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Discussions

Climate-driven interannual variability of water scarcity in food production: a global analysis

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Abstract

Interannual climatic and hydrologic variability has been substantial during the past decades in many regions. While climate variability and its impacts on precipitation and soil moisture have been rather intensively studied, less is known on its impacts on freshwater availability and further implications for global food production. In this paper we quantify effects of hydroclimatic variability on global "green" and "blue" water availability and demand in agriculture. Analysis is based on climate forcing data for the past 30 yr with demography, diet composition and land use fixed to constant reference conditions. We thus assess how observed interannual hydroclimatic variability impacts on the ability of food production units (FPUs) to produce a given diet for their inhabitants, here focused on a benchmark for hunger alleviation (3000 kilocalories per capita per day, with 80 % vegetal food and 20 % animal products). We applied the LPJmL vegetation and hydrology model to calculate spatially explicitly the variation in green-blue water availability and the water requirements to produce that very diet. An FPU was considered water scarce if its water availability was not sufficient to produce the diet (neglecting trade from elsewhere, i.e. assuming food self-sufficiency). We found that altogether 24 % of the global population lives in areas under chronic scarcity (i.e. water is scarce every year) while an additional 19 % live under occasional water scarcity (i.e. water is scarce in some years). Of these 2.6 billion people under some degree of scarcity, 55 % would have to rely on international trade to reach the reference diet while for 24 % domestic trade would be enough (assuming present cropland extent and management). For the remaining 21 % of population under scarcity, local food storage and/or intermittent trade would be enough secure the reference diet over the occasional dry years.

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1 Introduction

Climatic and hydrologic conditions vary significantly around the globe, both spatially and temporally (Zachos et al., 2001; Trenberth et al., 2007). The importance of interannual hydroclimatic variability has been reported for many ecologic (e.g. Notaro, 2008) and societal functions (Brown and Lall, 2006; Brown et al., 2010). Although the global interannual variabilities of precipitation (e.g. Fatichi et al., 2012; Sun et al., 2012), temperature (Sakai et al., 2009) and surface wetness (Ma and Fu, 2007) are rather well understood, less is known on variability in runoff or river discharge at global scale. The runoff mainly determines the available blue water resources (i.e. freshwater in rivers and aquifers) for aquatic ecosystems and human societies. It is thus crucial to understand its variations at global and smaller scales. Dettinger and Diaz (2000) and Ward et al. (2010) have assessed the variability based on observed discharge data, but due to low data coverage in various parts of the world, they could not cover the whole globe. Recently, global hydrological models have enabled to assess average conditions, variabilities and trends in global runoff and discharge with greater spatial coverage (Hirabayashi et al., 2005; Piao et al., 2007; Gerten et al., 2008; Haddeland et al., 2011), though interannual variability was not their focus, and model results may in some regions disagree with observed variations and trends (Dai et al., 2009). Furthermore, meteorological and hydrological droughts have been assessed globally, yet basically constrained to a hydroclimatological perspective (Sheffield et al., 2009; Dai, 2011). To our knowledge, no global assessment is available on interannual variability in water availability for food production.

Sufficiency of blue water to meet certain demands can be measured with simple scarcity indices (Falkenmark et al., 1989; Falkenmark, 1997; Vörösmarty et al., 2000; Alcamo et al., 2003; Arnell, 2004; Oki and Kanae, 2006; Kummu et al., 2010). Although blue water and irrigation are crucial for global food production, still around 60 % of food is produced with green water (i.e. naturally infiltrated rain, attached to soil particles and accessible on roots) resources on rainfed land (Rockström et al., 2009). This has led to a quest for integrated green-blue water (GBW) scarcity indicators. Rockström et al. (2009) found a global GBW shortage by referring to a threshold of available GBW resources that is needed to produce a diet of 1300 $m^3 cap^{-1} yr^{-1}$. Gerten et al. (2011) developed a locally specific GBW scarcity indicator by taking explicitly into account the water productivity, i.e. the amount of GBW resources needed to produce a benchmark for hunger alleviation (3000 $kcal\,cap^{-1} day^{-1}$, assumed to consist of 80 % vegetal food and 20 % animal products).

All of these have focused on water scarcity under long-term average climate conditions. Besides, recent global studies are available that have focused on average seasonal (i.e. intra-annual) blue water scarcity (Wada et al., 2011; Hoekstra et al., 2012). The interannual variability of water scarcity has remained, however, tenuously quantified at global scale. We argue that it would be imperative to understand the frequency of water scarcity in food production, as in agricultural systems under occasional scarcity requires essentially different adaptation measures as compared to chronic scarcity. Thus, quantitative knowledge of average water scarcity, assessed for example over 30 yr (Gerten et al., 2011) or 10 yr (Rockström et al., 2009), might not reveal the areas that suffer water scarcity occasionally during dry years, and on the other hand it might classify areas to be water scarce although the scarcity is not present every year.

In this paper we quantify the impact of interannual climatic variability on global GBW availability and requirements for food production, using the GBW scarcity index introduced by Gerten et al. (2011). Our analysis is based on climate forcing data for the past 30 yr (1977–2006) while diet composition, population and land cover settings are fixed to specific reference conditions. We thus assess how the hydroclimatic variability impacts on food producing units' (FPUs) ability to produce a given diet for their inhabitants. Moreover, we quantify whether the variability has changed over time by comparing two time periods (1947–1976 and 1977–2006). All calculations are performed with the LPJmL vegetation and hydrology model (Bondeau et al., 2007; Rost et al., 2008).

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2 Data and methods

In this study we kept the land cover, population, diet composition and agricultural management options constant in order to trace the sole impact of climate variability on green-blue water scarcity. We used year 2000 as a reference year, as for that year the most detailed and accurate data is available for all the needed datasets. Below the used methodologies and data to conduct the study are introduced.

2.1 LPJmL model and data

The process-based, dynamic global vegetation and water balance model LPJmL (Bondeau et al., 2007; Rost et al., 2008) simulates – among other processes – crop water requirements, crop water productivities, and green and blue water availabilities at a daily time step and on a global 0.5 × 0.5 degree spatial grid. It computes the growth, production and phenology of 9 natural vegetation types, of grazing land, and of crops as classified into 12 "crop functional types" (CFTs). The fractional coverage of grid cells with CFTs was prescribed here using datasets of the reference (around year 2000) cropland distribution (Ramankutty et al., 2008) and maximum monthly irrigated and rainfed harvested areas (Portmann et al., 2010). Seasonal phenology of CFTs is simulated based on meteorological conditions. Crop management is calibrated for the period around 2000 so as to ensure that simulated yields best match those reported by FAOSTAT (see Fader et al., 2010 for details).

In LPJmL carbon fluxes and pools as well as water fluxes are modelled in direct coupling with vegetation dynamics. Effects of atmospheric CO_2 concentration on plant growth and water use efficiency can be included in the simulations, but atmospheric CO_2 concentration was held constant here at 370 ppm, corresponding approximately to the year 2000 level. Water requirements, water consumption (i.e. evapotranspiration, distinguished into transpiration, evaporation and interception loss) and crop water productivity (water consumption per unit of biomass produced) are calculated for both irrigated and rainfed systems. On rainfed areas, all consumed water is green

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per definition, whereas on areas equipped for irrigation, we distinguish the fractions of green water and blue water (withdrawn from rivers, reservoirs, lakes and shallow aquifers to the extent required by crops and unfulfilled by green water, considering country-specific irrigation efficiencies). We assume that the irrigation water requirements of each CFT can always be met, implicitly assuming contributions from fossil groundwater, river diversions or other large-scale water transports (details in Rost et al., 2008; Konzmann et al., 2013). River flow directions are determined as in Haddeland et al. (2011), and reservoir distribution and management as in Biemans et al. (2011).

The areal distribution of CFTs and grazing land, the calibration parameters and the irrigation efficiencies are held constant at the year 2000 level throughout the simulation period. Thus, we disregard any effects of crop management and cropland expansion. Monthly values of temperature and fraction of cloud cover are taken from CRU TS 3.1 (Mitchell and Jones, 2005) and linearly interpolated to daily values. Monthly precipitation totals are taken from GPCC v5 (Rudolf et al., 2010; extended to cover the full CRU grid) and the number of monthly precipitation days is derived using the method from Heinke et al. (2012). Daily precipitation values are calculated from these two parameters by a statistical weather generator (Gerten et al., 2005).

2.2 Analysis and reporting scales

The model results, with resolution of 0.5°, are aggregated primarily to the FPU scale. FPUs divide the world into 281 sub-areas, being a hybrid between river basin and economic regions (Cai and Rosegrant, 2002; Rosegrant et al., 2002; De Fraiture, 2007) modified here as in Kummu et al. (2010). The final FPU set used includes 309 units with an average size of 467×10^3 km^2 and an average population of 19.6 million. We focus on FPUs, as they are at a hydro-political scale where the demand for water can assumed to be managed (Kummu et al., 2010).

We introduce another three reporting scales to further analyse and present our results, namely countries, administrative regions, and hydrobelts. The administrative regions divide the world into 12 regions (see Fig. S1a in the Supplement) based on the country borders. For this we use a regional dataset originating from United Nations (2000), which was further modified by Kummu et al. (2010). The hydrobelts divide the world into eight zones determined by specific hydrological characteristics and formed based on river basin boundaries (Meybeck et al., 2013). The country and administrative region scales are used for a multi-scale analysis that reveals the spatial scale of need for food storage and/or trade as an option to reach the reference diet (see Sect. 2.5).

2.3 Calculation of green-blue water availability, demand, and scarcity

The procedure to calculate water availability, requirements and scarcity are described in detail in Gerten et al. (2011) and only briefly summarised here. Water availability is defined as evapotranspiration from cropland during growing season and (partly) from grazing land (green water) and, respectively, as 40 % of the sum of runoff and water storage in lakes and aquifers (blue water). Note that green water availability thus depends not only on hydroclimatic conditions but also on the spatial extent of cropland and grazing land.

The total availability of green and blue water (GBW), aggregated to FPUs, is then compared with the amounts of green and blue water needed to produce the reference diet of 3000 kcal cap^{-1} day^{-1} (with 80 % vegetal and 20 % animal-based share) for all inhabitants of the spatial unit, following the method developed by Gerten et al. (2011). This value includes an assumption of food losses and waste, being in terms of calories on average 24 % (Kummu et al., 2012); subtracting these from the total production gives a food consumption of around 2280 kcal cap^{-1} day^{-1}. This is almost exactly the global Average Dietary Energy Requirement (country specific data averaged over 2007–2012) of 2245 kcal cap^{-1} day^{-1} defined by FAO (2013b). This justifies the above specified reference diet as a hunger alleviation diet in our analysis.

The GBW requirements result from the plant water productivity (determined at grid cell level and influenced by climate and management), the transpirational demand given by current meteorological conditions, and the current soil moisture. They are

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computed from both the water requirements to produce the vegetal calorie share on present cropland (represented by the CFTs) and from a provisional livestock sector. Contributions from the latter come from both grazing land and cropland (i.e. the shares used for feed production, assigned according to the scheme used in Gerten et al., 2011). The water requirements from grazing land are computed slightly differently as compared to Gerten et al. (2011): here we weigh the green water available on each country's/FPU's grazing land according to its water productivity, while Gerten et al. (2011) uses a water productivity relative to the global average for grass. GBW scarcity is given by the ratio between the GBW availability and the GBW requirements for producing the reference diet.

2.4 Methods for analysing the variability and change in variability

As GBW scarcity is assessed on the basis of GBW requirements and GBW availability, it is important to understand the impact of climate variation on both and, moreover, the resulting GBW scarcity. To quantify this variability we use the coefficient of variation (CV; i.e. standard deviation divided by mean) that is comparable between different areas, and also between the three variables. Further, we measure the frequency of years when an FPU in question is under GBW scarcity (i.e. when it does not have enough water to produce the reference diet). With this frequency analysis we are able to classify the FPUs into three main groups of which occasional GBW scarcity is further divided into four sub-groups:

1. no GBW water scarcity (enough GBW to produce the reference diet in 100 % of the years);
2. occasional GBW water scarcity:
   a. sporadic GBW scarcity (GBW scarcity in 1–25 % of the years);
   b. medium frequent GBW scarcity (GBW scarcity in 25–50 % of the years);
   c. highly frequent GBW scarcity (GBW scarcity in 50–75 % of the years);

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d. recurrent GBW scarcity (GBW scarcity in 75–99 % of the years);

3. chronic GBW scarcity (GBW scarcity in 100 % of the years).

Moreover, we analyse the average GBW scarcity for each FPU using the average values of GBW requirements and GBW availability over the study period of 30 yr. This reveals whether the area in question can produce enough food with available water resources under long-term average climate conditions – assuming the reference diet, and the extent of agricultural land and management practices around year 2000.

We also investigate whether there have been changes over time in GBW scarcity, as affected by changes in both the CV and average conditions. In so doing, we first test with a one-way ANOVA whether the mean values of these two parameters are equal in two 30 yr periods (1947–1976 and 1977–2006). Moreover, we analyse the changes in variability of GBW requirements and GBW availability within both 30 yr periods. We use the Brown-Forsythe Levene's test for equality of variances (Brown and Forsythe, 1974) to assess whether there is a difference in group variances between these two periods. All statistical tests are performed with SPSS v20. We also perform the frequency analysis of GBW scarcity for both periods and compare those.

2.5 Response options and stress drivers: multi-scale analysis and GBW matrix

We further conduct a multi-scale scenario analysis to scrutinise possible response measures on how each FPU under GBW scarcity could theoretically reach the reference diet of 3000 kcal cap^{-1} day^{-1}. The results from GBW scarcity analyses are used at FPU, country and regional scale to identify the possible response measures as follows (see also Table 2 in Sect. 3.3):

- *Perennial food self-sufficiency*: the FPUs that do not suffer from any degree of GBW scarcity are classified as FPUs that do not need any response measure to reach local food self-sufficiency.

- *Need of local food storage and/or intermittent trade*: if an FPU has some degree of occasional scarcity but is self-sufficient under average climate conditions it would need to store food in excess years to overcome the deficit years and/or import (export) food in deficit (excess) years.

- *Need of domestic trade*: in cases where an FPU is not self-sufficient under average climate conditions, but the country in which the FPU is located is self-sufficient, an FPU would need domestic trade to overcome the deficit years.

- *Regional and inter-regional trade*: if however a country in question is not self-sufficient under average climate conditions, an FPU is classified to need either regional trade (if the region of FPU in question is self-sufficient) or inter-regional trade (if it is not).

3 Results

3.1 Interannual variability of GBW scarcity

The GBW requirements for the reference diet under average climate conditions over our study period (1977–2006) show a distinct spatial pattern, due primarily to differences in climatic conditions and on-farm management. They are lowest ($< 650\,m^3\,cap^{-1}\,yr^{-1}$) in western Europe and large parts of North America, rather low ($650–1300\,m^3\,cap^{-1}\,yr^{-1}$) in southern parts of North America, South America and large part of Asia, and highest ($> 1300\,m^3\,cap^{-1}\,yr^{-1}$) in northern parts of Latin America, Africa (except the northernmost part) and South Asia (Fig. 1a). The GBW availability per capita is lowest in very dry areas (e.g. North Africa, Middle East) and in highly populated places, such as South Asia and China. The high requirements are often located in the same areas as low GBW availability (Fig. 1b), resulting in water-scarce conditions (Fig. 2a).

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The variability in GBW requirements is mostly rather low (CV < 0.1) except for some of the northern- and southernmost areas where CV exceeds 0.2 (Fig. 1c). In case of GBW availability, the variability is much higher and spatially more heterogeneous, being particularly high in dry areas, such as in North Africa, the Middle East, Australia, Central Asia and western China. The variability is rather low or very low in large parts of South America, Europe, Sub-Saharan Africa, South Asia and eastern Asia (Fig. 1d).

We find that 34 % of the global population at reference year live in FPUs affected by GBW scarcity under long-term (1977–2006) average climate conditions, i.e. the average GBW requirements for the reference diet were larger than the average available GBW resources (Table 1; Fig. 2a). When analysing the frequency in GBW scarcity due to interannual climate variability, we find that 44 % of world's population live in FPUs under some degree of scarcity (Table 1; Fig. 2b). Of these people water is chronically scarce for around half (24 % of global population) while for the other half the scarcity is occasional. The occasional scarcity is distributed rather evenly between the four classes, although the classes with most population are the highest (recurrent GBW scarcity) and lowest (sporadic GBW scarcity) categories (Table 1).

The GBW scarcity areas form a belt-like pattern from the western-most tip of North Africa towards eastern China (Fig. 2a and b). Majority of the FPUs under scarcity in the Southern Hemisphere falls between the Equator and Tropic of Capricorn (23.4° S) while in the Northern Hemisphere they fall mostly in both sides of the Tropic of Cancer (23.4° N) (Fig. 2). The most intense GBW scarcity frequencies are found in the region from the Middle East and South Asia (Fig. 2b), where over vast majority of population live under some degree of GBW scarcity (Fig. 3a; Table S2; see region division in Fig. S1a) and 75 % in scarcity under long-term climatic conditions. In North Africa around 84 % of population live under GBW scarcity, but only half of them in scarcity under long-term climatic conditions.

According to our analysis, North America and Australia & Oceania are the only regions where our results do not indicate GBW scarcity (Figs. 2b and 3a), being a bit counter-intuitive, given the drought proneness of both areas and particularly Australia.

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This is probably due to two factors: (i) both areas are very large food exporters (FAO, 2013a) and it seems that even during the driest years the FPUs have enough GBW resources to produce the reference diet for local population; and (ii) the FPU scale might be in some cases too large to identify local scarcity. FPUs in Central America and Western Europe do not suffer long-term scarcity but some are under occasional GBW scarcity (Figs. 2b and 3a).

When the GBW frequency results are aggregated by hydrobelts (see division in Fig. S1b), they reveal that in Northern and Southern Dry belts over half of the reference population suffer some degree of GBW scarcity while in other belts less than half live under scarcity (Fig. 3b). The lowest scarcity occurs in boreal and equatorial belts, where 0 % and 3 % of population, respectively, live under occasional scarcity. The belts in the Northern Hemisphere have relatively higher GBW scarcity than their southern analogues (Fig. 3b), mostly due to their much higher population densities (Kummu and Varis, 2011; Meybeck et al., 2013).

3.2 Change in GBW scarcity over time

When comparing the 30 yr period before 1977 to our study period of 1977–2006, we find that the average GBW requirements for reference diet decrease statistically significantly ($p < 0.05$) in 98 FPUs while they increase in only 13 FPUs (Fig. 4a). It should be noted, however, that as the variability in GBW requirements is relatively small (Fig. 1c), these changes are in most cases results of rather small absolute changes, corresponding on average around 5 % of the mean value. Spatially the areas with significant changes are concentrated in East Asia, Africa and west coast of Central and North America. Changes in variability of GBW requirements are less pronounced, with rather few FPUs showing significant changes (Fig. 4c).

In the case of GBW availability, the most distinct changes in average GBW availability have occurred in West Africa and Southeast Asia, where the availability decreased significantly ($p < 0.05$) within the latter 30 yr period (Fig. 4b). In large part of Europe and southern part of South America, on contrary, the second period is wetter compared to

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the first one. Because of relatively large variability in GBW availability (Fig. 1d), the absolute change in the FPUs with significant change over time is larger (i.e. in average 14 % of the mean value) compared to the changes in GBW requirements (5 %). The spatial pattern of changes, and extent of those, in GBW variability (Fig. 4d) is less distinct than in case of average GBW availability (Fig. 4b).

These changes in GBW requirements and GBW availability impact on the GBW scarcity frequency, particularly in Northern and East Africa and Central and East Asia (Fig. 4e). The frequency increases in large parts of Northern Africa and in East China, while it decreases in Central Asia, few FPUs in Central America and large part of East Africa. Globally, the climate in the period before our study period resulted in a slightly lower population exposed to GBW scarcity (Table 1).

3.3 FPU dependency on trade and food storage

Over half of the global reference population would be able to reach FPU level food self-sufficiency (when measured with reference diet) with local GBW resources, while for another 9 % the local storage and/or intermittent trade (import in deficit years and export in excess ones) would be enough to reach the reference diet (Table 2). The multiple-scale analysis thus reveals that FPUs inhabited by about two thirds of the world population are not theoretically dependent on either domestic or international annual trade to reach local food self-sufficiency. Of those living in FPUs dependent on trade (34 % of global population), 70 % depend on international or inter-regional trade while for the rest 30 % domestic trade (FPUs with 48 million people supported with national storage) would be enough to secure the reference food supply (Table 2).

The spatial analysis of these response options reveals that FPUs depending on inter-regional trade are located in South Asia and the Middle East, being the only regions not able to produce intra-regionally the reference diet for all inhabitants with available GBW resources (Fig. 5). The FPUs dependent on intra-regional trade are mainly located in North and East Africa and Central Asia while the FPUs under domestic trade response option are mainly located in China. In Europe, Central America and Southeast Asia, the FPUs under occasional water scarcity would be able to reach food self-sufficiency with local storage and/or intermittent trade (Fig. 5).

4 Discussion and conclusions

Interannual climate variability has not been previously included in water scarcity studies, despite its crucial role on any agricultural activity. By including this variability, we thus provide a fundamental extension to the existing methodology, concept and knowledge on water scarcity and its impact on food production across the globe, as further discussed below. Our calculations indicate that 44 % of the planet's population (relative to the year 2000 reference population) dwell in areas characterised by at least some level of GBW (i.e. green-blue water) scarcity, i.e., the GBW availability is insufficient for producing the reference diet.

4.1 Main results and uncertainties

In this article we analyse, for the first time, the interannual variability in global water scarcity (as imposed by climatic variability) over several decades. We use the GBW scarcity indicator developed by Gerten et al. (2011), measuring the ability of a given spatial unit to produce a reference diet of 3000 kcal cap^{-1} yr^{-1} on reference agricultural areas, management practices and population level with available green-blue water resources. Our analysis extends the current knowledge of water scarcity (Vörösmarty et al., 2000; Alcamo et al., 2003; Arnell, 2004; Oki and Kanae, 2006; Falkenmark et al., 2009; Rockström et al., 2009; Kummu et al., 2010; Gerten et al., 2011) by assessing the frequency of GBW scarcity (i.e. whether an area suffers from occasional or chronic water scarcity) instead of using only the average climate conditions over several years/decades. By combining the frequency of GBW scarcity and average GBW scarcity over multiple scales, we are able to reveal possible response options to reach food self-sufficiency, for areas under scarcity.

The LPJmL model used here has been comprehensively validated in terms of biogeochemical, agricultural and hydrological simulations (Gerten et al., 2004; Bondeau et al., 2007; Rost et al., 2008; Biemans et al., 2009; Fader et al., 2010). To evaluate our present results, we compare the computed GBW availability (Fig. 1d) to other studies. Our findings agree well with the few interannual variability analysis using surface observations of streamflow (Dettinger and Diaz, 2000) and precipitation (Fatichi et al., 2012). Fatichi et al. (2012) further used three gridded datasets (NCEP–NCAR, ERA-40, and GPCC Full Reanalysis) to assess the interannual variability in precipitation and the patterns of our discharge variability agree rather well with those, except in the case of eastern Siberia. There our results show rather high variability in GBW availability (Fig. 1d), while that is not shown in the precipitation variability of Fatichi et al. (2012). It should be noted, however, that although precipitation is the key driver in GBW availability, also other factors are relevant (e.g. Gerten et al., 2008), such as crop growing periods and vegetation production.

We further found that the GBW requirements for the reference diet and GBW availability have changed over time due to changes in climate. The patterns of changes in variability (Fig. 4d) of GBW availability are rather similar to the trend in the variability of precipitation as compiled from seven databases for the years 1940–2009 (Sun et al., 2012). Further, the changes in mean GBW availability (Fig. 4b) are similar to (modelled) trends in blue water availability, i.e. river discharge (Gerten et al., 2008). It should be noted though that our timescale was different to these studies and we only mapped statistically significant changes.

The GBW requirements for the reference diet were also found to change over time and are significantly lower in many areas during the second 30 yr study period compared to the first one (Fig. 4a), although the absolute change between these periods is not very large. Spatially explicit identification of the underlying mechanisms requires further analyses. The variability in GBW requirements does not, however, change significantly between these two periods (Fig. 4c and d). The changes in GBW availability

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and GBW requirements do not impact significantly on global population under GBW scarcity (Table 1), although local changes occurred (Fig. 4e).

In sum, it should be noted that our findings are subject to the model assumptions and maybe even more to the forcing data used (Biemans et al., 2009). Given these restrictions, we recommend interpreting our results only at regional and global scales. To increase the robustness of our results, multiple forcing data, and even models, could be used. Also, we performed the calculations for a single year's reference population (year 2000), hence we recommend that the impact of demographic changes be investigated separately.

4.2 Response options beyond storage and trade

To facilitate the discussion of possible response options to reach food self-sufficiency at FPU level, we designed the GBW matrix concept (see Fig. S2 in the Supplement). In the matrix the GBW requirements for the reference diet (y-axis) are plotted against the GBW availability ratio (x-axis; i.e. GBW availability vs GBW requirements). When plotting all FPUs grouped by response options (Table 2) in the GBW matrix, we see that the majority (90 %) of the FPUs that depend on international trade have GBW requirements larger than 1300 $m^3\ cap^{-1}\ yr^{-1}$ (Fig. 6). This indicates rather high water requirements to reach the reference diet. Thus, the possible response options for these FPUs, and others with high GBW requirements would involve better management strategies resulting in higher crop yield per used GBW resources, and/or cropland expansion.

Indeed, Fader et al. (2013) found that theoretically many countries would be able to produce the required food on their own – even under increasing population in the future – if management practices would continuously improved at current rates. Yet, in some countries the local food self-sufficiency would require the expansion of their cropland. Cropland expansion, however, introduces notable challenges to environmental sustainability (Wirsenius et al., 2010; Tilman et al., 2011) and the potential has been known to be quite limited in most parts of the world already over several decades (Kendall and Pimentel, 1994; Pfister et al., 2011). Foley et al. (2011) conclude that

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when better management practises (closing yield gaps and increasing cropping efficiency) are combined with shifting diets and reducing waste, global food security can be increased significantly. Political priorities related to food self-sufficiency should be brought into the picture as well, we argue; otherwise such discussions remain quite theoretical.

The FPUs under GBW scarcity with low GBW requirements (i.e. 1300 $m^3\,cap^{-1}\,yr^{-1}$) (Fig. 6) have fewer response options, as their management level is already rather high. For these areas the option to ensure production of the reference diet (from GBW view) would be either expanding the croplands (to get access to the green water on these areas) or transferring blue water from elsewhere. Long-distance water transfer is already happening in many parts of the world, including China where water is being diverted from the water-rich south to the water-scarce north (Liu and Zheng, 2002). Northern China is where most of the country's FPUs under GBW scarcity are located (Fig. 2b). Indeed, in these areas cropland expansion is not anymore feasible (Liu et al., 2005; Pfister et al., 2011).

4.3 Further research directions

In this study we kept the land cover, population, diet composition and agricultural management options constant in order to trace the sole impact of climate variability on GBW scarcity. Follow-up studies should examine each year's actual water limitations, accounting for historic land use, and the dynamics in population and variability in diets. This kind of historical assessment would give important insight on how cropland extension (and thus increased green water availability) is linked with population growth and migrations over time. Moreover, such studies could analyse in more detail the historical record on the impact of climate variability – and climatic extremes, namely droughts – on water scarcity during different periods or in individual years. This would increase the understanding of the extent and character of the required responses and their evolution over time, such as the presently soaring trend in virtual water trade (Carr et al., 2013).

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It should be noted that many FPUs that are today under GBW scarcity, or are approaching that, are facing rapid population growth and thus, the situation can be expected to become even more challenging in the near future (Gerten et al., 2011; Fader et al., 2013; Suweis et al., 2013). Or it might actually already be so since 13 yr have passed since the conditions of our population reference year. The projected climate change, as well as demographic growth, thus adds another extra stress dimensions, particularly in regions such as the Middle East, northern and southern Africa, and parts of Australia. Therefore, it would be important to assess how the projected increase in hydroclimatic variability in the future (e.g. Boer, 2009; Wetherald, 2010) might impact on frequency of GBW scarcity. As the future climate would concur with population projections, showing rapid growth in many areas under water scarcity (UN, 2011), much more FPUs would turn from water abundant to water scarce (as suggested by Arnell, 2004; Arnell et al., 2011 for the river basin scale). Thus, it would be desirable to investigate the impact of climate variability in the future, in order to extend the current knowledge of adaptation options to secure the food supply to everyone.

The policies related to food self-sufficiency should also be systematically investigated within the context of studies such as ours. Our analysis reveals the theoretical potential of FPUs to reach perennial or potential food self-sufficiency, or if self-sufficiency cannot be reached, the dependence level on either domestic or international food trade. We strongly encourage the linking of our study and approach to investigations on national and regional food policies across the globe in order to bridge the calculations of theoretical potentials to actual policy level priorities for meeting the demand for food.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/10/6931/2013/hessd-10-6931-2013-supplement.pdf.

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Table 1. Global population (in millions) under green-blue water (GBW) scarcity. Frequency of scarcity over the period (1977–2006) and over the 30 yr period before that (1947–1976). Bottom row ("average scarcity") represents the GBW scarcity under average climate conditions within those periods. See also Figs. 2 and 4e. Note that the calculations were made for constant reference population (year 2000 situation) but varying climate within the indicated time periods.

	Population under GBW scarcity (in millions)			
Frequency	1977–2006	% of total	1947–1976	% of total
0 %	3,471	57.4 %	3524	58.3 %
0–25 %	332	5.5 %	247	4.1 %
25–50 %	197	3.3 %	240	4.0 %
50–75 %	212	3.5 %	198	3.3 %
75–100 %	375	6.2 %	370	6.1 %
100 %	1456	24.1 %	1463	24.2 %
Total	6042		6042	
Average scarcity	2027	33.6 %	1,885	31.2 %

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Table 2. Response options for FPUs, depending on the ability of to reach reference diet of 3000 kcal cap^{-1} yr^{-1} (see map in Fig. 5 and FPUs in GBW matrix in Fig. 6). Scarcity frequency refers to the frequency of GBW scarcity (see Fig. 2b) and average scarcity on GBW scarcity under average climate conditions (see Fig. 2a) over our study period of 1977–2006.

	FPU			Country			Region		Population	
Scarcity frequency	0 %	> 0 %	> 0 %	0 %	> 0 %	> 0 %				
Average scarcity	No	no	yes	no	no	yes	no	yes	10^6	%
No response needed	×								3471	57.4 %
Local food storage and/or intermittent trade		×							544	9.0 %
Domestic trade			×	×					563	9.3 %
National storage & domestic trade			×		×				48	0.8 %
Regional trade			×			×	×		266	4.4 %
Inter-regional trade			×			×		×	1163	19.0 %

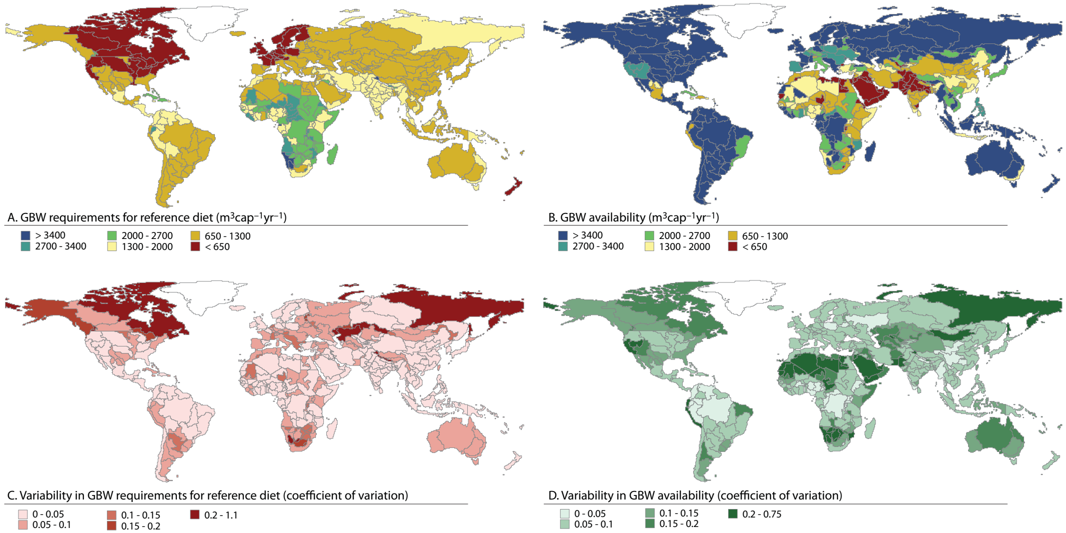

Fig. 1. Green-blue water (GBW) requirements for reference diet and GBW availability. **(A)** Average GBW requirements over 30 yr study period; **(B)** average GBW availability over 30 yr study period; **(C)** variability in GBW requirements measured with coefficient of variation (CV); and **(D)** variability in GBW availability measured with CV.

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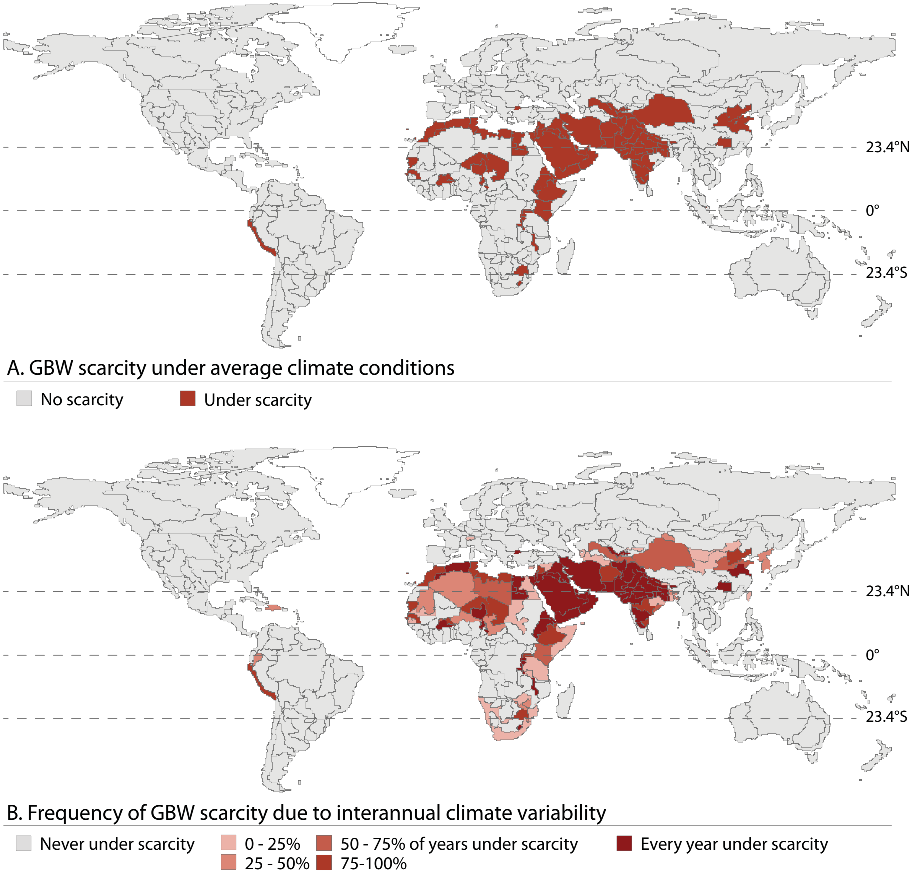

Fig. 2. Green-blue water (GBW) scarcity mapped by FPUs. **(A)** GBW scarcity under average climate conditions over 30 yr study period; and **(B)** frequency of GBW scarcity due to interannual climate variability. The marked latitudes represent Tropic of Cancer (23.4° N), Equator (0°), and Tropic of Capricorn (23.4° S).

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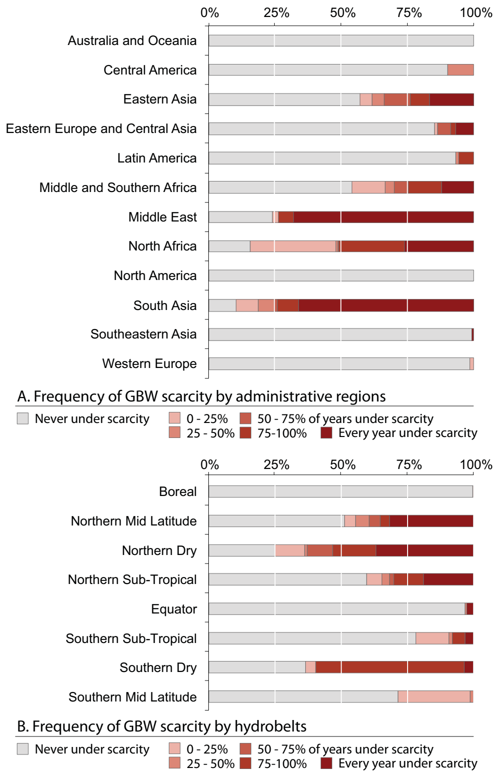

Fig. 3. Frequency of green-blue water (GBW) scarcity aggregated by **(A)** administrative regions, and **(B)** hydrobelts. See maps of the administrative regions and hydrobelts in the Supplement (Fig. S1a and b, respectively).

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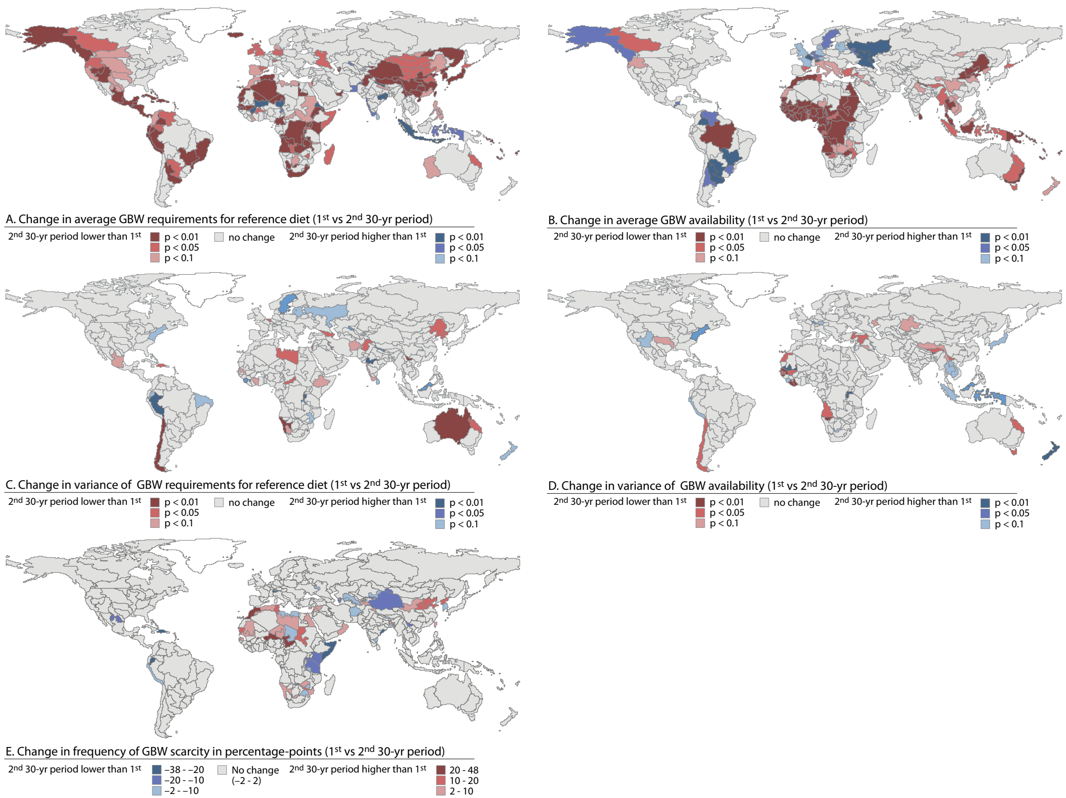

Fig. 4. Comparison of two 30 yr periods (i.e. model forced by hydrometeorological data of 1947–1976 vs. 1977–2006). **(A)** Change in average green-blue water (GBW) requirements for the reference diet; **(B)** change in average GBW availability; **(C)** change in variance of GBW requirements; **(D)** change in variance of GBW availability; and **(E)** change in frequency of GBW scarcity. The change assessment in average values was conducted with One-way ANOVA and the change assessment in variability was conducted with the Leven type Brown-Forsythe test.

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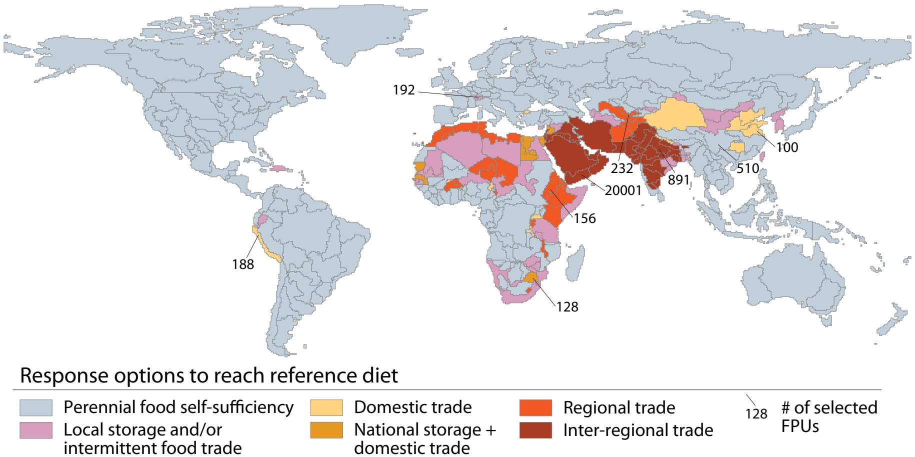

Fig. 5. FPU response options that would be needed to reach the local reference diet of 3000 kcal cap^{-1} day^{-1} (see Table 2 for more information). Selected FPUs are identified with their code; see Fig. 6 for their location in GBW matrix.

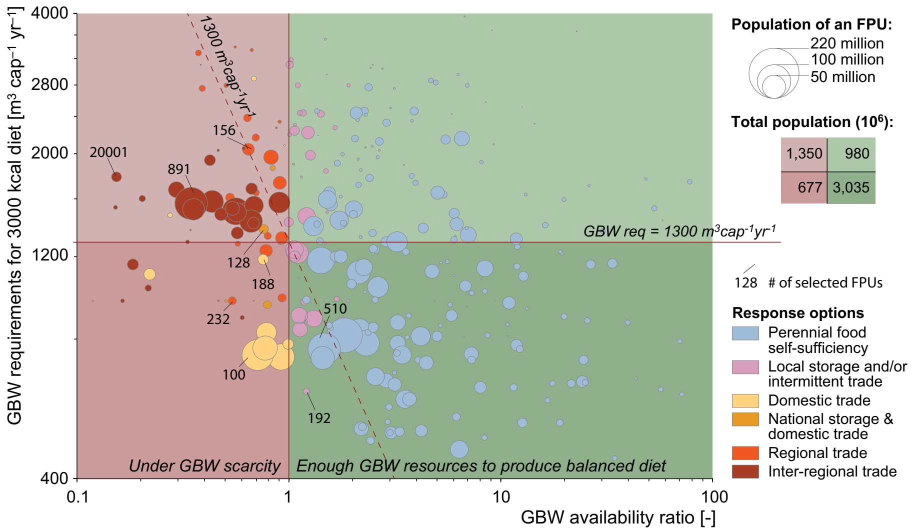

Fig. 6. FPUs mapped in the GBW matrix, grouped by response options. The location of an FPU is based on green-blue water (GBW) requirements for the reference diet (y-axis) and GBW availability ratio (x-axis; i.e. GBW availability vs GBW requirements) under average climate conditions. Thus, the FPUs with response option of "local storage and/or intermittent trade" are under occasional scarcity although not under average GBW scarcity. See Table 2 for more information of these options, and Fig. S2 in the Supplement for the concept of GBW matrix. The selected FPUs are identified with their code; see Fig. 6 for their location in a map.

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