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Past and present biophysical redundancy of countries as a buffer to changes in food supply

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Past and present biophysical redundancy of countries as a buffer to changes in food supply

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Abstract

Spatially diverse trends in population growth, climate change, industrialization, urbanization and economic development are expected to change future food supply and demand. These changes may affect the suitability of land for food production, implying elevated risks especially for resource-constrained, food-importing countries. We present the evolution of biophysical redundancy for agricultural production at country level, from 1992 to 2012. Biophysical redundancy, defined as unused biotic and abiotic environmental resources, is represented by the potential food production of 'spare land', available water resources (i.e., not already used for human activities), as well as production increases through yield gap closure on cultivated areas and potential agricultural areas. In 2012, the biophysical redundancy of 75 (48) countries, mainly in North Africa, Western Europe, the Middle East and Asia, was insufficient to produce the caloric nutritional needs for at least 50% (25%) of their population during a year. Biophysical redundancy has decreased in the last two decades in 102 out of 155 countries, 11 of these went from high to limited redundancy, and nine of these from limited to very low redundancy. Although the variability of the drivers of change across different countries is high, improvements in yield and population growth have a clear impact on the decreases of redundancy towards the very low redundancy category. We took a more detailed look at countries classified as 'Low Income Economies (LIEs)' since they are particularly vulnerable to domestic or external food supply changes, due to their limited capacity to offset for food supply decreases with higher purchasing power on the international market. Currently, nine LIEs have limited or very low biophysical redundancy. Many of these showed a decrease in redundancy over the last two decades, which is not always linked with improvements in per capita food availability.

1. Introduction

Spatially diverse trends in population growth, climate change, industrialization, urbanization and economic development are expected to change future agricultural practices, as well as food supply and demand. This will also have an effect on the international flows of agricultural products, opening new opportunities

for agribusiness, but potentially implying risks for resource-constrained, food-importing countries (Fader *et al* 2013, D'Odorico and Rulli 2013, Rulli and D'Odorico 2014). In this dynamic context, it is important to understand to what degree countries are resilient to long-term changes in food supply, whether they originated domestically or through changes in international trade, stocks, and prices. Resilience in this case can be defined as the capacity of a system to absorb shocks or changes without losing its essential characteristics (Weichselgartner and Kelman 2015). Hence, from the perspective of national food security, resilience is the capacity to adapt to changing conditions to maintain adequate food supply. Changes in food supply, as mentioned above, might originate domestically, for example by reduction in domestic production due to climate trends, large-scale pollution events, soil degradation, etc. Alternatively, they can be connected to changes in the international market of agricultural goods, for example due to export bans in large exporters, long-term changes in commodity prices, and new preferences of trade partners (Jones and Hiller 2015).

In many systems where system reliability is important, redundancy of components or resources is considered a key element of resilience. In ecology, stability and productivity of ecosystems is linked to diversity, as it provides redundancy in ecological functions (Walker 1992), an effect often termed the 'insurance hypothesis' (Naem and Li 1997). In this study we focus on stand-by redundancy, which refers to the case when extra components are idle and will be taken into the process if the principal component fails. For example, in hospitals, power generators are normally installed and kept in stand-by in addition to the normal power source (Horwitz 2000). Hence, in the case of food supply, we might consider which redundancies exist in the critical resources for food production, and how these redundancies confer resilience.

Focusing only on the biophysics of food production, the critical resources are the availability of unused water and fertile land as well as the possibility of increasing agricultural productivity (i.e. increasing the rate of outputs per unit of input). This study addresses the evolution of national and global biophysical redundancy by analysing how many additional calories countries could have produced with their unused water, land and unexploited productivity potentials from 1992 to 2012. This period is the longest continuous time for which data exists with consistent political units (after the last decolonization processes and the Perestroika) and consistent data reporting methodology (the FAO applied new methodologies concerning missing data from 1990 onwards). We assume here that countries with large yield gaps and substantial amounts of renewable water resources and unused fertile land have higher redundancy and, thus, are biophysically more resilient to long-term changes. Note that we focus on national

biophysical redundancy, i.e. the biotic and abiotic environmental conditions for potential crop development. Hence, socio-economic factors affecting food security and depending on biophysical conditions of other countries, most notably food availability through imports, are not taken into account.

Many authors have analyzed subcomponents of biophysical redundancy as defined in this study. In a review of different methodologies, Lobell *et al* (2009) found that the difference between potential and actual yields averaged 20% for irrigated agriculture and 50% for rainfed agriculture. A very recent estimate shows even higher numbers with 24% for irrigated land and 80% for rainfed agriculture (Pradhan *et al* 2015). And even after eliminating fertilizer overuse, yield increases of 30% seem to be realistic for some major cereals (Mueller *et al* 2011).

Eitelberg *et al* (2015) offer a detailed review and comparison of different estimates of spare land, showing a wide range of 2–3580 Mha. Differences are due not only to varying consideration of biophysical factors but also in the various criteria of what type of land should be excluded from agricultural use (Eitelberg *et al* 2015). This is an important point for sustainability, since there is vast evidence about the negative consequences arising from conversion of natural ecosystems to agricultural land, including greenhouse gas emissions, biodiversity loss, alteration of the water cycle, and increased erosion (Laurance *et al* 2014). Assessments of spare land normally lack estimates about the potential food production of those areas, with the global agro-ecological zones (GAEZ) approach presenting a prominent exception. This approach quantifies land suitability for different crops and various levels of inputs coming to a global land suitability of about 3457 Mha, for mixed inputs under rainfed and/or irrigation conditions (very suitable, suitable and moderately suitable land, Fischer *et al* 2002).

Assessments on water availability have made important advances in recent years, pointing to declining groundwater tables (Wada *et al* 2010) and recognizing the predominant role of green water in food production and water scarcity mitigation (Rockström *et al* 2009a, Fader *et al* 2011). For example, 83% of humanity's water consumption comes from green water use (Fader *et al* 2011). Other important points recognized in recent years were the necessity of considering water for environmental flow requirements (Gerten *et al* 2013) and the strong influence of dam construction and water withdrawal on the water cycle, especially in some parts of Asia and the United States (Haddeland *et al* 2014). Very few assessments have integrated water, land and productivity potentials. Foley *et al* (2011) assessed solutions for increasing food production and came to the conclusion that closing yield gaps, increasing water and land use efficiency, shifting diets and reducing waste could double food production. However, they did not detail the

redundancy of biophysical resources connected to these solutions. Steffen *et al* (2015) defines boundaries for freshwater use and land-system change, indicating that humans have used tropical forests in Asia and Africa as well as freshwater in some regions of the Mediterranean, North America and the Middle East beyond their safe thresholds. They did not consider any potential productivity increases. Fader *et al* (2013) integrates water and land availabilities with model-based potentials for productivity increases to point out that some countries will need to increase imports to support their future population. However their study focused on future scenarios and did not include the past evolution of the resource availabilities and pro-ductivity increases.

The present study contributes to this research agenda, filling some of the identified gaps by pursuing the following objectives:

(1) Quantifying the potential food production of available land and water resources for each country from 1992 to 2012. While doing so, we assess the influence of conservation measures (maintenance of environmental flow requirements and protec-tion of pristine natural areas), the potential water constrains due to high precipitation variability, and the sensitivity of the land availability quantifica-tions connected to the consideration or disregard of managed grasslands.

(2) Quantifying the changes in national yield gap closure during the last two decades and computing the potential additional food production from its closure.

(3) Assessing the uncertainty of the potential produc-tion of unused areas using different productivity assumptions.

(4) Demonstrating the resulting biophysical redun-dancy (i.e. the interplay of water, land and produc-tivity redundancy) for each country over the last two decades.

2. Methods

In order to assess the potential food production with unused (i.e. available or redundant) resources and through yield gap closure, we assessed six water redundancy scenarios, six land redundancy scenarios, and four yield gap closure scenarios that we call here 'productivity redundancy scenarios'. Analysing differ-ent scenarios is necessary for two reasons. First, it is unclear what the real availability of water and land resources was and is, and what part of it should be considered as 'available', 'unused' or 'accessible to agriculture'. Second, it is uncertain how productive those resources would be if they were used for agriculture. In the sections 2.1–2.3 we will shortly explain the different land, water and productivity

scenarios, the details of which can be found in the sections A.1.1–A.1.4 and tables A.1–A.3 of the SI.

The potential food production from the water, land and productivity scenarios was then divided by population and normalized by the standard caloric nutritional needs per person (see section 2.4). Differ-ent land, water and productivity redundancy scenarios were combined to yield three scenarios of biophysical redundancy (see section 2.5).

2.1. Production potential with available water resources

The potential agricultural production with available renewable water resources (WA) was calculated at the national level using six combinations of water avail-ability, water productivity and water reserves for environmental flow requirements (table A.1, equation (A.1)). Using the AQUASTAT database (FAO 2015b), we subtracted the total water withdrawal as sum of municipal, agricultural and industrial withdrawal—(TWW) from the total actual renewable water resources of each country (TARWR). TARWR includes internal and external (coming from other countries) surface and groundwater resources. In some scenarios we additionally subtracted the amount of water reserved for environmental requirements (EFR) and the water that is difficult to access due to high variability of precipitations (S). EFR was repre-sented as either 36% or 57% (Gerten *et al* 2013) of TARWR. For S we calculated two scenarios, the first one assuming that the variability of precipitation, including concentration of rainfall in one season, has no influence for water accessibility. Thus, water availability was not reduced in this scenario. In the second one, this term has values of 10%, 20% or 30% of (TARWR–TWW) depending on the average seaso-nal precipitation variability of the country. This means that in this scenario we assume that, in regions with highly variable precipitation, water is more difficult to store, manage and access, and water availability is accordingly reduced by 10%, 20% or 30% depending on the coefficient of variation (see section A.1.1 of the SI for more details).

The resulting water availability (in m^3) was then multiplied by the area-weighted (rainfed and irrigated) water productivity (WP in kcal m^{-3}) in the country for each year as simulated by the agro-ecosystem model LPJmL (Bondeau *et al* 2007, Rost *et al* 2008, Fader *et al* 2010, 2015, Schaphoff *et al* 2013, Waha *et al* 2013) for the main groups of crops worldwide. This yields the potential caloric production with available water resources. In order to account for the possibility that WP of unused areas is lower than in cultivated areas, we also calculated an alternative scenarios assuming that WP is 30% lower (see section A.1.1 of the SI for more details).

2.2. Production potential of available land resources

The potential agricultural production of fertile, spare land (LA) was calculated at national level using six combinations of land available and agricultural productivity associated with it (table A.2, equation (A.2)). From the total area of the country (TA) we subtracted unsuitable land (NS) and land estimated for settlements and infrastructure (NAG). TA, NS and NAG were extracted from the GAEZ (Fischer *et al* 2002). The result represents the extent of very suitable, suitable, moderately suitable and marginally suitable land, taking into account climate, soil, elevation and terrain constraints. We then subtracted the agricultural area (LU) from HYDE 3.2 (Klein Goldewijk, personal communication, 2015). We calculated two scenarios, one with LU including only cropland (i.e. not comprising managed grasslands), and one with LU including cropland and managed grasslands (see more details in section A.1.2 of the SI).

In some scenarios we additionally exclude protected areas (IUCN classes I and II, from UNEP-WCMC (United Nations Environment Program-World Conservation Monitoring Centre) 2007) and areas worthy of protection (the union of Greenpeace's Intact forest landscapes and WRI's frontier forest, see Greenpeace International 2005, and Bryant *et al* 1997).

The resulting land availability (in ha) was multiplied by the average yield of the country ($\bar{Y}$ in t ha^{-1}) reported by FAOSTAT (2015). This yields the potential caloric production with available water resources. In order to account for the possibility that actual yields are lower on unused areas, we also calculated an alternative scenarios assuming that $\bar{Y}$ is 30% lower (see more details in section A.1.2 of the SI).

2.3. Yield gap closure on used and spare land

Potential calorie production due to productivity increases on cultivated areas (YG) was calculated by the difference between potential and actual yields, divided by the number of crops grown in a country, and multiplied by the harvested area (see equation (A.3) and section A.1.3).

Potential productivity increases on unused areas (YG_E) were calculated by multiplying spare land (see section 2.2) by the difference between potential and actual yields (section A.1.4 and equation (A.4)).

Actual yields and harvested area were taken from FAOSTAT (2015), potential yields from Mueller *et al* (2011). Mueller *et al* (2011) estimated potential yields by using data from other regions with similar precipitation and growing degree day characteristics (i.e. comparable climatic conditions). In some scenarios we assumed potential yields to be as high as on used areas (and thus equal to the values in Mueller *et al* 2011). In other scenarios we assumed them to decrease as a function of actual yields, i.e. potential yields are lowered by 30% of actual yields. The assumption in the latter case is that countries with

Table 1. Scaling and classification of water, land and yield gap results.

Redundancy to produce calories for … % of population	Scaled values	Label for land, water, productivity and biophysical redundancy
<0[*]	0.001	Very low redundancy
0–25	0.002–0.25	Very low redundancy
25–50	0.25–0.5	Limited redundancy
50–100	0.5–1.0	High redundancy
>100	1.0	High redundancy

[*] Values can be lower than zero when countries exploit marginal land, use areas worth of protection or water needed by aquatic ecosystems in the sustainable scenarios, have higher yields than the potential yields or exploit fossil groundwater aquifers.

high actual yields are already using the most productive areas, while countries with low actual yields might have high productive areas as part of their spare land (see table A.3 for more details on the yield gap scenarios).

2.4. Scaling and classification

The resulting potential food production from the former sections was divided by population numbers from FAO (2015a). The results were then divided by the amount of food production need per capita for one year (3000 kcal cap^{-1} d^{-1} including food waste; see Rockström *et al* 2009a, Kummu *et al* 2012, FAO 2012).

To summarize our data, we use the following classification: countries that have redundant resources for producing the caloric nutritional needs for at least 50% of its population for one full year were considered to have *high water, land or productivity redundancy* (see table 1). Countries with values between 25% and 50% were considered to have *limited water, land or productivity redundancy*. And countries that have redundant resources for producing the caloric nutritional needs for less than 25% of its population have *very low water, land or productivity redundancy*. Note that this refers to potential calories production *in addition* to current production.

2.5. Biophysical redundancy

We quantified the overall biophysical redundancy in three scenarios (R_{low}, R_{middle}, R_{high}) that combine different scenarios of the scaled values of LA, WA, YG and YG_E (see tables 1 and 2).

All three scenarios follow the calculation scheme of equation (1):

$$R_x = \frac{\min(\text{LA}, \ \text{WA}) + \text{YG} + \text{YG\_E}}{nInd}, \qquad (1)$$

where *nInd* is the number of terms in the nominator of the equation for which there is data in the different datasets and scenarios used. For countries with a full set of data *nInd* is equal to 3.

The minimum values of LA and WA were taken under the assumption that water and land are

Table 2. Characteristics of biophysical redundancy scenarios. PYM = Potential yields as in Mueller *et al* (2011).

Biophysical redundancy scenario	Reserves for environ-mental flow require-ments (% of RWR subtracted)	Water productivity on unused areas (% of productivity on used areas)	Inaccessibility of water due to precipitation seasonality (% of RWR subtracted)	Protected areas and areas worth of pro-tection banned for agriculture?	Managed grasslands included in spare land?	Potential yields on used areas	Actual yield on unused areas (% of actual yield on used areas)	Potential yield on unused areas	Combination of scenarios (see table A.1–A.3 of the SI)
R_{low}	57	70	10–30	Yes	No	PYM	100	PYM	Land: SUS_NORM_GR Water: SUS43_LOW_CV Yield gap on used areas: NORM Yield gap on unused areas: SUS_NORM
R_{middle}	36	70	10–30	Yes	Yes	PYM	70	PYM minus 30% of actual yields	Land: SUS_LOW_NGR Water: SUS64_LOW_CV Yield gap on used areas: NORM Yield gap on unused areas: SUS_LOW
R_{high}	0	100	0	No	Yes	PYM	100	PYM	Land: NOTSUS_NORM_NGR Water: NOTSUS_NORM_NOCV Yield gap on used areas: NOTSUS_NORM Yield gap on unused areas: NOTSUS

complementary factors, i.e. the lack of one of them would render the presence of the other one useless in terms of potential food production.

The R_{low} scenario is designed to represent very constrained redundancy for all countries: managed grasslands are considered as used and thus not available, protected areas and areas worth of protection are assumed to be not available for agricultural production. Moreover, precipitation and seasonality of precipitation are assumed to reduce accessibility of water resources by 10%–30% (depending on the variation coefficient of precipitation) and environmental flow requirements are assumed to be high and met by every country. Additionally, water productivity on unused areas is assumed to be lower than on used areas (see table 2).

On the other end, the R_{high} scenario is meant to represent the least constrained redundancy: managed grasslands are considered available, protected areas and areas worth of protection are assumed to be available for production, potential yields of unused areas are considered to be as high as in used areas, precipitation and seasonality of precipitation are assumed not to affect the accessibility of water resources, water productivity on unused areas is assumed to be as high as on used areas, and no water is reserved for environmental flow requirements.

Finally, R_{middle} represents a scenario in the middle of the range: managed grasslands are considered available, protected areas and areas worthy of protection are assumed to be unavailable for agricultural production, spare areas are considered to be 30% less productive than used areas, potential yields are assumed to be lower on unused areas than on used areas, precipitation and seasonality of precipitation are assumed to reduce accessibility of water resources by 10%–30% (depending on the variation coefficient of precipitation), environmental flow requirements are assumed to be lower than in R_{low} but they are assumed to be met.

Results shown in the next sections correspond to the R_{middle} scenario, with a discussion on the differences between R_{low}, R_{middle} and R_{high} in section 3.4.

3. Results

3.1. Current interplay of water, land and productivity redundancy

Figure 1 shows water, land and productivity redundancies, and the combined biophysical redundancy for the year 2012. Overall redundancy changes across different geographical areas affected by the different specific characteristics. In Asia redundancy ranges from limited to very low (figure 1(e)), with very low productivity redundancy being a major factor in South East Asia. In the Middle East very low water redundancy has a strong impact instead. Europe is

particularly affected by limited productivity redundancy. Some American countries have very low biophysical redundancy due to both very low productivity and land redundancy. The African and South American tropics have mostly high overall redundancy due to high land, water and productivity redundancy on spare land. This is notable since in the medium scenario (R_{middle}) protected areas and areas worth of protection are considered unavailable for food production.
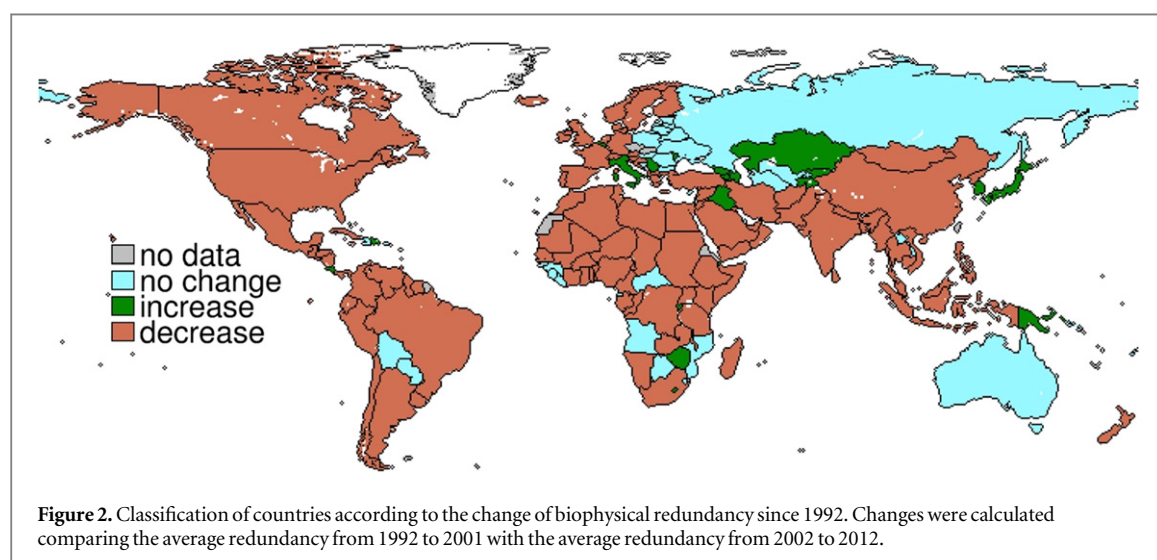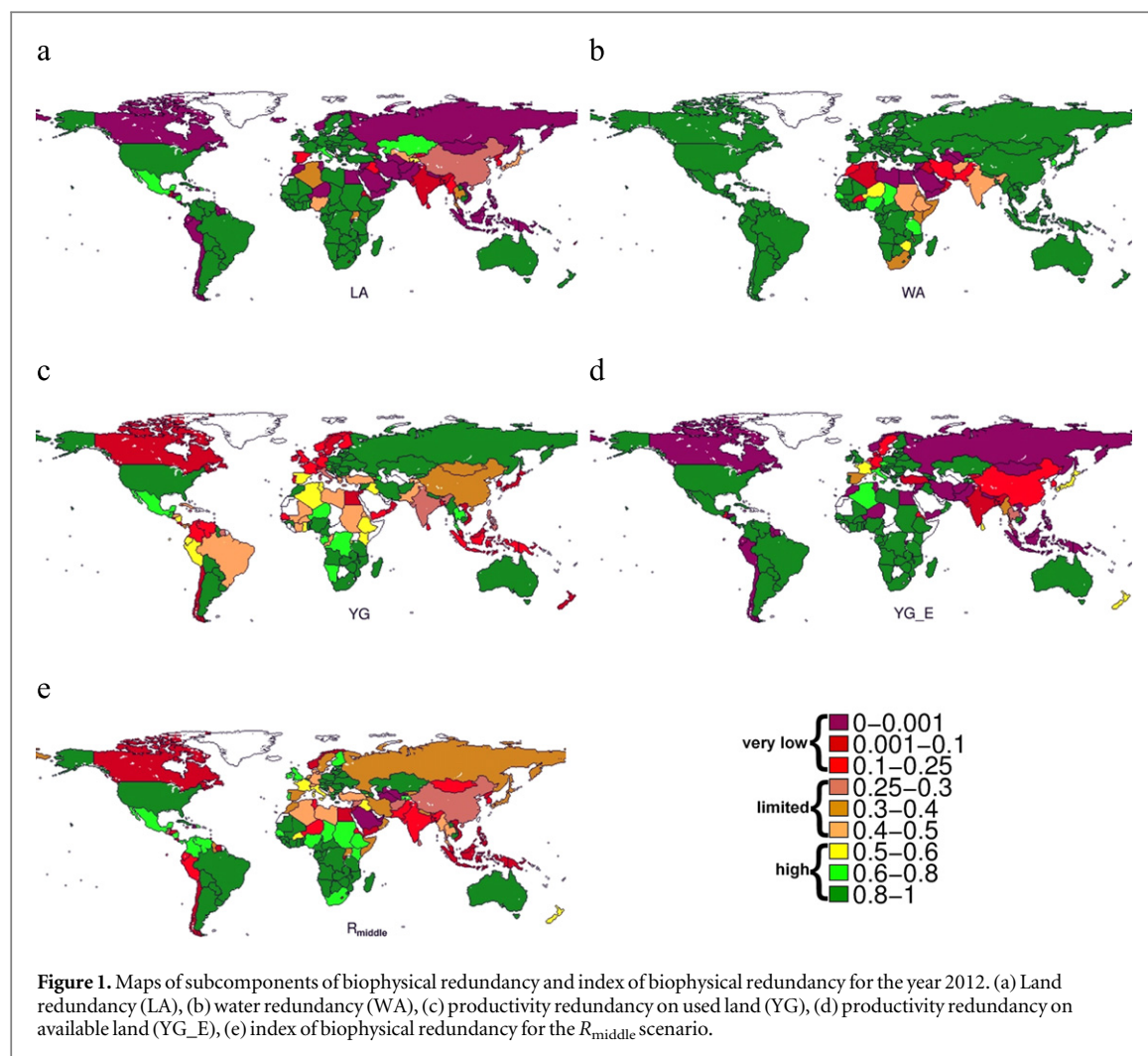
Overall there are 75 (48) countries that could not feed at least 50% (25%) of their population during a year with *redundant* resources (figure 1(e)). Those 75 countries are home to 4.8 billion people or around 70% of the world population.

3.2. Changes from 1992 to 2012

Biophysical redundancy has decreased over the last two decades in most countries (figure 2). Most of the exceptions to this pattern are former Soviet Union countries, where large agricultural areas were abandoned after the end of the Cold War.

Not all decreases in biophysical redundancy are linked with category changes, i.e. changes in the redundancy classes. Figure 3 shows only countries with time series that have sustained negative trends in biophysical redundancy and underwent category changes. While eleven countries, many of them in Europe, have made a transition from high to limited biophysical redundancy (figure 3(A)), nine other countries, most in Asia and South America, went from limited to very low biophysical redundancy (figure 3(B)).

These changes are caused by the change in the drivers that affect the subcomponents of redundancy (see equation (A.1)–(A.4)). The role of yield improvement is especially complicated because it diminishes the yield gap, and thus, the productivity redundancy. At the same time, it increases the potential production of food on spare land, which is also true for an improvement in water productivities. Figure 4 offers a more detailed look into the drivers of redundancy change for some selected countries with changes in categories towards very low redundancy. In all cases population growth was an important factor. Additionally, Vietnam, Ecuador, Mongolia and Honduras have a decrease in redundancy due to improvements in yields that caused a smaller productivity redundancy on used areas. This is combined with a complete depletion of spare land, and thus, no increase in the productivity redundancy on available areas (compare also figure 1). In Pakistan, depletion of water resources also contributes to the trend. Canada, despite a less significant improvement in yields, shows a positive trend in the last decade that is combined with high variability of land use.

Figure 1. Maps of subcomponents of biophysical redundancy and index of biophysical redundancy for the year 2012. (a) Land redundancy (LA), (b) water redundancy (WA), (c) productivity redundancy on used land (YG), (d) productivity redundancy on available land (YG_E), (e) index of biophysical redundancy for the R_{middle} scenario.

Figure 2. Classification of countries according to the change of biophysical redundancy since 1992. Changes were calculated comparing the average redundancy from 1992 to 2001 with the average redundancy from 2002 to 2012.

3.3. Low income economies (LIEs)

LIEs present an interesting case to examine because they have very limited financial resources to react to external or internal disruptions of food supply, due to their very low capacity to pay a higher price for agricultural commodities in the world market. Thus,

redundant resources might be their only option for counteracting a disruption in food supply.

The World Bank designates a country as a LIE if it had a Gross National Income per capita of $1045 or less in 2014 (World Bank 2015). Currently, 28 countries of the world, mainly situated in Africa, are LIEs,
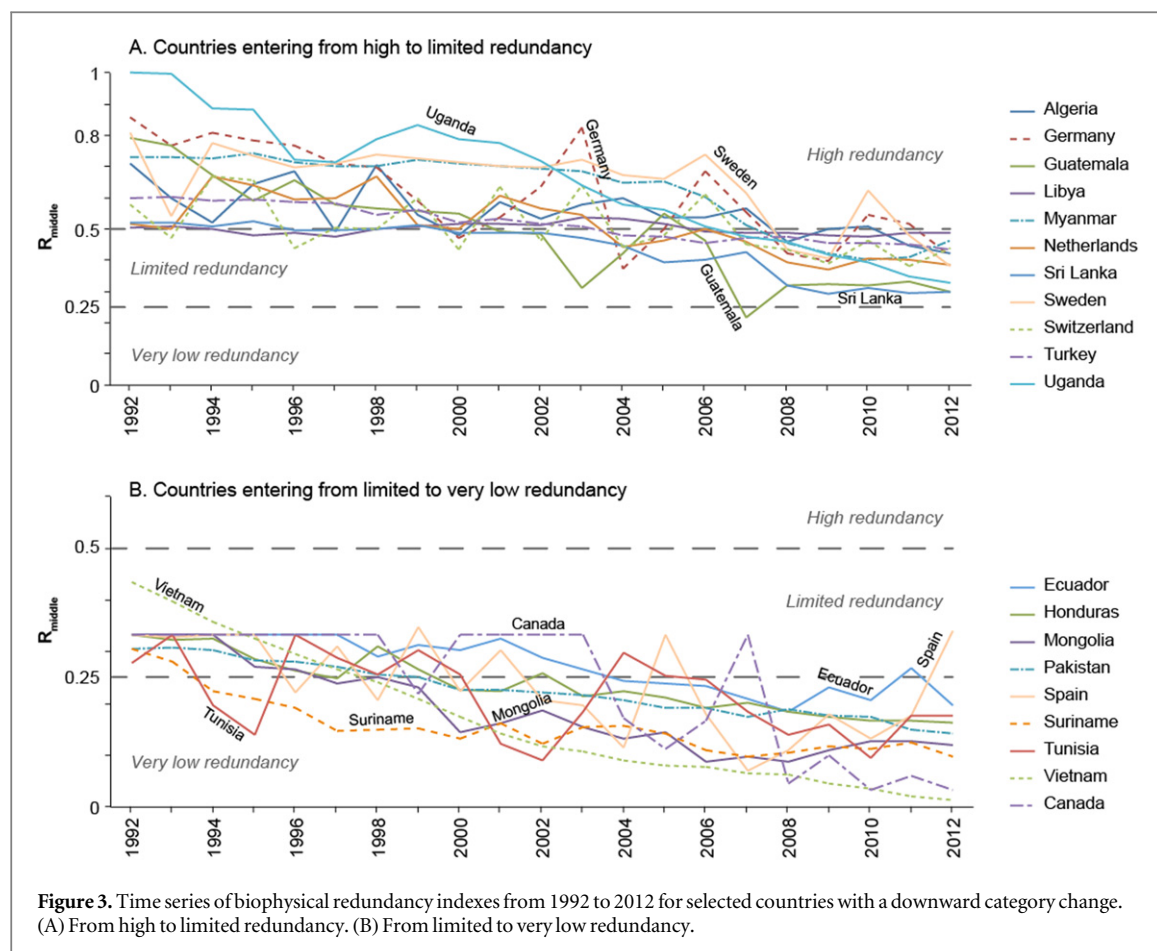
Figure 3. Time series of biophysical redundancy indexes from 1992 to 2012 for selected countries with a downward category change. (A) From high to limited redundancy. (B) From limited to very low redundancy.

with a total population of about 558 million people. Our results show that four LIEs (Haiti, Rwanda, Niger, Eritrea) currently have very low biophysical redundancy, and five LIEs (Burundi, Afghanistan, Nepal, Uganda and Somalia) have limited biophysical redundancy. Of these countries, Eritrea and Uganda went through a sustained transition from high to limited (Uganda) and to very low redundancy (Eritrea). These nine countries together have a total population of around 158 million people.
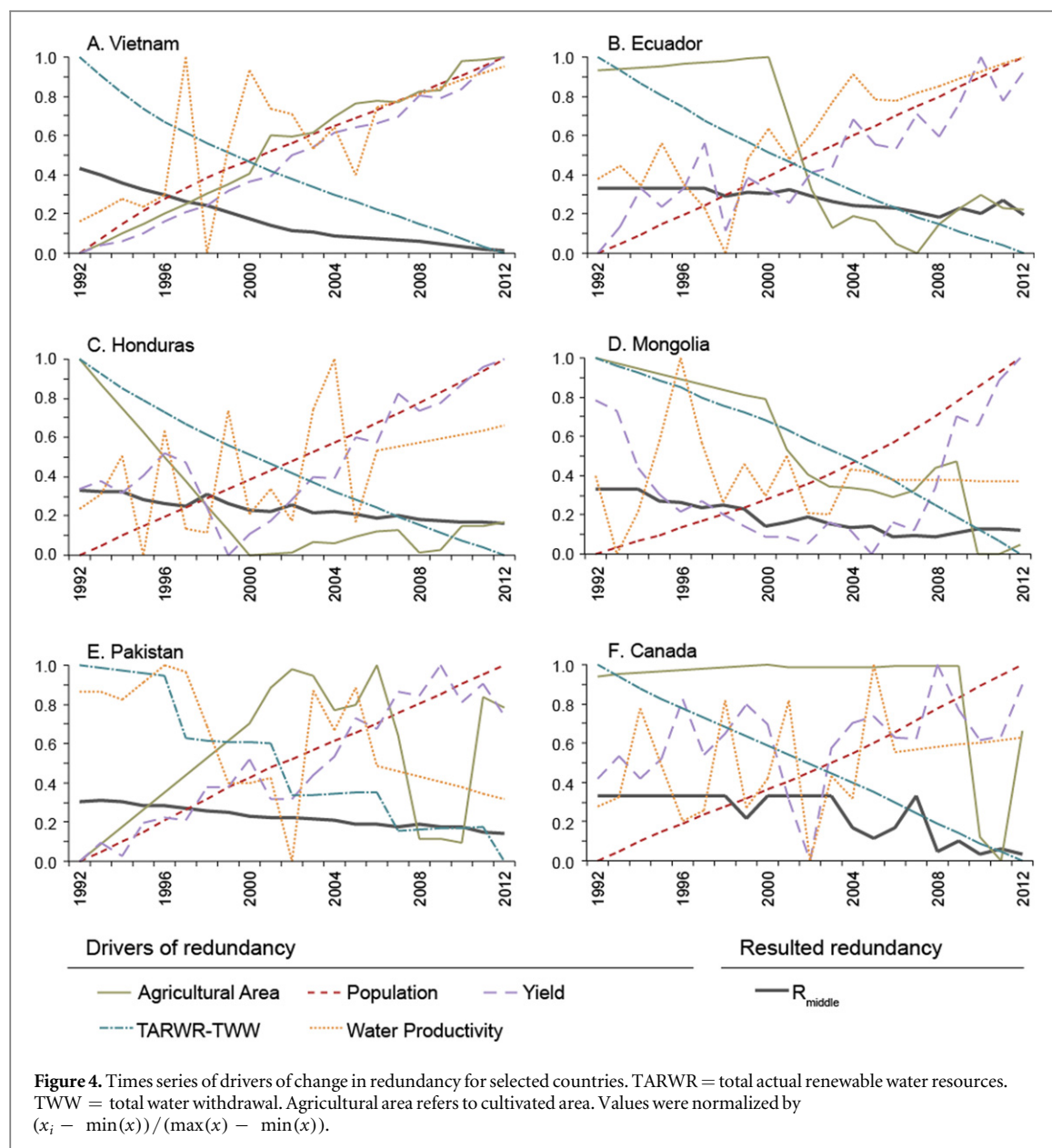
The rest of the LIEs consistently had high redundancy over the last two decades. While most of them have sustained high redundancy values, Sudan, Ethiopia, Chad, Malawi, Togo and Tanzania have negative trends in biophysical redundancy. Should these trends continue in future, they would surpass the threshold to limited redundancy in the next 50 years.

It is important to note that a decreasing redundancy could be an indication of productivity gains or expansion of agriculture and, thus, of a better caloric nutritional situation today compared to two decades ago. Indeed, the LIEs as a group have made a transition in food production from $\sim$2300 kcal cap^{-1} d^{-1} to $\sim$3400 kcal cap^{-1} d^{-1}. Currently, there are 13 LIEs that produce less than 3000 kcal cap^{-1} d^{-1}, as opposed to 18 of them in 1992. However, the picture at national level is heterogenous. Cambodia, Malawi, and Sierra Leone had considerable increases in domestically produced food, surpassing 3000 kcal cap^{-1} d^{-1} during the last two decades. In contrast, many other LIEs show no significant change in food availability per capita from domestic production, with Eritrea, Uganda, Sudan, Burundi, Zimbabwe and Somalia having negative trends in production per capita.

3.4. Differences between the R_{low}, R_{middle} and R_{high} scenarios

The overall redundancy of China, Canada, Russia, Japan, and some countries in Latin America and Southeast Asia is higher in the R_{high} scenario, mainly due to the consideration of protected areas and areas worthy of protection as available for food production (figure 5). Also, some Sub-Saharan countries and countries with monsoon precipitation have higher water redundancy in the R_{high} scenario due to the assumptions that precipitation variability and seasonality does not constrain the accessibility of water resources and that water productivity is as high on unused areas as on used areas (figure A.3). While both precipitation variability and water productivity have an influence on water redundancy, assuming lower water productivities has a stronger effect than assuming constraints in accessibility due to precipitation variability (data not shown).

Figure 4. Times series of drivers of change in redundancy for selected countries. TARWR = total actual renewable water resources. TWW = total water withdrawal. Agricultural area refers to cultivated area. Values were normalized by $(x_i - \min(x))/(\max(x) - \min(x))$.

Not considering managed grasslands as redundant resources (R_{low}) has by far the largest influence on overall biophysical redundancy. It decreases the biophysical redundancy of Australia and most American countries to the limited redundancy level, and it drives Northern African, Asian, and European countries to very low redundancy levels (figure 5).

Comparing the water redundancy from the R_{low} and the R_{middle} scenario highlights the influence of assuming high instead of middle high environmental flow requirements (36%–57%) in addition to precipitation variability. This pushes countries of Eastern and Southern Africa as well as Niger and Nigeria to lower redundancy categories (figures 1 and A.3).

There are almost no differences in LIEs when comparing the R_{midlle} and R_{high} scenarios. Only Somalia shows a significant change, having high redundancy in the R_{high} scenario and limited redundancy in the R_{middle} scenario. However, there are substantial differences when comparing the R_{middle} and R_{low} scenarios: from nine countries in the limited and very low redundancy categories in the R_{middle} scenario, to 17 countries in the R_{low} scenario. These 17 countries are home to around 380 million people. This result indicates that the consideration or not of managed grasslands as redundant resources is very important in poor countries.

The percentage of world population living in 2012 in countries with very low and limited redundancy diminishes from 70% to 60% when going from the R_{middle} to the R_{high} scenario. However, moving to the R_{low} scenario increases the total to 92%, with 70% of the world population in countries with very low redundancy (35% in R_{middle}).

The world as a whole shows a decreasing trend in biophysical redundancy in the last two decades, with considerable differences among the R_{low}, R_{middle} and R_{high} scenarios (figure 6). Simple global means (i.e.
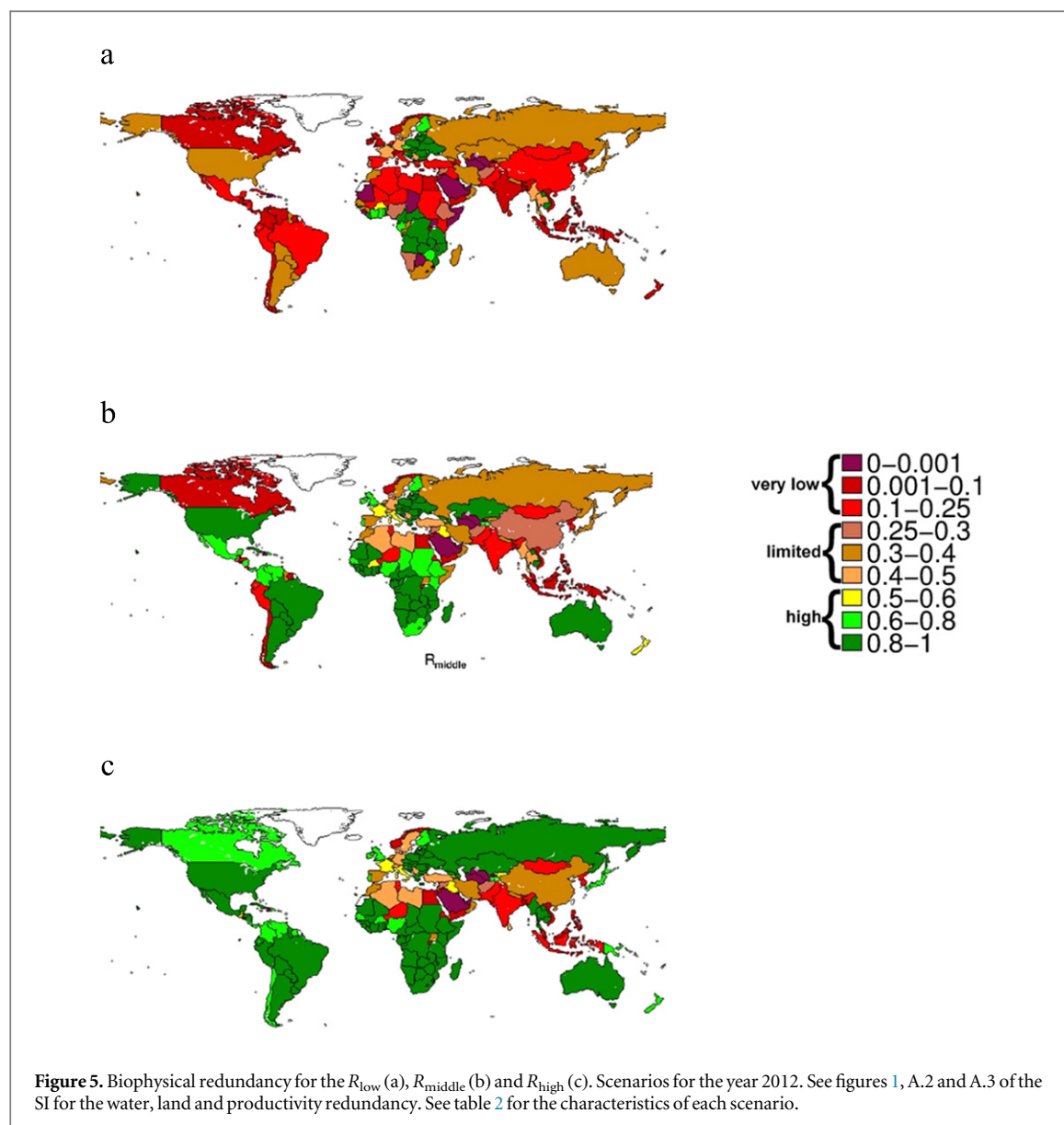
Figure 5. Biophysical redundancy for the R_{low} (a), R_{middle} (b) and R_{high} (c). Scenarios for the year 2012. See figures 1, A.2 and A.3 of the SI for the water, land and productivity redundancy. See table 2 for the characteristics of each scenario.

average regardless of country size, population and agricultural area) have a much smoother trend than those means calculated by weighting country values by their agricultural area or population. In the R_{middle} scenario the simple mean and the mean weighted by agricultural area start in the high redundancy class and are approaching the 0.5 threshold of the limited redundancy category. When the global mean is calculated by weighting national redundancies by country population, the global redundancy of R_{middle} starts and stays within the limited redundancy class and has a slightly steeper trend. This indicates that countries with higher populations have lower redundancies and steeper decreases in redundancy through time. In the R_{low} scenario, the global values calculated by weighting with population just transgressed the threshold from limited redundancy to very low redundancy. This indicates that the role of managed grasslands in redundancy calculations is especially important in highly populated countries. It is worthwhile noting

that in the present study we restrict attention to the last two decades. If this period were to be extended, greater variability and non-linearities in the biophysical redundancy trend may appear, possibly as a result of historical events such as population decimation through pests, rapid irrigation expansion and transitions connected to the green revolution.

4. Discussion

We have analyzed the evolution of biophysical redundancy at the country level, as captured by different metrics relating to spare land, available water resources and potential for productivity increases. To our knowledge, our study is the first to assess past trends in biophysical redundancy of countries and show that the world as a whole has decreased its biophysical redundancy over the last two decades. The intensity and the drivers of change in biophysical redundancy vary widely from country to country.

Figure 6. Evolution of biophysical redundancy for the world as a whole. See table 2 for the characteristics of each scenario.
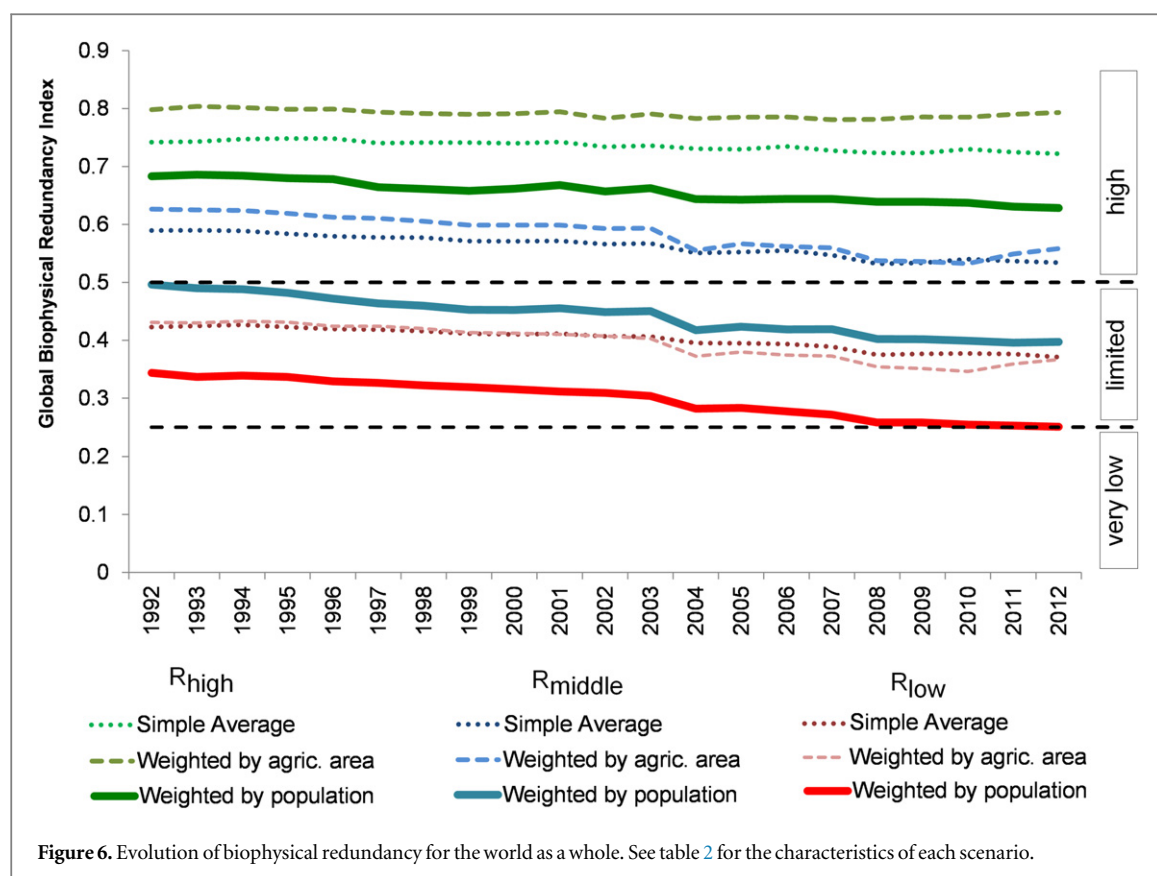
However, population growth appears to be connected to decreasing biophysical redundancy in a number of countries. Detailed monitoring and reporting of technological, economic and infrastructural developments would help to build up the databases needed to better understand the drivers of change in biophysical redundancy. Since economic development has been shown to be statistically connected with per capita food demand (Tilman *et al* 2011), obtaining specific details about the characteristics, causes, technological advances and sectoral patterns of economic development may contribute to better predict the dynamics of the components of biophysical redundancy.

Currently, there are 75 countries that could not feed at least 50% of their population during a year with redundant resources within their borders (R_{middle}). And there are 48 countries that could not feed at least 25% of their population during a year with redundant resources. These are mainly situated in North Africa, Western Europe, the Middle East and Asia. These countries are vulnerable to long-term food supply changes and they thus need to develop other means, such as strong national economies, to adapt to possible long-term food shortage.

4.1. Robustness and flexibility of the approach
Our results are in line with former studies. Namely, our calculations suggest closing the yield gap on used areas could increase production by 4.32 + E15 kcal in

2011, an estimate very close to the 5 + E15 kcal from Foley *et al* (2011).

Our estimates of spare land are 2476 Mha, 1492 Mha, and 303 Mha for the R_{high}, R_{middle} and R_{low} scenario, respectively. The latter two are in very good agreement with the medium (1376 Mha) and low (317 Mha) estimates of Eitelberg *et al* (2015). However, they have higher values for the high estimate (3783 Mha), possibly because they included barren and sparsely vegetated land. Potential food production was not calculated in that study and, thus, cannot be compared with our estimates.

Our calculation of available water resources is 51 096 km^3 (R_{high}), 26 655 km^3 (R_{middle}) and 17 909 km^3 (R_{low}). The high estimate is in good agreement with LPJmL simulations of water availability (48 292 km^3, Fader *et al* 2013) and the value 55 375 km^3 from Gleick (2000). The lower estimate agrees very well with the value of Gerten *et al* (2013) for 'accessible blue water resources': 16 300 km^3 and is not far away from 12 500 km^3, the estimate by Rockström *et al* (2009b).

Our results are the outcome of a flexible methodology that can be applied using other production data, different datasets of resources use and alternative values for caloric nutritional needs, including changes in the composition of diets. It is worthwhile noting that our use of a reference diet of a 3000 kcal cap^{-1} d^{-1} from crop products does not account for the fact that most human diets include animal products such as

meat, milk, or egg, which are partly produced using feed, and require several calories of feed crops to be produced. Even though the use of animal calories can be easily accounted for in our framework (Davis *et al* 2014), here we refer only to staple food and other food crops because the reliance on animal calories is likely to drop in conditions of severe food shortage. Thus, the reference to a plant base diet is here used as a baseline to evaluate the number of people that could be fed in each country by the redundant biophysical resources.

4.2. On the link of biophysical redundancy and international trade

Our study focuses on biophysical redundancy and thus intentionally disregards the influence of imports on food security. However, water and land use as well as the intensity of the agricultural management are influenced by the status and evolution of the agricultural and non-agricultural trade balance of each country. This indirect influence was implicitly included in our study by using historical data on production, resource use and agricultural yields. Additionally, in exporting countries, the area and water used for the production of export goods were not considered redundant resources. However, in situations of food shortage, countries might choose to stop exporting and use their natural resources for securing the food supply of their population (Jones and Hiller 2015). This has not being taken into account in this study, mainly because we consider that the revenues of exports are necessary for the national economies.

The relation of international trade, and especially trade liberalization, with food security, is a complex one. Not only due to the challenge of measuring food security, but also to the difficulty of attributing socioeconomic developments to trade policies. While a full analysis of these issues is certainly out of the scope of this study, it is important to note that there is an ongoing debate both in political and academic spheres that determines policies that will, in turn, directly affect the biophysical redundancy level. And this is a good reason to include some lines on these issues here.

The neoclassical trade theory assumes a world with perfect competition, where no country or firm is capable of influencing prices, and full internalization of external costs is in place, thus ruling out environmental externalities by construction. Under this theory, trade promotes long-term economic growth, maximizes the total potential economic welfare and ensures efficient resource use, by allocating production to sites where the resources needed for that production are abundant (keywords here are 'comparative advantage' and the Heckscher–Ohlin theorem). FAO (2003) lists some studies that show empirical evidence on the relationship between economic growth and free trade, and other authors show

evidence that international trade avoids higher levels of land use change (e.g. Fader *et al* 2011). FAO (2003) also points to the unrealistic character of the assumptions of the neoclassical theory and makes a strong effort to summarize the risks connected to liberal trade policies. This book concludes that there is a need for protection of vulnerable groups and of understanding the complex relationships between income, income distribution and access to food availability, at national and household level. Lambin and Meyfroidt (2011) contribute to the debate pointing to processes amplified by globalization that may increase deforestation and land scarcity, changing future biophysical redundancy. These processes include displacement of environmental costs to other territories, indirect land use change, increase in resource use due to new technologies that make that use more efficient and thus cheaper, and the influence of remittance of migrants on the change, intensification or expansion of agricultural activities (Lambin and Meyfroidt 2011).

However, trade does allows increasing food supply in times of national crisis by increasing imports (in countries that can afford them) and allows countries to sell products in moments of food surplus, increasing the financial resilience of some economic groups to a degree. But it also facilitates the propagation of shocks through higher connectivity, the coupling with the energy market, financial speculation in the international food commodities market, and a potentially harmful dependency on food produced in other countries that may, out of necessity or convenience, restrict food supply (Fader *et al* 2013, Suweis *et al* 2013, 2015).

Finally, foreign land investments, also called 'grabbed' land, could be used as a mechanism for artificially increase biophysical redundancy of the investor countries, decreasing correspondingly the biophysical redundancy of host countries. Currently, there are almost 37 Mha contracted land deals, of that, 17 Mha is in Africa (Land Matrix 2015). There is a clear need for better data on these deal's conditions, the destiny of products and the local impacts on accessibility and availability of natural resources.

Collectively, these results demonstrate that there is a clear need to go beyond the biophysical aspects. In this sense, this study paves the way for integrating biophysical redundancy with trade dynamics and socioeconomic development indicators in order to quantify the overall resilience of countries to food supply changes.

4.3. Time is ripe for discussing the role of biophysical redundancy in food security

Lambin (2012) presents an interpretation of Malthusian and Ricardian views over global productive land that is useful for the debate on resources scarcity and human technological capacities to overcome physical constraints. From a Malthusian perspective, land and water availability are hard constraints for population

growth. As population grows over the carrying capacity of the Earth, violent conflicts and food insecurity are expected to increase, and welfare is expected to decrease. In contrast, a Ricardian view would propose that limits can be sequentially upgraded when marginal land and water use become increasingly profitable (Lambin 2012). Neither of these views would consider that resources could be intentionally excluded from production. Our findings suggest, however, that the time is ripe for asking whether there is a 'desirable' level of redundancy in biophysical resources that play a fundamental role in food production. That is especially true because eminent climate and socio-economic changes are likely to modify food supply and demand in the near future.

In this study, redundancy of critical resources for agricultural production has been introduced as a mirror concept to redundancy in engineering and ecology. As such, our concept of biophysical redundancy is equivalent to the 'stand-by redundancy' in engineering, i.e. equipment that does not take part in the process and is most of the time idle, until a failure of a system component occurs (King 1990). There are at least three points worthwhile mentioning in connection with this 'stand-by' character.

First, spare land and available water resources are not 'idle', in fact they play a major role in the provision of ecosystem services that are also fundamental for agricultural production (e.g. provision of pollinators, water purification, etc) (Godfray *et al* 2010). Also, agricultural intensification, on the one hand, might avoid conversion of natural areas to agricultural production, increasing 'spare' land, and thus, land redundancy. On the other hand, intensification increases actual yields, diminishing the yield gap and, thus, reducing the productivity redundancy. But most importantly, high or low redundancy does not imply environmentally friendly or unfriendly practices. When intensification is linked to mechanization and increases in chemical inputs and irrigation, it may have detrimental effects on both land suitability (salinization, water logging, soil degradation, soil compaction, etc) and ecosystem functioning (nutrient leaching, pollution, etc) (Montgomery 2008). Extensification, on the other side, is linked to increased greenhouse gas emissions, biodiversity loss and hydrological alterations (Gibson *et al* 2011, Tilman *et al* 2011).

Second, this study does not analyze the feasibility of using redundant resources in response to food supply changes nor recommends using them in cases of food supply shortage. It is worthwhile to note that the use of redundant resources can be difficult under some circumstances. For example, Alexandratos (2005) mentions the remoteness and prevalence of highly infectious diseases in some LIEs as impediments for land conversion. Also, some studies point out that yields gaps, besides being connected to physical factors, like slope and irrigation, are highly linked to market-related issues, management practices, labor force

and inequality (Neumann *et al* 2010, Allouche 2011, Dietrich *et al* 2012). These factors might be as important as the availability of redundant resources in shaping the response to long-term food supply changes.

Third, in this study, countries with large areas of fertile, spare land, untapped freshwater resources, and a combination of low actual yields and high potential yields are assumed to have high redundancy. The reason for this would be that they have a buffer with the potential to compensate—to certain extent—internal or external supply shortcomings by increasing domestic production. However, it has to be noted that we refer to medium and long term changes, since the stand-by character of the resources discussed here does not allow for a response to sudden disruptions, shocks or price spikes. In this context, other factors like the diversity of domestic production before the shock and the availability of financial means for increasing imports may play a much more decisive role in maintenance of food security (Porkka *et al* 2013).

5. Conclusions and implications

In this study we assessed the redundancy potential to increase food production. We found that biophysical redundancy has decreased over the last two decades in the majority of the countries. The drivers of change are complex and highly variable across different geographical areas, but we show that improvements in yields and population growth have been central causes behind movements towards the very low redundancy category. In countries with low redundancy, it would be important to integrate this knowledge with an analysis of the evolution in other economic sectors and a critical view of changes in agricultural trade balance. This could help to determine whether the trend in redundancy is linked with an increase in vulnerability to food supply changes. Additionally, this study has two main implications; one is for future research and the other for development organizations and policy makers.

In terms of the future research implications we highlight that different definitions and calculations of the subcomponents of redundancy had a strong influence on our results. Importantly, the inclusion or exclusion of managed grasslands as redundant resources (potentially available for conversion to agricultural production) had a large influence at the global and national levels. This clearly shows that spatially-explicit research on the potential agricultural production of managed grasslands and the environmental consequences of their conversion to other uses is urgently needed in order to determine the flexibility of their use in a context of dynamic food supply.

In relation to policy, we show that LIEs are particularly vulnerable as they have limited or very low biophysical redundancy. Several of these countries show a

decrease in redundancy in the last two decades and these decreases are not always linked with improvements in food availability. Due to the limited capacity of LIEs to compensate food supply changes by increasing imports (potentially at a higher price in periods with lower supply), it is crucial that governments and the international development agencies understand the interplay between dynamics of domestic food production and biophysical redundancy.

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