potentially negative impacts on food security and water availability when scaling up biofuel production in the future. Dominquez-Faus et al. (2009) analyzed the water requirements for maize as energy crop in the US, concluding that a major shift to such an energy source would have large detrimental effects regarding water availability and environmental health. Fingerman et al. (2010) examined the water impacts of producing bioethanol in a comprehensive environmental assessment with a case study for California, finding that the production of ethanol from maize or sugar beets would require enormous amounts of water with up to 5100 L/L ethanol. Yang et al. (2009) calculated the land and water requirements for biofuel production in China and its potentially adverse consequences for food supply and the environment. Using the WATERSIM model, Fraiture et al. (2008) looked at international biofuel policies and their implications for water demand in the agricultural sector on a global level. They put emphasis on the countries China and India, where a fast growing energy demand and limited water resources could lead to strong resource competition in the future were biofuels utilized as one of the main transport fuels. Globally they estimated irrigation water withdrawals for bioethanol of 30.6 km^3/yr in 2005, an amount that could rise to 128.4 km^3/yr in 2030.

Given current consumption patterns, a high per capita supply of food and energy, rising global population numbers, and socio-economic development, all calling for high natural resource inputs, and their resulting ecological consequences like climate change aggravating regional resource scarcity, every one of the WE(L)F studies undertaken so far picture an increasing resource demand for the coming decades, and consequently underline the necessity for better, integrated management measures to avoid or alleviate resource competition. Their results show that current practices and development trends would lead to an increased demand for food, water, energy, and land, and that targeting multiple resource use goals at once can lead to higher management efficiency with regard to sustainability. What none of them has done, however, is to examine the effects that sectoral specific changes – both technological and behavioral – could have on such future resource demands. This is important, both because sector-specific changes may represent the best leverage points for policy, and because it may be that the opportunities for resource conservation in one sector may dominate those in all other sectors. It is the issue we now address.

3. Methods

3.1. Modeling framework

For our own quantitative approach we focused on water consumption (here synonymous with water demand) for food and energy at the supply stage. We chose not to include water withdrawals of these two sectors, as this might lead to a multiple accounting of the same water resources used and re-used for various purposes in both sectors. Rather than only extrapolating current trends and consumption patterns as done in previous studies, which necessarily lead to an increase in resource use in absence of policy interventions that directly target water use efficiency as well as technological improvements, we explored the variability within those patterns. As this variability might potentially influence water demand within and trade-offs between the two sectors, we tested the extent to which preferences for certain food sources as well as electricity and transport fuel sources could indirectly drive overall future regional and global water demand.

We developed a scenario approach for which we use population projections until the mid-century and built a two-part accounting and linear optimization model calculating water consumption associated with food and energy demand. To be able to detect potential drivers, water saving opportunities and possible trade-offs between the agriculture and energy sector with regard to future water use, we tested three potential dietary and two energy demand trends in the form of changed global consumption patterns in 2050 compared to today's food and energy source preferences. Fig. 1 displays an overview of our methodological approach.

3.2. Underlying scenarios and data

The Shared Socio-economic Pathways (SSPs) constitute a framework for climate change research that describes plausible alternative developments in society and economy without integrating climate change or new climate policies. For our study they serve as reference point mainly regarding population growth as well as for assumptions on general socio-economic development. We took the average population projections from the framework's five global world regions, Asia (ASIA), Latin America (LAM), the Middle East and Africa (MAF), the OECD countries (OECD), and countries from reforming economies of Eastern Europe and the former Soviet Union (REF). In all SSP projections overall growth of population numbers as well as GDP is projected in ten-year steps until 2100 (O'Neill et al., 2013; IIASA, 2013), we selected the year 2050 as projection point for our own analysis for which we estimated a total global population rise to roughly nine billion people. Fig. 2 presents an overview of the SSP world regions and their associated population projections.

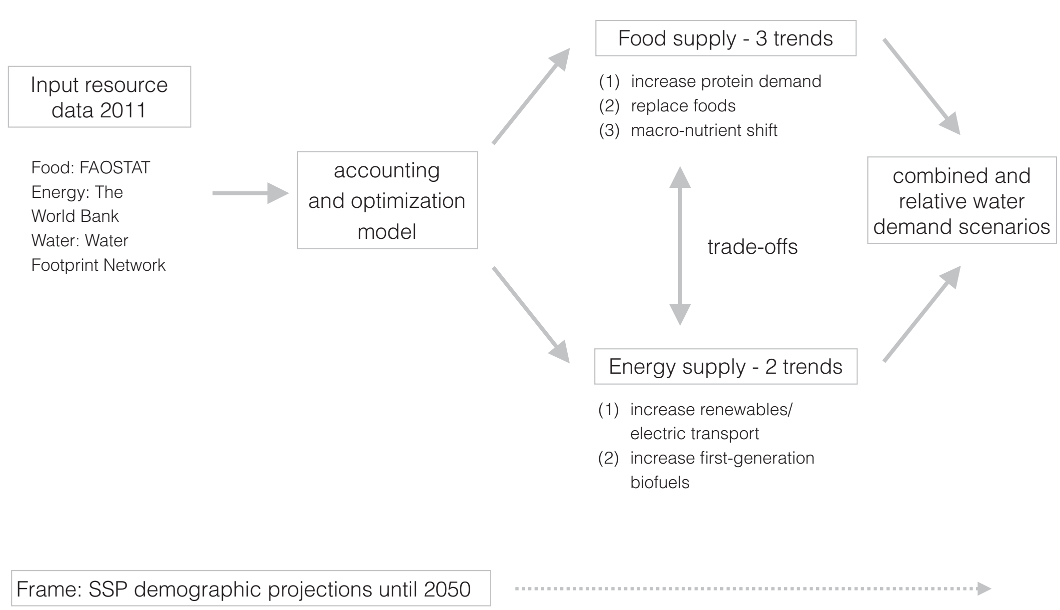


Fig. 1. Methodological approach for testing a set of potential dietary and energy source demand trends with regard to water consumption, starting in 2011.

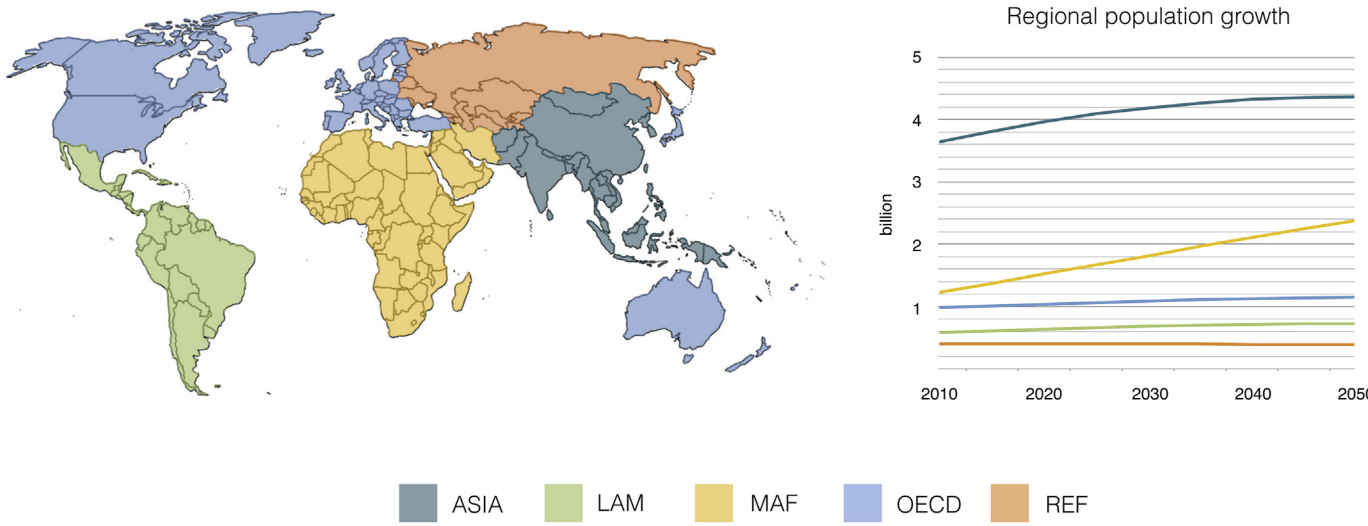


Fig. 2. SSP world regions and population growth as projected for each region. The map displays the five world regions Asia (ASIA), Latin America (LAM), MAF (Middle East and Africa), OECD countries (OECD) and the countries from reforming economies of Eastern Europe and the former Soviet Union (REF). The graph on the right presents the projected population growth for each world region until 2050.

We chose 2011 as reference year as this year marks the most recent consistent point in time for data collection on global food and energy supply. FAO's online database (FAOSTAT 2014) offers data on annual food supply (food sold on markets and in stores) on a country level for major foods and food groups. This information reflects actual food consumption only to some extent, as post-supply food waste rates and shares vary from food group to food group and region to region (Gustavsonson et al., 2011) and does not include supplies from subsistence farming. Of course, food waste occurs already between production stages and final supply and this also varies between regions, as shown in the database as well, but shares do not distinguish waste associated to the edible part of the product and non-edible but otherwise used parts. For each of the five SSP regions we calculated the average food supply (weight and energy content) based on population shares within the region for the following main food groups and their individually listed foods: cereals, starchy roots, sweeteners, pulses, nuts, vegetable oils, vegetables, fruit, meat, animal fats, eggs, dairy, and fish—43 products in total. The World Bank energy database offers annual data on electricity and transport fuel supply, giving main energy sources technology shares on a country level (The World Bank, 2015). We aggregated these data for each world region and adapted global assumptions on the shares of energy plant cooling technologies from Davies et al. (2013) for the electricity sector of each region.

For calculating the water consumption of the global food supply as well as for first-generation biofuel production we collected data from the global Water Footprint (WFP) Network. It forms an often-applied approach to assess the water consumption that occurs when producing a certain good (Mekonnen et al., 2011; Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2008). The Water Footprint is defined as the volume of fresh water appropriated to produce a product, taking into account the volumes of water consumed and polluted in the different steps of the supply chain

Table 1
Model constraints for regional food supply and trade. This Table lists and explains the model's restrictions and boundaries with regard to water consumption (blue and green water), regional diet patterns and nutritional assumptions concerning regional food supply. Single foods included in the analysis are wheat and wheat products, rice, barley, maize and maize products, rye, oats, sorghum, other cereals (cereals); cassava, potatoes and potato products, sweet potatoes, yams, other roots (tubers); sugar and sweeteners; beans, peas, soybeans, other pulses (pulses); nuts; soybean oil, groundnut oil, sunflower seed oil, rapeseed oil, cottonseed oil, palm(kernel) oil, coconut oil, sesame seed oil, olive oil (plant oils); vegetables; fruit; beef, goat, pig, poultry, offal, other meats (meat); animal fats incl. butter; eggs; dairy; fish.

Objective	Limitation
No increase of current water stress through food imports (Hoekstra and Mekonnen, 2012)	No increase in blue water trade Increase in green water trade limited to a maximum of 10% (New) foods added to the current diet only consume water resources stemming from within the region
No fundamental changes in dietary patterns assumed (compare Last et al., 2015)	Must keep at least 50% of a region's staple food (e.g. rice and wheat in ASIA) No increase in uncommon foods within a region, e.g. sorghum in OECD
Mitigate potential health risks from sugar overconsumption (Fried and Rao, 2003; Shapiro et al., 2011)	No increase in sugar and sweeteners
Mitigate potential health risks from dairy consumption: only about 30% of the global population are able to digest lactose (Lomer et al., 2007)	No increase in dairy
Mitigate potential health risks from soy overconsumption (Gilani et al., 2012; Cederroth et al., 2012)	Soy and soy products are limited to a maximum of 100 kcal/cap/d
Limit biodiversity loss (Koh and Wilcove, 2008; Burgess et al., 2013)	No increase in palm(kernel) oil consumption No increase in seafood consumption
Limit potential water demand changes for meat, as soybean oil cake is widely used as animal fodder	Limit potential increase of soybean oil to 10%
Ensure variety in nutrient supply (Foote et al., 2004)	Keep all main foods within each region's typical diet Keep current vegetable and fruit consumption stable
Include quality assumptions when comparing plant and animal protein sources (Friedman, 1996; Sarwar, 1997)	Combine grains and legumes to provide sufficient protein source, including lower quality assumptions of about a third compared to average animal protein

(direct and indirect water consumption). It is mostly used when assessing the virtual water trade that accompanies international product trade. The database lists the average blue, gray and green water consumption for agricultural products by product on a sub-national level, calculated using the global CROPWAT model (Hoekstra et al., 2011). For bioenergy production Gerbens-Leenes et al. (2008) list blue and green water consumption. Blue water is defined as the fresh surface and groundwater. Gray water is water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards. Green water is the precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. For this analysis we chose to focus primarily on to the blue water demand of different agricultural products (Ridoutt and Pfister, 2012; Sulser et al., 2010). As the WFP Network offers data on the national and sub-national level, we calculated the average water consumption (blue water) of a product for each region when produced within this region. These numbers however do not include the amount of water required for associated fertilizer and pesticide production. For biofuels we selected the three most prominent energy plants in each region. Regarding global food trade, we combined trade data from the FAO and ITC databases, providing trade shares and information on trading partners (FAOSTAT, 2014; ITC, 2014). We determined the two to three main trading partners (world regions) for each imported product and hence were able to estimate the amount of water that is imported through a certain food product (virtual water trade). The WFP Network database provides water use for unprocessed agricultural products as well as processed food products. For estimating the amount of water that gets attributed to the final food product, we chose averages for final uncooked foods that align with the food supply data from FAO. Regarding the water demand of specific electricity and fuel technologies, we applied a set of data collected by Damerau et al. (2015).

3.3. Model and constraints

In order to integrate all collected resource demand data, we developed a two-part accounting model that allowed us to calculate the water demand (blue, green and gray water separately) for each selected food per kcal within each region, including the regional water amount from imported products. Listing the associated food group and specific macro-nutrient content of each food created the basis for a rough qualitative comparison between single foods and food groups. In a next step, we added a model function in the form of a linear optimization module using the programming language R (Venables et al., 2015). This made it possible to limit the amount of energy, macro-nutrients, food groups, and single foods as listed in the caption to Table 1, as well as green and gray water use, when optimizing, i.e. minimizing the water demand (blue water) of a given or assumed daily nutritional intake within a region. We followed the same methodology for the energy sector, where instead of food supply in kcal we listed the water demand per GJ for electricity and transport fuel supply, including virtual water imports from imported fossil fuels for the latter.

To be able to run the optimization model for food supply and potential future dietary patterns without compromising variety and health or excluding staple foods typically consumed in a certain world region, as well as limiting virtual water trade, we compiled a list of assumptions and restrictions as presented in Table 1.

For our energy model we also defined a set of constraints. After calculating the specific electricity technology shares for coal, gas, nuclear, oil, combined cycle, biomass, concentrating solar power (CSP), photovoltaic, wind, geothermal, and hydropower—all technologies that are represented in the World Bank database (The World Bank, 2015), and if applicable their associated cooling technologies for each of the five world regions, we made the baseline assumption that the specific energy technology shares do not change over time within each region. This first step represents a simple extrapolation from current energy supply conditions that later allows a comparison to possibly changing technology mixes and their associated water demand in the energy sector in the future. Such shifts in technology shares are reflected in possible changing demands for certain energy technologies that do not directly target water saving goals. We accounted for water consumption from hydropower separately as this water use stems mainly from evaporation losses at hydropower reservoirs, which are often used for multiple purposes and thus make assumptions on attributable water losses due to power production problematic. Electricity generation from biomass is here assumed to be provided by waste matter and does not require the additional planting, and therefore irrigation of energy crops.

Regarding transport fuels, we included virtual water imports from fossil fuels extracted and exported from the Middle East and North Africa, a region contributing about 40% to global oil exports today (BP, 2013). For biofuels, we used assumptions on conventional first generation biofuels such as bioethanol from sugar cane or biodiesel from rapeseed oil. From the WFP Network data on bioenergy we determined the (partially weighted) average water consumption for three main biofuel crops planted within each world region. To these numbers we added the water demand for processing and converting these crops into liquid transport fuels (Van Vliet et al., 2009).

3.4. Alternative scenarios incorporating shifts in food and energy consumption patterns

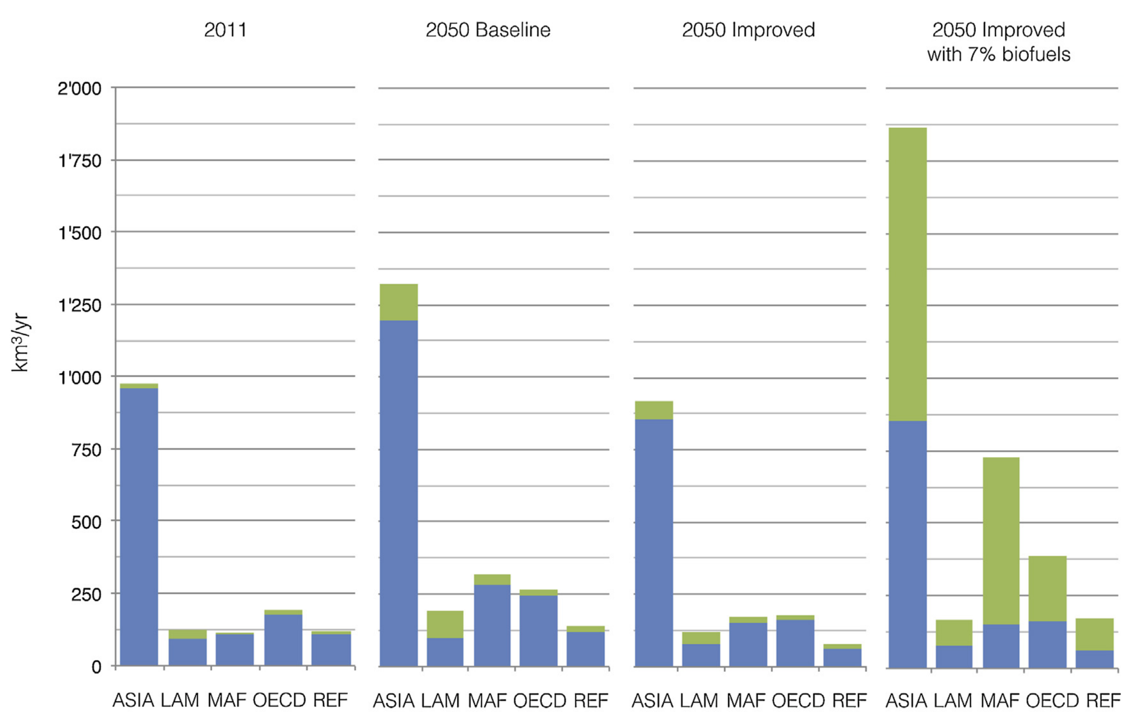
Global development goals include food and energy security for a large number of people for which both food and energy demand (absolute and per capita) are likely to increase over the coming decades. FAO's food security definition states that food security exists when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life (FAO, 1996). From there, one can make very different assumptions about potential changes in future consumer preferences and their motivation. We assumed an overall desired trend towards more balanced diets (sufficient and proportionally adequate supply of all essential macro- and micro-nutrients) that target health, longevity, and optimal physical and cognitive performance. We did not assume extreme changes in global dietary patterns, but rather examine the effect of how more moderate shifts towards more nutritious and safe foods can have on the water demand for future food supply. For this purpose we specified three concurrent dietary shifts.

The first is an increase in protein supply in all regions except the OECD region to levels comparable to those in OECD, which we assumed to be nutritionally sufficient for supporting basic metabolic processes and physical performance. In OECD countries we calculated an average supply (not consumption) of protein of approximately 110 g/cap/d with a share of about 40% plant and 60% animal protein. For closing this 'protein gap' globally we compared potential animal and plant protein sources for each selected region, foods that are already available and consumed within every region, using linear optimization to identify possible protein sources that show lowest regional water demand. Given the lower overall nutritional quality of most plant proteins in comparison to animal protein, and hence the necessity to combine different plant foods for a sufficient amino acid supply, we took average digestibility data from various studies, assuming a 50/50 protein share from grains and legumes and an average digestibility factor of 1.5 compared to animal protein sources; i.e. one needs to consume 50% more plant protein to reach similar bioavailability as average animal protein (Friedman, 1996).

In the second shift, without changing the macro-nutrient shares typical for today's diets – on a global level roughly 60% carbohydrates, 10% protein, and 30% fat (FAOSTAT, 2014) – we looked for possibilities to swap to some extent certain foods with each other. Staying within the main food groups and overall macro-nutrient shares of an average regional diet, an example for such an exchange would be the replacement of one plant oil in the diet with another, potentially more nutritious one when compared directly (USDA, 2014; Siri-Tarino et al., 2010; Deol et al., 2015).

In the third shift, we examined the potential effects a decrease in absolute and relative total carbohydrate share from roughly 60% today to 40% and hence an increase in the fat share of a diet. Such a trend would be driven by current empirical and clinical evidence on the potential negative health effects of long-term high-carbohydrate diets (Sondike et al., 2003; Bazzano et al., 2014; Westman et al., 2007). This shift can be considered as a profound change of the average diet of a large number of people, while carbohydrates would still represent the highest macro-nutrient share within such a diet. In this step we also included increased protein levels in ASIA, LAM, MAF and REF as calculated for trend one and kept overall energy supply stable in each region, as the average energetic supply of each world region's diet appears to be sufficient if not excessive in some regions, though certain macro- and micro-nutrient needs might not be met by modern (Western) diets (Gosby et al., 2014; Hunt, 2003). In all of these three potential basic trends, water savings are not assumed to be the primary goal, but can be supported by smart choices regarding the resource intensity of different foods.

For the energy sector, we envisioned two concurrent developments reflecting potential consumer preference changes until 2050. The first is an increased awareness of climate change and engagement to meet climate mitigation goals, leading to a higher demand for renewable energy sources such as solar and wind power. The second is growing health concerns associated with noise and air pollution from traffic relying mainly on fossil fuels (Anderson et al., 2012; Curran et al., 2013), leading to higher shares of electric transport and/or biofuels, such as bioethanol and biodiesel. Over the last decade a number of countries have defined various goals for future biofuel shares in their transport fuel mix, often ranging from 10 to 20% (Lane, 2014). Producing their own biofuels would increase those countries' energy independence, though a competition of bioenergy with food production could be one of the potential downsides. Besides, first-generation biofuels can have large negative ecological impacts, not only with regard to water (Creutzig et al., 2014). The European Union therefore revised their biofuels targets until 2020, limiting first-generation biofuels to a share of 7% (The Economist, 2015). We adopted this goal for our global estimates and tested both possible trends, estimating the effect they would have on regional and global water resources without directly targeting future water availability. Additional



	2011 ASIA	LAM	MAF	OECD	REF	2050 Baseline ASIA	LAM	MAF	OECD	REF	2050 Improved ASIA	LAM	MAF	OECD	REF	2050 Improved with 7% biofuels ASIA	LAM	MAF	OECD	REF
energy	12	29	6	16	11	125	90	40	23	20	65	45	20	14	15	1,010	90	578	225	109
food	962	93	110	175	109	1,196	100	281	245	120	853	77	150	163	64	853	77	150	163	64
global total, energy supply [km³]	74					298					159					2,012				
global total, food supply [km³]	1,449					1,942					1,307					1,307				

Fig. 3. Total current and potential future water demand for food, electricity, and liquid fuel supply by region. Extrapolating the water demand of both sectors in ASIA, LAM, MAF, OECD and REF to meet the goal of today's OECD consumption patterns for the entire future population results in a substantial increase in water demand. Dietary shifts and technological changes can lead to improvements in water efficiency for both food and energy supply. However, an increase in biofuel supply to meet 7% of the future population's transport fuel needs would lead to a drastic rise in water demand, potentially exceeding water requirements for food supply.

factors that might influence or counteract the trends we detected will be evaluated in the discussion section of this study.

4. Results

Fig. 3 displays our first set of results regarding combined and relative water demands on a global level, comparing water consumption for food and energy supply by region for 2011, 2050 in a baseline scenario as well as 2050 in an improved scenario with and without a major expansion of first-generation biofuels. As our baseline scenario shows, extrapolating current food and energy consumption to a global population in 2050 would inevitably lead to a large increase in water demand, much more so in the agricultural sector than in the energy sector. An increase in food supply in the form of a higher global average protein demand comparable to OECD levels in 2050 would results in a higher calorie demand of 40–60% depending on the protein source chosen. If at the same time energy demand were to increase to per capita levels we currently see in OECD countries, assuming no changes in the energy technology shares, we would see a total rise in energy demand by 180%. Both rising resource demands would lead to an increase of overall freshwater consumption by 50% compared to current global water requirements, 15% of which would be required in the energy sector. In our improved scenario, where we consider three shifts regarding food consumption patterns, and one shift in the energy sector towards more renewables (and/or dry-cooled thermal power production in general) and electric transport until 2050, we see a slight decrease for the combined water demand of both sectors by 4% despite a global population growth to nine billion people. The water savings for food supply outweigh growing water requirements for electricity and transport fuels. Compared to the baseline scenario, this projection shows an in total 35% lower water consumption in 2050. One caveat, however, is presented in the last scenario with an expansion of first-generation biofuels to globally 7% of total transport fuels. This would result in a water demand for energy supply higher than for the current food supply, total global water demand in this scenario would more than double.

In Fig. 4 we present a second set of results illustrating the specific effects single trends would have on the water demand for food supply in each world region. Daily per capita water intensity of food supply is currently highest in the REF region, and lowest in MAF. This present water consumption is put into relation with (1) a potential driver of water consumption in the form of increased protein demand in four out of five world regions, and two water-saving trends: (2) more nutritious food sources could to some extent replace current food items, and (3) a combination of food replacements and a macro-nutrient shift from 60 to 40% carbohydrates in the average diet by 2050. Overall results show that in all five regions a considerable reduction in water demand could be achieved indirectly through dietary changes.

4.1. Increasing protein supply

Reaching the level of protein supply as observed in OECD countries today, including a high animal protein share, would lead to an increase in dietary protein and calories associated with these protein sources in all other world regions, ASIA, LAM, MAF, and REF. In ASIA and LAM animal protein sources would lead to slightly stronger water demand increase than plant protein sources, while in REF plant protein requires slightly more water. The biggest difference between the water requirements for different protein sources was found in MAF, where animal protein (goat) would require considerably less water than a maize/pea mix. In all regions

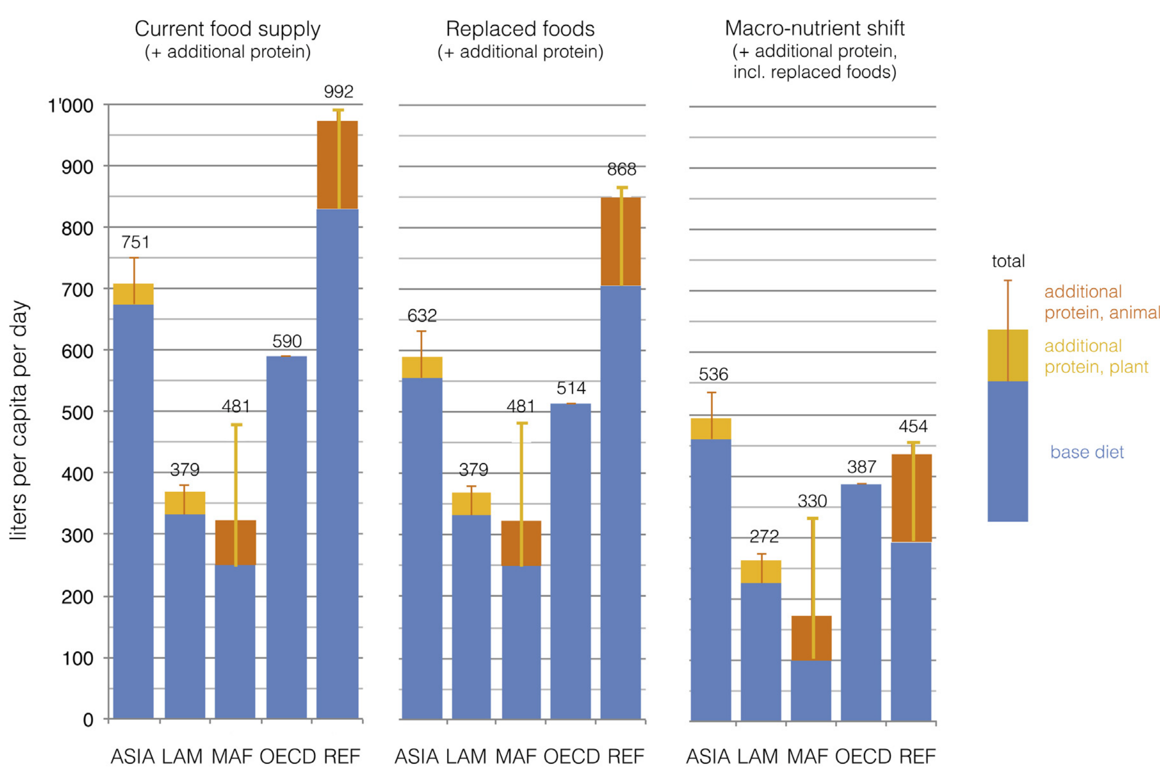


Fig. 4. Current regional water demand for food supply and effects of potential dietary shifts. Water demand in liters per capita and day increases when animal (orange) or plant (yellow) protein sources are added to the average diet. In three regions, ASIA, OECD, and REF, substituting half of the amount of certain foods with less water-intensive ones reduced overall water demand significantly. An even greater effect can be reached in all regions through a shift from carbohydrate sources towards more fat sources. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

an increase of protein supply through plant protein sources would also lead to a considerably higher increase in energy supply than that for animal protein, exceeding current OECD levels of roughly 3500 kcal/cap/d.

4.2. Replacing foods

In LAM and MAF we did not find single significant foods where an exchange would lead to substantially lower water requirements. In ASIA however, a hypothetical replacement of half its wheat and rice consumption with more nutritious tubers such as sweet potatoes and yams would lead to an 18% reduction of overall water intensity of the average Asian diet. In OECD and REF we find similar saving potentials. Given the relatively high dairy consumption, a 50% replacement of dairy products with either eggs in OECD countries or goat/sheep meat in REF countries would lower water demand by 6–10%; also, replacing 50% of these regions' current soybean and safflower oil supply with rapeseed or coconut oil would lead to a reduced water demand of another 5%. Such shifts could potentially offset water demand increases from rising population demands as discussed above, while increasing the micro-nutrient content of the average diet.

4.3. Shifting macro-nutrient composition

This trend includes a slight increase in protein to OECD levels (as calculated for trend one) as well as potential water savings described for trend two. We assumed additional protein sources to be supplied by animal sources, which show lower carbohydrate loads. In all five regions a trend away from very high carbohydrate supplies towards diets higher in fat, in four regions animal protein, and also micro-nutrient content, would lead to a per capita water demand of the average global diet lower than seen today (from 560 to 400 l/cap/d). Depending on the region, we detect a number of drivers for this trend including a shift away from grains (and sugar) towards tubers (though the other way around in LAM), more plant oils such as coconut oil, less dairy but more meat sources such as goat, sheep and in MAF also poultry, and more eggs and animal fats in OECD countries. We find a decrease in per capita water consumption between 12% in LAM and 45% in REF. Adding up these potential saving over the whole global population, we see a decrease in total water demand for global food supply in 2050 by 10% despite the demographic growth.

Fig. 5 illustrates a third set of results by comparing current water demand for electricity and transport fuel supply to (1) a global increase to per capita energy intensity as currently observed in OECD countries, (2) a scenario in which 50% of the this energy supply goal could be met by renewables and/or dry-cooled energy technologies, including a 50% share of electric transport, and (3) an increase of first-generation biofuel share to globally 7%.

4.4. Extrapolating current technology shares

Meeting the potential future electricity and transport fuel demand in ASIA, LAM, MAF, and REF would result in an increased water demand by a factor of 2.5 in REF to factor of 8 in ASIA. When compared to today's consumption levels, a considerable share would be required for increased fossil fuel production, also leading to a significant rise in associated virtual water trade with MAF. Not included in these estimates is water contributing to hydropower production. Without hydropower we would see a global increase in water consumption for electricity and transport fuel production by

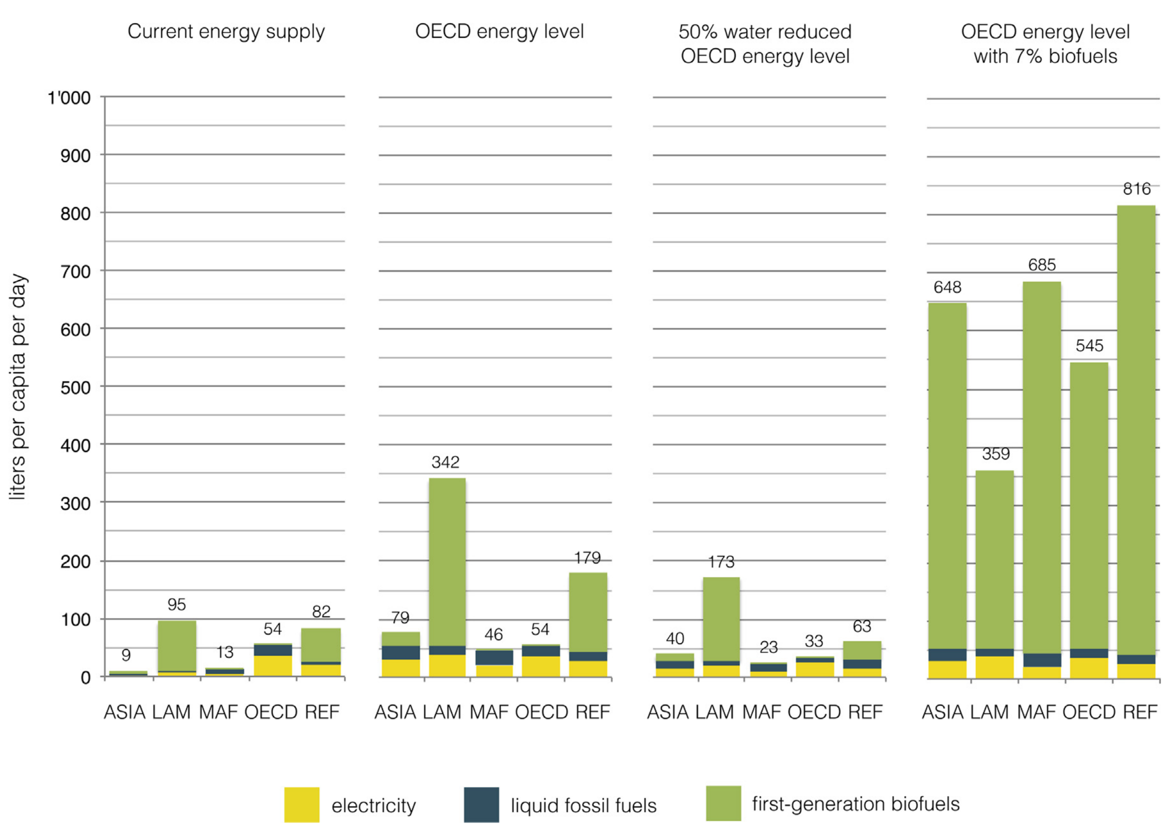


Fig. 5. Current regional water demand for electricity and liquid fuels and effects of changing demand patterns. Increasing the per capita energy demand in all regions to current OECD levels also leads to an increase in water demand of the energy sector. Water savings can be achieved through shifts towards wind or photovoltaic but also dry-cooled thermal power capacities. A significant increase in first-generation biofuels, however, would increase the overall water demand for energy dramatically. Water demand for hydropower is not included in this graph.

a factor of four, from 74 km^3/yr to 298 km^3/yr. This is a significant increase that might indeed lead to increased competition for water resource in water-stressed areas. Compared to the potential increase in water use for food supply, i.e. increased protein supply, from 1449 to 1942 km^3/yr this trend in the energy sector still appears minor, though not trivial. If hydropower needs were included in this extrapolation, this would add another 1580 km^3/yr of water consumption, an almost 12 times higher amount than today's estimates. In this scenario highest increases in water consumption associated with large hydropower appear in the MAF region, followed by ASIA and REF.

4.5. New energy technologies in the electricity mix

New power plant capacities are required either to replace outdated plants or increase overall electricity supply. Some technologies require negligible amounts of water to operate such as photovoltaic and wind turbines. In the case of thermal power plants dry or seawater cooling technologies can be employed to reduce the water demand by about 90%. Hence, if 50% of the electricity plants in 2050 were to either use wind or photovoltaic, or dry/seawater-cooled technologies such as CSP, geothermal or biomass/waste plants, the water demand of the electricity sector could be almost cut in half. The same holds true for the transport sector, if fossil fuels were to be replaced with electricity from those water-saving technologies.

4.6. Increase in first-generation biofuels

If in 2050 global average per capita fuel demand would reach OECD levels and 7% of this demand would be met by first-generation biofuels, that are produced within each world region, using the currently most common energy crops, total water consumption for energy would increase from 74 km^3/yr today to possibly 2012 km^3/yr, 97% of which for growing biomass. This amount of water would equal the amount of water required for increased food supply when not assuming potential dietary shifts.

5. Discussion

In contrast to previous studies, our work is able to show that an increase in water demand for food production in future is not inevitable, while a rise in water consumption in the energy sector appears in every scenario we examined. Because the use of water for food is currently in most cases more than one order of magnitude larger than for energy depending on world region, there is an overall potential to save water across the two sectors. At the same time, increased reliance on biofuels could easily change this story, making energy the larger water consumer, overshadowing any potential gains in the food sector.

A globally considerable intensification in blue water demand of 50% as estimated by us in the first step of this study is comparable to findings of other authors (OECD, 2012), and potential mitigation measures are discussed in many WE(L)F studies as cited in the Background section. Indeed, if we were to simply extrapolate current per capita OECD consumption patterns to the global level in 2050, regional and local water competition is likely to increase, and might even lead to potential resource conflicts (Bogardi et al., 2012). Still, on a regional and global scale water demand for energy remains minor when compared to resources used for food supply. Interconnections between the two sectors with regard to water therefore so far appear as a potential environmental and social issue predominantly on a sub-regional and local scale (Apipalakul et al., 2015). Additional sectoral water demands can stem from for example hydrogen generation, an element that is required for fertilizer production but also oil and natural gas refining. These water needs are not included in our global analysis, and currently amount to a volume about four magnitudes smaller in comparison to overall blue water demand for food and energy supply. However, in areas that already experience water stress, such auxiliary requirements have the potential to further increase resource competition.

In the part of our study looking at water requirements for food supply, we investigated how potential changes in food consumption, i.e. changing dietary patterns, and energy preferences could affect regional and global freshwater consumption. We chose to look at three potential, overlapping trends in food demand over almost four decades. Dietary trends within modern societies can only be observed over a relatively long timespan of several decades before they become statistically visible (USDA ERS, 2008). Our goal was to illustrate the effects such trends could have on overall water demand; these trends do not constitute dietary recommendations. We find that possible and plausible changes in food preferences, partly in combination with a shift to less water-intensive food sources, both potentially driven by personal health and performance goals, could indeed result in a lower overall water demand for food supply than today despite rising population numbers. We focused on blue water demand for this analysis, as we made the assumption that potential savings in green water use would practically not increase actually available water supply for both food or energy production (Wichelns, 2004). However, we restricted the potential increase of green water use and trade to a maximum of 10% in our scenarios to avoid a significant, and potentially unfeasible increase of those water resources.

The trends investigated in this study do not fundamentally affect regional and local cuisines and traditions, as mostly broad averages for regional food supply were used that do not compromise food variety and traditional choice of meal ingredients. However, the demand for more nutrient dense diets could also lead to other plausible changes in food preferences such as an increase in vegetable and fruit consumption. Such a trend would counteract potential water savings, as both food groups show high freshwater consumption rates. It is also worth to look at each world region separately as water footprints can vary significantly between regions. Regarding food sources that provide protein, adequate plant protein does not necessarily require less water than comparable animal protein sources.

Another important point to make is that food supply does not equal agricultural production (compare results from Chartres and Sood (2013)). Plant and animal products often satisfy multiple purposes besides delivering food, such as providing seeds, fodder, leather, or ingredients for personal hygiene products. Therefore the losses and waste that occur between the production of the agricultural product and the final food product in retail are difficult to allocate. This is the reason we chose to focus on food supply rather then agricultural production data concerning water requirements for food production within the broader context of the water-energy-food nexus. The largest share of food waste (on average 30%) occurs after the supply stage at retail points and in private households (Gustavsonson et al., 2011). The data we applied for food supply therefore do not reflect average food consumption, and do not include private food production on a household level. Above, in high-income countries food waste shares after retail are often higher compared to those in low-income countries. A reduction in food waste could therefore additionally lower the intensity of natural resource use without assuming any demand or technological changes in the global food system.

In contrast, in the energy sector water demand will likely grow, even when considering an increasing share of renewable technologies. When assuming high per capita energy intensity in the future on a global average, energy supply capacities have to be expended drastically to satisfy the growing demand. This increase would also likely lead to a non-trivial rise in water demand for energy, as shown by our own estimations as well as other previous studies (Hardy et al., 2012; Stillwell et al., 2011). Regarding electricity supply, energy technologies showing negligible water consumption rates such as wind and photovoltaic, and if applicable, relying increasingly on the use of sweater for cooling purposes at thermal power plants, could limit this growing water demand. There is another possibility that we considered in our analysis, which could reduce the water demand for thermal electricity generation: installing dry instead of wet cooling systems. Such a development would lead to lower power plant efficiencies compared to wet cooled systems, hence larger energy plant capacities were required to meet the estimated future energy demand, increasing electricity cost to some degree (Damerau et al., 2011).

In the fuel sector, an increase in first-generation biofuels could easily lead to large additional water requirements, possibly exceeding those for food. Above, also the demand for cropland would rise, which might lead to additional competition for land with food production (Rathmann et al., 2010). One possibility to reduce the water requirements for first-generation biofuel production would be a shift towards energy crops that show lower water demands but are currently less often used, though overall water use for bioenergy would still remain high. However, a general restriction of first-generation biofuels as well as the deployment of freshwater-cooled thermal energy technologies in the future would also limit the additional water (and land) demand in the energy sector, an increase that could be more than offset by changes in the food sector. Due to this potential trade-off, an overall increase in water demand in both sectors is not necessarily an unavoidable trend. Our results provide valuable new insights and information for integrated natural resource management and policy, in particular with respect to biofuel targets. Mitigation measures as discussed in previous studies can further improve water efficiency, especially in regions where water availability might decline over the next decades as a consequence of climate change and other potential ecological changes.

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