Quantification of regional and global sustainability based on combined resource criticality of land and water

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The overall global food sustainability is limited by the simultaneous availability of primary resources at regional scales, although the international trade network can redistribute available (surplus) food. Assessments based on isolated resource (like water) or demand (like food) cannot provide correct estimates of sustainability. We define a novel criticality index on the basis of simultaneous regional availability of arable land and water to quantify sustainability. Analyses at regional and global scale show that while a relatively small fraction of world population is subcritical in terms of food availability, much larger fractions are becoming subcritical in terms of food production. The combined resource criticality implies stronger constraints for sustainability.

Keywords: Agricultural sustainability, carrying capacity, criticality index, food sustainability, water sustainability.

AGRICULTURAL processes driven by various demands and consumption patterns are critical components of the ecological system; thus the status of basic sustainability in food and water is a good indicator of ecological balance. The basic sustainability trajectory of the world depends on its two primary resources: arable land and utilizable water[1–6]. While the international trade network can redistribute available (surplus) food and, to some extent, water through associated trade of virtual water[2,7], the world sustainability is limited by the overall production[8–10] and demand[11–15]. The growing demand due to increasing population[10,11,15,16] and changing consumption pattern[12,17] combined with limited and even decreasing primary resources (arable land and water)[18–26] due to other demands on them can create criticality even if productivity increases. Further, changing climate can introduce more severe constraints and vulnerability through extreme conditions[27–30]. It is clear that the dynamics of the primary resources, and their effects, will vary with region and emerge at different times; however, there are definite indications of such emerging regional stress[12,21,22,24,31,32]. These regional stresses, especially for countries with large populations, can affect global sustainability as a whole through change in demand and surplus. It needs to be emphasized, however, that production of food will be constrained by the simultaneous availability of both land and water in a region.

Several studies have highlighted the impact of primary resources on food sustainability[1–5,22,24] and developed indices for the quantification of the state of these primary resources[24,32–37]. These indices emphasize different issues like water scarcity at both regional[24,32,38] and global scales[35] as well as their relations to policy planning[37] and socio-economic impacts[3]. Thus, these indices can provide diverse results and conclusions. While attempts have been made at more integrated assessments on specific scale like a basin, or specific sector like agriculture, a combined analysis of water and arable land is missing[15]. Such assessments also need to consider scenarios of growing population and changing consumption patterns at regional and global context. It must be noted that even a temporary global deficit can have a large impact on world food sustainability and starvation. The carrying capacity in terms of combined criticality is expected to be different from that based on isolated resource[39,40]. While several studies have provided estimates of population that is sustainable, it is necessary to re-examine these estimates in terms of combined resource criticality[41,42].

A basic water sustainability index can be defined as the ratio of total water demand to the total water available. The total water demand is considered as the sum of minimum water required per capita for various usages like domestic, industrial and agricultural purposes, and is estimated at 1700 m^3 per year[43,44]. The per capita water demand is, however, dynamic and varies with irrigation practices and water use efficiency. The water use efficiency basically depends on agricultural practices and technology uses. Similarly, the availability of arable land is driven by several interacting socio-economic processes[45] such as growing population and land uses for non-agricultural purposes like residence, industries and infrastructure[18,19,45,46]. Thus estimates of these demands as well as requirements vary. It is evident that overall sustainability requires minimum availability of both these

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resources together and estimates based on an isolated resource cannot provide an accurate picture of sustainability.

The main objective of the present study is to examine sustainability in terms of such combined availability of primary resources. We define a criticality index based on arable land and utilizable water. This index is then applied for (re)assessment of water and food sustainability at regional and global contexts in terms of different population and consumption patterns where a related estimate is the critical dependence on import (world surplus)[23]. Finally, scenarios of uniform global consumption are considered to examine global sustainability.

Methodology, data and formulation

We have considered observed data for agricultural area and producitivity, food production, population, per capita food consumption, export, import and food wastes of 162 countries obtained from a public domain like FAOSTAT for all crops. The observed data for water required for agriculture, domestic and industrial purposes, the per capita and the total water availability was taken from AQUASTAT for the period 1956–2011 (ref. 42). The countries are selected based on the availability of observed data in FAOSTAT and AQUASTAT[41,42]. The term 'all crops' means food crops, foodgrains, vegetables, fruits, pulses, oil crops, roots and tubers (excluding non-food crops like rubber, tobacco, jute and fibre). The data for land used for non-agricultural purposes in India is obtained from the Department of Agriculture and Cooperation. Since such data is not available for all countries, we have considered in general, per capita land required for non-agricultural purposes to be equivalent to India's per capita land requirement for the same. The minimum per capita arable land required to sustainably support a person is 700 m^2 and this assumes that all required nutrients for humans come from vegetarian diets with no land degradation or water shortages, virtually no-post harvest waste, and farmers who know precisely the best agricultural practices[39,44]. Similarly, the basic requirement of water for domestic purposes like drinking, sanitation, bathing and food preparation is considered to be ~18.2 m^3/capita/year (or daily 50 litres). This total water required for one person per day is the minimum per capita water required to sustain life in a moderate climate and excludes the water required for agricultural purposes. A spatial variability is found in the per capita water use for countries due to availability of primary resources, climate change and water use efficiency. In addition to domestic food production, the main uses of water are for agriculture and industry sector. Globally, 68% of the withdrawals are for agriculture, 19% for industry and 9% withdrawals are for municipal and domestic purposes. Regionally, these ratios vary significantly. In India, 93% of water use is for agriculture purposes while for Kuwait (arid area), it is around 12%. Similarly, water needed to fulfill the minimum requirement of a person varies from 640 m^3 (African countries) to 1830 m^3 (USA). The standard value of per capita water use for agriculture, domestic and industry is ~1700 m^3 (ref. 38).

Projections and saturation of population for India, China, USA and the world are obtained from the United Nations Population Projection Division. The data for food waste and food losses for India, China, USA and the world has been taken from the FAO report on global food losses and food waste[47]. The water required for domestic and industrial purposes is calculated as the ratio of sum of water withdrawal for domestic and industrial purposes to the total population. Similarly, water required to produce one tonne of food is calculated as the ratio of total water used for agricultural purposes to the total food produced.

Per capita food consumption varies among countries due to several factors like per capita income, GDP growth, food price and availability of food. Thus, the arable land requirement for one person is calculated as the ratio of per capita food consumption to agricultural productivity. The agricultural productivity can be different due to water use efficiency, infrastructure, better agricultural practices and climate.

We have analysed the indices of land, water, criticality and dependency on import for the current as well as the standard scenarios. In the standard scenario, per capita water requirement for domestic, industrial and agricultural purposes is 1700 m^3 (ref. 44) and the arable land required to feed one person (350 kg/capita/year) is 700 m^2. In the current scenario, the per capita water requirement, per capita food consumption, agricultural productivity, population and arable land used are for the year 2010. These parameters are different for each country and depend on the country's primary resource availability, food availability and agricultural practices. The total export is the sum of exports of all food commodities. Similarly, total import is the sum of imports of all food commodities.

Assessment of primary resources

We have considered 162 countries for which annual/periodic data on primary resources, consumption and other parameters were available in the public domain (FAOSTAT, AQUASTAT). The amount of arable land available in year n for a country i is calculated as

$$A_g(i,n) = A_{\max}(i) - A_U(i) * N_T(i,n), \tag{1}$$

where $A_g(i, n)$ and $A_{\max}(i)$, respectively, represent arable land in year n and the maximum possible arable land for a

Table 1. Description of parameters used in this study

Parameter	Unit	World	India	China	USA
Arable land (A_{max})	10^{10} m^2	1400	165	124	189
Current population	million	6900	1220	1300	300
Saturation population (UN estimates)	million	9000	1540	1460	
Current per capita food consumption	kg/capita/year	450	350	650	510
Water requirement for agricultural production	m^3/ton/year	455	1185	250	314
Water requirement for non-agricultural use	m^3/capita/year	170.2	60.54	141	916
Arable land requirement for food production	m^2/capita/year	1125	1166	541	1700
Current agricultural productivity	kg/m^2	0.4	0.3	1.2	0.3
Coefficient of food loss by consumer sector (α_C)	kg	57	15	80	110
Coefficient of food loss through production and retail sector (α_P)	kg	153	110	160	185
Coefficient of total food loss (fraction of total food production) (α_L)	Average (1960–2009)	0.28	0.43	0.49	0.18
Total food loss (fraction of total food production) (α_L)	Current (2009)	0.23	0.37	0.28	0.15
Standard per capita arable land	m^2	700	700	700	700
Standard water required to feed one person	m^3	1700	1700	1700	1700

country (i), or the world (Table 1). The second term on the right hand side of eq. (1) represents loss of agricultural land due to demands for non-agricultural activities like habitat, infrastructure and industries[18,19,45,46]. The minimum per capita land use, $A_U(i)$, for non-agricultural purposes varies among countries; however, we have assumed this demand to be proportional to the population, $N_T(i, n)$, of the respective country (FAOSTAT).

The requirement of arable land, $A_D(i, n)$, to meet the food demand can be defined as

$$A_D(i,n) = A_{CP}(i,n) * N_T(i,n), \tag{2}$$

$$A_{CP}(i,n) = \frac{F_{CP}(i,n)}{A_P(i,n)}. \tag{3}$$

Here $A_{CP}(i, n)$ represents minimum per capita arable land required to produce food for one person with per capita consumption $F_{CP}(i, n)$ and agricultural productivity $A_P(i, n)$ of the country i for the year n; the standard values of these variables are given in Table 1.

Similarly, the total water demand $W_D(i, n)$, is defined as

$$W_D(i,n) = W_{CP} * N_T(i,n) + F_D(i,n) * W_{PO}, \tag{4}$$

Here W_{CP} is the per capita water requirement for domestic and other non-agricultural purposes and W_{PO} is the water required for production of food (m^3/kg); a representative value of $W_D(W_{CP} + W_{PO})$ is 1700 m^3/capita/year (ref. 44). It is clear that W_{PO} varies spatially and temporally due to climatic conditions and water use efficiency. We have therefore used data for the respective country. $F_D(i, n)$ is the total food demand of the country i for the year n.

Production, demand and availability of food

Food production and total food demand are estimated as

$$F_P(i,n) = A_g(i,n) * A_P(i,n), \tag{5}$$

$$F_D(i,n) = F_{CP}(i,n) * N_T(i,n). \tag{6}$$

Here $F_P(i, n)$ and $F_D(i, n)$, respectively, represent the total food production and the total food demand of the country i for the year n.

The total food available for consumption $F_A(i, n)$ is estimated as

$$F_A(i,n) = F_P(i,n) + F_I(i,n) - F_E(i,n) - F_L(i,n). \tag{7}$$

Here $F_E(i, n)$ and $F_I(i, n)$ denote, respectively, total export and the total import of food commodities. $F_L(i, n)$ represents the total loss of food that accounts for both avoidable and unavoidable losses. The avoidable (equivalent) loss accounts for that fraction of food production which deals with costs of irrigation, seed, feed, fertilizers and transport. The unavoidable loss is due to the inevitable losses associated with the processes of distribution and consumption. We thus estimate the food loss as

$$F_L(i,n) = F_{LW}(i,n) + F_{LP}(i,n), \tag{8}$$

$$F_{LW}(i,n) = \alpha_L(i) * F_P(i,n), \tag{9}$$

where

$$\alpha_L(i) = \frac{1}{N}\sum_{n=1}^{N}\frac{\alpha_C(i) * N_T(i,n)}{F_P(i,n)} + \frac{1}{N}\sum_{n=1}^{N}\frac{\alpha_P(i) * N_T(i,n)}{F_P(i,n)}.$$

The loss of food, $\alpha_L(i)$, is the sum of losses through consumers and retail sector: $\alpha_c(i)$ (in kg) and the loss during production, $\alpha_P(i)$ (in kg), expressed as averages over the years N and fraction of production (Table 1). The per capita loss and waste of food for European countries and North America is about 280–300 kg/capita/year, while in Sub-Saharan Africa and South/Southeast Asia it is about 120–170 kg/capita/year (ref. 47). Similarly, the per capita food loss by consumers for European countries and North

America is in the range of 95–115 kg/capita/year (ref. 47), while for Sub-Saharan Africa and South/Southeast Asia, it is in the range of 5–11 kg/capita/year. As the food loss due to production and retails cannot be accurately estimated separately, we have assumed the combined loss of food due to retails and production processes. In the most optimistic (wealthy country) scenario, we assume that the costs of all processes like irrigation, transport, operation and fertilizers can be obtained from other sources, and hence $F_{LP}(i,n) = 0.0$. The other term, $F_{LW}(i, n)$, is assumed to be proportional to the population, food consumption and agricultural production.

Indices of criticality and import dependence

The index of criticality due to arable land, $I_A(i, n)$, is defined as

$$I_A(i,n) = \frac{A_g(i,n)}{A_D(i,n)} - 1. \quad (10)$$

We have a state of land sustainability if $I_A(i, n) > 0$. The index of water sustainability is similarly defined as

$$I_W(i,n) = \frac{W_A(i,n)}{W_D(i,n)} - 1, \quad (11)$$

where $W_D(i,n)$ and $W_A(i, n)$, respectively, represent the total water demand and the total water available.

As against the sustainability index for isolated resource, the criticality index, $I_C(i, n)$, based on the combination of two primary resources (arable land and available water) is defined as

$$I_C(i,n) = I_A(i,n) * I_W(i,n)$$
$$= \begin{cases} 1 & \text{if } I_A(i,n) > 0, \text{ and } I_W(i,n) > 0 \\ 0, & \text{otherwise} \end{cases}. \quad (12)$$

In addition to the primary sustainability expressed by $I_C(i, n)$, we also consider index of food criticality in terms of food production, $I_{FP}(i, n)$ and food available, $I_{FA}(i, n)$ against demand, which is defined as

$$I_{FP}(i,n) = \frac{F_P(i,n)}{F_D(i,n)} - 1 = \frac{A_g(i,n) * A_P(i,n)}{N_T(i,n) * F_{CP}(i,n)} - 1, \quad (13)$$

$$I_{FA}(i,n) = \frac{F_P(i,n) + F_I(i,n)}{F_D(i,n)} - 1. \quad (14)$$

In defining $I_{FA}(i, n)$, we assume zero export and zero loss for the most optimistic scenario.

Although international trade cannot add to the overall global sustainability, its dependence is a good measure of regional sustainability. We define an index of import dependency $I_{ID}(i, n)$, as

$$I_{ID}(i,n) = \frac{F_P(i,n) - F_D(i,n)}{F_{p\max}(i)}. \quad (15)$$

Here $I_{ID}(i, n)$ represents the index of dependency on food import with the condition $F_P(i, n) < F_D(i, n)$. $F_{p\max}(i)$ is the potential food production, which is determined by the maximum arable land and the agricultural productivity (in year n).

In the observed consumption scenario, we consider per capita food and water for each year for the respective country. These values range from 350 to 650 kg/capita/year for food (FAOSTAT). In addition, we consider a standard (hypothetical) uniform world-wide consumption of 350 kg/capita food (700 m^2/capita arable land) and 1700 m^3/capita water per year. Thus the observed consumption includes much higher consumption than the standard scenario for many countries. Carrying capacity and criticality are assessed by considering population as well as consumption as variables, with their current (year 2010) values for the respective country as the reference.

Results and discussion

Criticality with respect to primary resources

Both the primary resources per capita show comparatively decreasing trends for the world (Figure 1 *a*). At regional scale, this rate of decline is the highest for India (Figure 1 *b*) and the lowest for USA (Figure 1 *d*). However, in the world scenario, both of these are fairly above criticality level. The per capita arable land currently available for the world (2000 m^2) is about three times the minimum arable land (700 m^2) required. At the current rate of decrease (–1.5%/year), the world land sustainability is not immediately threatened. Similarly, the current water available per capita for the world (~7000 m^3) is about four times the standard per capita water requirement (1700 m^3). However, this surplus is unevenly distributed and the global surplus does not imply regional sustainability. For India (Figure 1 *b*), the current per capita arable land (~1000 m^2) is somewhat above its critical value (700 m^2, left *y*-axis); however, it has become sub-critical in terms of water availability (Figure 1 *b*, right *y*-axis). Similarly, China, while still above criticality in terms of both arable land (Figure 1 *c*, left *y*-axis) and water (Figure 1 *c*, right *y*-axis), is approaching water criticality due to decreasing trends. Only USA is found to be well above criticality in both the primary resources, but with slow declining trends (Figure 1 *d*). Similar conclusions hold for most of the countries and the 20 most populous countries in the world are now approaching sub-criticality in both arable land and utilizable water (Figure 2). Indeed, the

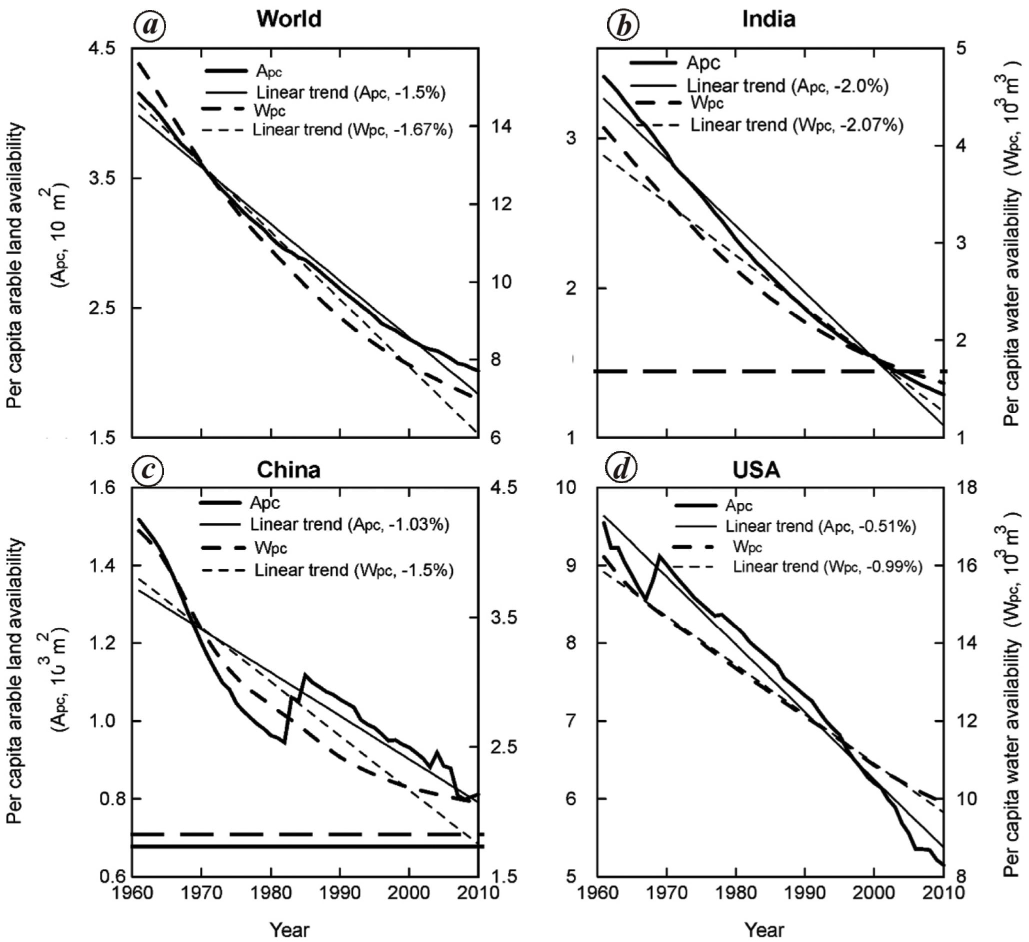

Figure 1. Availability of the primary resources (arable land, available water) for (***a***) world, (***b***) India, (***c***) China and (***d***) the USA. The horizontal solid line represents the per capita arable land (700 m^2) requirement for producing food for one person; the horizontal dash line represents the minimum per capita water requirement (1700 m^3). The numbers in the brackets represent coefficients of linear trend as percentage of the respective mean (1960–2010) for the corresponding cases.

patterns of decline are quite similar for the countries with only a few exceptions like Brazil, which seems to have a nearly steady value in per capita arable land in recent years (Figure 2). Similarly, after a sharp decline during 1960–1980, France now has a nearly steady value of per capita arable land (A_{PC}). The per capita water availability (W_{PC}), however, continues to decline for most countries (Figure 2). The decline in primary resources for each region is consistent with the growing demands that are beginning to approach and exceed production (Figure 3). For the world, India and China, there are now periods of deficits (demand > production), implying import dependence. The USA had a rising surplus until about 1980, which is now reduced to about 15% of its national demand (Figure 3 *d*). It needs to be emphasized that while individual countries can compensate deficits through surplus, deficit at the world level cannot be compensated through import. As already mentioned, even temporary global deficit due to inter-annual variability can have big impact on world food and eventually lead to starvation (Figure 3).

The significance of criticality index is clear from the fact that the number of critical countries in terms of combined availability is more than land-critical countries or water-critical countries (Figure 4). For observed per capita food consumption, the number of subcritical countries has increased from about 20 in 1960 to about 38 in 2010 (Figure 4 *a*). In terms of percentage of world population, more people are at the critical level for combined resources than the isolated resources for observed consumption (Figure 4 *b*). However, while more countries are food-critical than resource-critical for observed consumption (Figure 4 *a*), there has been an increasing number of resource-critical countries for standard uniform global consumption for per capita consumption (food 350 kg/year, water 1700 m^3/year; Figure 4 *c*). In particular, while water criticality is the predominant one for observed consumption, land criticality becomes the determining factor for standard consumption. In terms of population also, more people are found to be critical in terms of combined criticality than in terms of land- or water-criticality. Generally, criticality in population

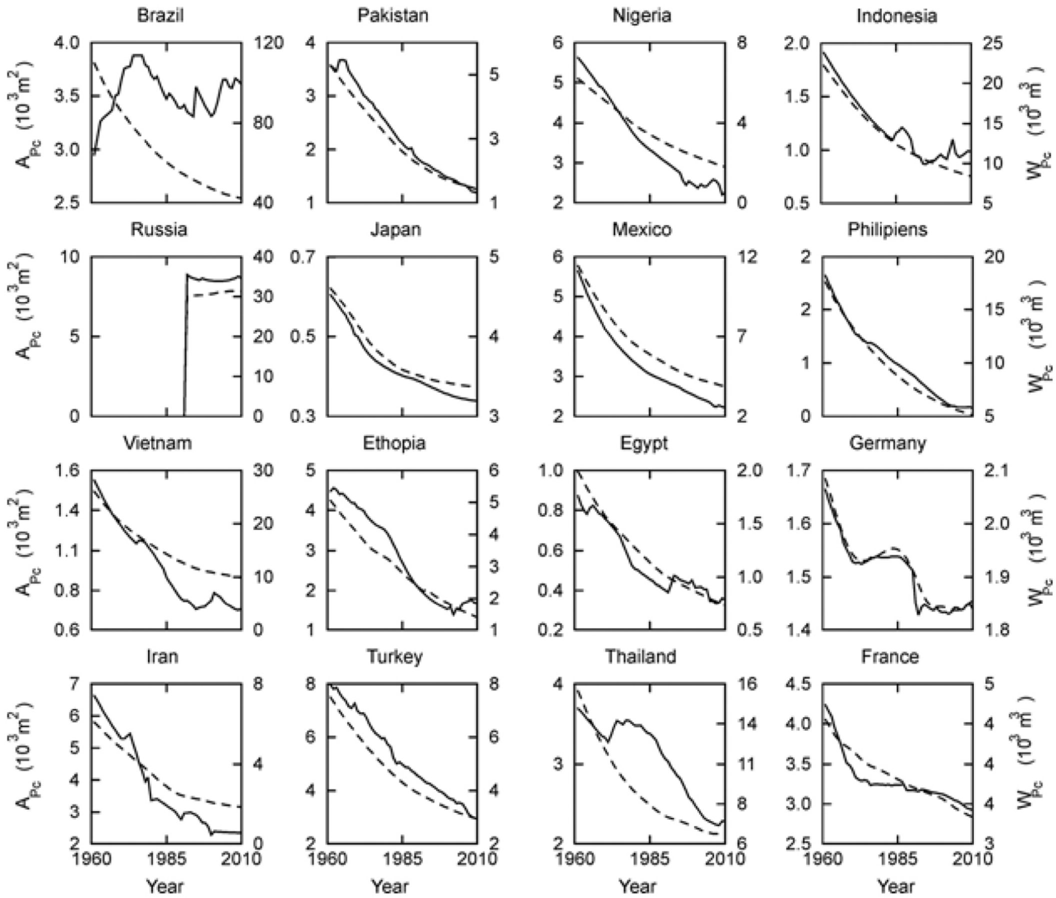

Figure 2. Observed per capita availability of arable land (A_{pc}, solid line, left y-axis) and per capita availability of water (W_{pc}, dash line, right y-axis) for 20 most populous countries. The observed data for arable land and water, respectively, are adapted from FAOSTAT and AQUASTAT.

fluctuates as nations with large population sometimes become subcritical (Figure 4 *d*).

In case of carrying capacity, a cent percent increase of population for the respective country would imply increase in the number of both land-critical and water-critical countries (Figure 5). For observed per capita consumption, this increase in subcriticality is from around 35 countries to above 75 countries (~50% of total countries) and essentially follows land criticality (Figure 5 *a*). However, for standard consumption, this increase in subcriticality is much higher, from around 52 countries to above 100 and does not strictly follow either of the isolated resources (Figure 5 *b*). While food criticality rises from below 50 countries to nearly 125 countries for 100% increase in population for observed consumption, its growth is less for standard consumption, i.e. from 40 to nearly 100 (Figure 5 *b*).

Impact of per capita food consumption on criticality

Another factor that affects subcriticality is consumption through increased demand on land, and water. With growing number of countries and population with higher consumption will have major impact on criticality (Figure 6). In particular, at global scale, the number of countries with per capita consumption of 350 kg or more has increased from around 40 in 1961 to nearly 80 in 2010 (Figure 6 *a*). Though this growth is slow, it is still present in countries with higher consumption (Figure 6 *a*). The world consumption pattern, however, looks different in terms of percentage of world population, as even a single country with large population can raise consumption (Figure 6 *b*). Though affordability might increase in terms of non-critical items, a region will still be constrained to certain per capita consumption (Figure 7). While such constraints will result from land (Figure 7 *a* and *b*) as well as water (Figure 7 *c* and *d*) and food sufficiency (Figure 7 *e* and *f*), it is the combined criticality that will imply the most restrictive condition (Figure 7 *g* and *h*). Thus subcriticality is likely to set in for most regions as well as the world, although many of these regions may be above criticality for individual resource (Figure 7). For its current population, India (Figure 7, dotted line), for example, can become subcritical for smaller per capita consumption than that for China (Figure 7, dash line) for its current population. The only exception is the USA

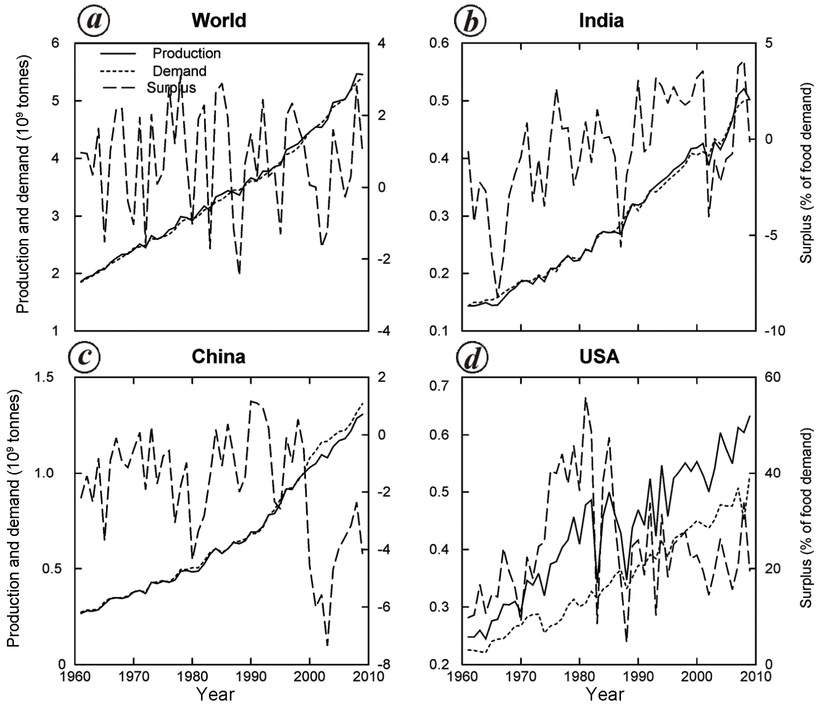

Figure 3. Food production (left *y*-axis, solid line), food demand (left *y*-axis, dotted line) and surplus (production + import-export) as percentage of food demand (right *y*-axis, long dash line) for the world, India, China and the USA. Current food production for world is 5459 mt. India, 502 mt; China, 1306 mt and the USA, 632.5 mt.

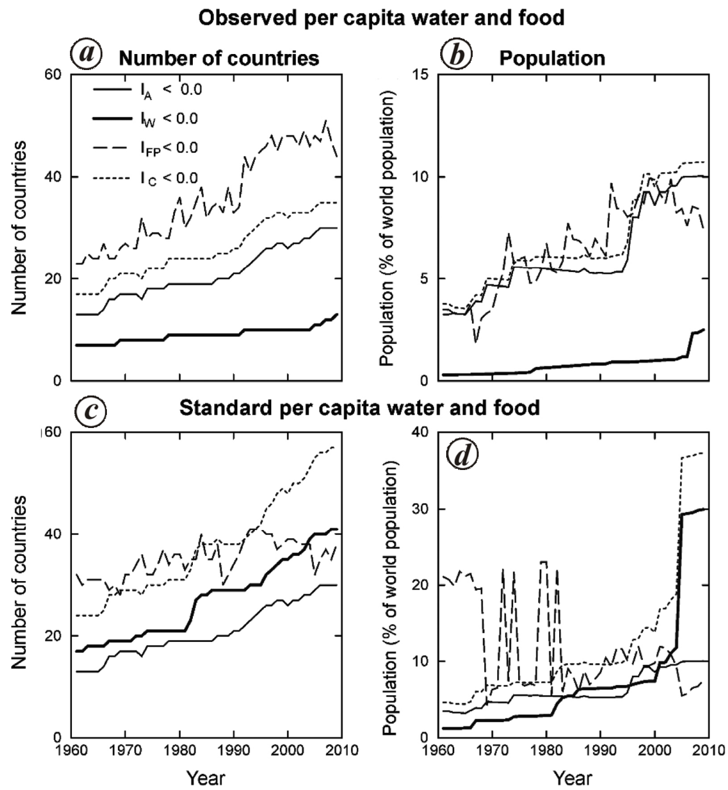

Figure 4. Number of subcritical countries (left panels) and population (percentage of world population, right panels) as a function of time *t* in terms of negative indices of land (I_A, thin solid line), water (I_W, thick solid line), food (I_{FP}, long dash line) and criticality (I_C, dotted line) for observed per capita consumption of food and water (***a***, ***b***) and standard per capita consumption of food and water (***c***, ***d***) for the period 1961–2010. The total number of countries considered here is 162 for which the observed data for water is taken from AQUASTAT and for population and arable land data it is taken from FAOSTAT.

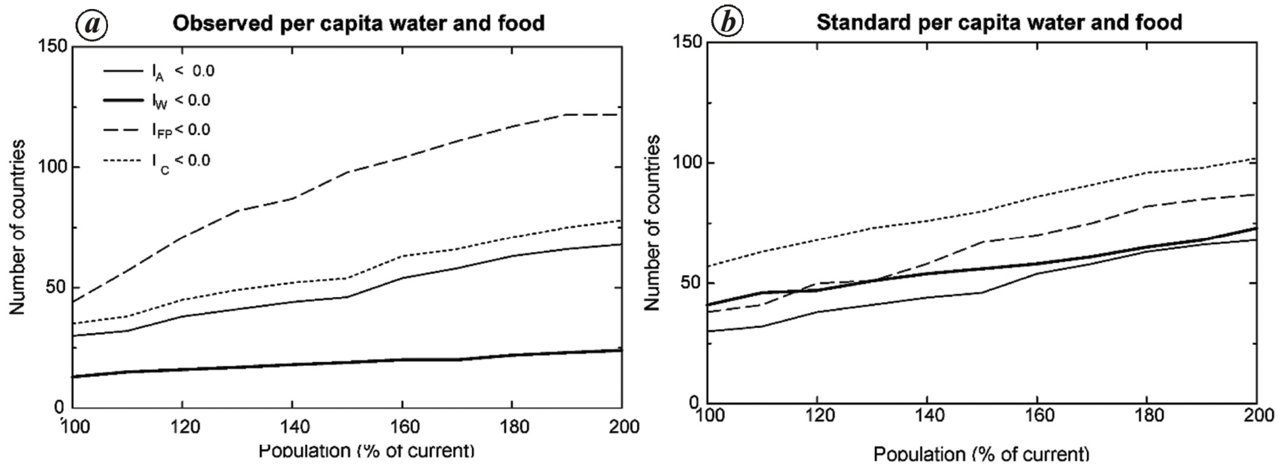

Figure 5. Number of subcritical countries as function of population (percentage of current) in terms of negative indices of land (I_A, thin solid line), water (I_W, thick solid line), food (I_{FP}, long dash line) and criticality (I_C, dotted line) for observed per capita consumption of food and water (***a***) and standard per capita consumption of food and water (***b***) for the period 1961–2010. The total number of countries considered here is 162 for which the required data is available. The observed data for water is adopted from AQUASTAT; for population and arable land data it is adopted from FAOSTAT.

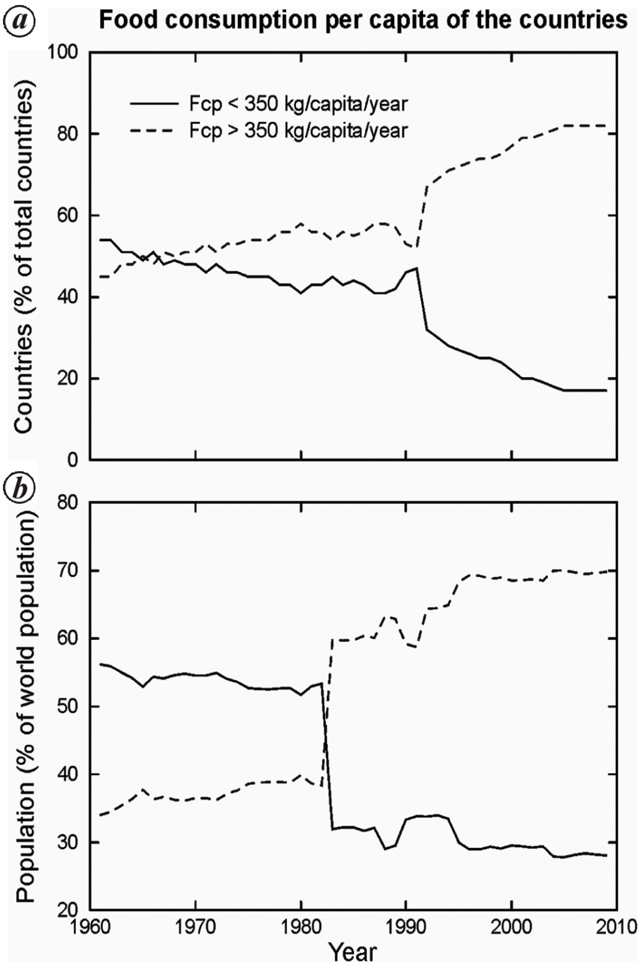

Figure 6. Number of countries (percentage of total countries) and population (percentage of world population) for two categories of per capita food consumption: ≤350 and >350 kg/capita/year. ***a***, Number of countries as percentage of total number of countries (162 countries). ***b***, population as percentage of world population.

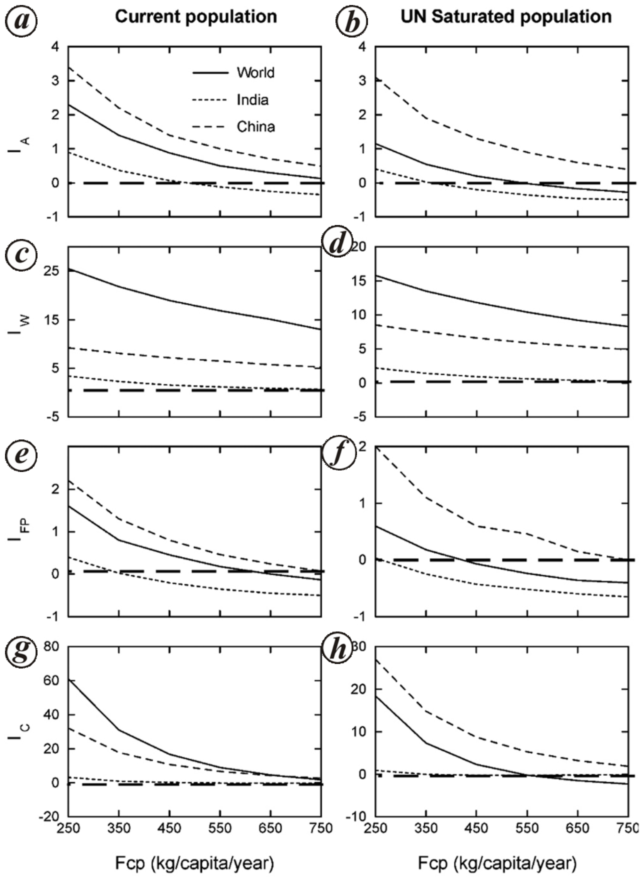

Figure 7. Indices of land sustainability (first row), water sustainability (second row), food sufficiency (third row) and combined criticality (fourth row) as functions of per capita food consumption for the world (solid line), India (dotted line) and China (long dash line). The ***a***, ***c***, ***e*** and ***g*** represent the current population while ***b***, ***d***, ***f*** and ***h*** represent results for population projected by the United Nations Population Division. These estimates are based on current agricultural productivity and current arable land, of the respective country. The horizontal thick dash line represents the state of criticality.

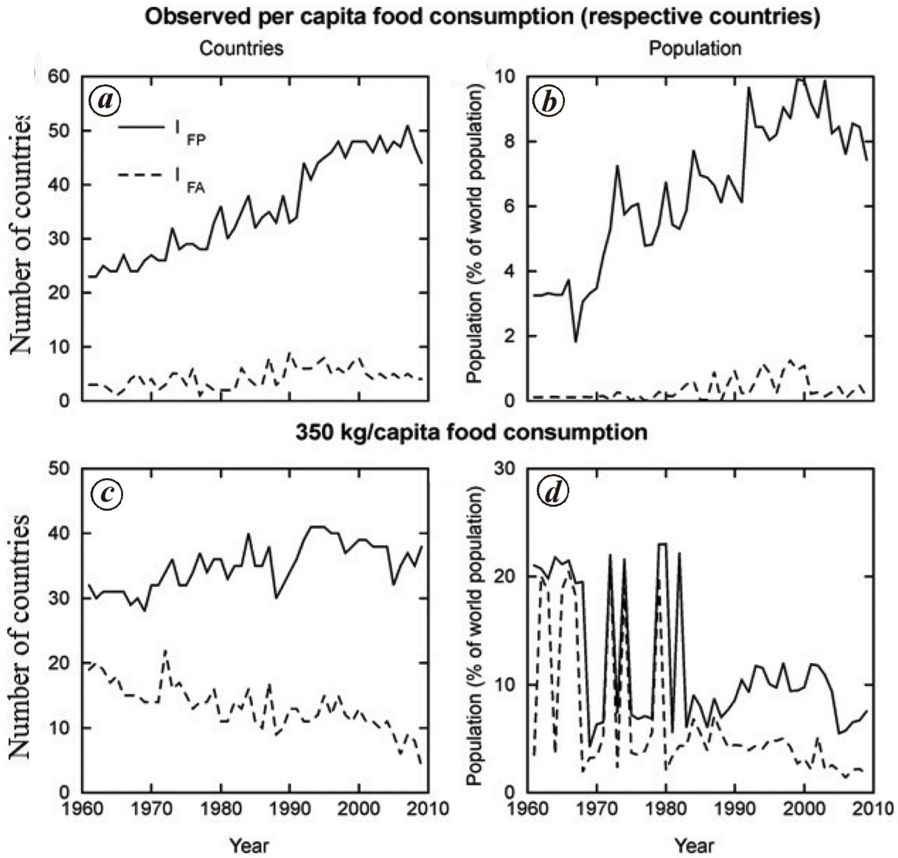

Figure 8. Number of countries and population (percentage of world population) with negative indices of food sufficiency in terms of food production (I_{FP}, solid line, eq. (13)) and food available (I_{FA}, dash line, eq. (14)) for the period 1961–2010. Number of countries have shown for the observed per capita food consumption (***a***) and 350 kg/capita/year (***c***). While, population have shown for the observed per capita food consumption (***b***) and 350 kg/capita/year food consumption (***d***).

which was found to be above criticality for per capita consumption of up to 700 kg/year. The number of countries with negative food sufficiency index (I_{FP}) in terms of food production is higher than those in terms of food available (I_{FA}) for current per capita food consumption (Figure 8). Similarly, the number of countries with negative food sufficiency index for standard consumption for both availability and production of food (Figure 8 *b*) is lower than that with the observed per capita food consumption (Figure 8 *a* and *b*). The fraction of population for 350 kg/capita food consumption for both scenarios is higher than that for observed per capita food consumption (Figure 8 *c* and *d*).

Import dependence

Food deficient countries maintain food sustainability through external sources like import or technology. However, decline of primary resources, and hence production (perhaps compensated by increase in productivity), at regional scale automatically implies more dependence on external sources (import). Thus another important measure is the dependence on import. There is a dramatic increase in the number of import-dependent countries from just above 20 in 1960 to nearly 50 in 2010 (Figure 9 *a*). This number can easily cross 100 (out of 162) countries for current per capita food consumption for a 100% increase in the population of the respective country (Figure 9 *b*). Even for a uniform standard consumption, more than 50% of the countries will be critically import-dependent for a doubling of population.

Additional food requirement for food sustainability

An estimate of additional production required (as percentage of current production) to maintain food sustainability shows a need for more than 100% increase in the current production for certain population-consumption scenarios (Figure 10). While the current country-wide population can be supported with no additional production up to per capita consumption of 650 kg/year for the world as a whole, countries like India cannot support its population with per capita consumption of more than 350 kg/year with its current production. On the other

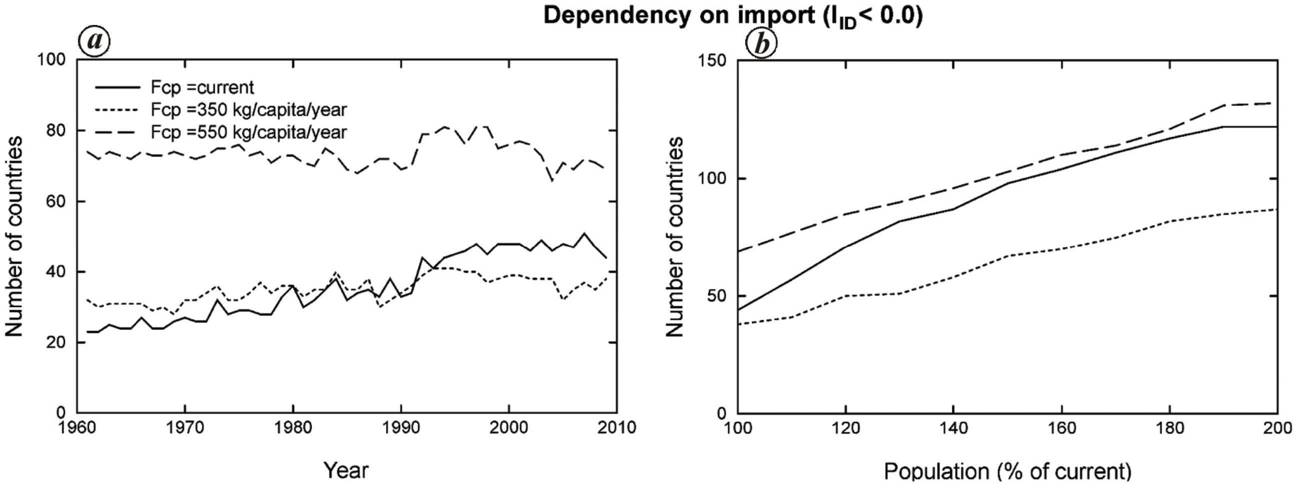

Figure 9. Number of import dependence countries as (***a***) function of time and (***b***) population (based on eq. (14)) for three per capita food consumption: current (respective countries) (solid line), 350 kg/capita/year (dotted line) and 550 kg/capita/year (long dash line) in terms of production of food. The total number of countries considered here is 162 for which the required data is available in FAO database.

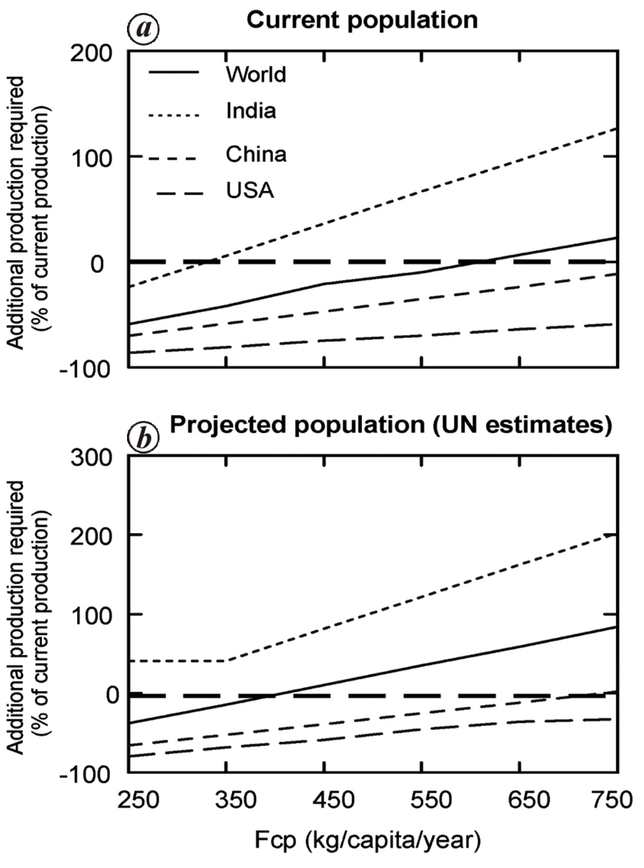

Figure 10. Additional food production required to maintain food sustainability ($I_F = 0.0$) as function of per capita food consumption for the world (solid line), India (dotted line), China (dash line) and the USA (long dash line) for two population scenarios: ***a***, Current population; ***b***, projected population by United Nation Population Division. The horizontal dash line represents the state of food sufficiency (no additional food required). The projected population is given by the United Nations Population Division for the world (10853 million), India (1644 million), China (1453 million) and USA (462 million).

hand, China and USA can afford a per capita consumption of more than 650 kg/year for its population with its current production (Figure 10 *a*). For UN estimated country-wide saturated populations, additional production (through increase in arable land or productivity) would be required to support per capita consumption beyond 350 kg/year (Figure 10 *b*).

Conclusions

Sustainability at both global and regional scales is governed by complex dynamics of resources, international trade and technology innovations (productivity). However, trade can only redistribute surplus available somewhere and productivity can be assumed to have limits. Thus global sustainability is ultimately constrained by the simultaneous availability of primary resources – land and water in a region. This combined criticality imposes stronger constraints on sustainability than the criticality of isolated resource.

Our study shows that the combined criticality index provides a more accurate estimate of sustainability and that the primary resources together will eventually determine the supply, while population and consumption patterns will determine demand. Although in some regions productivity may still increase due to new or more intense applications of technologies, they will eventually saturate while the primary resource criticality will remain the same, or worsen.

The primary conclusion from our study is that there is a growing subcriticality at both global and regional scales in terms of combined criticality than in terms of isolated resource criticality. The subcriticality in primary resources automatically implies decrease of sustainability in dependent sectors like food and nutrition. Thus estimates based on isolated resource need revision based on combined criticality. In this case our estimates of criticality are based on several optimistic assumptions like wealthy country scenario and hence, thus actual criticality may be more severe.

Food production has regional variations due to various factors such as climate variables like solar radiation (or photosynthetically active radiation), rainfall and temperature. It is a basic fact that trade distributes food (or any product) across the globe. However, this distribution cannot change the overall global sustainability; for N global population and F_{CP} per capita food consumption, we need a minimum amount of food ($N \cdot F_{CP}$). Thus even if food from surplus areas is distributed to deficit areas, there will be storage somewhere, if the overall surplus is less than the overall demands. Besides, as the overall deficit increases, there may be a bias in the distribution from the surplus areas and naturally, the poorer countries will be the hardest hit.

In estimating land criticality, we have assumed that the entire available arable land could be used for food production. However, there are other non-food but vital agricultural products that will further restrict the use of arable land for food. Additional constraints may be imposed by climate change, however, its impact can be highly regional[27–30]. Other factors that may reduce sustainability are dietary habits and consumption pattern[13,17].

We have considered current agricultural productivity in calculating production. Agricultural productivity can be increased through many ways and through technological advances. A parameter that is likely to change through technology design is the agricultural productivity. Thus one application of our formalism is the design of mitigation solutions for maintaining sustainability. While any estimate of such future technologies would be qualitative at best, the productivity required to maintain the world food sustainability for different sizes of population was found to vary between 0.2 and 0.8 kg/m^2 depending on per capita food consumption.

It must also be emphasized that most criticality issues also apply at smaller (intra-country) scale with significant implications. On the whole, such criticality can lead to initiative policies to optimize land and water management. The combined criticality in turn will drive and induce ecological transformations at global and regional scales. The likely impacts of climate change, such as induced hyper-aridity and altered hydrological cycle, can introduce further complexity into the dynamics of food, water and hence ecological sustainability.

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