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Assessing changes in availability of land and water for food (1960–2050): An analysis linking food demand and available resources

M.J. Ibarrola Rivas[1] **and S. Nonhebel**[2]

Abstract

Future global food demand will require more land and water. We group the global population into six “Gross Domestic Product groups” and study changes in the availability of land and water for food in relation to demographic and nutrition transition theories. We show large differences in land and water availability between rich and poor countries. Inequality will strongly increase due to the projected large population growth in poor countries. By 2050, the richest quarter of the global population will have three times more arable land per person than the rest. Those changing diets to a more affluent consumption will be the ones with less available resources per person. More than two-thirds of global population will not have enough land to produce the food for an affluent diet by 2050. Thus, the large land and water constraints of the poor will result in significant challenges for food security than predicted in previous studies.

Keywords

global analysis, arable land, water resources, historical trends, future food security

Introduction

Global food demand is expected to increase in the coming decades due to increasing global population and changing food consumption patterns (Alexandratos and Bruinsma, 2012; Foley et al., 2011; Godfray et al., 2010a; Godfray et al., 2010b). The production of this food will require large amount of resources (Tilman, 1999) including land as cropland and pastures (Alexandratos and Bruinsma, 2012; Ramankutty et al., 2008), water (Rockstrom, 2003) and energy inputs mainly as fertilizers and machinery (Smil, 1999; Woods et al., 2010). The amount of resources needed to feed a population depends firstly on the size of the population: more people need more food; secondly on the consumption patterns of this population: diets rich in animal products require more than vegetarian diets mainly based on staple foods; and thirdly on the agricultural production system (Kastner et al., 2012; Leach et al., 2012; Mekonnen and Hoekstra, 2011; Xiong et al., 2008). Agricultural production systems with high crop yields require less land than systems with low crop yields, but to obtain these high yields a trade-off exists with a larger use of energy and water resources (Evans, 1980; Licker et al., 2010).

Most countries in the world are self-sufficient in food to a certain extent. Globally, only 12% of domestic food supply originates from imports (data for 2009: FAO 2012). The availability of land and water is a key to achieve food self-sufficiency. Land and water inputs are local resources in contrast to energy inputs which can be imported. So, the availability of land and water in a country is crucial to achieve national food self-sufficiency (Fader et al., 2013). Fader et al. (2013) studied the availability of land and water for food production throughout the world. They showed that some countries have strong constraint in land and water which currently results on 16% of global population being dependent on food imports. Future population growth can strongly increase this proportion up to 50% which would similarly affect food security for these countries. Thus, food security is strongly dependent on the availability of land and water for food production.

The aim of this article was to assess global food supply in relation to the economic development of the population and the availability of agricultural resources: the difference in resource availability between poor and rich countries. In contrast to Fader et al. (2013), we study the availability of land and water per capita not from a geographical

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perspective but from a demand perspective. We choose to do this because the drivers of food demand (size of population and type of diet) are strongly related to the economic development of the population. An increase in socioeconomic development results, firstly in a decline in population growth (demographic transition; Chesnais, 1992; Lutz and Samir, 2010) and secondly in dietary changes from those based on staple foods to more affluent diets including sugar, vegetable oils and animal products (nutrition transition; Kearney, 2010; Poleman and Thomas, 1995; Popkin, 1993). We use the differences in welfare throughout the world as the starting point of our study because of the relationships between socioeconomic development and the drivers of food demand.

With this approach, our analysis diverges considerably from previous studies on global food supply (Ausubel et al., 2013; Fader et al., 2013; Foley et al., 2011; Licker et al., 2010; Lobell et al., 2009; Ray et al., 2013) which used the geographical situation as the starting point. They determined production possibilities under various climates and soil conditions which determine yield potentials to analyse whether agricultural production is sufficient to feed the population. In this study, we first analyse what is needed and then assess the availability of agricultural resources to supply the food demanded. We use land and water available per capita as indicators to assess the potential of future food supply for several economic development groups.

Methodology

We conducted a global analysis of the distribution of land and water availability for food production. In order to take a demand perspective, our analysis focuses on the relationship of socioeconomic development of the population. To do this, we classified the global population into groups based on their average national income level. Two of the largest countries in relation to population (China and India) accounted each to around one-sixth of global population in 2010. Due to their relevance, we left them as one group each and the rest of the countries we clustered them in groups for which each group account to around one-sixth of global population. As a result, we analysed six Gross Domestic Product (GDP) groups. We collected data for 187 countries from 1960 and 2010 on food consumption (FAO, 2012), land availability (FAO, 2013b), water availability (FAO, 2013a), GDP per person (World Bank, 2014), population and expected population for 2050 with medium fertility rate (United Nations, 2011). These countries accounted for 99% of the global population in 2010. For the average diet, we aggregated food consumption data into five categories: staple food (cereals, roots and pulses), affluent vegetal (sugars, vegetable oils, vegetables and fruits), meat (bovine, pig, poultry and fish), other animal (milk, eggs and animal fats) and other (alcoholic beverages, tree nuts, stimulants and spices). For water availability, we used the "total renewable water resources (actual)" reported by Aquastat (FAO, 2013a) which is the annual amount of surface water and groundwater available in a country. For data on water and arable land in 2050, we used the same figures for 2010. Water availability was relatively stable from 1960 to 2010 (FAO 2013a).

Agricultural land consists mainly of arable land and pastures. We first analysed the global distribution of these two land-use categories. We then focused on the distribution of arable land to assess the potential for food production since, globally, most of the food is produced on arable land. Agricultural land changes over time due to different land-use changes. But, even though arable land is projected to increase for 2050, the rate of increase is expected to be lower than in previous decades, globally "only" 4% (Alexandratos and Bruinsma, 2012). It will expand differently among different regions (Alexandratos and Bruinsma 2012), with projections depending on assumptions regarding agricultural expansion. Therefore, in our analysis, we assumed no agricultural expansion to avoid the impact of accumulated assumptions.

First, we looked back historically and discuss the changes in availability of land and water over the last five decades. Based on this analysis, we understand the relationship between the changes in food demand and the availability of land and water to produce food. Then, we assessed the future availability of land and water. We ordered the countries according to their GDP per capita in 2010. We then clustered the countries into six "GDP" groups. The population in each group in 2010 was between 0.7 billion and 1.4 billion people to be relevant for a global analysis (Table 1). The countries in each group were the same for 1960, 2010 and 2050. We used a 5-year average for the calculations as follows: for 1960, the average of 1958–1962 for water and the average of 1961–1965 for GDP and land; and, for 2010, the average of 2008–2012 for water, GDP and land. Countries and groups are given in the Supplementary Data.

The groups were renumbered 1 to 6 in order of increasing GDP per capita, that is, from poor to rich. These groups contain countries from different regions. For example, group 1 includes almost all countries in Sub-Sahara Africa and some from Asia such as Pakistan, Vietnam and Bangladesh. Group 3 includes countries from all over the world including the Philippines, Egypt, Indonesia, Guatemala and Ukraine. Group 5 is a mixture with Iran, Brazil, Russia, Mexico, Turkey, Thailand, South Africa and others. Group 6 includes Western Europe, the United States, Korea, Japan and others. Groups 2 and 4 are comprised of only one country each, India and China, respectively, because of their large populations. Thus, the countries in each group do not necessarily originate from the same continent or climatic region; but the population in each group follows similar trends in terms of the drivers of food demand because they have similar levels of economic development.

Changes in the drivers of food demand

Figure 1(b) shows the characteristics of diets in 2010. In the first two groups (GDP less than US$600 per capita per

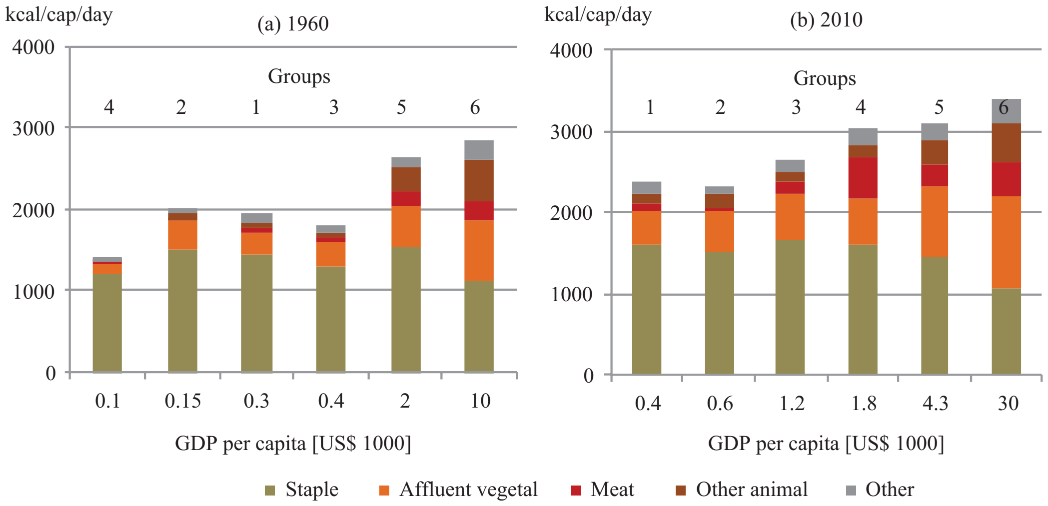

Figure 1. The composition of the diets in the six groups considered in 1960 (a) and 2005 (b). Data based on FAO (2012) and United Nations (2011).

year), the population on average consume around 2200 kcal per person per day with 80% of their calories originating from staple food (cereals, roots and pulses). This is in stark contrast to the richer groups where only 30% of calories consumed are derived from staple food, 30% originates from animal and 30% from affluent vegetal (sugars, vegetable oils, vegetables and fruits). The groups in the middle range show a gradual change from staple based diets to more affluent diets, by reducing the proportion of staple foods and increasing the proportion of animal products and affluent vegetables. Figure 1(a) shows the equivalent data from 1960. Again, the groups with GDP values below US$1000 per person per year have diets based mainly on staple food; the two richest groups show more affluent consumption patterns. Up until recently, such nutrition transition has been studied at a country level. Here, we show that the nutrition transition can also be recognized in these “GDP” groups.

It is important to point out that the groups in Figure 1(a) and (b) are not in the same order. In 1960, group 4 was the poorest, while group 1 was ranked third. The shift in position is caused by different economic growth rates. The demographic transition theory is reflected in Table 1: the groups with low GDP have the highest population growth rates. With exception of group 4 which shows lower growth rates than groups 5 and 6, because group 4 is China with its one child policy. The population of each group changes over time due to differences in population growth rates. This is clearly shown in Table 1 and Figure 2. Figure 2 shows the distribution of population, total land of the countries and water availability in each group. In 1960, two-thirds of the global population lived in groups 4, 5 and 6. In 2050, these groups will account for only one-third of the global population. Note that in 1960, global population was 3.2 billion people; in 2010, 6.9 billion and in 2050, it is projected to be 9.3 billion people. The largest proportion of these 2.5 billion additional people will be born in groups 1, 2 and 3.

Table 1. Changes in population.[a,b]

	Population (Billion people)			Average annual population growth rate (% per year)	
Group	1960	2010	2050	1960–2010	2010–2050
1	0.4	1.4	2.7	4.8%	2.5%
2	0.5	1.2	1.6	3.1%	0.9%
3	0.2	0.7	1.0	4.1%	1.3%
4	0.7	1.4	1.4	2.0%	0.0%
5	0.7	1.2	1.5	1.8%	0.5%
6	0.7	1.0	1.1	0.9%	0.3%

[a] Data based on United Nations (2011).
[b] We use data of population projections for 2050 with medium fertility rate. Only for this table, we have excluded all ex-USSR countries to calculate the average annual population growth rate.

Differences in land and water availability on a global scale

We calculated the distribution of total available land and water among the groups, and compared this with the distribution of global population in 1960, 2010 and 2050 (Figure 2). The unequal distribution is striking: 64% of the land and 58% of the water are available for groups 5 and 6. Since the population is more equally distributed among the groups, land and water availability per capita shows enormous variations. For instance, in group 5, 17 times more land and 23 times more water are estimated to be available per capita compared with group 2. Only a share of the total land is used for agricultural practices. This proportion changes over time: as natural habitat areas are gradually converted into agricultural production areas or vice versa: when agricultural land is abandoned and nature takes over or when agricultural land is needed for infrastructural development purposes (housing, roads). Between 1960 and 2010, the change in agricultural land area was relatively small: globally it only increased by 10% (FAO, 2013b).

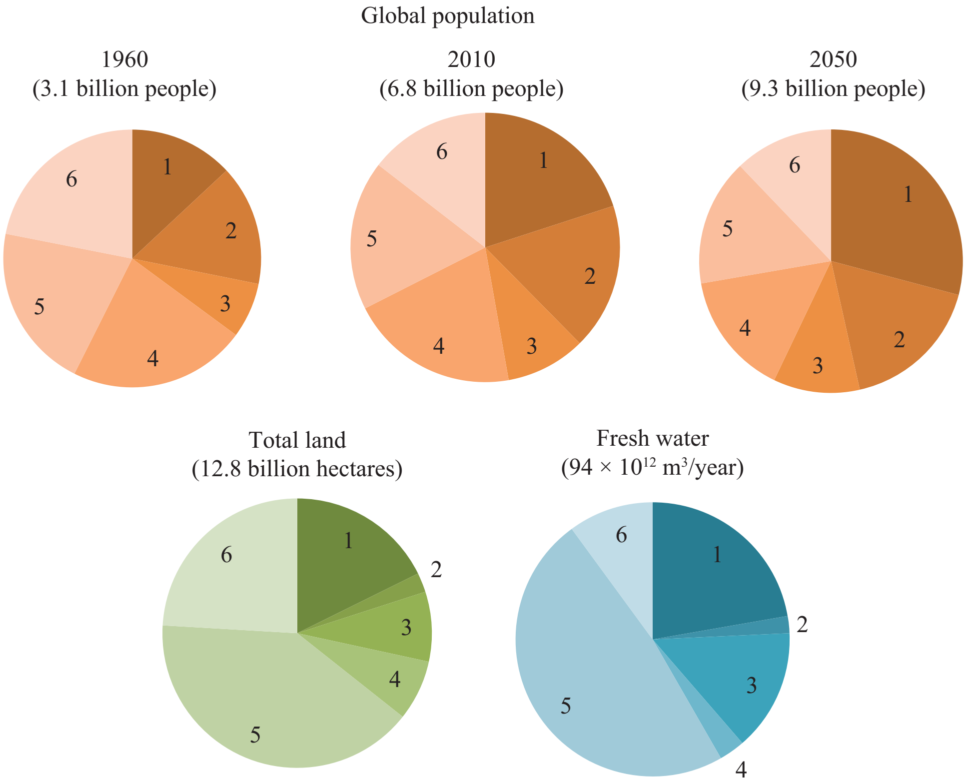

Figure 2. Distribution of global population, total land and fresh water (groundwater and surface water) among the six groups. The numbers in the pie charts indicate the group number. The global water data is from the year 2010; and population projections for 2050 are with medium fertility rate. Data based on FAO (2013a,2013b) and United Nations (2011).

Table 2. Share of agricultural area (arable land and pastures) from the total land for each group.[a,b]

	1960		2010	
Group	Arable land	Pastures	Arable land	Pastures
1	8%	26%	12%	28%
2	54%	5%	57%	3%
3	7%	31%	13%	30%
4	11%	26%	14%	42%
5	8%	20%	9%	24%
6	12%	26%	11%	22%

[a] Data based on FAO (2013b).

[b] We used FAO data as follows. The data for arable land was based on FAO's definition of arable land and permanent crops which include temporarily agricultural crops, meadows and fallows, and long-term crops. The data for pastures was based on FAO's definition of 'permanent meadows and pastures' which include the agricultural land used permanently (more than 5 years) to grow crops.

The distribution of agricultural land also shows variations between groups. For example, group 5 only uses 33% of their total land for agriculture; while group 2 uses as much as 60% (Table 2). In general, groups with a small total land area use a large proportion of it for agricultural production, and conversely countries with a large land area use a smaller proportion of it for agriculture. In groups 1–5, the agricultural land area has increased over the last 40 years, while in group 6 it has declined. Groups differ in whether the land is used for pastures or for arable land. Group 2 has a very small proportion of land used for pastures, while in the other groups, pastures are the largest share of agricultural land use.

To assess the availability of land per capita for food production, we focus on arable land and not pastures or other types of agricultural area, since arable land is responsible for producing the most food (FAO, 2013b). Figure 3 shows the arable land and water availability per person for the six groups; the data shows how this is decreasing for all groups. The factors driving the changes in the per capita land and water availability are both changes in population growth and changes in land and water availability. The strong decline shown in Figure 3 is due to population growth, since changes in population have occurred more quickly than changes in availability of water and land. In fact, water availability has been relatively constant throughout the period and only small changes in total agricultural area took place (Table 2). The decline rates differ among the groups because the population growth rate is different (Table 1). As a result, the poor groups have a stronger decline in the availability of land and water per capita.

Not only are the rates of changes in land and water availability different but so too are the absolute values. In 2010, group 5 had 3800 m^2/cap for arable land; in contrast, group 2 had 1400 m^2/cap and group 4 have only 900 m^2/cap. Differences in water availability are stronger. Group 3 and 5 have as much as 21,000 m^3/cap and

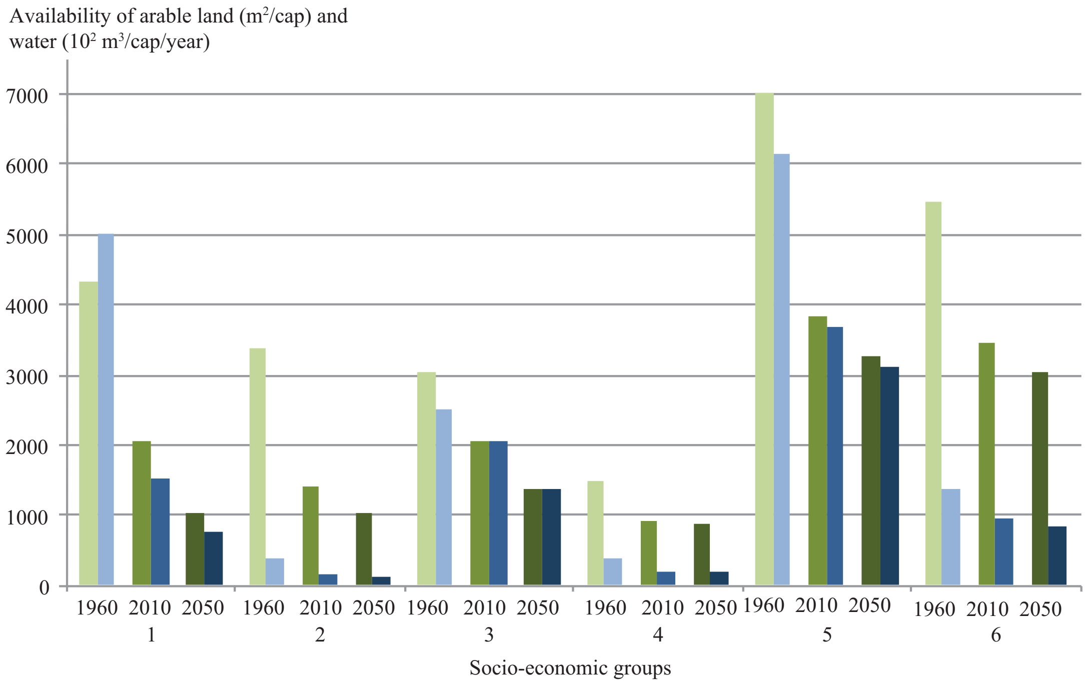

Figure 3. Arable land and water availability per person and changes over time. The green bars indicate the arable land per capita and the blue bars indicate the availability of water. Data based on arable land from FAO (2013b), water from FAO (2013a) and population numbers from United Nations (2011).

37,000 m^3/cap, respectively, while group 2 and 4 have only 1600 and 2000 m^3/cap, respectively. Changes on water availability per capita depend mainly on how the population changes, since water availability is relatively stable throughout the period (FAO, 2013a). Changes in arable land availability, on the other hand, depend on both population growth and the availability of arable land because arable land changes due to agricultural expansion (Table 2). For this reason, changes on arable land and water show different patterns. This is clearly illustrated in group 1 which showed in 1960 how the arable land area per person was relatively lower than water availability per person, but in 2010, the arable land allocation per capita was relatively higher (Figure 3).

Future implications

Currently, two-thirds of the total arable land and freshwater resources are available to one-third of the global population (groups 5 and 6). These people also have the highest welfare levels. They have passed the nutrition transition: their diets contain a large amount of affluent products and so no major changes in their future consumption patterns are expected. In addition, these countries also went through the demographic transition phase: the expected population growth is small due to a low fertility rate. Therefore, it can be expected that these countries will not need additional resources to feed their population in the future. In group 4, the situation is less positive. Even though the rate of population growth is low (Table 1), which makes land availability per person relatively constant (Figure 3), this group is in the middle of the nutrition transition phase. Diets are changing rapidly: meat consumption has doubled over the last 20 years as well as the consumption of other affluent products (FAO, 2012). Their consumption patterns are still not as affluent as the ones consumed in group 5 and 6 (Figure 1); and large increases in consumption of affluent food items are expected in the coming decades. Kastner et al. (2012) showed that for this group, the changes in diets were the major cause for the increase on land demand for food. In this group, more land and water will be demanded for food due to dietary change but not due to population growth.

The present situation in groups 1 and 3 shows some similarity (Figure 3). In 2010, both groups had similar levels of arable land availability and water per capita. However, the expected population growth rate in group 3 is lower than in group 1. This will have a large impact on the future availability of resources, for example, availability of arable land in group 3 will drop from 2000 m^2/cap to 1400 m^2/cap; while in group 1 will drop from 2000 m^2/cap to only 1000 m^2/cap; and water availability in group 3 will drop from 20,000 m^3/cap to 14,000 m^3/cap and in group 1 from 15,000 m^3/cap to 8000 m^3/cap. Note that in 1960 group 1 had twice the amount of water compared to group 3, and in 2050 group 1 will only have half the amount of group 3. This shows the strong impact of population growth on the availability of resources. In both groups, diets are mainly based on staple foods. With the increase in welfare standards, a change to a more affluent food patterns is expected and more resources per person will be needed to produce these affluent foods. Future demand of resources will result from the combination of high population growth and a change to more affluent diets which will result in a challenging situation for future food supply.

The projections for group 2 show the most challenging situation. The arable land and water availability per capita are the lowest among the groups and will decrease further in the coming decades. Agricultural expansion might be limited since 60% of the land is already used for food production (Table 2). Almost all the agricultural land is arable land which is the high productivity land. This group still shows high population growth rates (Table 1) and the nutrition transition phase has yet to start (Figure 1: 80% of calories are derived from staple food). Conversely, this group represents India where the majority of the population is Hindu with a vegetarian diet. This may result in a relatively smaller demand for resources per capita than the resources required for diets dependent on a large amount of animal products as in other parts of the world.

The projections in land and water availability per capita could deviate from the trends shown in Figure 3 depending on how the population will grow. Figure 3 was calculated using a population projection assuming a medium fertility rate (United Nations, 2011). The Supplementary Data shows four scenarios for water and land availability per person with different fertility rates. It shows that land and water availability with a high or constant fertility rate will be lower than Figure 3. Thus, a scenario with a low fertility rate is more desirable. However, the differences among the groups are still three orders of magnitude for all scenarios with different fertility rates as shown in Figure 3. This shows that the inequality in the potential for food production between poor and rich will still be present with the most optimistic scenario of population growth. Thus, in the short term, the situation in group 4 is the most urgent, but in the forthcoming decades countries, in groups 1 and 2 will also face similar problems.

The data we used for the 2050 projections were based on arable land and water availability in 2010. This assumption might be either an underestimation or overestimation considering that water availability might change with climate change (Wheeler and Kay, 2010), and arable land will expand (Alexandratos and Bruinsma 2012). Therefore, it is obvious that our results cannot be considered as absolute values, but rather they should be considered as an order of magnitude that helps us understand and recognize the underlying patterns. We don't predict the future with our analysis; we only show the impacts of the demographic and the nutrition transition on future per capita availability of arable land and water.

In this article, we studied food security from the demand side: number of people and their diets, and we used the economic situation of the individual countries as the starting point. We disconnected the population from their geographical location. The Supplementary Data shows the countries in each group and highlights that within one group, countries from different continents and from different climatic zones are grouped together. Within one group, climates can differ from mainly tundra to the wet tropics. As a consequence, the agricultural production potential will differ a lot. In wet tropics, up to three harvests per year are possible while in the northern latitudes, the cold winter only allows one harvest per year. So, the choice for starting from the demand side makes it difficult to assess whether there is enough land and water to feed the people (production side), since we cannot ascertain exactly what can be produced. However, Kastner et al. (2012) calculated that to produce an affluent diet (including meat) using a high yielding agricultural production system (group 6), 2300 m^2 of arable land per person was required. Only in groups 5 and 6 is such area of arable land currently available per person and due to the limited population growth it will also be available in 2050. In group 2, the total land area in 2050 will be smaller (1800 m^2/cap) so there is no option that 2300 m^2 of arable land per person will be available in future to feed its population. In groups 1, 3 and 4, arable land expansion will be needed to achieve this amount of arable land per person.

In relation to water, Mekonnen and Hoekstra (2011) calculated the water required to produce the food for several countries, termed the 'water footprint'. They showed large variations driven by the type of diets and agricultural systems with a global average diet requiring 1390 m^3/cap/year of water (Mekonnen and Hoekstra, 2011). Groups 2 and 4 will have 1500 and 2000 m^3/cap/year, respectively, by 2050, which mean that in order to use the global average requirement of water, they need to use almost all their water available, which presents major infrastructure and management challenges.

The most striking result of this analysis is the pending huge inequality in available arable land and water per person between the poor and rich nations. In 2050, the richest population (groups 5–6) will have three times more arable land per person than the rest of the world (groups 1–4). These people representing 72% of the global population (groups 1–4) live in countries where arable land will be less than half the amount needed to produce the food for an affluent diet (2300 m^2/cap) based on Kastner et al. (2012). Also, the strong land and water constraints will have effects on global food markets, as shown by Fader et al. (2013). Here we show that these people will be the poorest on Earth. It is very likely that the poor countries will increase their food imports, and the rich countries with larger availability of agricultural resources will turn into large food exporters.

Here we only studied the availability of resources for food production to assess future global food supply. However, the amount of food that can be produced depends not only on these resources but also on the agricultural practices (production side), which were beyond the scope of this article. These agricultural practices are usually related with economic development. High income countries generally have high productivity systems with high crop yields (Licker et al., 2010; Hengsdijk and Langeveld, 2009; Lobell et al., 2009). These efficient systems are possible due to optimal conditions on infrastructure, access to technical and management knowledge and access to investments for fertilizers, irrigation, crop protection, soil conservation, etc. (Lobell et al., 2009; Godfray et al., 2010a). These factors are usually lacking in low income countries resulting in low productivity systems.

Conclusions

The aim of our study was to analyse differences in arable land and water availability and to discuss the potential for food production. The drivers for arable land and water availability per person are both changes in population numbers and in availability of arable land and water. Since changes in population numbers overrule changes in water and agricultural land use; then, the main driver in our study is the changes in population numbers. The main factor that drives changes in population numbers is the socioeconomic development of the population (Chesnais, 1992). Therefore, the starting point in our analysis was the grouping of countries based on their current GDP situation. By doing this, it has been possible to first illustrate how the distribution of global land changes throughout time in relation to the number of people of each group; and secondly to illustrate how GDP changes differently between countries. We studied the availability of land and water to assess the potential for food production in each socioeconomic group. It is outside the boundaries of our research whether the land is used for food crops for national consumption, cash crops for food export or non-food crops such as biofuels, tobacco or cotton. However, this should be addressed in further research.

Our analyses show that people who will have major arable land and water constraints in the coming decades will be the poor. So, with a present low agricultural technological situation, these countries will encounter strong socioeconomic and political challenges to achieve high agricultural productivity. The other solution to overcome resource constraints, apart from agricultural productivity, is to increase food imports; but depending on food imports can have strong risks for national food security especially in poor countries. Thus, in the coming decades, the challenge in attaining food security for the poor will become stronger because of their huge land and water constraints; and so the potential to achieve food security will become more unequal between the rich and the poor.

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Supplemental material

The online data supplements are available at http://oag.sagepub.com/content/by/supplemental-data.

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