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Causes and trends of water scarcity in food production

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Abstract

The insufficiency of water resources to meet the needs of food production is a pressing issue that is likely to increase in importance in the future. Improved understanding of historical developments can provide a basis for addressing future challenges. In this study we analyse how hydroclimatic variation, cropland expansion and evolving agricultural practices have influenced the potential for food self-sufficiency within the last century. We consider a food production unit (FPU) to have experienced green–blue water (GBW) scarcity if local renewable green (in soils) and blue water resources (in rivers, lakes, reservoirs, aquifers) were not sufficient for producing a reference food supply of 3000 kcal with 20% animal products for all inhabitants. The number of people living in FPUs affected by GBW scarcity has gone up from 360 million in 1905 (21% of world population at the time) to 2.2 billion (34%) in 2005. During this time, GBW scarcity has spread to large areas and become more frequent in regions where it occurs. Meanwhile, cropland expansion has increased green water availability for agriculture around the world, and advancements in agronomic practices have decreased water requirements of producing food. These efforts have improved food production potential and thus eased GBW scarcity considerably but also made possible the rapid population growth of the last century. The influence of modern agronomic practices is particularly striking: if agronomic practices of the early 1900s were applied today, it would roughly double the population under GBW scarcity worldwide.

1. Introduction

The possible insufficiency of land and water resources to meet the needs of humanity, particularly those of agriculture, is a pressing issue that is currently affecting roughly a third of the world's population (Kummu *et al* 2010, 2014, Hoekstra *et al* 2012). Projected future developments, such as population growth (Gerland *et al* 2014) and increasing climatic and hydrologic variability (Coumou and Rahmstorf 2012, Ward *et al* 2014), are likely to further aggravate resource scarcity with implications for food security (Foley *et al* 2011, Steffen *et al* 2015).

Food availability has increased considerably over the past decades (Alexandratos and Bruinsma 2012, Porkka *et al* 2013). Development of agriculture has indeed been tremendous over the past century. While population has almost quadrupled, global agricultural land has more than doubled during this time, increasing the green water (GW) available for agriculture (Klein Goldewijk *et al* 2011), i.e. rainwater available in soil on cropland and pasture land (Rockström *et al* 2009). Between 1965 and 2005, average global crop yields increased by 87%, meaning that the use of agricultural land has gotten more and more efficient (Foley *et al* 2011). Available blue water (BW) resources, however, can be assumed to have remained relatively unchanged, and in many regions, expanding agriculture has passed the limits of safe land use change (Steffen *et al* 2015). The resources to feed the growing population have thus gotten scarcer relative to demand and may have limited sufficient food production in the past.

The existing studies on past BW scarcity suggest a sharp increase in scarcity since the 1960s (Kummu

Table 1. Variables used to calculate GBW scarcity and their principal underlying drivers.

Variable	Definition	Underlying drivers
Blue water availability ($m^3\ yr^{-1}$)	Runoff in rivers and aquifers (only renewable fraction) and temporary storage in lakes and reservoirs), reduced to 40% to account for environmental flow requirements	Climate (precipitation, temperature, radiation) and its variability, river flow directions, spatio-temporal distribution of lakes and reservoirs, upstream water consumption
Green water availability ($m^3\ yr^{-1}$)	Evapotranspiration from cropland during growing periods, 1/3 of evapotranspiration from grazing land	Agricultural area and its expansion, climate, crop type
GBW requirement ($m^3\ yr^{-1}$)	Plant water requirements per 3000 kcal $cap^{-1}\ yr^{-1}$	Crop type and management (yield), climate, irrigation extent and efficiency

et al 2010, Wada *et al* 2011, Veldkamp *et al* 2015). These, and other existing water scarcity studies (e.g. Falkenmark *et al* 1989, Falkenmark 1997, Vörösmarty 2000, Oki and Kanae 2006, Alcamo *et al* 2007) use scarcity indices that describe the sufficiency of BW (water in rivers, reservoirs, lakes and aquifers) to meet certain criteria. Although BW and irrigation are essential factors in food production, over 60% of global food supply is still produced on rainfed lands, i.e. solely with GW (Rockström *et al* 2009). Consequently, GW accounts for about 90% of agricultural water consumption (Rost *et al* 2008, Liu *et al* 2009, Hoekstra and Mekonnen 2012). Therefore, in order to measure water scarcity in food production, it cannot be neglected.

This notion has led to the development of combined green–blue water (GBW) scarcity indicators (Rockström *et al* 2009, Gerten *et al* 2011). Most recently, Kummu *et al* (2014) used a GBW scarcity index developed by Gerten *et al* (2011) to quantify the effect of interannual climatic variability on global GBW scarcity. This index takes into account local water productivity, and is based on GBW availability and the volume of water needed to produce a reference food supply of 3000 kcal $cap^{-1}\ d^{-1}$ (assumed to consist of 80% vegetal food and 20% animal based food) that is considered a hunger prevention target.

A global analysis of historical GBW limitations in food production that also accounts for changes in population, land use and agronomic practices does not exist. It would be, however, highly important to increase the understanding of historical development, as that could provide a stronger basis for addressing future challenges: studying the past enables us to identify patterns and drivers of water scarcity, and responses to it. Here, we thus assess the development of global GBW scarcity over 1901–2009 using the GBW scarcity index introduced by Gerten *et al* (2011). We analyse how four components, hydroclimatic variability, cropland extent, agricultural management practices and population have affected GBW availability and GBW requirement of producing a sufficient food supply for the inhabitants of each food production unit (FPU) over time. We thus measure the potential of reaching FPU-internal food self-sufficiency.

2. Data and methods

GBW availability and requirement estimations, are performed with the LPJmL vegetation and hydrology model (Bondeau *et al* 2007, Rost *et al* 2008, Schaphoff *et al* 2013) at 30 arc-min resolution and aggregated to the level of FPUs for GBW scarcity calculations. LPJmL computes the growth and productivity of the world's major vegetation types, nine natural plant functional types and 12 crop functional types, in direct coupling with associated fluxes of water and carbon in the vegetation–soil system (described in detail in supplementary text S1). We use spatially explicit historical datasets of climate, land cover, extent of area equipped for irrigation (see references in supplementary text S1) and population density (Klein Goldewijk *et al* 2011), as introduced below. Each decade, crop management intensity is calibrated to adjust simulated yields to best match the values reported in FAOSTAT (FAO 2015) for years 1961–2009 and reconstructed yields over 1901–1960 based on International Historical Statistics (Palgrave Macmillan Ltd 2013) (described in detail in supplementary text S2). Below we give a brief introduction to the used methods.

2.1. Scale

The results of the LPJmL model were aggregated from the 30 arc-min resolution gridded format to the scale of FPUs, which divide the world into 281 areas that are hybrids between river basins and economic regions (Cai and Rosegrant 2002, Fraiture 2006). The original FPUs were slightly adjusted by splitting some larger regions that were crossing country borders into smaller units (Kummu *et al* 2010), which resulted in 309 units (see Supplementary figure S1). We present FPU level results also aggregated to regional and global levels (see figure S1 for regional devision).

2.2. GBW availability, requirement and scarcity

Water availability is defined as the sum of green and BW resources. The GW resource is calculated as the evapotranspiration of GW from cropland, and 1/3 of the evapotranspiration from grazing land (following a simple assumption as in Gerten *et al* 2011), during the growing season. Thus, it is defined not only by hydroclimatic conditions but also by the extent of agricultural area within an FPU (table 1). BW availability is given by renewable water flowing in rivers and recharging to groundwater (also including temporary storage in lakes and reservoirs)—thus it represents the BW volume that is potentially available for (irrigation) withdrawal. The data from Siebert *et al* (2015) provide information on the historical evolution of irrigated area and, thus, on the fraction of a grid cell that is equipped for irrigation. Based on this information, LPJmL models the plant water requirement of the crops on these areas. Historical changes in the number of reservoirs are taken into account following Biemans *et al* (2011). In LPJmL, it is assumed that irrigation demand can always be fulfilled from BW resources (i.e. in case no sufficient water volumes are available in a grid cell, the assumption is that the remainder is taken from fossil groundwater or rivers diverted from other areas). Irrigation management (i.e. country-specific type of irrigation system and irrigation efficiency as in Rost *et al* 2008) was assumed to have been the same in the past as around 2000. For more detailed descriptions, see Gerten *et al* (2011) and Kummu *et al* (2014).

To account for environmental requirements in a simple way, only a part of GW and BW resources was assumed to be available for food production. According to Steffen *et al* (2015), the area of forested land as a percentage of original forest cover should be >85% in tropical and boreal regions and >50% in temperate regions. As a simplified application of this planetary boundary concept, we assumed that 15% of land area is available for agriculture (cropland and grazing land) in tropical and boreal regions (based on FAO 2013) and 50% in other regions. These thresholds were calculated for each FPU individually, based on the fractions of different ecological zones within an FPU (see FPU level thresholds in figure S7(A)). In each FPU, the agricultural area exceeding the threshold was not taken into account when calculating GW availability. To also account for river ecosystems' flow requirements, which are an element of the planetary boundary for human freshwater use (Gerten *et al* 2013), only 40% of the BW resource (after its calculation as described above) was assumed to be available for food production (as in Gerten *et al* 2011).

We analysed water scarcity by examining the FPUs' potential to produce an adequate food supply for their inhabitants with available GW and BW resources. Specifically, within each FPU, we compared the GBW availability with the water requirements of producing the raw products of a reference food supply that is defined as:

- Reference food supply: 3000 kcal cap^{-1} d^{-1} (80% or 2400 kcal vegetal and 20% or 600 kcal animal based food). Assumed to remain constant.
- Reference diet: composition of the reference food supply. Varies temporally and spatially based on crops cultivated in each FPU at different times.

The 3000 kcal cap^{-1} d^{-1} production target implicitly includes food losses and waste along the whole supply chain. Assuming global average food waste percentages (currently about 24%, see Kummu *et al* 2012), it corresponds to an average food consumption of 2280 kcal cap^{-1} d^{-1}.

GBW requirement of the reference food supply depends on plant water requirements and productivity, influenced by climate, soil moisture and crop management (table 1). The vegetal part of the GBW requirement per kcal of food produced was estimated by calculating the total amount of kcal produced in each FPU (simulated based on the 2400 kcal cap^{-1} d^{-1} target) and relating it to the total amount of GBW consumed. Following Rockström *et al* (2007), we assumed that compared to vegetal GBW requirement, an eightfold amount of water is required to produce the same amount of animal calories. This includes the water requirements from both grazing land as well as cropland for feed production (Gerten *et al* 2011). Finally, GBW scarcity was defined by the ratio of GBW availability and GBW requirement of the reference food supply, with values <1 indicating water scarcity.

2.3. Past development scenarios

To assess the drivers and mitigation measures of GBW scarcity, we create and compare three development scenarios, each using different sets of data to calculate GBW scarcity (table 2). To explore how FPUs have adapted to growing population, the scenarios focus on three variables that influence each FPU's level of GBW scarcity, namely BW availability, GW availability and GBW requirement of the reference food supply.

The 'No Development' scenario (NODEV) assumes no development in GBW availability or GBW requirement of the reference food supply since the beginning of the 20th century. The 'Dynamic Climate' scenario (CLIMBLUE) captures the effect of climate on BW, by taking the variability of BW availability into account. In the 'Agricultural Land Expansion' scenario (LANDEXP), the variability and trends of both BW and GW availability are taken into account, so in addition to climatic conditions this scenario also acknowledges changes in cropland extent and highlights their effect on GBW scarcity (climatic conditions also affect GW availability but their effect is minimal compared to land expansion). Finally, the 'Enhanced Agronomic Practices' scenario (AGROPRAC) acknowledges the trends and variability of both GBW availability and requirements of the reference food supply. The addition of GBW requirement trends mainly illustrates how changes in agronomic practices have influenced GBW scarcity. These include e.g. extension of irrigation infrastructure (data from Siebert *et al* 2015), changes in fertiliser and pesticide use and innovation in agricultural machinery and farming techniques. We took these into account by calibrating the crop management intensity in LPJmL

Table 2. Data used to create development scenarios. 'Dynamic' refers to the actual observed/modelled development of each variable while 'fixed' refers to conditions in the beginning of the 1900s. For blue water availability 'fixed' means 30 year average conditions over 1901–1930, and for green water availability and GBW requirements, 10 year averages over 1901–1910. See table 1 for principal drivers behind variables.

Scenario	Population (—)	Blue water availability ($m^3\ yr^{-1}$)	Green water availability ($m^3\ yr^{-1}$)	GBW requirements of reference food supply ($m^3\ cap^{-1}\ yr^{-1}$)	Explanation
NODEV	Dynamic	Fixed	Fixed	Fixed	No development in water availability or per cap GBW requirements
CLIMBLUE	Dynamic	Dynamic	Fixed	Fixed	Difference between CLIMBLUE and NODEV: effect of changing climate
LANDEXP	Dynamic	Dynamic	Dynamic	Fixed	Difference between LANDEXP and CLIMBLUE: effect of changing agricultural land extent
AGROPRAC	Dynamic	Dynamic	Dynamic	Dynamic	Difference between AGROPRAC and LANDEXP: effect of changing agronomic practices

so that modelled yields meet the observed (FAO 2015) and reconstructed (see supplementary data) yield data for historic periods.

3. Results

We first present results based on the comprehensive ACROPRAC scenario where each of the variables affecting GBW scarcity are dynamic (table 2). We then analyse the factors influencing GBW scarcity by comparing the four different development scenarios.

3.1. From isolated occurrences of GBW scarcity to a global phenomenon

Early in the 20th century, GBW scarcity occurred mainly in East and South Asia and Western Europe in the AGROPRAC scenario (figure 1; see also figures S2 and S3). Together with smaller GBW-scarce areas around the world, roughly 360 million people were affected, which at the time accounted for 21% of the world population (table 3). In subsequent decades population under GBW scarcity grew relatively slowly, amounting to 450 million (20%) in 1935. By 1965, however, this number had more than doubled, and 29% of the world population lived in FPUs that were under GBW scarcity, which by then had spread to new regions in e.g. Southeast Asia and Southern Africa (figures S2 and S3). In other words, roughly 990 million people lived in FPUs that did not have enough water resources to produce the reference food supply for their inhabitants—the remainder may have been imported by trade, or local food supply may actually have been less than 3000 kcal $cap^{-1}\ d^{-1}$ on average (see discussion). During the first half of the century, GBW scarcity was particularly severe in East and South Asia, where in many FPUs it occurred 75%–100% of years (figures 1(A) and (B)) and affected a large share of population (table 3).

During 1961–1990 GBW scarcity spread to new regions (figure 1(C)). Many FPUs in the Middle East and various parts of Africa were now experiencing GBW scarcity at least 50% of years. By 1985 the number of people under GBW scarcity had reached 1.5 billion (30%) (table 3). Much of this development can be explained by population growth that started to accelerate in most regions of the world after the 1960s. The effect of population on GBW scarcity can be clearly seen in e.g. the Middle East, where water scarcity skyrocketed around the time when population of the region passed the 100 million mark (figure S2(A)).

In the more recent decades (1990–2009), GBW scarcity became even more severe and widespread (figure 1(D)) and by 2005, was affecting already 34% of the 6.6 billion world population (table 3). Practically all of the Middle East and South Asia as well as various FPUs in Eastern, Western and Northern Africa were experiencing GBW scarcity 75%–100% of years (figure 1(D)). However, China for example, was somewhat less affected by GBW scarcity than in the previous time period, indicating effective response options, as shown in the next sections.

3.2. GBW availability—major increase in absolute terms but cuts in relative terms

Although GBW scarcity aggravated clearly during the last century, total GBW availability actually increased notably in most regions of the world (figure S6). Due to cropland expansion, global GW availability rose by 56% (figure S4(B)), and in some regions, e.g. South America and the Middle East, even doubled (figure S4 (A)). Western Europe is the only region where GW availability did not see a detectable increase.

While there was notable interannual variation in regional BW availability due to climatic and hydrologic conditions, we did not detect a clear trend in most regions (figure S4(A)). Some increase in BW availability could be detected in North America (10%) and Eastern Europe and Central Asia (15%). By contrast, GB availability decreased in East Asia by 19% and in Southern Africa, the Middle East and Northern Africa by 10%. These patterns could be partly explained by precipitation, as they match well with the

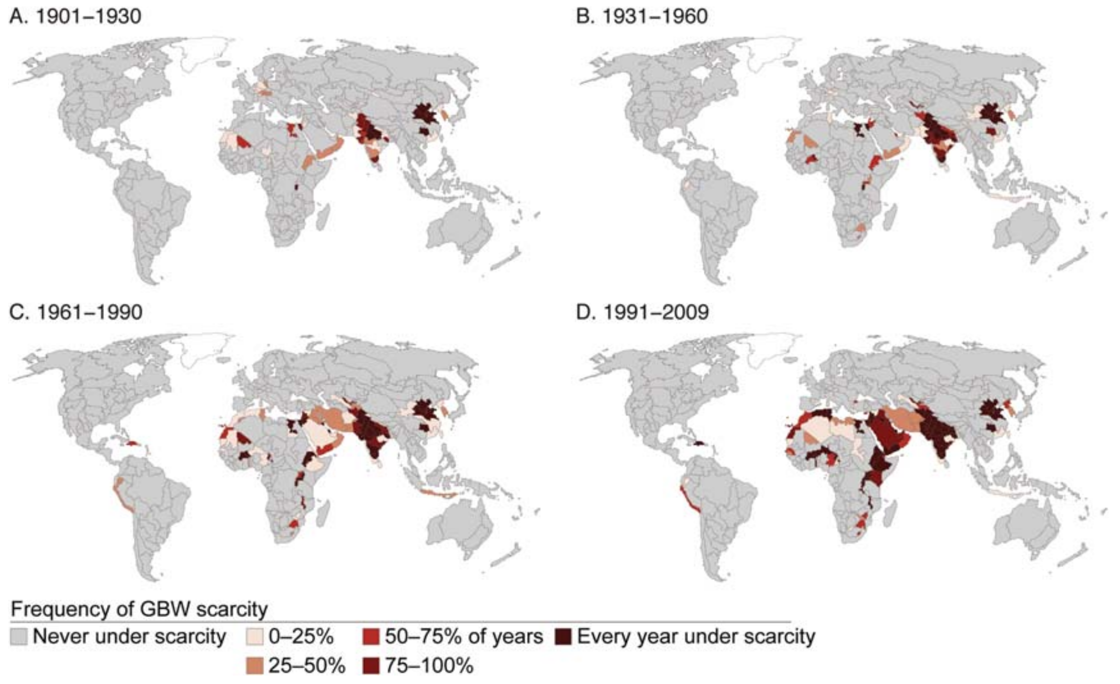

Figure 1. Frequency of years when FPUs are under GBW scarcity in the AGROPRAC scenario in 1901–1930 (A), 1931–1960 (B), 1961–1990 (C) and 1991–2009 (D).

Table 3. Regional and global population under GBW scarcity in the AGROPRAC scenario. Numbers are 5 year averages aggregated from FPU level results.

	Population under GBW scarcity (in millions)				
Region	1905	1935	1965	1985	2005
Australia and Pacific	—	—	—	—	—
Central America	—	—	2 (2%)	13 (10%)	19 (10%)
East Asia	170 (35%)	207 (34%)	342 (37%)	436 (34%)	546 (35%)
Eastern Europe and CA	—	3 (1%)	12 (4%)	24 (6%)	33 (9%)
Middle East	1 (2%)	3 (5%)	9 (9%)	88 (47%)	118 (42%)
North America	—	—	—	—	—
Northern Africa	1 (1%)	2 (3%)	4 (5%)	34 (26%)	74 (38%)
South America	—	—	2 (1%)	5 (2%)	17 (4%)
South Asia	158 (47%)	219 (56%)	505 (78%)	783 (76%)	1128 (75%)
Southeast Asia	—	1 (1%)	77 (30%)	4 (1%)	6 (1%)
Southern Africa	4 (4%)	8 (6%)	39 (16%)	100 (23%)	292 (39%)
Western Europe	28 (11%)	3 (1%)	—	—	—
WORLD	361 (21%)	447 (20%)	992 (29%)	1488 (30%)	2232 (34%)

observed changes in annual precipitation over 1951–2010 by the IPCC *et al* (2015).

Due to population growth (figure 2(A)), both blue and GW availability per capita decreased considerably in every region (figure 2(B)). At the end of the study period, global per capita BW availability was a third of what it was in the beginning, and in some regions the decline was as high as 80%. Global per capita GW availability decreased by about 60% during the study period, suggesting that cropland expansion and the consequential increase in GW availability was not able to keep up with population growth. This has lead to pressure to produce more food with less land and water resources—or to increase the import of food to many countries.

3.3. GBW requirements decreased worldwide

GBW requirement of producing the reference food supply decreased remarkably during the study period, particularly in the last 50–60 years. Global average requirements nearly halved since 1901 (figure S5(B)), indicating that by 2009 the same food supply could be produced with half of the water it took a century earlier. The steepest declines were found in East Asia (–69%), North America (–68%), Western Europe (–65%) and Southeast Asia (–61%) (figure S5(A)).

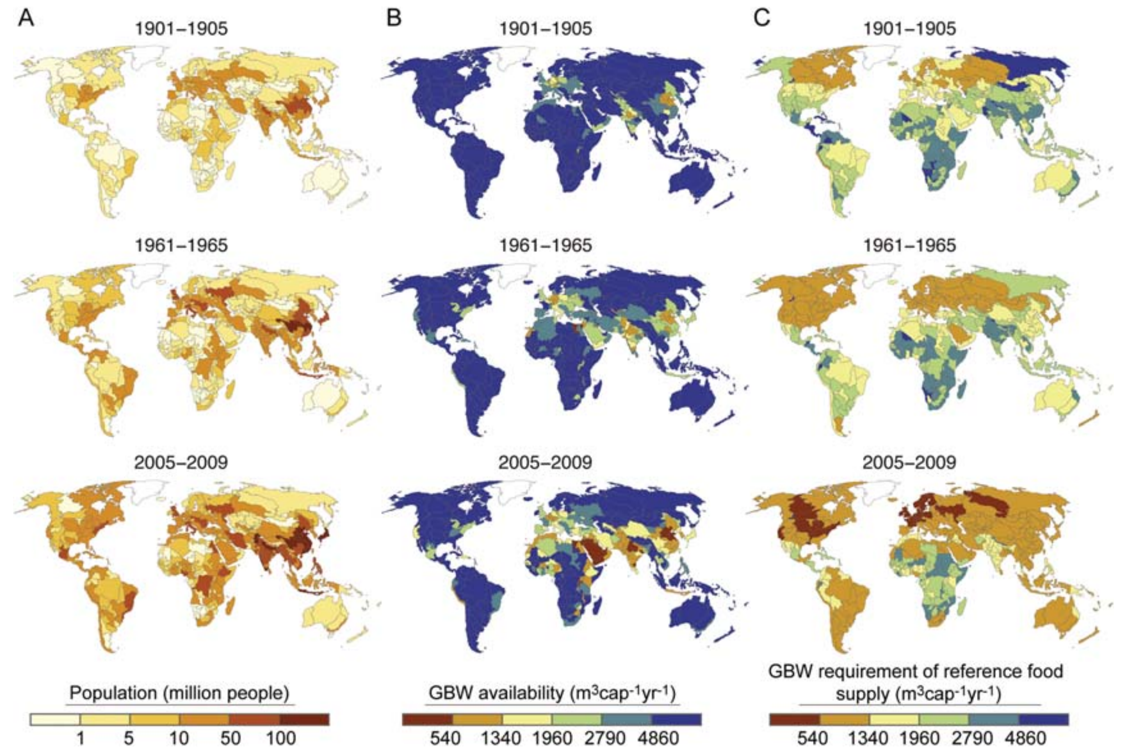

Figure 2. Population (A), GBW availability per capita (B) and GBW requirements per capita (C) mapped for three time steps. To minimise the effect of extreme years, numbers used are five year averages. See total GBW availability and GBW requirement maps in figure S5 of the supplement. Classification for GBW availability and requirement is based on the 2.5%, 25%, 50%, 75% and 97.5% quantiles of the GBW requirement data spanning 1901–2009.

However, improvements were below the global average in Northern Africa (–16%), Southern Africa (–28%) and Middle East (–35%).

To compare the development of GBW requirements in different parts of the world in more detail, we calculated the quartiles of the 109 year spanning GBW requirement data ($Q_1 = 1340\ \mathrm{m^3\ cap^{-1}\ yr^{-1}}$, $Q_2 = 1960\ \mathrm{m^3\ cap^{-1}\ yr^{-1}}$ and $Q_3 = 2790\ \mathrm{m^3\ cap^{-1}\ yr^{-1}}$). In the beginning of the 20th century, GBW requirement of the reference food supply was above the median value (Q_2, $1960\ \mathrm{m^3\ cap^{-1}\ yr^{-1}}$) in most FPUs (figure 3(C)). Until the 1950s, roughly 85% of world population lived in FPUs with GBW requirement $>Q_1$ (figure S2). By 2005–2009, however, larger areas with GBW requirement higher than the median could only be found in Africa, and the majority of FPUs, with roughly 60% of world population, was now within Q_1. However, most of India and areas in South and Central America were still behind the rest of the world (figure 3(C)). Throughout the study period GBW requirements were highest in Central and Southern Africa, Central America and South Asia.

As we will analyse in detail below, the clear declining trend of GBW requirements per capita can be explained by differences in climatic conditions and agronomic practices. The latter in particular have improved notably during the last century, including e.g. extension of irrigation infrastructure (Siebert *et al* 2015), increased use of synthetic fertilisers (Foley *et al* 2011), breeding of crop varieties (Tester and Langridge 2010), and modernisation of agricultural techniques (Matson *et al* 1997). The combination of these developments has increased crop yields in many regions of the world (see supplementary data). The fact that requirements remain high in Central America, South Asia and particularly in the African continent suggests that improvements in agricultural management have not reached their full potential there. Indeed, previous studies have found that many of these areas experience large yield gaps, where productivity is limited by agronomic practices, particularly water and nutrient management (Foley *et al* 2011, Mueller *et al* 2012).

3.4. Actions to ease GBW scarcity

To quantify the effect of different drivers of the past century on GBW scarcity, we compared the four scenarios described in Methods section and table 1. Without accounting for other drivers than population growth (NODEV scenario), GBW scarcity was quite severe already in 1965, particularly in parts of India, China and Egypt (figure 3(A)), affecting roughly 1.5 billion people (43%) (figure 4(B)). By 1985 this number over doubled (3.0 billion, 60%) and by 2005 tripled (4.3 billion, 66%). In 2005, practically the whole South Asia, coastal parts of East Asia and several

FPUs in the Middle East and Africa were under severe GBW scarcity (figure 3(A)).

When additionally taking the variability of BW availability into account in CLIMBLUE scenario, GBW scarcity rose quite drastically in arid areas of Northern Africa and Asia, by over 50% at worst, indicating a negative effect of climatic variation (figure 3(B)). By contrast, especially in northern latitudes, scarcity declined in CLIMBLUE compared to NODEV. In 1985 the same pattern was even stronger and more widespread, however, in 2005 declining BW availability aggravated GBW scarcity again mainly in arid regions (figure 3(B)). Although the pattern seen in figure 3(B) might suggest notable changes in GBW scarcity in some regions, the number of people affected differed very little between scenarios NODEV and CLIMBLUE—notably only in Western Europe—(figure 4(A)), suggesting that the changes observed occurred mainly in sparsely populated areas.

When taking into account GW availability in LANDEXP scenario, GBW scarcity decreased in most FPUs compared to CLIMBLUE (figure 3(C)), suggesting that cropland expansion has been one of the measures to address the increasing demands of growing population. Yet, the world population under GBW scarcity was only slightly lower in scenario LANDEXP compared to scenario CLIMBLUE (figure 4(B)). There were, however, regions where the influence of agricultural expansion was quite remarkable (figure 4(A)): in Central America around 1970–2000 and the Middle East starting in the 60s, expansion of cropland and grazing land lifted a considerable share of the population out of GBW scarcity.

Finally, changes in GBW requirement of the reference food supply, reflected in AGROPRAC scenario, had a notable effect on GBW scarcity worldwide (figure 3(E)). Already in 1965, GBW scarcity decreased in most FPUs compared to LANDEXP (figure 3(D)), and by 2005, food production potential more than doubled in a majority of FPUs (scarcity index change >100%). There were, however, some areas, particularly in Africa, where the effect of agronomic practices was a lot smaller, or in some FPUs even negative.

The number of people under GBW scarcity in the AGROPRAC scenario was considerably lower compared to the other three scenarios in nearly all regions and years (figure 4). Globally, the effect could be seen starting from the 1950s, and resulting in world population affected by GBW scarcity nearly halving by 2005 (figure 4(B)). The effect of enhanced agronomic practices was tremendous particularly in East Asia, where practically all of the region's population in 2005 (94%–99% depending on the scenario, roughly 1.5 billion) would have lived in FPUs affected by GBW scarcity if agronomic practices of around 1900 had been applied then (figure 4(A)). With modern agronomic practices, this number dropped to 35% (0.5 billion). Indeed, Chinese food production has developed rapidly since the 1950s, with e.g. wheat yields rising sixfold with increased irrigation and fertiliser use and adoption of improved crop varieties and modern technologies (Wang *et al* 2009).

4. Discussion

In this study, we analysed historical GBW scarcity in food production, with a particular focus on factors contributing to it and actions taken to alleviate it. Our spatially explicit analysis has been made possible with the recently published dataset of historical irrigation extent (Siebert *et al* 2015) and the historical yield reconstruction for the entire 20th century we performed for this study (see supplementary text S2). Existing studies on historical water scarcity are based on indices that generally do not account for GW (Kummu *et al* 2010, Wada *et al* 2011), despite its crucial role for food production (Liu *et al* 2009). By including GW into the analysis, we considerably extend the current knowledge of the development of water scarcity and its effect on food production. Moreover, our temporally and spatially explicit scenario analysis sheds light on the actions taken to ease scarcity, providing crucial understanding of the past development.

Our calculations indicate that GBW scarcity has increased notably during the last century, as the share of population living under GBW scarcity has risen from 21% (360 million) in 1905 to 34% (2.2 billion) in 2005 (table 3). GBW scarcity has spread to considerably large areas during the last few decades, and scarcity events have become more frequent (figure 1). Responses to GBW scarcity are evident: during the last century, agricultural land expansion has increased GW availability in most FPUs (figure 3(C) and S4), while improvements in agronomic practices have boosted the production and decreased the water requirement of producing food (figures 3(D) and S5). These measures have increased global food production immensely, which on the one hand has eased GBW scarcity in areas where it occurs, and on the other hand has made the population explosion of the last century possible. The importance of enhanced agronomic practices is particularly striking: applying the agronomic practices of the early 1900s today would almost double the global population under GBW scarcity and worsen the situation for many more.

4.1. Securing food supplies under GBW scarcity

Our analysis measures the potential of reaching FPU-internal food self-sufficiency. Currently, global food trade is crucially important for ensuring sufficient food supplies (D'Odorico and Rulli 2013, MacDonald 2013, Porkka *et al* 2013, D'Odorico *et al* 2014), and previous research suggests that many areas with water and land constraints in particular have needed to turn to imports as one of their main sources for food

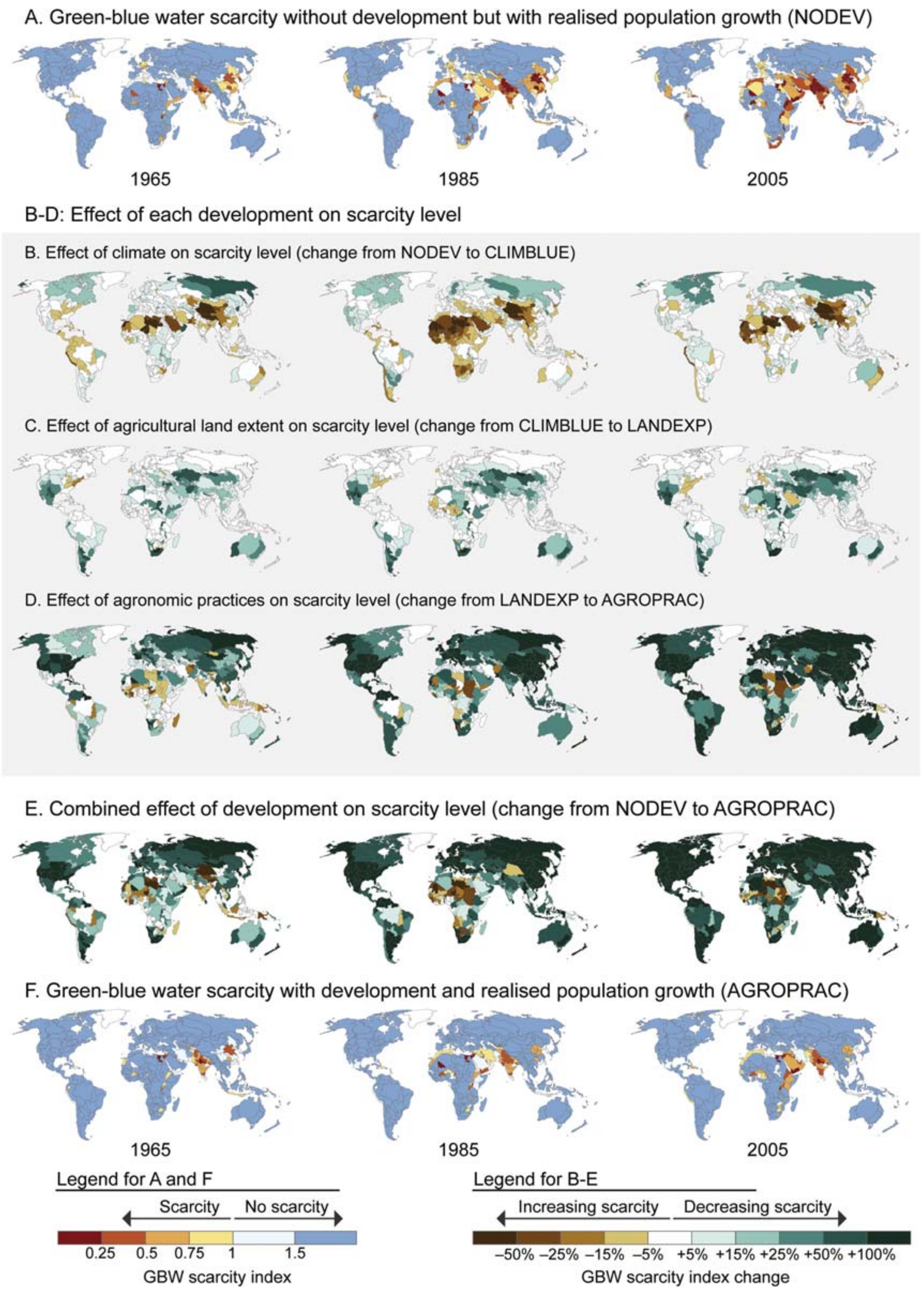

Figure 3. GBW scarcity in NODEV (A), effect of drivers on GBW scarcity level (B)–(E) and GBW scarcity in AGROPRAC (F). See description of the scenarios in table 2. As much of the development affecting GBW scarcity, such as population growth and technological advancements, have taken place during the latter half of the century, results are presented here at three time steps in 1965, 1985 and 2005.

(Islam *et al* 2006; e.g. Fader *et al* 2013). To see whether the trends and patterns we observed support these findings, we compare our results to those in a study by Porkka *et al* (2013) who analyse global food availability, food self-sufficiency and food trade during 1965–2005. Porkka *et al* (2013) consider sufficient food supply to be 2500 kcal $\text{cap}^{-1}\,\text{d}^{-1}$, which after taking distribution and consumption waste into account, corresponds to average food consumption of about 2300 kcal $\text{cap}^{-1}\,\text{d}^{-1}$—the same as implied in

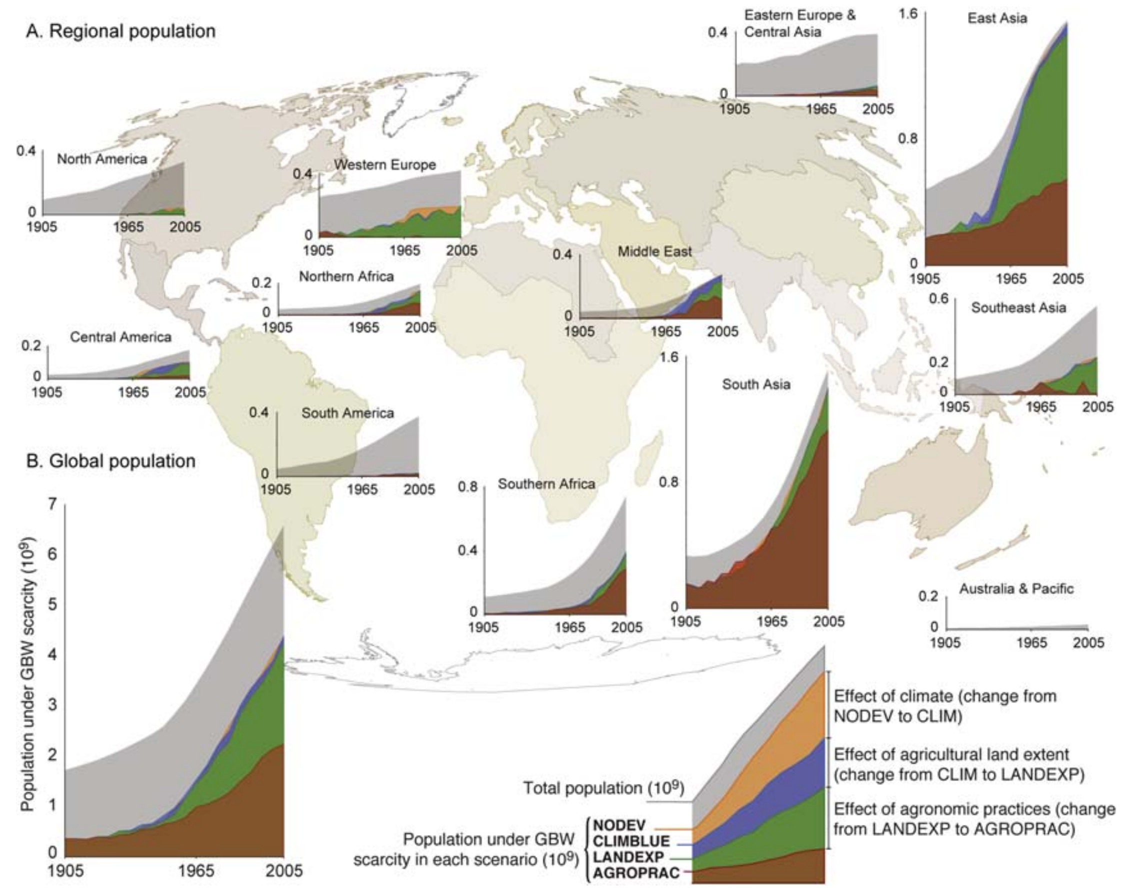

Figure 4. Regional (A) and global (B) population under GBW scarcity in different scenarios during 1905–2005. To minimise the effect of extreme years, five year average populations are used. The areas of different colours show the effect that moving from one scenario to another has on the number of people experiencing GBW scarcity. Regional and global results are based on aggregation of FPU level results. See description of the scenarios in table 1.

our food production target of 3000 kcal cap^{-1} d^{-1} after losses along the whole food supply chain (see methods).

In Northern Africa and Middle East, food imports started to increase in the 1960s (see figure 3(C) in Porkka *et al* 2013)—around the same time that GBW scarcity started to spread (figure S3) and affect more people in the region according to our findings (figure 1). China—where some areas were/are under severe GBW scarcity—has been a net food importer throughout the latter half of the last century. Particularly in recent decades, these three regions have been able to compensate their low food production potential (relative to population) with imports (Liu *et al* 2007, Yang *et al* 2007), resulting in sufficient or even high food supply (figure 3(A) in Porkka *et al* 2013). However, in South Asia where GBW scarcity affects three quarters of the population (table 3), imports have not been enough to secure food supplies, which have been insufficient through 1965–2005 (figure 3(A) in Porkka *et al* 2013). Securing food supplies with imports requires a sufficiently strong economy (de Fraiture and Wichelns 2010, Porkka *et al* 2013), which might explain these differences between regions. Interestingly, in Sub-Saharan Africa there are areas where we detect no GBW scarcity, yet Porkka *et al* (2013) find that local food production is insufficient and the production gap is not compensated by imports (figure 3 in Porkka *et al* 2013). Lack of sufficient imports is likely to be an economic issue, but insufficient food production despite no occurrences of GBW scarcity suggests that in these areas the relatively low food production may be linked to other factors than biophysical constraints, such as conflicts, poverty or the widespread HIV pandemic affecting labour force (Clover 2003).

4.2. Importance of GW for water scarcity

Previous studies on historical water scarcity (Kummu *et al* 2010, 2016, Wada *et al* 2011) have focused on BW resources and their sufficiency. To examine the importance of GW for water scarcity, we compare our results (figure S3) with BW scarcity maps presented in Kummu *et al* 2016 and Wada *et al* (2011). This comparison reveals that BW scarcity has been much more widespread than GBW scarcity throughout the last century. This is evident particularly in parts of Middle East until the 1990’s, Western United States, South-Eastern Australia, areas in Central Asia and African FPUs in the Sahara and Western Africa, where according to our results, food production potential was sufficient despite BW scarcity (see figure 3 in Kummu *et al* 2016; figure 8 in Wada *et al* 2011 and figure S3 in this study). This illustrates the importance of GW for food production stated before (Rost *et al* 2008, Liu *et al* 2009, Rockström *et al* 2009). However in some areas, such as the Western US and South-Eastern Australia, BW stress observed in Kummu *et al* (2016) and Wada *et al* (2011) is likely due to high agricultural production aimed for exports. Although hypothetically there might be enough water for local people, the BW stress index applied in these studies considers actual water use, and thus captures the excessive irrigation water use.

Despite the importance of GW, increasing its availability through agricultural land expansion is no longer a viable option for alleviating the aggravating GBW scarcity in food production (Foley *et al* 2011, Steffen *et al* 2015). Based on our simple criteria, most GBW scarce FPUs have passed the level of sustainable agricultural land extent (see description in methods), and for example in parts of Western Africa, China and India, agricultural land had exceeded these limits multifold already in the early 20th century (see figure S7 (B)). It should be noted that our analysis leaves out any GW available on agricultural land beyond the limits of sustainability, and these restrictions may somewhat overestimate the actual experienced GBW limitations in these regions. The only GBW scarce areas where agricultural land extent is still within the limits of sustainability are located in regions such as Northern Africa and the Middle East, where both BW availability and suitable agricultural land are limiting the expansion of agriculture (Fader *et al* 2013). Alarmingly, agricultural land has expanded far beyond the limits of sustainability also in many areas that do not experience GBW scarcity, such as the tropical regions of South America and Southeast Asia (figure S7), likely due to food exports and cultivation of non-food crops (Sodhi *et al* 2004, Martinelli *et al* 2010, Gauder *et al* 2011). In 2009, for example, Indonesia, Malaysia and Thailand were the top three producers of both palm oil and rubber, and Brazil was among the largest exporters of agricultural products (FAO 2015).

4.3. Future research directions

We used FPUs as our analysis unit, as they represent a scale at which food production and water resources are assumed to be managed. The choice of areal unit of analysis inherently has an effect on the results (Vörösmarty 2000, Salmivaara *et al* 2015). Particularly in global studies, such as this one, finding a single, suitable analysis unit is difficult. For example, in some parts of the world much of food is still produced and consumed locally, while in others, food is transported from further away. This division is highlighted in the case of large cities, where using a high spatial resolution could result in misleading conclusions about water scarcity (McDonald *et al* 2014). Therefore, future assessments of water scarcity would benefit from exploring other possible units of analysis and their effect on assessment results.

In this paper we used simple criteria to limit GW and BW available for agriculture to account for environmental requirements (see methods). In many cases the actual land (e.g. India, see figure S7) and water use (e.g. the Middle East, see Wada *et al* 2011) have passed these limits a long time ago. Therefore, it can be argued that using these limits gives an unrealistic picture of the actual, experienced GBW scarcity in food production. Nevertheless, we argue that the unsustainable use of resources cannot be neglected, and therefore in this paper chose to examine the potential of FPUs to *sustainably* feed their population. However, in future studies the criteria for sustainability could be looked into in more detail, to better take into account local conditions.

Due to data limitations, our analysis assumes the same reference food supply throughout the study period and across the globe with a fixed food waste percentage and share of animal products. In reality, dietary energy requirements, food losses and animal food consumption vary somewhat from one FPU to another. To examine the effect the target supply and diet have on our GBW scarcity analysis, we calculated two additional examples using different reference food supplies (see supplementary text S3 with table S1). We found that the trends of population under GBW scarcity are very similar between all reference food supplies. However, particularly the share of animal products in the reference diet has a visible effect on the number of people experiencing GBW scarcity. Future assessments would therefore benefit from using a more locally specific reference supply and diet that also accounts for differences in energy requirements.

This paper scratched the surface of the implications of GBW scarcity and food production potential for food security. Global food supply is increasingly interlinked through international trade, which has improved food security in many countries (Porkka *et al* 2013, D'Odorico *et al* 2014). However, a food supply based on international trade is extremely sensitive to shocks in the system, as was seen for example in 2010, when agricultural failures in some producer countries resulted in export bans, which came at the expense of countries dependent on food trade (Fader *et al* 2013, Suweis *et al* 2015). We therefore argue that both potential for local food production and food trade are essential for the stability and resilience of food supply. Thus, we strongly encourage linking our approach with future studies assessing food security and particularly the resilience of food systems in different parts of the world.

5. Concluding remarks

In this letter we explored the trends and causes of GBW scarcity in food production over 1901–2009. Specifically, we examined the effect hydroclimatic variability, agricultural land extent and developing agronomic practices have had on FPUs' potential for food self-sufficiency. We found that GBW scarcity has increased considerably over the past century, and currently roughly a third of the world population lives in areas that experience GBW scarcity. While growing population has been a strong driver of the increasing relative resource scarcity, agricultural land expansion and especially improving agronomic practices have increased local food production potential in most FPUs. Without these developments, a much larger share of the current population would experience GBW scarcity.

World population will continue to grow in the future, and much of that growth is expected in regions that already struggle to feed their population. While cropland expansion is not anymore feasible in most parts of the world, efforts to tackle resource scarcity in food production should concentrate on more efficient use of land and water resources. Crop yields have increased tremendously particularly during the latter half of the 20th century, but our findings indicate that there are still regions where food production potential could be improved by focusing on better management and resource use efficiency. Such efforts could focus e.g. on improving irrigation systems, which has a significant water savings potential (Jägermeyr *et al* 2015). Moreover, reducing food waste (Kummu *et al* 2012) and eating less animal based food (Jalava *et al* 2014) have a potential to increase food supplies considerably without increasing the use of resources. In addition to focusing on local food self-sufficiency, it is likely that agricultural trade will continue to play a key role in food security around the world. Efforts should therefore also be put on improving global trade policies to create a more just and sustainable global food system.

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