Assessment of agricultural sustainability in changing scenarios

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Agricultural sustainability is an important parameter for policy design. The primary variables for agricultural sustainability, like available arable land and water, depend on competing demands from other sectors as well as natural factors like climate change. The other critical factor that determines sustainability is demand, which changes with population and dietary habits. The supply also depends on external sources (import); thus a comprehensive and quantitative assessment of sustainability is a major scientific challenge. Here we present an assessment of agricultural sustainability for India. Import requirement, potential surplus and sustainability index are used to estimate India's food sustainability.

Keywords: Agricultural sustainability, carrying capacity, degree of dependency, import requirement, trade balance.

BASIC food sustainability can be defined as the ratio of total food available to the total food required for a population[1–3]. Food sustainability for most countries, of course, is primarily determined by domestic production through agriculture; thus, assessment of agricultural sustainability is of considerable interest[4,5]. Several studies have highlighted the need for agricultural sustainability[6,7], and challenges involved in such assessment[8–16], especially for Asia. The importance of comprehensive assessment and policy planning with respect to food security has been also discussed in several studies[15–18]. The actual demand for food needs to take into account the variety and other factors like nutritional requirements[19,20] and consumption patterns[9,20,21]. Besides, agricultural food availability depends not only on domestic production but also on external sources (import); however, external sources will implicitly and explicitly depend on available surplus, affordability and bilateral relations between countries. Domestic production capacity itself is limited by the primary resources like agricultural land and water. On the demand side, both growth in population and change in dietary patterns[9,21] play important roles. On the supply side, ongoing and foreseeable developments in technology can improve production. A comprehensive and quantitative analysis of agricultural sustainability, therefore, is complex. At the same time, such assessments are critical for proactive policy planning. It is now possible to access data on various parameters like domestic production, import and the reserve for all major countries; however, a quantitative synthesis can provide important inputs for policy planning.

The complexity in quantitative analysis of food sustainability arises from the fact that production (supply) and demand depend on a number of changing parameters like the amount of arable land, agricultural productivity[22–24], demand (population and consumption) and supply (production and import). The total agricultural area can increase due to conversion of barren land and cultivable waste land (if available) and decrease due to demands for non-agricultural activities like habitat, industries and infrastructure[9,25–27]. The production can also change (increase) due to agricultural practices and better technology. The other resource that critically restricts agricultural production is water[28–30]. Assuming that for the timescales considered here the groundwater is of infinite storage capacity (although with increasing cost of withdrawal with increasing demand), the available water is then constrained by the available surface water. As we are only interested in long-term sustainability, we do not consider the year-to-year variability of rainfall. However, in spite of these optimistic assumptions, the water availability can reduce due to effects like climate change. In addition, the carrying capacity of a region depends on the multi-faceted impacts of the dynamics of climate change, and especially impact on agriculture and water[31–33].

The objective of our study is the assessment of the status of agricultural sustainability for India through a synthesis of trend in arable land, agricultural productivity and water resources, increasing food demand and growing population as well as dependence on import.

Methods and observed data

We have used data for arable land, agricultural area, agricultural productivity, export, import, agricultural production and food consumption per capita from the Food and Agricultural Organization Statistics Division (FAOSTAT). For calculation of the surplus and import

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requirement, we consider a scenario of maximum arable land and higher agricultural productivity. Food surplus is calculated as the difference between total agricultural production (food items only; non-food items have not been included) to the total food demand and the import requirement is calculated as the difference between the total food demand and the total food production. Food production is calculated as the product of arable land and agricultural productivity. Potential agricultural production is calculated as the maximum arable land to the higher possible agricultural productivity. Food demand is calculated as the product of per capita food consumption and population for the country.

Formulation

Agricultural sustainability, the ratio of food production to the total food demand, is calculated as

$$S_{\mathrm{P}}(t)=\frac{F_{\mathrm{P}}(t)}{F_{\mathrm{D}}(t)}, \tag{1}$$

A more stringent definition of sustainability index is based on the fraction of production available for consumption.

$$S_{\mathrm{A}}(t)=\frac{F_{\mathrm{A}}(t)}{F_{\mathrm{D}}(t)}, \tag{2}$$

where $F_{\mathrm{P}}(t)$ and $F_{\mathrm{A}}(t)$ respectively, are the total food production and total food available for distribution and $F_{\mathrm{D}}(t)$ is the total food demand.

Food production depends on available arable land and agricultural productivity and is calculated as

$$F_{\mathrm{P}}(t)=A_{\mathrm{P}}(t)*A_{\mathrm{g}}(t), \tag{3}$$

where $A_{\mathrm{P}}(t)$ is the agricultural productivity and $A_{\mathrm{g}}(t)$ is the agricultural land at the time (year) t.

The potential production of food is calculated as

$$F_{\mathrm{P_{max}}}=\max(A_{\mathrm{P}}(t))*\max(A_{\mathrm{g}}(t))), \tag{4}$$

where $\max(A_{\mathrm{P}}(t))$ may be equivalent to the current agricultural productivity of the world, China, USA or other developed/developing countries that have agricultural productivity more than India and $\max(A_{\mathrm{g}}(t))$ represents the maximum available agricultural land in India.

Food demand is calculated as

$$F_{\mathrm{D}}(t)=F_{\mathrm{cp}}(t)*N(t), \tag{5}$$

where $F_{\mathrm{cp}}(t)$ is the food consumption per capita and $N(t)$ is the population at time (year) t.

The total food availability depends not only on production, but also on external sources like import. We define an index of (import) dependence, $I_{\mathrm{D}}(t)$, that estimates the import required to meet food demand

$$I_{\mathrm{D}}(t)=\left[1-\frac{F_{\mathrm{P}}(t)}{F_{\mathrm{cp}}(t)*N(t)}\right]. \tag{6}$$

The food surplus, as fraction of total food demand, is calculated as

$$F_{\mathrm{S}}(t)=\left[\frac{F_{\mathrm{P}}(t)}{N(t)F_{\mathrm{cp}}(t)}-1\right]. \tag{7}$$

The trade balance, as percentage of total food demand, is calculated as

$$T_{\mathrm{R}}(t)=\left[\frac{F_{\mathrm{E}}(t)-F_{\mathrm{I}}(t)}{F_{\mathrm{D}}(t)}\right]*100, \tag{8}$$

where $F_{\mathrm{E}}(t)$ and $F_{\mathrm{I}}(t)$ respectively, are the total export and total import of the agricultural products (only food items; non-food items excluded).

The total food availability is calculated as

$$F_{\mathrm{A}}(t)=F_{\mathrm{P}}(t)\{1-F_{\mathrm{L}}(t)\}+F_{\mathrm{I}}(t)-F_{\mathrm{E}}(t). \tag{9}$$

Here, $F_{\mathrm{L}}(t)$ is food loss as the fraction of the food production during production and consumption (including storage and distribution). Thus, $F_{\mathrm{L}}(t)$ can be represented as

$$F_{\mathrm{L}}(t)=F_{\mathrm{LP}}(t)+F_{\mathrm{LC}}(t). \tag{10}$$

Here $F_{\mathrm{LP}}(t)$ represents the food loss due to production and retail sector (around 110 kg/capita/year) and $F_{\mathrm{LC}}(t)$ represents the food loss due to consumers (15 kg/capita/year). The typical value of total food loss during production and consumption is 125 kg/capita/year (ref. 34). As the food wasted in consumption is already implicit in food consumption per capita ($F_{\mathrm{LC}}(t)=0$), the food lost is essentially due to production and retail sector and is represented as

$$F_{\mathrm{LP}}(t)=\alpha*F_{\mathrm{P}}(t). \tag{11}$$

The parameter α is estimated as

$$\alpha=\frac{1}{J}\sum_{t=1}^{J}\frac{\alpha_{\mathrm{L}}*N(t)}{F_{\mathrm{P}}(t)},$$

where J is the number of years and α_{L} is the per capita food loss in the production and retail sector; the typical value of α_{L} is 110 kg/capita/year[34]. Thus, a representative value of the parameter α is 0.26.

The water required for irrigation is calculated as

$$W_{IR}(t) = W_{IH} * A_{IR}(t), \quad (12)$$

where W_{IH} represents the water required for irrigation per hectare and $A_{IR}(t)$ represents the observed irrigated area (FAOSTAT)[35].

Results

Assessment of primary resources and external sources

One of the critical primary resources for food production is arable land which, for most countries, is only a fraction of the total land area. The agricultural area for India has shown saturation and decline in the recent years (Figure 1 *a*, left *y*-axis); this decrease is consistent with the increasing demand on land for non-agricultural activities. The current per capita availability of arable land is about 60% of the minimum arable land required to produce food for one person, while it was about 150% in 1960 (Figure 1 *a*, right *y*-axis). The other parameter that affects agricultural sustainability the most is water. The water required for irrigation has increased from 1800×10^9 m^3 to 5000×10^9 m^3 in 50 years (from 1960 to 2010; Figure 1 *b*, left *y*-axis), while the per capita water availability has declined from 4000 m^3/year to around 1500 m^3/year in the last 50 years (Figure 1 *b*, right *y*-axis). Thus, there is reduction in primary resources[35].

The agricultural productivity can be improved through input like fertilizers and pesticides. The fertilizer utilization for India has increased about 200 times in the period 1960–2010 (Figure 1 *c*, left *y*-axis), while the pesticides utilization per hectare has shown decrease during the period 1990–2000, but increase in the recent years (Figure 1 *c*, right *y*-axis)[35].

Assessment of supply and demand

Food production has to saturate and is already near estimated values of saturation (Figure 2 *a*, left *y*-axis); especially in the recent years. The potential food production (as percentage of food demand) also has shown a declining trend in the period 1960–2010 (Figure 2 *a*, right *y*-axis). The per capita food consumption (Figure 2 *b*, left *y*-axis) and the total food consumption (Figure 2 *b*, right *y*-axis) have shown increasing trends in the recent years.

Assessment of degree of dependency (import requirement) and sustainability

A measure of dependence on external sources is expressed by the index of dependency or degree of dependence on external sources, which is the import requirement to meet the food demand. The import requirement for India has decreased in the recent years due to increase in food production (Figure 3).

The trade balance (export–import) has shown increasing trend in the recent years, while it showed decreasing

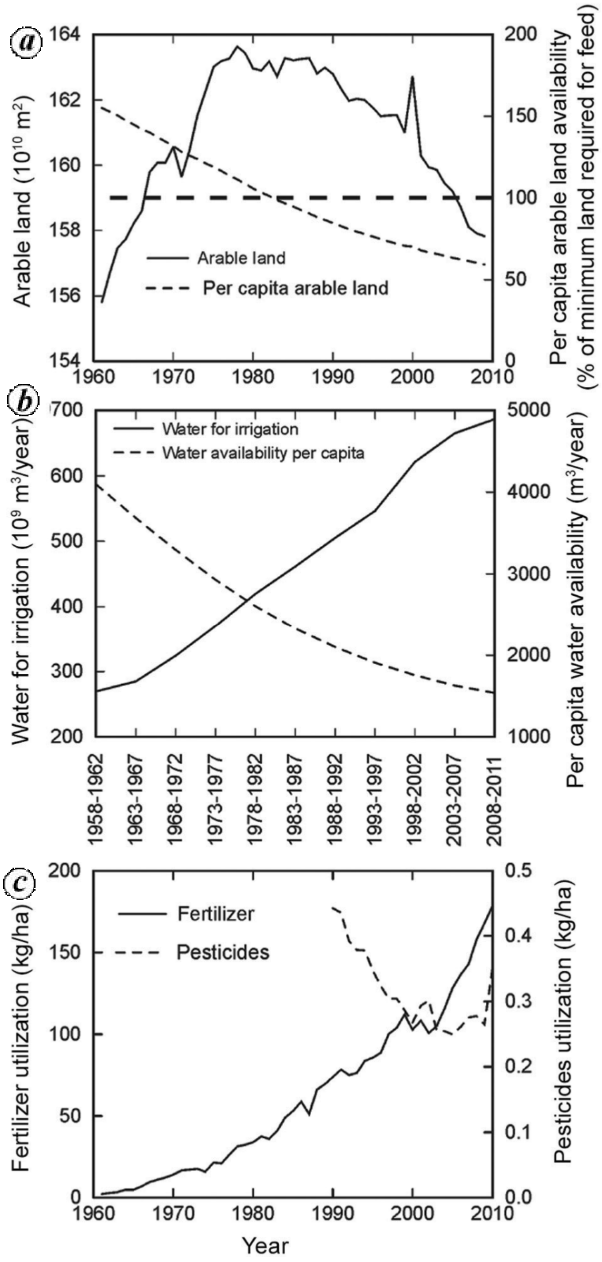

Figure 1. Availability and status of the primary resources for India. ***a***, Total arable land (left *y*-axis, solid line) and per capita land availability (right *y*-axis, dashed line), expressed as the percentage of minimum land needed to produce food for one person (0.22 ha; http://www.gdrc.org/sustdev/fao-100.pdf). ***b***, Water use for irrigation (left *y*-axis, solid line) and per capita water availability (right *y*-axis, dashed line) for different epochs. ***c***, Fertilizer utilization per hectare (left *y*-axis, solid line) and pesticides utilization per hectare (right *y*-axis, dashed line). The observed data for fertilizer utilization and arable land are taken from FAOSTAT; the data on pesticides are adopted from Department of Agriculture and Cooperation, Government of India[36].

trend in the past (Figure 4 *a*). The observed export (percentage of food production, left *y*-axis) and import (percentage of food demand, right *y*-axis) are shown in Figure 4 *b*.

Import requirement (food demand–food production) in the current agricultural productivity estimated as percentage of the total food demand (Figure 5, left *y*-axis) for the per capita food consumption of 350 kg/year (shaded histogram) for India (Figure 5, left *y*-axis) shows a steady but nonlinear growth with increasing population. Once again, this dependence increases for higher per capita food consumption of 450 kg/year (non-shaded histogram, Figure 5). For India, maximum arable land and the current agricultural productivity of the world (0.4 kg m^{-2}, Figure 5 *e*) and China (1.2 kg m^{-2}, Figure 5 *b*) have been used to calculate potential food production. The surplus (food production–food demand) is calculated as percentage of the potential food production for two per capita food consumption scenarios; 350 kg/capita/year (right *y*-axis solid line) and 450 kg/capita/year (right *y*-axis, dashed line) of India.

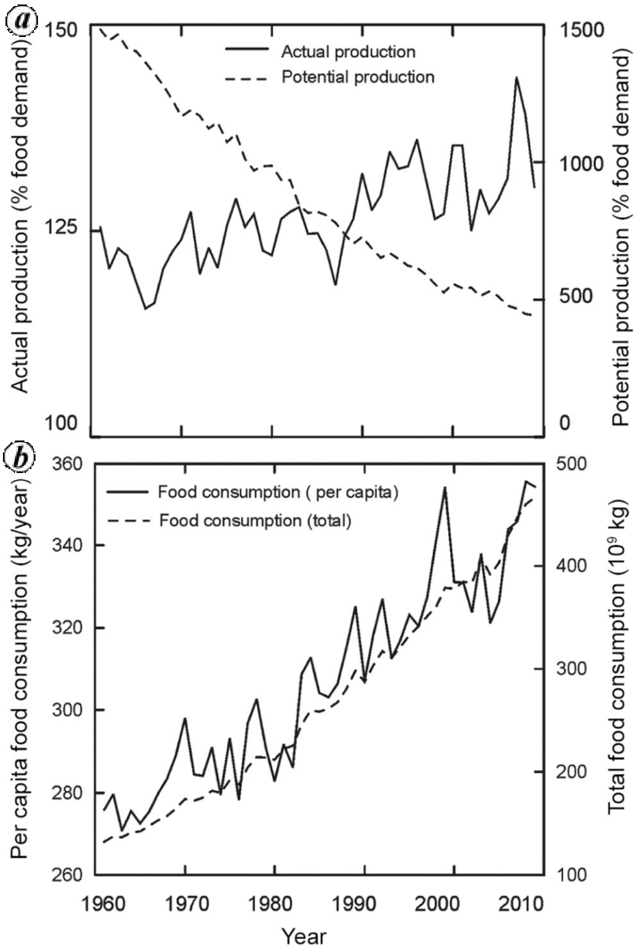

Figure 2. Supply and demand of food for India during 1960–2010. ***a***, Actual production (left *y*-axis, solid line) and potential food production (right *y*-axis, dashed line) as percentage of food demand for India. Potential food production is calculated as the multiple of total available arable land and high agricultural productivity (1.2 kg/m^2). Food production is calculated as the multiple of utilized (current) arable land and current agricultural productivity. ***b***, Per capita food consumption (left *y*-axis, solid line) and total food consumption (right *y*-axis, dashed line). The data for per capita food consumption and total food consumption are adopted from FAOSTAT.

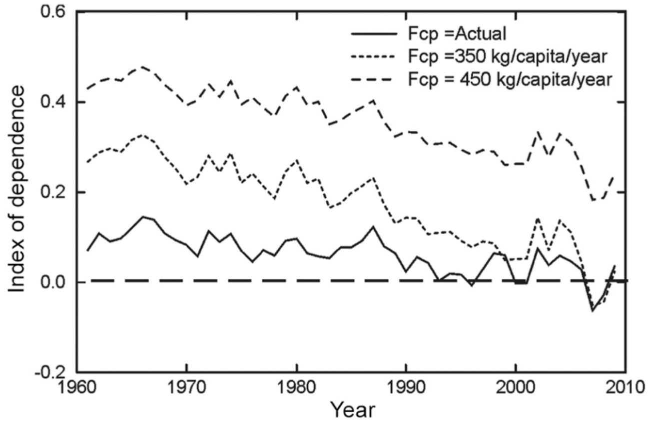

Figure 3. Index of dependence indicates the fraction of population that needs import to meet food demand (eq. (6)) in three scenarios of per capita food consumption: actual (solid line), 350 kg/capita/year (dotted line) and 450 kg/capita/year (dashed line).

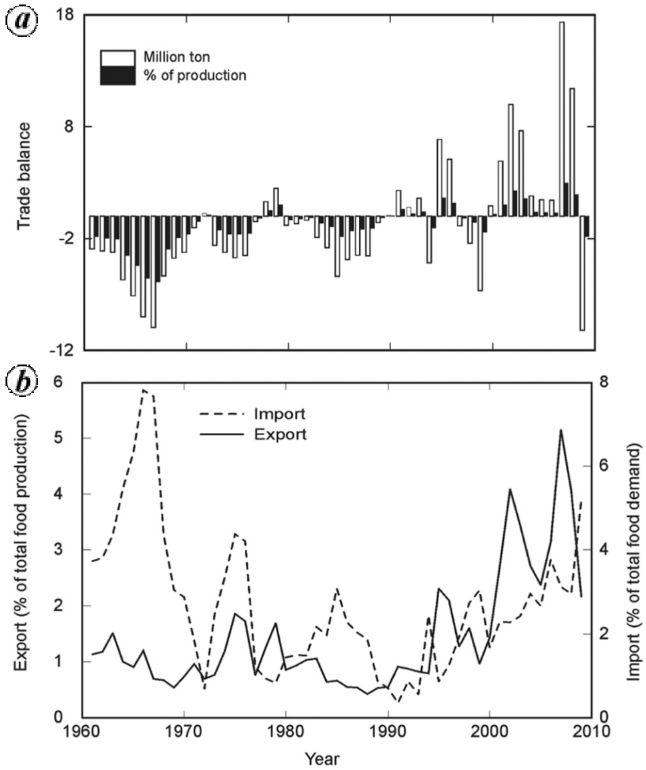

Figure 4. ***a***, Trade balance (export–import) and ***b***, export (percentage of total food production; left *y*-axis, solid line) and import (percentage of total food demand; right *y*-axis, dashed line) of food commodities. The actual trade balance (non-shaded bars) and the trade balance as percentage of food production (shaded bars) are also given in (***a***). The observed data have been adopted from FAOSTAT.

The production-based sustainability index in terms of actual annual data starts above 1.2 in 1960 and shows marginal increase with time since around 1980, along with strong inter-annual variability. In contrast, sustainability index based on available food with actual consumption began with a value much less than 1 around 1960, but has reached a value close to 1 around 1990 (Figure 6 *a*, solid line); however, there has been no significant increase in the sustainability index based on available food since around 1990, merging with the line around 2010 (Figure 6 *a*, solid line). For the period 1960–2000, the sustainability index $S_A(t)$ is well below the critical value for the scenario of per capita consumption of 350 kg/year. While $S_A(t)$ for per capita food consumption of 350 kg/year has now reached 1, it is still not a stable scenario (Figure 6 *b*, solid line); naturally, a higher per capita food consumption would bring $S_A(t)$ below unity. Expectedly, $S_P(t)$ is higher than $S_A(t)$, and is above 1 for all the years since around 1970; thus, the two indices provide different time lines for planning and decision support (Figure 6 *b*).

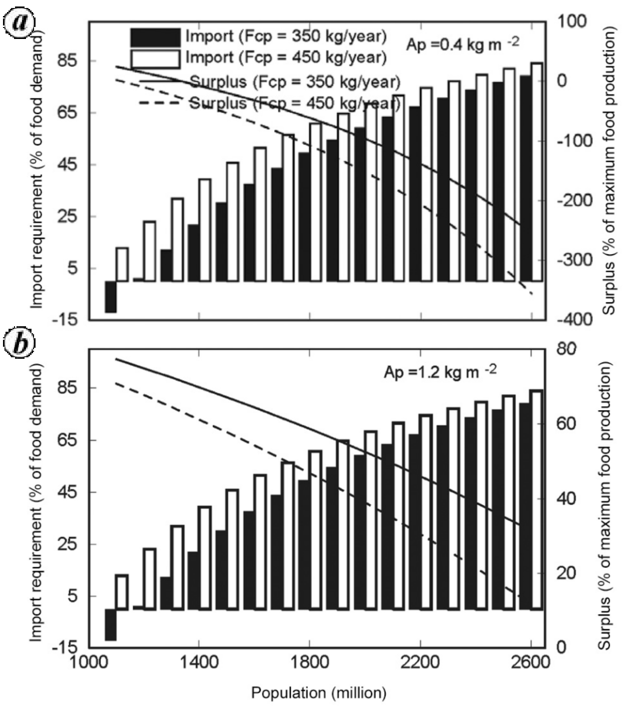

Figure 5. Trade (import) requirements (demand–production) to meet food demand as a function of population for India. Trade (import) requirement (left *y*-axis) expressed as percentage of total food demand of India to meet food demand and world surplus (percentage of the world food demand, solid line) for two scenarios of per capita food consumption; 350 kg/year (current per capita food consumption of India; non-shaded bar) and 450 kg/year (current per capita food consumption of the world; shaded bar). The right axis for $F_{cp} = 350$ kg/capita/year (solid line) and $F_{cp} = 450$ kg/capita/year (dashed line) shows the corresponding surplus, as percentage of potential food production is calculated as the difference between food production and food demand for two scenarios of productivity: 0.4 kg/m^2 (***a***) and 1.2 kg/m^2 (***b***). The potential food production is calculated as the maximum available arable land and agricultural productivity.

Discussion

The basic objective of our study has been to provide a quantitative and consistent framework for agricultural sustainability. An important conclusion from our study is that the primary resources for agriculture are on the decline, and as such the supply will have to increasingly depend on external resources like import. We have considered here a wealthy-country scenario, in which the agricultural products are not used to support associated costs like fertilizer, irrigation, transport, etc. (except perhaps seeds). Further constraints will be implied for agricultural sustainability if a nation depends on its income from agriculture to support these activities. In accordance with our concept of agricultural sustainability, the estimates are essentially for basic survival (minimal agricultural product requirement). These estimates will have to be accordingly revised, if proper considerations of nutritional as well as dietary demands are included[12,21].

A more comprehensive analysis of agricultural sustainability may require inclusion of marine products. However, the restrictions of finite arable land and productivity also apply to marine products. Similarly, inclusion of animal protein is likely to only reduce agricultural sustainability; the amount of land needed for producing a given weight of meat is much more than that needed for producing vegetables. Since we have not considered the contribution of reserve food due to excess of production,

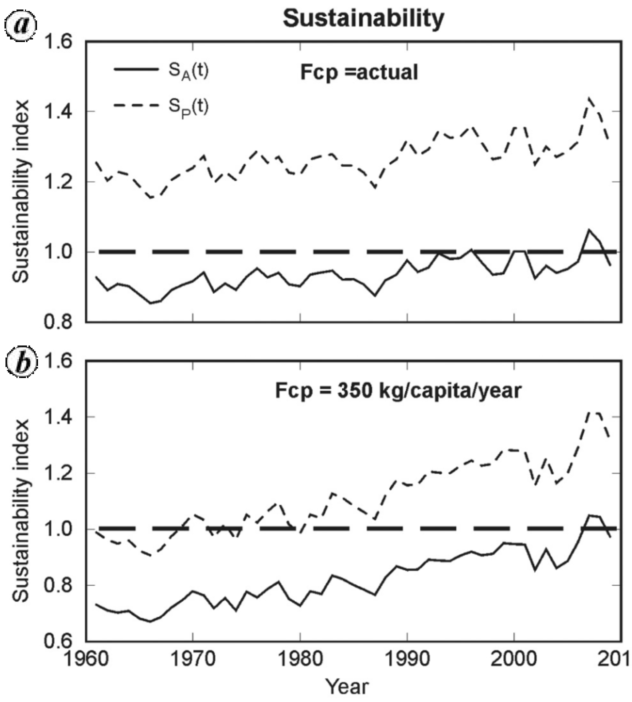

Figure 6. Agricultural sustainability index (eqs (1) and (2)) based on total food production (dashed line) and total food available (solid line) for two consumption scenarios. ***a***, Actual food consumption per capita. ***b***, Per capita food consumption of 350 kg/capita/year. The horizontal dashed line represents the status of agricultural sustainability based on the equality of supply and demand.

the actual onset of loss of agricultural sustainability may be somewhat delayed than estimated here; but these factors will not change the conclusions in any significant manner.

An important result from our study is the difference in sustainability based on production and available food. As food available from production is primarily determined by wastage, better management of storage and distribution emerges as an important factor in attaining food sustainability. While various measures like ascertaining food security are important for a modern society, our results show that this may not be sustainable with a growing population, declining primary resources and static productivity. While the production deficit may be offset through external sources, this will come at an increased dependence on import with its geo-political implications.

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