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Is the available cropland and water enough for food demand? A global perspective of the Land-Water-Food nexus

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ABSTRACT

Land and water are essential local resources for food production but are limited. The main drivers of increasing food demand are population growth and dietary changes, which depend on the socioeconomic situation of the population. These two factors affect the availability of local resources: population growth reduces the land and water per person; and adoption of affluent diets increases the demand for land and water per person. This study shows potentials of global food supply by linking food demand drivers with national land and water availability. Whether the available land and water is enough to meet national food demand was calculated for 187 countries. The calculations were performed for the past situation (1960 and 2010) and to assess four future scenarios (2050) to discuss different paths of diets, population numbers and agricultural expansion. Inclusion of the demand perspective in the analysis has shown stronger challenges for future global food supply than have other studies. The results show that with the “business as usual” scenario, 40% of the global population in 2050 will live in countries with not enough land nor water to meet the demands of their population. Restriction to basic diets will be the most effective in lowering both land and water constraints. Our results identify both food production and food demand factors, and the regions that may experience the strongest challenges in 2050.

1. Introduction

Land, water and energy are essential resources to assure food security, and research is increasingly addressing their interrelationships in the so-called Water-Energy-Land-Food nexus (Ringler et al., 2013). The strong trade-offs and complex linkages among them indicate an urgent need for an integrative approach when evaluating the use of water, energy and land for food (Bazilian et al., 2011; Ringler et al., 2013; Bhaduri et al., 2015). An integrative approach can identify sustainable paths in the efficient use of agricultural resources to assure human wellbeing and environmental sustainability (Ibarrola Rivas, 2015).

Land and water are local resources whose availability determines the potential for food production (Kumar et al., 2012; Fader et al., 2013). This means that land and water for food production cannot be brought from other places. On the contrary, energy inputs (such as fertilizers and fuel for machinery) can be brought from other places. For this reason, in this paper we analyse the land-water-food nexus.

The amounts of land and water needed are closely related with food demand factors, mainly the number of people and their consumption pattern (Ibarrola Rivas, 2015: chapter 1). These factors differ widely

throughout the world and have responded differentially to socioeconomic and cultural factors (Chesnaïs, 1992; Caballero and Popkin, 2002; Nonhebel and Kastner, 2011). Per capita use of cropland (Kastner et al. 2012) and water (Hoekstra and Mekonnen, 2012) differs markedly because of differences mainly in production systems (specifically in the crop yields obtained) and in the type of diet. In general, basic diets have large consumption of cereals, roots and pulses and require lower amounts of resources than affluent diets (Hoekstra and Mekonnen, 2012; Kastner et al., 2012). Affluent diets are generally rich in animal products, sugars, vegetable oils, vegetables and fruits (Caballero and Popkin, 2002).

This paper presents a global analysis of the drivers of food demand (socioeconomic situations, population growth and dietary changes) and links them with the availability of land and water per capita in order to discuss production possibilities to fulfil food demand. We use the values of Kastner et al. (2012) and Hoekstra and Mekonnen (2012) as references in discussing limits to the fulfilment of food demand in relation to the pattern of consumption. We discuss changes in past decades (1960–2010), and assess whether resources in 2050 will be enough for four scenarios with different projections of population growth, dietary changes, and agricultural expansion. Our two main research questions

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Table 1

Four scenarios for 2050 based on population projections, agricultural expansion and changes in diets. The bold letters indicate the determinant that differs between each scenario and the BAU.

Source of data of the projections and assumption: ¹United Nations (2011); ²Projections for arable land expansion per sub-continent from Alexandratos & Bruinsma 2012, Table 4.8; ³Projections of GDP per capita for scenario SSP2 from IIASA SSP Database (2015); ⁴Assumption for future dietary changes based on data from Kastner et al. (2012) for cropland and Hoekstra and Mekonnen (2012) for water. The value of basic diet includes all countries with less than \$2000/cap in 2010, and affluent diets include all countries with more than \$10,000/cap.

Scenarios	BAU (Business As Usual)	Basic diets	No deforestation	Low population growth
Population projection	Medium fertility rate ¹	Medium fertility rate ¹	Medium fertility rate ¹	Low fertility rate¹
Cropland availability	Agricultural expansion ²	Agricultural expansion ²	NO Agricultural expansion	Agricultural expansion ²
Dietary pattern	Dietary changes based on projected GDP (SSP2) ³ Low income ⁴ : 1460 m ² & 1100 m ³ Transition ⁴ : 1800 m ² & 1430 m ³ Rich ⁴ : 2140 m ² & 1760 m ³	All population with Basic diets⁴ (1460 m ² & 1100 m ³)	Dietary changes based on projected GDP (SSP2) ³ (See data in BAU)	Dietary changes based on projected GDP (SSP2) ³ (See data in BAU)

are: 1. Are national water and land resources for food sufficient to fulfil future national food demand? 2. What proportion of the global population will live in countries with land and water constraints?

2. Materials and methods

2.1. Data

We have used country-level data of 187 countries for the years 1960 and 2010 and projections for 2050. The data are: (1) average income in 1960 and in 2010, Gross Domestic Product (GDP) per capita (World Bank, 2014) and projections for 2050 (IIASA, 2015); (2) population records of 1960 and 2010, and projections for 2050 (United Nations, 2011); (3) area of arable land and permanent crops available in 1960 and in 2010 (FAO, 2013a); and (4) water availability in 1960 and in 2010 (FAO, 2013b). We used GDP per capita data to discuss the main drivers of food demand, i.e. population growth and dietary changes (see Section 3.1).

We calculated the per capita availability of cropland and water for 1960 and 2010. For cropland, we used data on arable land and permanent crops (FAO, 2013a) since these are the high-quality sources of food production, and for each year we calculated a 3-years average value. For water, we used data on the total renewable water resources defined by AquaStat (FAO, 2013b), which includes the annual amount of surface and ground water available in the country and the average of 3 years. For every country and every year, we divided the data of arable land and permanent crops (FAO, 2013a) and water (FAO, 2013b) by the population (United Nations, 2011). For 2050, we assumed that the water availability will remain stable as in recent decades (FAO, 2013b), and we considered two scenarios regarding cropland: one with cropland expansion and one without. We divided the projected cropland and water of each country by two different population projections: one with medium fertility rate, and one with low fertility rate (United Nations, 2011). Section 2.3 describes in detail the four scenarios analysed in this paper.

To discuss the expected dietary changes in 2050, we used data of projected GDP from the SSP database (IIASA, 2015). IIASA presents country-level data of GDP and population numbers in 2050 for several scenarios with different socioeconomic pathways (O'Neill et al., 2015). We used the projections of scenario SS2 which refers to intermediate socioeconomic challenges; see O'Neill et al. (2015) for details on assumption of the scenario. We divided the GDP by the population of each country of scenario SS2 in order to obtain the GDP per capita in 2050. Table S4 shows the data of each country and each year.

The type of food consumption pattern is related with the socioeconomic development of the population (Dietary transition theory); therefore, we linked the income level of the population with a type of dietary pattern. Hence, the GDP per capita is an indicator of the type of

diet. Nonhebel and Kastner (2011) show that countries with GDP values less than US\$2000 per capita have basic diets, countries with GDP values between \$2000 and \$10,000 per capita have transition diets and countries with GDP values higher than \$10,000 have affluent diets.

2.2. Linking availability of resources with food demand: the LWF nexus

To assess potentials to fulfil national food demand, we compared the availability of cropland and water with the demand for them for food production by the population. With this we defined the LWF nexus. For each country, we linked the available cropland and water per capita (data of Table S1 in 2010) with the demand for land and water per capita of each country; this demand depends on the type of diet. We used data from Kastner et al. (2012) and Hoekstra and Mekonnen (2012) to define the demand for land and water per capita for each country (see Table S2 in the Supplementary materials).

2.3. Scenarios for 2050

We focussed on three of the main determinants of the future potential for each country to fulfil food demand: population growth, dietary changes (based on income projections) and agricultural expansion. We designed four scenarios with different projections for the three determinants (Table 1).

For each determinant, we selected two different projections: the Business As Usual (BAU) projection and a more sustainable projection. We designed 4 scenarios for which only one determinant changes in order to identify the individual impact of each projection. The BAU scenario has all determinants as BAU, the basic diets scenario has the sustainable dietary projection, the no deforestation scenario has the sustainable projection for agricultural expansion, and the low population growth scenario has the sustainable projection for population growth.

For population growth, the BAU is the projected growth with a medium fertility rate, and the sustainable projection is the projected growth with a low fertility rate (United Nations, 2011). For cropland expansion, the BAU is the projected expansion from the FAO (Alexandratos & Bruinisma, 2012: see Table 4.8). The FAO projects, for seven regions of the world, an annual growth of arable land expansion from 2007 to 2050. We use these data to project the cropland expansion for 2050, our BAU scenario. The sustainable projection is to assume no cropland expansion.

Finally, for the dietary projections, we used GDP projections from IIASA SSP Database (2015) for the BAU scenario (see Section 2.1). We assigned to these projections a type of dietary consumption as described in Section 2.1: basic diets if GDP will be lower than \$2000/cap; transition diets if GDP will be between \$2000/cap and \$10,000/cap; and affluent diets if GDP will be higher than \$10,000. To define the demand

of land and water for each type of diet we calculated the average use of land and water for each type of diet in 2010 using the following equation:

$$A_{avg} = \frac{\sum A_i P_i}{\sum P_i}$$

where A_i is the demand of land or water per capita of each country given by Kastner et al. (2012) and Hoekstra and Mekonnen (2012), and P_i is the population in 2010. The index i indicates the group of countries for each type of diet depending on the country's GDP per capita in 2010. A_{avg} is the demand of land or water per capita for the basic or affluent diet, resulting in 1460 m²/cap/yr and 1100 m³/cap/yr for a basic diet, and in 2140 m²/cap/yr and 1760 m³/cap/yr for an affluent diet. See Table S6 in the Supplementary material for details on the calculation.

For the countries with transition diets, we assumed that half the population have basic diets and the other half have affluent diets, since in transition countries diets do not change equally for all population, owing to income inequality. Hence, the average per capita demands in transition countries are for 1800 m²/cap/yr of cropland and 1430 m³/cap/yr of water. For the sustainable scenario, we assumed that all countries have basic diets.

3. Results

3.1. Drivers of food demand

Food demand in a region depends on the number of people who live there and on their type of diet (Ibarrola Rivas, 2015). Population growth is high in low-income countries and it reduces as income level rises (Demographic transition theory: Chesnais, 1992). Low-income countries generally have basic diets, and as income level rises the consumption of affluent food products increases (Nutrition Transition theory: Caballero and Popkin, 2002). So, the average income of the population (Gross Domestic Product per capita, GDP per capita) is an indication of whether an increase in food demand is attributable to population growth or dietary changes. Nonhebel and Kastner (2011) show how these drivers have changed in recent decades in relation to values of GDP per capita: population growth has been the main driver for countries with less than \$2000 per capita, dietary changes has been the main driver for countries between \$2000–\$10,000 per capita, and food demand in countries with more than \$10,000 has been stable. We first discuss the present and future GDP values and the main food demand drivers (Fig. 1).

In 1960, the world was mainly divided in high-income and low-income countries (Fig. 1a). Europe, North America and Australia were mainly high income countries, and most of Latin America, Africa and Asia were low-income countries, with the exception of a few transition countries (yellow). From 1960 to 2010, the transition countries emerged. In 2010 (Fig. 1b), the majority of Latin-American and Asian countries were in transition, and Africa was mainly low income. This suggests that marked changes in diets had increased the demand for food. The increase in food demand would have been not only for more food but also for a more affluent type of food: more animal products, vegetable oils and sugars (Alexandratos and Bruinsma, 2012). In the low-income countries, population growth was still high, so food demand would have been driven mainly by an increase in consumers but with the diets unchanged.

The projections for 2050 (Fig. 1c) indicate that most countries, except in Africa, will have average GDP per capita larger than \$10,000 and hence will have affluent diets. Most countries in Africa will be in “transition”, their population growth will slow down and diets will change to an affluent consumption. Few countries will still have basic diets and large population growth.

3.2. Availability of land and water 1960–2050

The availability of land and water per capita is changing, and has markedly decreased because of population growth and will have further decreased by 2050. From 1960 to 2010, the global per capita availability of cropland halved (from 4360 m²/cap/yr to 2280 m²/cap/yr), while population doubled (from 3.1 billion to 6.7 billion (United Nation, 2011)) and total cropland increased only 13% (from 1.3 billion ha to 1.5 billion ha (FAO, 2013a)). For 2050, it is expected to decrease 30% to 1660 m²/cap/yr (assuming medium fertility rate and agricultural expansion). Similarly, per capita water availability halved due to doubling of population since total availability of water was relatively stable (from 26,100 m³/cap/yr in 1960, to 14,000 m³/cap/yr in 2010 (FAO, 2013b)). See Table S1 in the Supplementary material for the values of each country. The regions with the strongest constraints will be Africa and Asia.

Both land and water affect the potential for food supply, so availability of land and of water should be discussed together. For instance, in 2010, although Congo, Colombia and Vietnam had plentiful water (>10,000 m³/cap/yr; Table S1), they had <1000 m²/cap/yr of cropland and this presented a challenge in fulfilment of food demand. Food demand differs: in Congo and Vietnam food demand is driven by high population growth, whereas in Colombia the main driver of food demand is dietary changes (Fig. 1), so the food system must change to supply affluent food products requiring more resources per person.

3.3. Land-Water-Food nexus in 2010

The Land-Water-Food nexus show the link between availability and demand for resources (Fig. 2).

In 2010, most countries had enough land and water for food production to fulfil demand. The countries with insufficient land but enough water were in south and east Asia, with dense populations and wet climates. The countries with enough land but not enough water were in regions with dry climates (mainly in Africa). The few countries with insufficient land and water included Egypt, Israel and Cyprus (high population density in a dry climate) and Korea (very high population density).

When we count the number of people involved, we get a different picture.

In terms of the world population in 2010, the largest share has enough water, whereas 57% do not have enough land (Table 2); the majority of these live in low-income and transition countries (Figs. 1 and 2). The countries with not enough land or water account for 210 million people, only 3% of the global population, of whom the majority live in low-income countries.

Since the impact of the lack of sufficient resources depends on the magnitude of the shortfall, the “missing” fraction was determined for each country for both cropland and water (Table S3); these values were then aggregated by region (Table 3). The countries in each region are specified in Table S5 in the Supplementary material.

Lack of land was more severe than of water, and was most conspicuous in Asia (Table 3 and Table S3 in the Supplementary material).

3.4. Scenarios for 2050

Fig. 3 shows the LWF nexus approach considered for the four future scenarios from Table 1.

The BAU scenario will present the strongest challenges for future food security, particularly in Africa and Asia. Countries in Latin-America will have enough water, but many will not have enough land. The other three scenarios show more positive projections and further studies are needed to consider combinations of these three sustainable solutions.

The global impact of each scenario is illustrated in the number of people which will live in countries with not enough land or water

Fig. 1. Changes in GDP per capita: an indicator of the drivers for food demand. Green (< \$2000), population growth is the main driver; yellow (\$2000–\$10,000), dietary changes are the main driver; and dark red (> \$10,000), food demand stable since population growth is stable and diet is constantly affluent. Data source: World Bank (2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Table 4). With the BAU scenario, 40% of global population (3800 million people) will not have enough land nor water to fulfil food demand. The differences between the BAU and the basic diets scenarios show that adoption of a basic diet by all people is the sustainable solution that can have the stronger global impact since its share of the global population with not enough land or water is the lowest: 71% for land availability and 24% for water availability; a basic diet would have the greatest impact on water sufficiency, since >45% of the global

population would still not have enough water under any of the other scenarios.

Since the low population growth scenario will result in the smallest global population, it will result in the least number of people with land constraints.

Restriction of agricultural expansion (no deforestation scenario) should result in an increase of biodiversity which can enhance global sustainability particularly in developing countries. Nevertheless, this

Fig. 2. LWF nexus in 2010 based on data of per capita use of land (Kastner et al., 2012) and water (Hoekstra and Mekonnen, 2012); and availability of land and water (FAO, 2013a & 2013b).

Table 2

Numbers (millions) of people worldwide in 2010 grouped according to the relationship between their income and whether national land and water is enough to fulfil national food demand in 2010.

GDP per capita	Not enough land or water	Enough land, Not enough water	Not enough land, enough water	Enough land, enough water	Total
< US\$2000/cap/yr	100	100	1800	800	2800 (43%)
US\$2000–10,000/cap/yr	10	100	1500	1000	2600 (41%)
> US\$10,000/cap/yr	100	20	400	600	1000 (16%)
Total	200 (3%)	200 (4%)	3700 (57%)	2300 (36%)	

Note: The values of the table are rounded to hundred values for an easier comparison of orders of magnitude. Therefore, the total values do not add up exactly. Table S7 in the Supplementary material present the exact values of this table.

Table 3

Shortfalls in cropland and water in 2010 expressed as fractions of the demanded resources.

	Cropland	Water
North America	0.07	0.02
Central & South America	0.13	0.00
Northern Africa	0.03	0.01
Sub-Saharan Africa	0.05	0.00
Central & Western Asia	0.30	0.00
South, East & South-East Asia	0.28	0.00
Europe	0.15	0.00
Oceania	0.04	0.02

limiting of land available for food production will have a lower global impact on reaching food security than the other scenarios (Fig. 3), having virtually the same outcome as the BAU scenario.

Although Table 4 suggests that land constraints will be much

stronger than water constraints, the assumptions are based on an overestimation of water availability (all water resources in the country) and an underestimation of land availability (only considering cropland availability); the implications are discussed in Section 4.

As for 2010 (Table 3), the “missing” fraction of land and water in 2050 was determined for each scenario for both cropland and water for 2050 (Fig. 4); the values were then aggregated by sub-continent (Table 5).

Expressed as a fraction of the available resources, the shortfall in water will be much lower than the shortfall in land, and will occur in the continents with high population density (Africa, Asia and Europe). In contrast, the fraction of cropland missing can be as much as what is available (values closer to 1). This means that the demanded land will be twice what is available. The basic diets scenario will have the lowest fraction of land lacking and hence the greatest potential to lower land constraints for future global food security.

3a. BAU

3b. Basic diets

3c. No deforestation

3d. Low population growth

Fig. 3. LWF nexus for the 4 scenarios in 2050: BAU, basic diets, no deforestation and low population growth (Table 1).

Table 4

Number (in millions) of people for each scenario for which their country does not or does have enough land and water. Numbers based on Fig. 3.

Scenarios	Not enough land, Not enough water	Enough land, Not enough water	Not enough land, Enough water	Enough land, Enough water	Total: Not enough land	Total: Not enough water
BAU	3800	500	3800	1500	7600 (80%)	4300 (45%)
Basic diets	1800	500	5000	2300	6800 (71%)	2300 (24%)
No deforestation	4100	200	3800	1400	7900 (83%)	4300 (45%)
Low population growth	3300	500	3000	1700	6400 (75%)	3800 (45%)

Note: The values of the table are rounded to hundred values for an easier comparison of orders of magnitude. Therefore, the total values do not add up exactly. Table S7 in the Supplementary material present the exact values of this table.

4. Discussion

4.1. Our results in perspective

We have adopted a top-down approach towards global food supply in the context of the Land-Water-Food Nexus. This required several assumptions on production potentials; for instance, we only included the available cropland and water as variables. Most studies on food production potentials have a bottom-up approach to quantify production potentials based on agro-ecological indicators; whereas their results are more accurate regarding crop yield potentials, they do not include the food demand variables (Lobell et al., 2009; Gornall et al., 2010; Licker et al., 2010; Neumann et al., 2010; Ahmed and Stepp, 2016). Hence, our results give new insights based on the food demand perspective.

We have shown that a change to basic diets could have a larger global impact in reducing land and water constraints than will the other variables analysed.

The results identify regions with strong and urgent challenges, and identify the driver of the challenge, such as the availability of land and water, or the type of food demanded. It is thus possible to identify systematic solutions including all drivers of the food system and hence achieve more efficient solutions than by looking only at production possibilities. It is essential to include food demand variables in production potential analysis, since the type of diet strongly affects the demand for resources. Further research should include local variables for each region to identify more accurate production potentials.

4.2. Solutions for land and water constraints

The values of “not enough” land or water in our calculations do not necessarily mean that these countries have or will have food scarcity. They mean that these countries have or will have land and water constraints based on their available resources and what the population demands on the basis of their type of diet. The solutions to the shortfalls in land or water may vary as follows.

First, the land and water constraints could mean that food supply is met in part by food imports. Nowadays, 10% of global food supply derives from imports (FAO, 2013a), with some countries being mainly importers and some being exporters. The data on water (Kastner et al., 2012) and land demand (Hoekstra and Mekonnen, 2012) used here include land and water used by the food imports, the so-called “virtual land and water”. The countries identified in the present study as lacking land and water on the basis of their available resources could be importing food from countries with high availability of land and water.

Second, the present study defined land constraints in terms of cropland and the data on land demand are based only on cropland (Kastner et al., 2012). However, food is also produced on pasture lands mainly used for livestock production. The importance of pasture land for national food production differs among countries: in India 6 % of the total agricultural land is pasture and the rest is cropland (FAO, 2013a); in contrast, in China 75% of the agricultural land is pastures and meadows and the rest is cropland. Hence, in the present study, land constraints could mean that food is produced on pasture

lands.

Third, our analysis of future scenarios for 2050 are based on data of land and water demand in 2010 with present agricultural systems (Hoekstra and Mekonnen, 2012; Kastner et al., 2012). This indicates that present production systems are not enough to supply future food demand. Technological improvements might reduce land and water constraints. Studies of “closing yield gaps” (Licker et al., 2010) show the potential, particularly in developing countries, to increase crop yields and thereby reduce land constraints.

To conclude, the strong resource constraints discussed in this paper do not necessarily mean that those countries will not have enough food for their population. They mean that those countries have challenges to achieve changes in their food system. Options should be analysed in detail for each region: agricultural expansion, intensification (increase crop yields), food imports and dietary changes. Developing countries will face the strongest challenges because they will reduce their land and water availability per person (by rapid population growth), and they will increase food demand by changing to an affluent diet (owing to rapid socioeconomic growth). These changes require a rapid change in their food system. Policy implementation is essential in combination with food security programs focused on achieving an efficient and rapid change in agricultural production systems to increase production in a sustainable way.

4.3. Further challenges: land and water competition for non-food crops

The production of non-food crops (for fibers, biofuels, tobacco, etc.) is an additional pressure on land and water availability for food production (Rathmann et al., 2010), and the competition for land has been increasing (Harvey and Pilgrim, 2011). In respect to crops for biofuels, energy consumption will influence the demand for land and water, particularly in high-income countries (Nonhebel and Kastner, 2011). In this paper, we focused on the need of land and water for food production assuming that all cropland area and water is used for food production. However, these agricultural resources can also be used to produce non-food crops such as biofuels which could result in a strong competition for land and water between food and biofuels demand. Some studies have estimated present and future (2030) demand of land and water for biofuels production (van Lienden et al., 2010 ; Fischer et al., 2010). Comparing our results with these studies show that in 2030 demand of water for biofuels in North America will represent 34% of the water demand for food in 2050, and cropland demand for biofuels in Europe will represent 35% of the cropland demand for food in 2050. In contrast, in Africa and Asia's water demand of biofuels will represent less than 3% than the water demanded for food. These regions will have the strongest challenges for achieving food supply. Even though, the share of resources for biofuels will be smaller compared to food, it could put strong pressure in resource competition for food. The Supplementary Information 2 shows the comparison for other regions.

Further studies are needed to incorporate the demand for bio-crops within each country, as well as the demand to import bio-crops from other countries (generally developing countries) which we have shown that will have strong land and water constraints. Finally, the

Fig. 4. Shortfall of demanded land and water in respect to national availability of land and water in 2050 for the four scenarios.

Table 5

Shortfalls in cropland and water expressed as fractions of the demanded resources. Projections for 2050 for each scenario. The bold numbers indicate the lowest values of shortfalls in cropland.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Cropland	Water	Cropland	Water	Cropland	Water	Cropland	Water
North America	0.27	0.00	0.18	0.00	0.26	0.00	0.25	0.00
Central & South America	0.38	0.00	0.17	0.00	0.52	0.00	0.29	0.00
Northern Africa	0.20	0.02	0.10	0.01	0.20	0.01	0.17	0.02
Sub-Saharan Africa	0.50	0.00	0.27	0.00	0.73	0.00	0.39	0.00
Central & Western Asia	0.88	0.01	0.49	0.00	0.88	0.00	0.73	0.00
South, East & SE Asia	0.86	0.00	0.47	0.00	0.91	0.00	0.68	0.00
Europe	0.13	0.00	0.06	0.00	0.12	0.00	0.11	0.00
Oceania	0.19	0.00	0.07	0.00	0.23	0.00	0.14	0.00

implications of the land grabbing discussion should be included in the analysis (Borras et al., 2011).

4.4. Assumptions and further research

This paper underestimates land availability for food production since agricultural land includes both cropland and pastures. Therefore, our results regarding land constraints should be analysed to evaluate the availability of pastures and their role in food productions as well as the potential to increase agricultural land at the expense of natural areas. Values of water availability used in this paper can be understood as the maximum ideal possible water use of the country since it includes all renewable water of the country. Our results should be understood as a reference and as limits to production possibilities on the global scale. On the local scale, the real potential for food production will be influenced by the proximity of water to the cropland.

In addition, we assumed that the main driver of future dietary change is changes in GDP. Nevertheless, social factors such as culture and religion can result in different dietary paths for similar values of GDP (Ibarrola Rivas, 2015: chapter 6).

5. Conclusion

Two main drivers of food demand strongly affect the capacity to meet food demand: population growth reduces available resources per person, and dietary changes increase demand on resources per person. Both depend on the socioeconomic situation. Land and water constraints will increase, and developing countries will have the strongest challenges (with the lowest availability of resources and rapid changes in population and diets). Restriction to basic diets will be the most effective in lowering both land and water constraints. Our results identify both food production and food demand factors, and the regions that may experience the strongest challenges in 2050. Efficient and rapid changes in their food system in both production and consumption are needed to achieve a sustainable and secure food supply.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2017.09.018.

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