Dynamical formalism for assessment and projection of carrying capacity in different socio-climatic scenarios

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Increase in demand, decline in primary resources and impact of climate change make agricultural sustainability a complex function of many variables. A major gap is a consistent and quantitative formulation for assessment and projection of sustainability. We consider agricultural self-sustainability, defined as the condition of minimum food requirement from domestic production, and present a dynamical model of evolution of its constrained dynamics. The model is then applied to estimate and project agricultural self-sustainability, carrying capacity and import requirement with India as a case study in different socio-climatic scenarios. Unconstrained productivity is considered to determine technology demand for different scenarios.

Keywords: Agricultural self-sustainability, carrying capacity, degree of dependency, dynamical sustainability model, technology demand.

FOOD sustainability of a nation depends on many factors like population, production, consumption and import. However, self-sustainability, simply defined as the ratio of total food available to the minimum total food required at a given time, is a good measure of the state of a community or a people[1,2]. The concept and measure of agricultural sustainability have gained considerable attention in the recent years[3–5]. Several works have highlighted the need for, and the challenges involved in[6–8], the assessment of food sustainability, especially for regions with growing population and changing consumption pattern. For India, the primary resources like agricultural area already show saturation and decline[5,9,10]; the current per capita food consumption (F_{cp}) of 350 kg/year is likely to rise to the world level and may increase further if the economic growth continues. While agricultural processes like improved land use[11] and production[12] are important, there are also challenges related to decline in global food production (and thus availability for import) due to processes like ocean warming[13] and constraints with regard to natural resources[14]. The importance of comprehensive assessment and policy planning with respect to food security has been discussed in a number of works[15,16]. The actual demand for food needs to take into account the variety and other factors like nutritional requirements and changes in consumption patterns[17–19]. As against the assessment of general food sustainability, it is important to consider the status of self-sustainability as a reference state. An important requirement for long-term policy planning is quantitative and accurate projection of sustainability in a consistent and comprehensive framework. However, a dynamical formalism that allows quantitative assessment and projection of sustainability is essentially missing.

We introduce agricultural self-sustainability (ASeS), defined as a condition in which the entire minimum food requirement of a people is producible from its own agriculture[1,2]. Many studies have shown the need for self-sufficiency in food[20,21]. The concept of ASeS is also intimately related to the intrinsic carrying capacity. Unlike in some natural ecological systems, the carrying capacity for a human population, as measured in terms of the number of members (population) that can be supported in a self-sufficient manner, changes due to increase or change in demand or supply due to factors other than rise in population, such as consumption[22,23]. The actual carrying capacity will also depend on external factors like availability and affordability of import[22–24]. While there are several ways of estimating demand and supply, our focus here is on minimum requirement and maximum possible domestic availability for ASeS. Thus we consider maximum potential production and minimum requirement.

It could be argued that ASeS is not important for a country with enough or growing wealth to obtain food through import. However, while unlimited availability and affordability of food through trade can theoretically support an ever-growing population, in practice carrying capacity is also limited by competing demands on primary resources like land and water[25–29]. While ASeS needs to be considered in its own right as an important quantitative measure for policy design and assessment, it may also become increasingly relevant due to worldwide saturation and reduction in surplus[9,10,12,13]. While production can increase in response to demand, it is ultimately limited by the primary resources (arable land and water)[25–29], and technology such as agricultural productivity[30,31].

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As mentioned above sustainability and carrying capacity are dynamical variables due to their dependence on primary and secondary resources and demand that change with time. The total agricultural area, $A_g(t)$, can increase due to conversion of barren land and cultivable waste land (if available) and decrease due to demand for non-agricultural activities like habitat, industry and infrastructure[25,26]. The other resource that critically restricts agricultural production is water[29–31]. In addition, the carrying capacity of a region depends on the multi-faceted impacts of the dynamics of climate change, and especially on agriculture and water[32,33]. It is now possible to quantitatively examine various aspects like domestic production, import and the reserve for all the major countries. In what follows, we shall present a model of constrained dynamics of ASeS. It is a dynamical model in the sense that it describes time evolution of a member of inter-connected variables under certain constraints. This model is then applied to India to investigate the implications and also quantify the requirements of import and technology to meet ASeS. We consider a country (nation), here India, as a whole to implicitly allow unlimited domestic trade (in-country distribution).

The dynamical model of ASeS

The basic ASeS model considers evolution of land resource, per capita food available from agriculture and the minimum food required. We then define an index of ASeS as the ratio of the total available food to the total food demand:

$$S(t) = \frac{F_{\mathrm{A}}(t)}{F_{\mathrm{D}}(t)}, \tag{1}$$

where $F_{\mathrm{A}}(t)$ and $F_{\mathrm{D}}(t)$ respectively, represent the total food available and the total food demand. We have a state of ASeS when $S(t) \geq 1$ and the onset of loss of ASeS when $S(t) < 1$. The time t (year) at which $S(t)$ becomes persistently less than 1 is referred to as the year of the loss of agricultural self-sustainability.

Dynamics of population

For a non-trivial exploration of ASeS, we assume that while India's population will not decrease in future, it will not grow linearly either, and reach a saturation. We represent a population that restricts linear growth and reaches saturation as

$$\frac{\mathrm{d}N_T}{\mathrm{d}t} = \beta_{\mathrm{N}}\left(1 - \frac{N_{\mathrm{T}}(t)}{N_{\mathrm{TS}}}\right)N_{\mathrm{T}}(t), \tag{2}$$

where N_{T}(t), N_{TS} and β_{N} respectively, are the population at the time t, the saturation value and growth rate of the population (Table S2, see Supplementary material online).

Dynamics of primary resources: land and water

To arrive at the potential agricultural production, we consider the total agricultural area that can support agriculture. We consider a governing equation for the total agricultural area, $A_{\mathrm{g}}(t)$ as

$$\frac{\mathrm{d}A_{\mathrm{g}}}{\mathrm{d}t} = \alpha_{\mathrm{U}}\left(\frac{\mathrm{d}A_{\mathrm{F}}}{\mathrm{d}t}\right) - A_{\mathrm{U}}\frac{\mathrm{d}N_{\mathrm{T}}}{\mathrm{d}t}, \tag{3}$$

where A_{U} and α_{U} respectively, represent the minimum per capita land used for non-agricultural activities and the rate of conversion of fallow land for agricultural activities. The second term on the right hand side of eq. (3) represents the loss of agricultural land due to conversion for non-agricultural activities. The total agricultural area is defined as the sum of arable land, permanent crop land and permanent pasture. Here we assume that the total agricultural area is available for the production of food crops to assess ASeS.

Similarly, fallow area is assumed to change according to

$$\frac{\mathrm{d}A_{\mathrm{F}}}{\mathrm{d}t} = \alpha_{\mathrm{F}}\left(1 - \frac{A_{\mathrm{F}}(t)}{A_{\mathrm{FS}}}\right)A_{\mathrm{F}}(t). \tag{4}$$

Here α_{F} is the rate of change of fallow area to agricultural area and $A_{\mathrm{F}}(t)$ is the fallow area in the year t. The conversion of fallow land to agricultural area is assumed to progress based on demand for agricultural and non-agricultural activities[25,26].

Assuming that for the timescales considered here the groundwater is of infinite storage capacity, the available water is then constrained by the available surface water. In the best-case scenario, we assume that shifts of rainfall pattern within a year, such as shortening of the monsoon[34], do not affect overall agricultural production if the annual rainfall is unchanged. For our country-wide analysis, we consider total annual rainfall over the entire country, $R(t)$, in a year t. In general, only a fraction of the annual rainfall ($R(t)$) received at a location will be available for agricultural activities due to losses through evaporation, run-off and groundwater recharge. Typically, the utilizable water is about 40% of the annual rainfall. However, agricultural practices, such as crop choice, can be considered to have evolved over time to adapt to an expected value, which is proportional to $\bar{R}(\sim 0.3\bar{R})$, where $\bar{R}$ represents the long-term average of annual rainfall, $R(t)$.

Agricultural productivity and technology demand

A parameter that is likely to change through technology design is the agricultural productivity; a variety of technological inputs can contribute to improve productivity[30,31]. Productivity is a function of several factors like agronomic practices, climate change and agricultural technology. We therefore consider overall agricultural productivity as a control variable to determine carrying capacity and it is represented as

$$\frac{dA_P}{dt} = \gamma\left(1 - \frac{A_P(t)}{A_{PC}}\right)A_P(t). \tag{5}$$

Here A_{P0} is the agricultural productivity in the initial year and A_{PC} represents a saturation value of agricultural productivity, adopted to be 0.6 kg/m^2 as the current worldwide representative value.

Production, demand and availability of food

Thus, we define the total food production, $F_P(t)$, at a given time t (year), as

$$F_P(t) = A_g(t)A_P(t)\left(\frac{W(t)}{W_C}\right). \tag{6}$$

We assume a quantity W_C that defines a critical amount of water required for standard agricultural practices. The term $W(t)/W_c$, where $W(t)$ represents the water available for agriculture at a given time t, modulates production and contains the impact of climate change. We adopt a value of W_C proportional to $\bar{R}$. As both $R(t)$ and $\bar{R}$ have the same relation with respect to W_C, we ignore the constant of proportionality between W_C and $\bar{R}$ and replace $(W(t)/W_C)$ by $(R(t)/\bar{R})$. Using eqs (3) and (5), eq. (6) can be written as

$$F_P(t) = A_g(t)A_P(t)\left(\frac{R(t)}{R}\right). \tag{7}$$

The last factor in eq. (7) contains our assumption that higher (lower) rainfall than the current mean rainfall enhances (reduces) agricultural production. Although the deficit in the surface water from rainfall can be reduced through water efficient agricultural production.

The total (minimum) food demand depends on the total population and the per capita food consumption (F_{CP}), is represented as

$$F_D(t) = F_{CP} * N_T(t). \tag{8}$$

For calculation of the total food available for consumption, $F_A(t)$, we proceed as follows

$$F_A(t) = F_P(t) - F_L(t). \tag{9}$$

The term $F_L(t)$ represents the total loss of food that accounts for the avoidable (equivalent) loss for items like irrigation, seed, fertilizers and transport. The other (unavoidable) part is due to the inevitable losses associated with the processes of distribution and consumption. We thus write

$$F_L(t) = F_{LW}(t) + F_{LP}(t), \tag{10}$$

where

$$F_{LW}(t) = \alpha_{PW}F_P(t), \qquad \alpha_{PW} = \frac{1}{J}\sum_{t=1}^{J}\frac{\alpha_L N_T(t)}{F_P(t)},$$

J is the number of years.

Again, in the wealthy country scenario, we assume that the costs of all available losses due to storage and distribution can be met from other sources, and hence $F_{LP}(t) = 0$. The other term, $F_{LW}(t)$, is assumed to be proportional to the total production as well as the total population. The associated loss is estimated as about 125 kg/capita/year (α_L)[35], which works out to be about 37% of total food production at present for India.

Dynamics of import and export

The total import of the food, $F_I(t)$, is represented by

$$\frac{dF_I}{dt} = \alpha_D F_D(t) - \alpha_{PI}F_P(t) + a_R F_R(t) + a_{TB}F_{TB}(t). \tag{11}$$

Here $F_R(t)$ is the total food reserve ($F_R(t) = F_P(t) - F_D(t)$) and $F_{TB}(t)$ represents the trade balance of the food commodities ($F_{TB}(t) = F_I(t) - F_E(t)$). The value of the parameter α_R, obtained through the process of calibration, is given as

$$\alpha_R = \begin{cases} 0.02 & \text{if} \quad F_R(t) < 0.0, \\ -0.03 & \text{if} \quad F_R(t) > 0.0. \end{cases}$$

The total food exports, $F_E(t)$, is represented as

$$F_E(t) = \alpha_{EP}F_P(t) + \alpha_{ER}F_R(t). \tag{12}$$

Using eqs (9)–(12), eq. (8) can be represented as

$$F_A(t) = F_P(t) - F_E(t) + F_I(t) - F_L(t). \tag{13}$$

Methods

As many of the parameters that appear in eqs (1)–(13) cannot be assigned precise observed values, they are estimated following a calibration procedure for the period of 20 years (1961–1980). For calibration, all these parameters are allowed to vary within prescribed ranges to determine the set of parameters that provides minimum average absolute error in simulation with respect to observations over the calibration period (1961–1980). The calibrated model is then validated against observations for an independent and larger period of 30 years (1981–2009) to determine the acceptability of the model for projection. For calibration and validation, we define absolute error in the simulation of a variable X as

$$e_{\mathrm{s}} = |X_{\mathrm{s}} - X_{\mathrm{o}}|, \tag{14}$$

where X_{s} is the simulated variable and X_{o} is the corresponding observed value. The simulations are carried out using a FORTRAN code.

For calculation of the critical population for ASeS ($S(t) = 1$), we consider maximum available agricultural area (181.6×10^{10} m^2) and the worldwide representative value of productivity (0.5 kg m^{-2})[36] with zero export or import. A description of the model parameters and observed parameters along with their typical values, is given in Tables S1 and S2 respectively (see Supplementary material online).

Results

Simulation and validation of ASeS for India

The simulations of agricultural area, agricultural production, agricultural productivity, population, import and export for the calibration period of 20 years (1961–1980, thin solid line, Figure 1) match well with the corresponding observations (dashed line, Figure 1) with correlation coefficients between the observed and the simulated values significant at 99% confidence level. Similar conclusion also holds for the validation period of 30 years (1981–2009, thick solid line, Figure 1). In particular, the model simulations capture the observed downward trend in the agricultural area beyond 1990 (Figure 1 *a*). Similarly, the total agricultural production, given by eq. (10), also matches well with the corresponding observations for both the calibration and validation periods (Figure 1 *b*). Agricultural productivity, simulated according to eq. (5) also shows good agreement during the calibration and validation periods (Figure 1 *c*). The inset in Figure 1 *c* shows the saturation of productivity (eq. (5)) around the year 2100. The simulated population also matches well with the corresponding observations for both the calibration and validation periods (Figure 1 *d*). For a realistic estimate of ASeS, the population is restricted (eq. (2)) to saturate around 1720 million (inset, Figure 1 *d*). Similarly, the simulation of import (Figure 1 *e*, eq. (11)) and export (Figure 1 *f*, eq. (12)) matches well with the observations. As expected, the simulations do not contain the inter-annual variability present in the observations.

Evolution and projection of ASeS

The competing impacts of changes in agricultural land, agricultural productivity and water availability as well as demand due to growing population and consumption result in a complex evolution of ASeS (Figure 2). Starting from a low value close to 0.82 and a sharp increase due to the efforts during the green revolution in the next decades, India is currently in a position of ASeS (Figure 2 *a*; solid line) and is likely to maintain this situation (Figure 2 *a* and *b*) with current annual rainfall and per capita consumption. The growing demands of consumption, as well as decrease in agricultural area, however, imply a gradual but steady decline in ASeS (Figure 2 *b*). The situation may worsen, as expected, if the food consumption increases (Figure 2 *a*), or the annual rainfall decreases below the current mean rainfall (Figure 2 *b*). Even in the most optimistic scenario of low food consumption and enhanced annual rainfall, the loss of ASeS can be only postponed even if the population saturates as assumed.

Although a direct validation of simulation of sustainability index from observed data is not conceptually

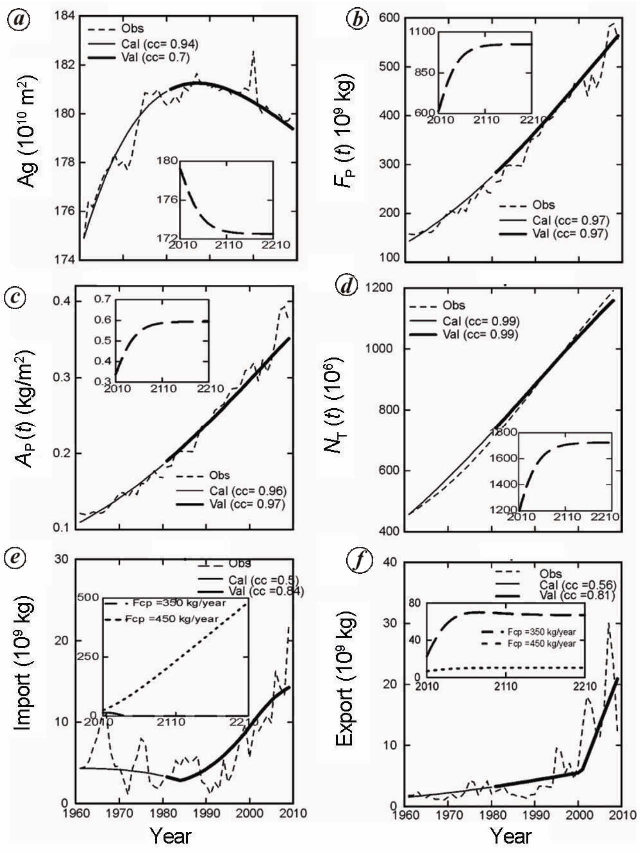

Figure 1. Calibration (thin solid line, 1961–1980) and validation (thick solid line, 1981–2009) of simulations of (***a***) agricultural area, (***b***) food production, (***c***) agricultural productivity, (***d***) population, (***e***) food import, and (***f***) food export. (Inset, (***a***)–(***f***)) Projections of the respective quantities for the period 2010–2200. The observed data (dashed line, 1961–2010) in each figure are adopted from FAOSTAT[36]. (Inset, (***e***) and (***f***)) Projection of food import and export respectively, for two values of F_{CP}: 350 kg/capita/year (long dashed line) and 450 kg/capita/year (dotted line). The correlation coefficients between the simulations and the observations for each period are given in brackets for the respective case.

possible, it is instructive to compare our simulation of ASeS with two quantities: the first is the ratio of the (observed) food available, F_{AO} (total agricultural production + import – wastage food) to the food consumption. The second quantity is the ratio of total agricultural production, F_{PO}, to the total food consumption for the period 1961–2007 (Figure 2 *c*). It should be noted that $F_{PO}/F_C(t)$ provides an upper bound, with imports included. On the other hand, $F_{AO}/F_C(t)$ provides a lower bound for $S(t)$.

Assessment of degree of dependency (import requirement)

As a measure of departure from ASeS, we have considered degree of dependence on external sources or the import requirement to meet the food demand with the current agricultural productivity. This dependency estimated as percentage of the total annual food demand (Figure 3, left *y*-axis, solid line) and percentage of the current agricultural gross domestic products (GDP) (Figure 3, right *y*-axis, dashed line) shows a steady but non-linear growth with increasing population. As expected, this dependence increases for higher consumption, from around 40% of the food demand for F_{CP} = 350 kg/year to nearly 60% for F_{CP} = 450 kg/year (Figure 3 *a* and *b*). In terms of percentage of current (2010) agricultural GDP, this dependence rises from 150% for F_{CP} = 350 kg/year to nearly 250% for F_{CP} = 450 kg/year (Figure 3 *a* and *b*). For a drier climate, these numbers are higher as expected (Figure 3 *c* and *d*). It is worth noting, however, that the response, especially in terms of food demand is not linear. Higher water availability in a wetter climate can reduce the dependence, but not too much (Figure 3 *e* and *f*). As explained earlier, these estimates are for optimistic scenario of utilization of maximum arable land and the higher agricultural productivity (0.5 kg/m^2). Similar conclusions also hold for higher consumption for both

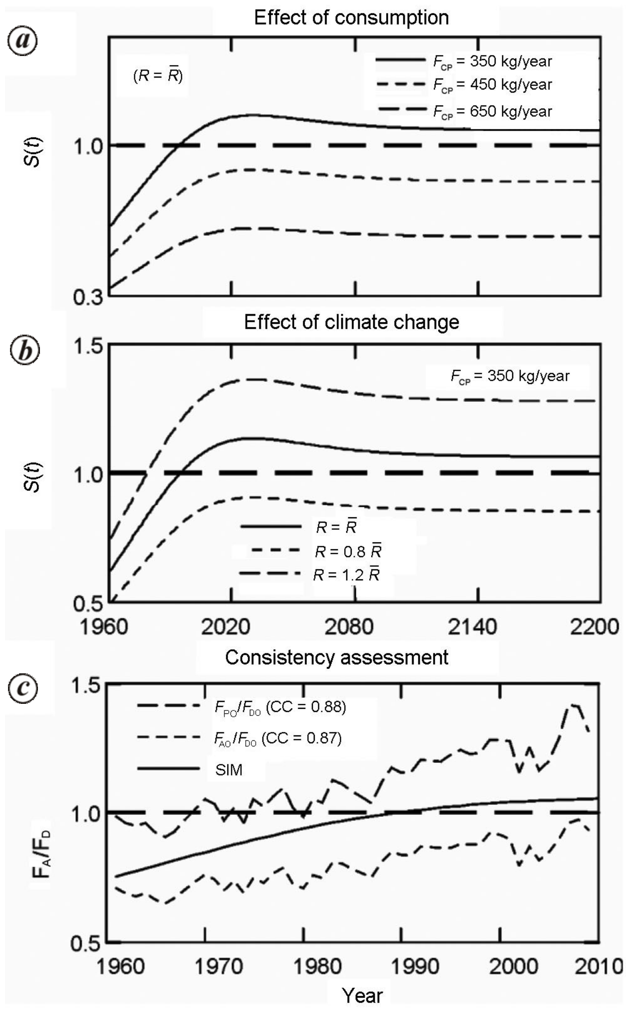

Figure 2. Index of agricultural self-sustainability (ASeS) in different scenarios of consumption and water availability. ***a***, Different scenarios of F_{CP} for the current all-India average rainfall. ***b***, Different scenarios of climate change (annual rainfall as a fraction of climatology of all-India annual rainfall) for F_{CP} = 350 kg/year. ***c***, Comparison of index of ASeS (thick solid line) with the ratio of observed total agricultural production to the food demand (long dashed line) and total food availability to the food demand (dashed line) for the period 1961–2010. The correlation coefficients between ASeS and the corresponding observed quantity are given in brackets. The horizontal, long dashed line represents the state of ASeS ($S(t)$ = 1).

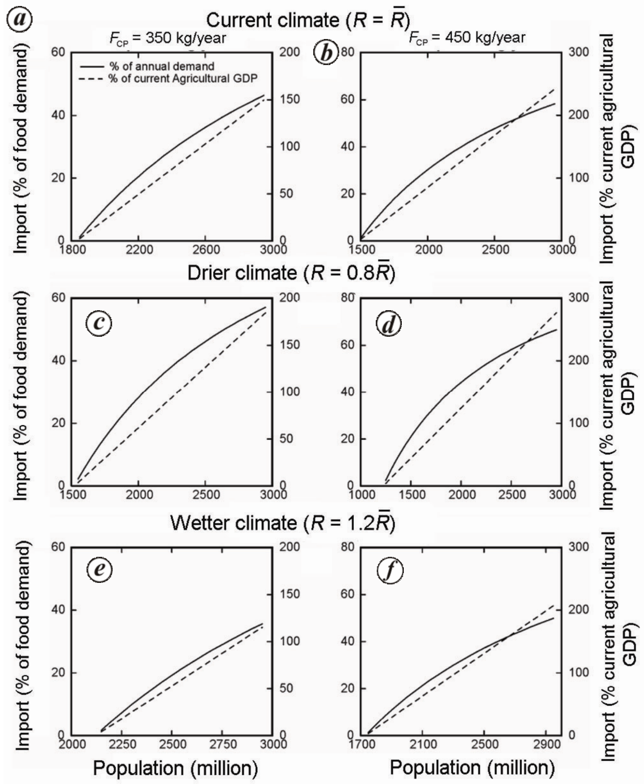

Figure 3. Dependency on import to maintain ASeS ($S(t)$ = 1) as percentage of annual food demand (left *y*-axis; solid line) and percentage of current agricultural gross domestic products (GDP) (right *y*-axis; dashed line), as a function of population in three scenarios of climate change: (***a***, ***b***) current climate, (***c***, ***d***) drier climate and (***e***, ***f***) wetter climate. The left and right columns show results for F_{CP} = 350 kg/year and F_{CP} = 450 kg/year respectively. The current agricultural GDP is considered as 17.98% of total GDP for the year 2010.

current and doubling population scenarios (Figure S1, see Supplementary material online).

Critical population load (carrying capacity)

ASeS as a function of population in different scenarios of climate change (in terms of rainfall fraction) and socio-economic conditions indicates a critical population load for India around 1850 million, for no change in the annual rainfall and high agricultural productivity (0.5 kg m^{-2}), for F_{CP} = 350 kg/year (Figure 4 *a*). As expected, for a scenario of ASeS, this value of population is higher than that projected by the United Nations Population Division (world population prospects database by United Nation Population Division, 2011) for India; thus actual critical population load or carrying capacity is likely to be lower. As expected, the critical population load is lower in a drier climate (Figure 4 *a*, $R = 0.8\bar{R}$ and $R = 0.9\bar{R}$) and higher in the wetter climate (Figure 4 *a*, $R = 1.1\bar{R}$ and $R = 1.2\bar{R}$). Higher consumption naturally implies lower critical population load (Figure 4 *b*); however, the response is not always linear.

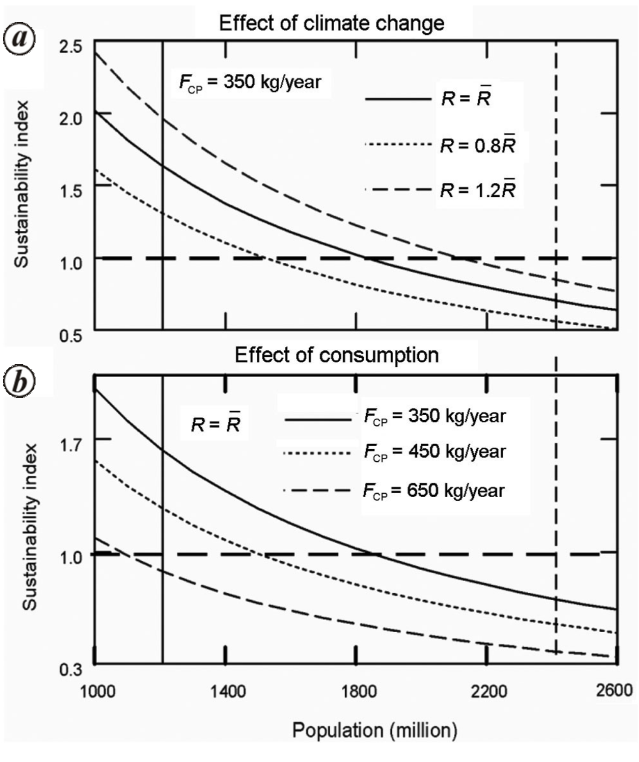

Figure 4. Carrying capacity for agricultural self-sustainability in terms of index of ASeS as a function of population load in different scenarios of climate and consumption. ***a***, Different values of average all-India annual rainfall for F_{CP} = 350 kg/year. ***b***, Different scenarios of F_{CP} for current average annual rainfall. The horizontal line represents the state of sustainability ($S(t) = 1$). The solid and the dashed vertical lines represents respectively, the state of sustainability at 1200 million (current population) and 2400 million (double the population).

Technology demand

With maximum agricultural area (181.6×10^{10} m^2), in different scenarios of climate change (annual rainfall as a fraction of climatology of all-India annual rainfall) for F_{cp} = 350 kg/year, productivity requirement varies between 0.2 and 1.0 kg m^{-2} in different scenarios of population (Figure 5 *a*). The productivity requirement varies from 0.2 to 1.5 kg m^{-2} in different scenarios of per capita food consumption for current climate (Figure 5 *b*). For all-India annual rainfall at about 80% of the current rainfall and per capita consumption of 350 kg/year, the agricultural productivity to support a population of 1650 million (projected by United Nations Population Division, 2011) is about 0.6 kg m^{-2} (Figure 5 *a*), which is approximately double its current value. Higher consumption naturally implies more technology demand to maintain ASeS (Figure 5 *b*). It is, of course, clear that quantum jumps in technology, or new inventions, could enable meeting these demands even for larger populations.

Discussion

Our basic objective in this work has been to present a dynamical framework for quantitative assessment and projection of ASeS and related parameters. ASeS can assume practical significance; wealth cannot necessarily buy food. It is clear that long before the onset of loss of ASeS scarcity of food will gradually set in, affecting people in the lower economic strata. It is, however, worth emphasizing that we are not proposing ASeS as a policy to be adopted but as an important input for policy assessment and design. So long as food is available through domestic production, and accessible and affordable through international trade, ASeS is essentially a theoretical limit.

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 ASeS if a nation depends on its income from agriculture to support these activities. However, the saturation value of the population load emerges as the most critical parameter. While the criticality of the population load in determining ASeS is not surprising, our results show that the carrying capacity ($S(t) = 1$) can change in a complex manner due to various factors. In accordance with our concept of ASeS, the estimates are essentially for basic survival (minimal agricultural product requirement); they will have to be accordingly revised if increases in nutritional and dietary demands, like inclusion of animal protein, are included; the amount of land needed for producing a given weight of meat is much more than that needed for producing vegetables.

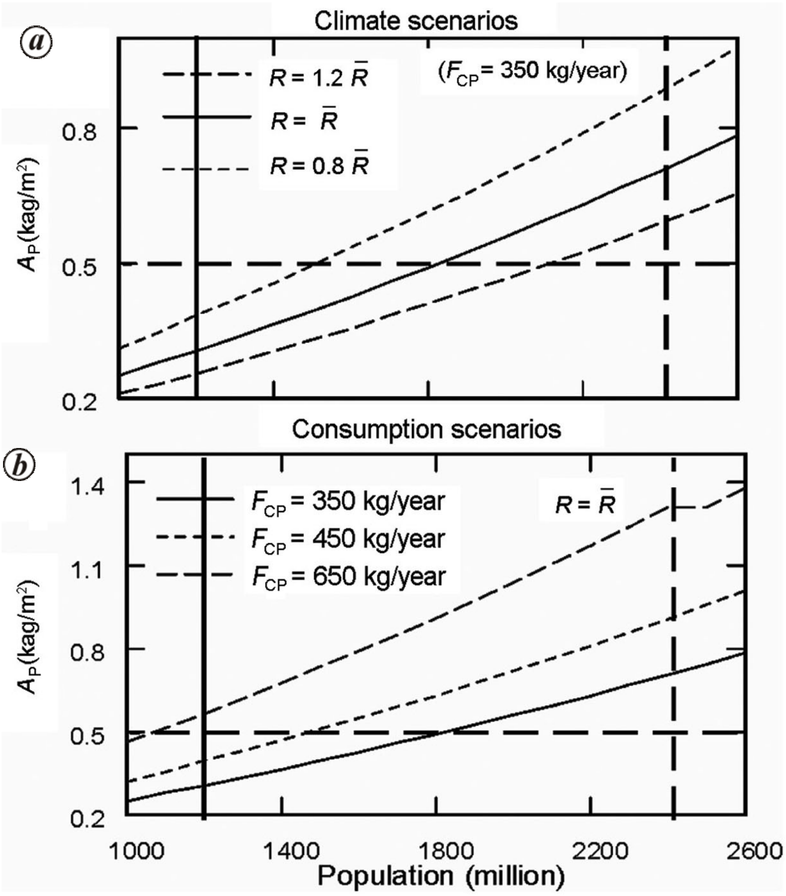

Figure 5. Technology demand (agricultural productivity) to maintain ASeS in different scenarios of climate change and consumption as a function of population. ***a***, Different values of all-India rainfall for $F_{CP} = 350$ kg/year. ***b***, Different scenarios of F_{CP} for current average all-India rainfall. The solid and dashed vertical lines respectively, represent the technology demand for the current population (1200 million) and double the population for India. The horizontal, long dashed line shows the worldwide representative value of productivity (0.5 kg/m^2) assumed.

In assuming import as a dynamical variable, we have implicitly assumed an infinite source of (world) supply; this also implies a benign international network. However, external sources of food can become less effective due to worldwide saturation, and even decline in arable land[25,26]. Inclusion of additional parameters like marine products in the analysis of ASeS may not change the basic conclusions.

It is clear that the values of the parameters like critical population load and the year of onset of loss of agricultural self-sustainability have to be considered as indicative due to the inherent uncertainties in the model parameters; however, these will not change our conclusions in any qualitative manner. The validation was carried out (as hind casts) for 30 years. For operational and continued application, it is possible to apply progressive calibration and validation with a given time window, say 20 years, for assessment. Although the model has been applied to India for specific estimates, the methodology is quite generic and can be applied to any country.

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