Effects of Natural Resource Limitation on Human Populations in Contemporary Societies

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A Dissertation presented to the Graduate Faculty
of the University of Virginia in Candidacy for the
Degree of Doctor of Philosophy

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August 15, 2022

Acknowledgements

Thanks to Stephen A. Macko, Herman H. Shugart, Thomas M. Smith, and Frank Dukes for their support and guidance throughout the conception, development, and realization of this project. The Department of Environmental Science, in the Graduate School of Arts and Sciences at the University of Virginia, provides a professional and instructive work environment, rich in human and material resources, which serves as an incubator for independent research. Family members – especially my son Duncan – have sustained me and my commitment to this endeavor.

Abstract

This investigation examines the socioeconomic effects of national ecosystem limitation, in order to (1) assess the incidence of national-scale ecosystem limitation of socioeconomic populations; and (2) assess relative effectiveness of possible policy interventions to alleviate the deleterious socioeconomic effects of limitation. It monitors ecological-socioeconomic material flows in pursuit of the former goal, applying methodology developed for measuring Human Appropriation of Net Primary Productivity (HANPP), and assesses national scale assistance policy choices for the latter, applying systems dynamics simulation modeling.

HANPP analysis of eight landlocked countries with agrarian economies indicates that ecosystem resource availability per capita is constant in two of the eight countries studied (Chad and Laos) and decreasing in four (Central African Republic (CAR), Democratic Republic of Congo (DRC), Rwanda, and Uganda, and increasing in Mongolia and Bolivia. Evidence of limitation effects is seen in Chad and the CAR, whereas mechanisms are in place in DRC, Laos, Rwanda, and Uganda that alleviate potential limitation pressure.

The system dynamics simulation of consumption-production interaction in the two countries coming under limitation pressure (CAR and Chad) assesses limitation effects on the relationship between ecological and socioeconomic systems in qualitative terms. The expected trajectory is towards intensifying scarcity of essential resources, especially food, causing increasing competition within the population. A fulsome response should address short term limitation effects promptly with direct aid, while simultaneously supplying technical expertise and inputs to improve domestic agricultural efficiency, and long-term technical assistance aiming at self-

sufficiency based on combined domestic production and international trade.

This research develops a methodological basis for anticipating national ecosystem limitation of socioeconomic welfare, thereby potentially improving international capacity to deliver timely, policy interventions, aimed at forestalling potentially disruptive levels of limitation. It presents environmental resource management as a high-priority, long-term component of sustained social welfare, both in national and international contexts. In addition to the specific applications noted, the approach outlined here has the potential to assist in detecting national sensitivity to socioeconomic limitation, on the one hand, and, on the other, developing preventative, multi-dimensional policy responses. With reasonable modifications, it could also help assess socioeconomic vulnerability. As the more countries become increasingly dependent on importation of NPP-derived goods (Fader et al. 2013), assessment of country risk in these circumstances becomes more valuable. The effects now on international food supplies caused by the 2022 Russian invasion of Ukraine illustrate this point vividly.

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Table of Abbreviations

Abbreviation	Full Designation
DGVM	Dynamic Global Vegetation Model
ES	Ecosystem
FAO	United Nations Food and Agriculture Organization
K	Carrying Capacity
K_h	Human Carrying Capacity
LPJmL	Lund-Potsdam-Jenna, managed land
NPP	Net Primary Productivity
NPP_a	Actual Net Primary Productivity
NPP_h	Harvested Net Primary Productivity
NPP_{luc}	Protentional Net Primary Productivity suppressed by land use
NPP_0	Potential Net Primary Productivity
PFT	Plant Functional Type
SS	Socioeconomic Subsystem
SD	System Dynamics
UN	United Nations
WB	World Bank

Chapter 1: Introduction

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1. Ecological System and Socioeconomic Subsystem

The early 1970s are a landmark for the American popular consciousness of the Earth as a finite space with limited resources. The famous 'Earthrise' photograph (NASA 2013) was taken on an Apollo mission in 1968, the same year Buckminster Fuller published *Operating Manual for Spaceship* Earth (Fuller, 2008). The first Earth Day was celebrated in 1970, and major environmental regulation occupied center stage on the U.S., as President Nixon shepherded the Clean Air and Clean Water acts through congress. In 1972, the Club of Rome commissioned a study entitled *Limits to Growth* (*LTG*, Meadows et al. 2004), which applied system dynamics analysis (then a new technique) to develop the World3 computer model. World3 was used to examine socioeconomic population, production and consumption trends at the global scale, against the background of estimations of limited planetary resources.

Several *LTG* scenarios projected population growth and resource consumption that would exceed the rate of aggregate resource regeneration, exhausting pre-existing stocks of natural capital, rising past a point of maximum food and industrial production (Fig. 1, Butzer 2011). In this scenario, the delay in population adjustment to output declines causes population 'overshoot,' which, in turn, cause famine, disease, and violent conflict, when rapid population decline ensues. These results were controversial at the time of publication and continue to be so after several updates of *LTG*. (Bardi 2011, Komiyama 2014).

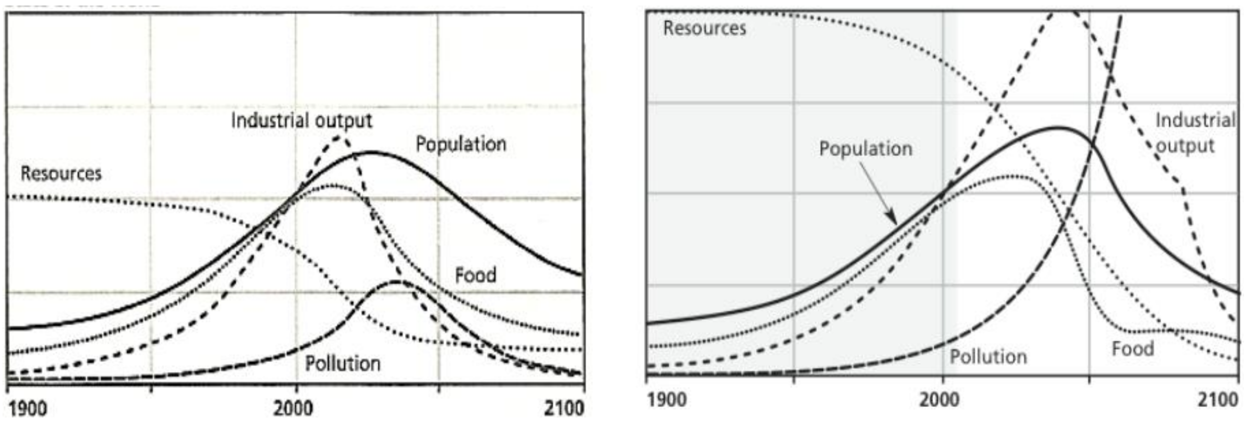

Fig. 1: *Limits to Growth* 'Business as Usual' (BAU) Scenarios 1 (left) and 2 (right), of World3 system dynamics model. Both BAU scenarios display an overshoot and collapse pattern of system behavior. Scenario 2 projects BAU system evolution assuming a larger initial resource reservoir (Meadows et al. 2004).

Innovative researchers have developed numerous analytic approaches, since the publication of *LTG*, to estimate socioeconomic limitation at global, regional, and national scale, focusing on global carrying capacity (Adam 2021, Binder et al. 2020, Godfray et al. 2010). The present investigation applies ideas and methods from this body of work to focus on a specific facet of the social sustainability question, *viz*., socioeconomic activity at the scale of the individual nation, in conditions of ongoing or imminent limitation pressure imposed by finite national ecosystem resources.

Advances in agricultural technology have substantially alleviated ecosystem limitation of socioeconomic system growth, at the human metapopulation scale, throughout the Holocene (Barker et al. 2015), and particularly in the decade preceding the publication of *LTG* (Hazell 2009, Pingalli 2012). The first phase of this examination, therefore, examines whether the phenomenon of socioeconomic population limitation by ecosystem resource constraints is occurring now under specific conditions. The second phase analyzes plausible outcomes of continuous, unregulated socioeconomic system growth in these conditions, relative to growth in simulated trajectories expected after policy interventions.

2. Socioeconomic Effects of Limitation Pressure

2.1. Humans in Environment

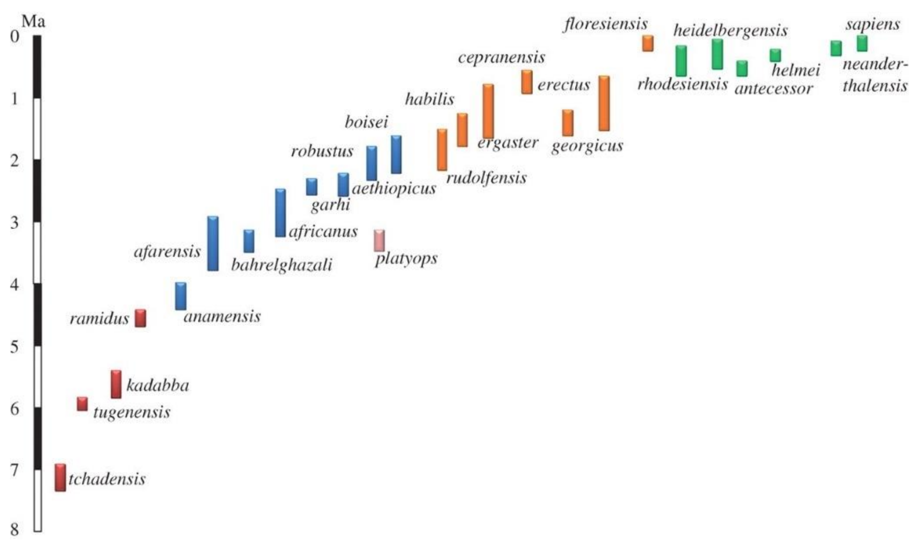

Fig. 2. Hominin evolution. First and last appearance ages of recognized hominin taxa provide chronological ranges. The color coding indicates major groupings that represent adaptive shifts. Red bars, earliest hominins; blue bars, australopithecines and allies; orange bars, smaller-brained *Homo*; green bars, larger-brained Homo (Foley et al. 2009).

Humans have been present in their contemporary form for only about 200,000 years (Stringer 2016), emerging recently in the Earth's history. Since their emergence, they have been subject to the same fundamental limitations affecting other species, and their viability relies on a foundation of four billion years of biosphere evolution. Unlike other organisms, humans have been able to substantially moderate the effects of local limiting conditions, as evidenced by their global presence and long-term exponential growth rate. Humans have achieved this success partly by leveraging their unique capacity for language abstract thought to develop unprecedented technologies[1] of hunting and cultivation (Boyd et al. 2013). Another key component of human success has been the species' capacity to organize socially, evolving and differentiating culturally to adapt to a large number of different environmental conditions (Heinrich 2015). In an evolutionarily brief time span, humans have become the Earth's ultimate predator, its invasive species *non-pareil*, and a peerless ecosystem engineer, with a presence in every continent and biome.

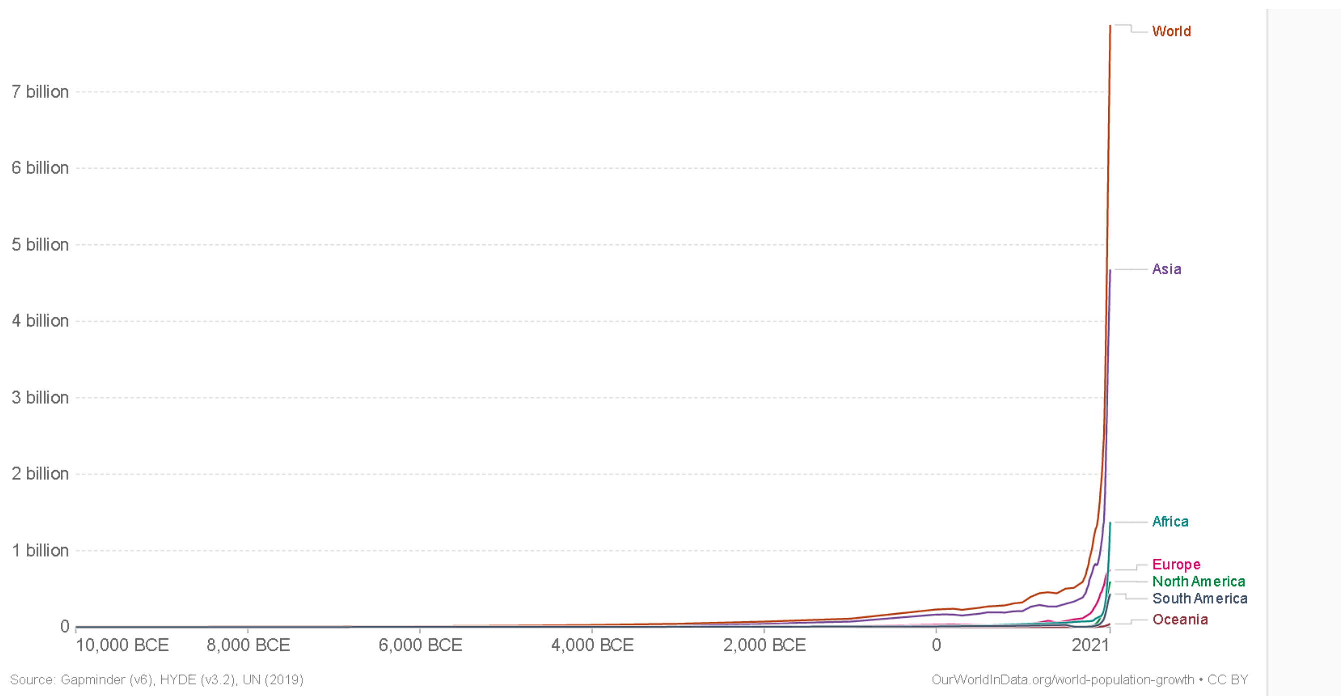

Fig. 3. World Population Growth from 10,000 BCE to 2021 CE (Population 2022).

[1] Technology here is used to mean any developed assemblage of techniques, not specifically industrial, mechanical, or information technology. Early humans developed primitive hunting technologies; during the neolithic

an agricultural technology.

The development of thermodynamic practice and theory in the 18^{th} century was a transition point for human communities (Weinberger 2013), laying the foundation for a socioeconomic metabolism comprising reservoirs of energy bound in paleo-photosynthetic product and available to perform work (Krausman 2013). Development of this technology and derivative applications caused a durable acceleration in food production, including the so-called green revolution technology of the late 20^{th} century, which alleviated potential environmental limitation of food production for hundreds of millions of humans in Asia and the (Pingalli 2012). Within this framework of species metapopulation success, humans at local scales have often remained subject to limitation effects imposed by finite abundances of essential resources in their environment.

2.2. Ancient and Historical Limitation of Socioeconomic Populations

The historical record is rich with examples of socioeconomic limitation by environmental conditions. Scientific reconstructions of the ancient Egypt's New and Old Kingdoms' demise (*ca.* 2200 and 1100 BCE, respectively; Butzer 2011), and that of the Classic Mayan Civilization (*ca*. 800 CE; Sabloff 1992), explain their breakdowns in terms of ecosystem limitation. Kaniewski et al. (2013) come to similar conclusions with respect to late Mediterranean Bronze Age collapse (*ca*. 1200 BCE), which affected cities and kingdoms all around the eastern coast of Mediterranean Sea, including the New Kingdom of Egypt, the Greek Mycenean kingdoms, and the Hittite empire in Anatolia. In each of these cases, researchers concluded that local populations overshot the productive carrying capacity of endemic ecosystems, and that subsequent population collapse was caused by a combination of continuous population growth and drought-induced depression of potential ecosystem production.

The limitation pressure was transferred to the tightly-coupled socioeconomic system, disrupting the advanced system of cities and regional intercity trade. The significance of the Bronze age collapse aligns with Malthus's characterization of similar situations (Malthus 1992). Large-scale regional emigration ensued, accompanied by disintegration of the city system into collections of seafaring marauders most of the significant cities of the Eastern Mediterranean were destroyed, along with the Ugarit and Amorite states. Trade was disrupted in the region, while cultural activity and literacy were substantially reduced.

Working at larger temporal and spatial scales, Hsiang et al. (2013) examined the record of socioeconomic disturbance caused by environmental limitation in 60 quantitative studies of instances from 8,000 BCE to the 21st century, discerning causal linkage between limitation and Malthusian social effects. Similarly, Zhang et al. (2011) surveyed 26 recent quantitative studies of recorded limitation instances between the 9th and 20th, on all inhabited continents, caused by contemporaneous changes in exogenous conditions, and found a correlation with onset of Malthusian social effects. In aggregate, this work documents the historical extent of local socioeconomic limitation and illustrates the potential significance of such events, including gross disruption of social organization linked with undernourishment, disease, and violent conflict.

2.3. Recent and Contemporary Limitation

This record of historical cases serves as a background for contemplation of comparable large-scale events in the 20th and 21st centuries, and sustainable society in general. Two of the largest known famines occurred in the 20th century: Russia (1921-22), in which and estimated 5 million humans perished (Gilbert 1993), and China (1958-1961), when more than 15 million humans died (Meng et al. 2015; estimates of death vary from 15 million to 55 million). Both of these humanitarian catastrophes illustrate the potential extreme Malthusian effects to large socioeconomic populations, supported by leveraged ecosystem resources, when anomalous limitation conditions are introduced. Noteworthy is that both were partially attributable to the socioeconomic variables of political leadership and administrative response. (Socioeconomic variables are not addressed in this study.)

Rwanda, Yemen and Sudan are recent examples of breakdown in regular social order, concurrent with ecosystem limitation pressure on national populations. Brander et al (1998) and Jared Diamond (2005) argued that the tight coupling of Rwanda's ecosystem and socioeconomic system in the early 1990s caused acute socioeconomic system sensitivity to ecosystem feedback effects. In this analysis, limitation of national food resources intensified intra-social competition for available resources. In 1994, social order broke down catastrophically along ethnic-political lines in response to political disruption, contributing to a genocidal massacre, causing the loss of 500,000 to 800,000 lives (BBC News 2019).

In Yemen, a combination of domestic food growth shortfalls, exacerbated by a hostile external blockade of aid and cross-border hostilities, have caused famine conditions by (UN News | Yemen 2022). Ethiopia and Kenya in the neighboring Horn of Africa have been relatively free of civil strife, but the effects of alternating drought and flooding on ecosystem resource bases, already stressed by a large embedded socioeconomic population, have diminished potential net primary productivity, imposing water and food shortages on 13 million people (UN News | Horn of Africa 2022).

Increasing limitation pressure has also caused large civilian displacement and emigration. The United Nations Statistics Division recorded nearly 69 million people forcibly displaced in 2017. Of this number, more than 25 million emigrated as refugees across national borders, and another 3 million have sought asylum status in other countries. Nearly 30% - 10 million - are stateless (UNHCR 2022). Those remaining may suffer worse hardship than those displaced: in Yemen, 462,000 children were recorded with severe acute malnutrition at the end of 2018; 2.2 million were in need of urgent care, and 8 million people of all ages were threatened by famine. Estimates of child deaths since 2018 range from 85,000 to more than 200,000 (UN News |Yemen 2021). Viewed in perspective with the socioeconomic system-ecosystem system linkages sketched above these cases illustrate the potential value of understanding the mechanisms and dynamics of these linkages.

2.4. The Future

Examining current circumstances and looking to the future, numerous investigations have examined the sustainable population size of individual countries or regions, including the China (Yue et al. 2008), the United States (Peters et al. 2016), and even states within the U.S. (New York: Peters et al. 2007; Maine: Campbell 1998). Other researchers have looked at regional-scale sustainability, including West Africa (Fricke, 2004) and Amazonia (Fearnside 1999).

Another line of investigated population limits at the metapopulation, world ecosystem scale, with varying outcomes. Cohen (1995) found that human population growth may be independent of environmental carrying capacity, because of unpredictable choices related to economics and cultural choices. Binder et al. (2020) developed a model of global human carrying capacity that emphasizes humans' capacity to repeatedly reset apparent carrying capacity through application of technology, concluding that the ultimate limiting factor will be rate of photosynthesis, rather than plant nutrient abundances. Frank et al. (2011) explicitly disagree with previous assertions of photosynthetic limitation, concluding instead that arable land will ultimately be the factor limiting population size.

Jared Diamond (2005) argued in *Collapse* that the global peril of linked ecosystem-socioeconomic catastrophe persists when the rate of population growth is slowed, if the metapopulation's material standard of living rises to that of the wealthiest national populations today. Contradicting this assertion is the theory of demographic transition pioneered by Warren

Thompson (Demeny et al. 2003 and subsequently elaborated by Landry (1987) and Lesthaeghe (2014), who proposed a second transition after the 1970s. In this analysis, as socioeconomic populations at low levels of affluence sustain high death rates (attributable to such conditions as poor nutrition, prevalence of disease, and poor public health) together with birth rates sufficiently high to maintain a positive growth rate. If affluence increases, in the generalized pattern, factors causing death ameliorate, as nutrition and health care improve, and the population growth rate increases. As affluence continues to grow, families employ contraceptive and other techniques to moderate birth rates, moderating the risk of maternal death in child birth, and the burden on family economic resources of large family size. In this second phase, typically, rate of net population growth slows or declines and stabilizes. In Lesthaeghe's conceptualization, additional social and behavior trends enabled within an urbanizing society with increasing income further change population-wide demographic trends.

The United Nations has embraced the interpretation of demographic data posited in the demographic transition theory, incorporating it in its projections and reporting since 2013 (Kirill et al., Shifting Demographics 2022), where it provides the basis for a predictions of global population stabilization at approximately 11 billion in *ca*. 2100. The self-regulating process will bring the population into a steady state with local resource availability, according to the United Nations, before scarcity and Malthusian effects cause widespread disintegration of social organization. The details of the projection are debated within the demographic science community (Adam 2021, Vollset et al 2020), and it does not directly address the contingency indicated by Diamond of resource caused by increasing rates of consumption and waste generation by a constant or declining population.

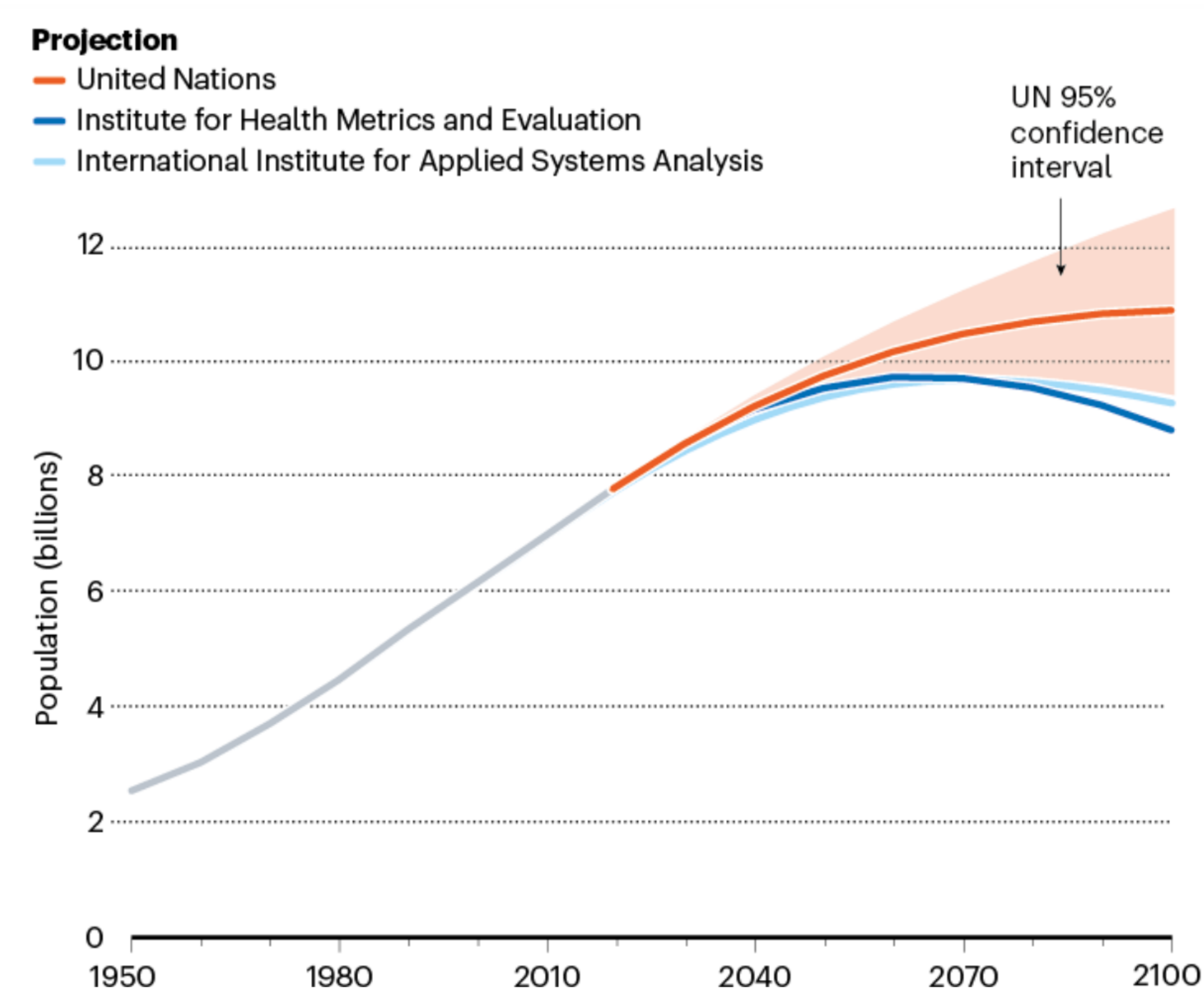

Fig. 4. Global human population projections (UN Population Division/IIASA/IHME).

These contrasting views illustrate the uncertainty of humanity's future in coming decades and centuries. At the present time, some national societies are increasing their wealth, while others persist under conditions of poverty and scarcity. A key conclusion of the *LTG* analysis was its elucidation of branching socioeconomic evolutionary pathways in coming decades, leading to population alignment with Earth's resources through self-regulating polices and management, on the one hand, or unrestrained consumption, on the other, when population regulation will occur through the attrition mechanisms of Malthusian effects.

2.5. Response to Contemporary Limitation Incidence

The *LTG* analysis was a global scale system dynamics analysis, this study the focuses on individual countries. Where limitation pressure is demonstrated at the national level, the potential consequences for affected populations, both directly and indirectly, potentially warranting policy intervention. Policy advocates energetically debate the value of response priorities. The institutional context for this debate includes the United States Agency for International Development (USAID), the world's largest bilateral donor, with a budget of $41b in 2021 (USAID 2022), and the United Nations Development Program (UNDP), the world's largest multilateral donor with a budget of $4.2b in 2019 (Annual Report 2020). USAID is active in 12 overlapping sectors, including humanitarian assistance, food security, nutrition, water and sanitation, and environmental resources management. The current UNDP framework of 17 Sustainable Development Goals overlaps with USAID objectives in the areas of sustainability, and elimination of poverty effects. Significantly, both USAID and the UNDP emphasize sustainability and self-determination of participating nations as overarching program goals. Well-balanced official aid packaging places combinations of short-, medium- to long-term assistance goals in perspective to end of effective response.

Systemic insight into ecological preconditions of socioeconomic catastrophes like those noted above can assist policy makers manage these resources, and may also help to anticipate state-failure events before they are imminent. Analytic tools that provide insight into this relationship can also contribute to domestic national planning and even super-national, regional planning. The efforts of all researchers working on issues related to sustainability contribute to “actionable knowledge” (Chapter 3.1) and have the practical effect of contributing to such insight.

3. Purpose

The purpose of this investigation is to assess the incidence of national-scale ecosystem limitation of socioeconomic populations, and then to assess relative effectiveness of possible policy interventions to alleviate the deleterious socioeconomic effects of limitation. Tthe results of this investigation will contribute to the kit of observational, analytical, and conceptual tools available to researchers, while providing evidence-based insights to policymakers confronting decisions about allocation of scarce resources.

Objectives

I. Assess existence of socioeconomic limitation in nations dependent on NPP and derived goods from local sources (within national territory)

Questions

1. In these conditions, are resident SS experiencing diminishing ES resource availability per individual, implying increasing ES-SS limitation pressure?
2. Are populations of these countries experiencing increasing competition for resources, causing Malthusian effects?

II. In limited national systems, assess future system behavior by simulating national-scale dynamics with an embedded SS population.

Questions

1. What feedback effects accrete to a growing socioeocnomic population as it appropriates a progressively greater proportion of ecosystem primary production?
2. Which system variables, within socioeconomic control, should be effective in promoting sustainable social welfare?

Fig. 5. Study objective and research questions.

4. Scope and Limitations

This study takes the nation state as its basic social unit (see Chapter 2.4) to examine feedback effects from ecosystem to socioeconomic system. Excessive burdening of ecosystem resources by an embedded socioeconomic subsystem may cause deleterious feedback effects in the guise of Malthusian effects. In sustained or extreme cases, these effects may cause state failure, entailing breakdown of national-scale social organization and potentially severe implications for both the domestic population and the international community.

4.1 Study Scope

The investigation's temporal scope is restricted to the late 20th to early 21st centuries. This time frame places nation-states within the world order prevailing since the end of World War II, and comports with availability of reliable social and ecological data. It also suggests that the nation-state is an appropriate study unit, in part because it already serves as a basic macro-scale unit of social administration, economic analysis, and international trade. This scale of resolution also facilitates several simplifying assumptions, such as constrained population mobility between functioning nation-states, and attendant reliance of populations on the resource endowment of their national territories. Chapter 2 provides a detailed rationale supporting this focus on the nation-state social unit, as well as the criteria applied to select countries for the study.

4.2 Study Boundaries

The scope of an investigation sets its limits. Ecosystems are complex and display chaotic behavior (Fussman et al. 2002); human social systems nested within ecosystems redouble the complexity (Liu et al. 2007). These systems are poorly-suited to deterministic analysis, but amenable to qualitative simulation yielding useful heuristic insights (Levins 1966, Wolstenholme 1999). Social analysis introduces additional difficulties: human systems are adaptive and ontically open (Nielson et al. 2011). Continuous recombination of human experience, understanding, and expression cause the emergence of new configurations of thought and practice in response to changes in environmental conditions. In addition, ethical objections are made to excessive objectification of humans, which can dehumanize both observer and observed (Warren et al. 2012). Because this study examines relationships between ecological parameters and social ones, therefore, the results will be qualitative and heuristic in nature, rather than quantitative and fundamental.

5. Project Road Map

5.1. Chapter 1: Introduction

Project context, significant, and purpose.

5.2. Chapter 2: Framework and Approach

Conceptual framework for the investigation, including a scan of the origins and development of the contemporary nation state and its selection as study unit for this investigation.

5.3. Chapter 3: Case Studies in Ecosystem – Social System Relationship

Incidence of contemporary national socioeconomic populations under limitation by available ecosystem resources. Applies the framework outlined in Chapter two to examine eight countries for limitation feedback effects and mechanisms of amelioration.

Objective I: Assess existence of ES-SS limitation in nations dependent NPP and derived goods from local sources (within national territory).

QUESTION 1

In these conditions, are resident SS experiencing diminishing ES resource availability per individual, implying increasing ES-SS limitation pressure?

QUESTION 2

Are populations of these countries are experiencing increasing competition for resources, causing Malthusian effects?

Fig. 6. Chapter 3 objective and research questions.

5.4. Chapter 4: System Dynamics Modeliing of Limited National Populations

Systems dynamics analysis of populations dependent on their national ecosystems under limiting conditions with weak or absent amelioration mechanisms. Simulation of socioeconomic subsystem evolution in response to policy interventions.

Objective II: In limited national systems, assess future system behavior by simulating national-scale ES dynamics with an embedded, mature SS population.

QUESTION 1

1. What feedback effects accrete to a growing SS population as it appropriates a progressively greater proportion of ES primary production?

QUESTION 2

Which system variables, within SS control, are effective in promoting sustainable social welfare?

Fig. 7. Chapter 4 objective and research questions.

5.5. Chapter 5: Conclusion

Recapitulation of main conclusions and discussion points, including possible improvements and directions for future research in this and related topics.

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Chapter 2 Framework and Approach

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1. Limitation, Carrying Capacity, and the Logistics Function

This chapter frames the conceptual-analytic framework for in the subsequent chapters. The concept of the limiting factor, a scientific commonplace, is central to this investigation. In a physical chemical reaction, abundance of one reactant will be exhausted before others as a reaction goes forward, whereupon the reaction ceases, regardless of unconsumed abundances of the remaining reactants (Himmelblau 2004). The reactant first exhausted is the limiting factor in this context. Analogously, in population studies, an aggregation of environmental inputs is necessary for maintenance and reproduction of a population. The environmental resource first exhausted, is the ecological limiting factor for that species. The population of any species in an ecosystem is subject to the effects of a series of limiting factors: alleviation of one allows the population to increase, until the available abundance of another essential factor is exhausted.

Limitation is implied in the concept ecological niche, used to generalize species habitats. The conceptualization of an ecological niche has undergone several elaborations: the Eltonian niche emphasizes viability in an environment based on assessment of a species particular traits, together with its resource and condition requirements*. The Grinellian niche incorporates, in addition, species' behavior adaptations and interactions with other organisms in the environment (Comte et al. 2016). The Hutchinsonian niche is conceived as an N-dimensional hyperspace, in which each dimension represents a critical requirement for residence by the species, defining a hypervolume that characterizes the environmental factors and abundances necessary for that species' viability (Holt 2009). In each case, the existence of a species niche in an ecosystem implies the presence of sufficient abundances of material resources, essential to the species, to sustain a population. Conversely, the concept of an ecological niche implies limitation of the population by environmental conditions and material abundances; otherwise the species population would be the whole ecosystem.

The logistics growth model (Fig. 1) is a general mathematical model of a simplified general population growth trajectory under limitation (Lehman et al. 2022). Originally developed by Pierre Francois Verhulst (Verhulst 1838) as a modification to the exponential growth curve posited by Thomas Malthus (1992) at the end of the 18th century,[2] it incorporates the negative growth effects of population density in limited environmental conditions. The logistics curve is graphical solution (Fig. 1) of the model under an assumption of constant limitation (implying a constant renewal rate of the limiting resource).

This model is a useful aid in thinking through the stages of growth rate evolution in delimited ecosystems. In the first half of the time range, growth rate is increasing, in the center is a flexion point at which the rate of change is equal to one, and the growth rate is negative in the second half of the growth period. In system terms, the change in growth rate in the second half

[2] Apocryphally, Verhulst developed the logistics model in response to Thomas Malthus's *Essay on the Principle of Population* (1798), which predicted the so-called Malthusian effects of population growth, based on presumed geometrically-increasing population growth competing for an arithmetically growing food supply. Because Malthusian effects are referred to frequently here, it is worth quoting Malthus's characterization.

> "… sickly seasons, epidemics, pestilence, and plague advance in terrific array, and sweep off their thousands and tens of thousands. Should success be still incomplete, gigantic inevitable famine stalks in the rear, and with one mighty blow levels the population with the food of the world.

represents environmental feedback to the population, caused by the declining quantity of the limiting factor available to each individual with each increase in the consuming population. The physical interpretation of this idealized model is that this decline in resource abundance per individual declines causes intra-species competition within the population to intensify once the curve flexion point has been passed. This competition causes the onset and progressive increase of so-called Malthusian effects within the population, as insufficiency of the limiting resource(s) causes increasing rates of malnutrition, vulnerability to disease vectors, starvation, or violent conflict, decreasing birth rates and increasing death rates simultaneously.

The curve's solution is:

$$f(x) = \frac{L}{1+e^{-k(x-x_0)}} \qquad \text{(Eq. 1)}$$

Where L is the upper limit, x is time, with x_0 denoting the time halfway through the process period, and k is the growth rate, corresponding to the curves steepness, and *f(x)* is the population size

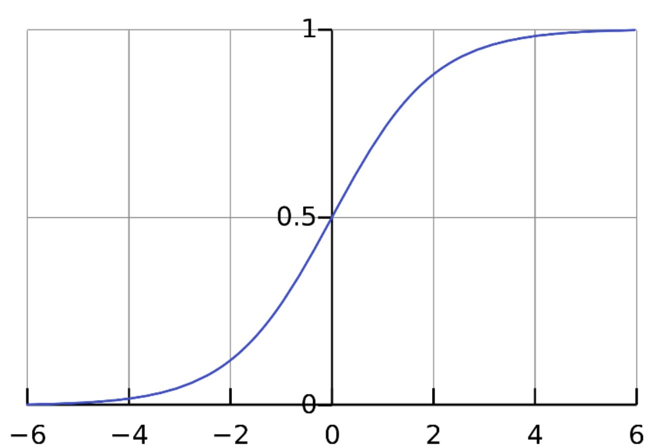


Fig. 1. Logistics function map, where *L* = 1, *k =1*, and *x* = 0

Equation is the solution to equation 2:

$$\frac{d}{dx}f(x) = f(x)(1 - f(x)) \qquad \text{(Eq. 2)}$$

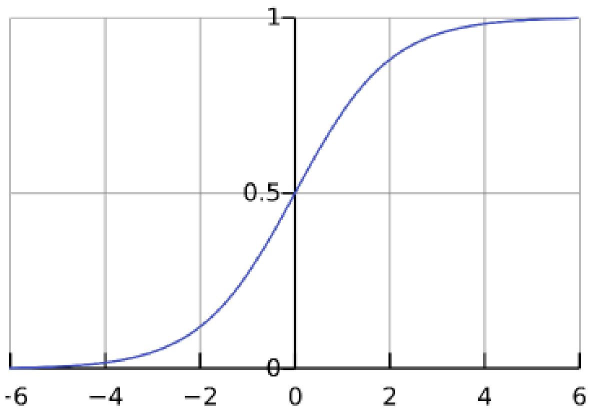
which forms the basis for the Lotka-Volterra equations of population dynamics in predator-prey and competition models. Amending this equation so that x = time and *f*(*x*) = population size = N, it can be changed to

$$\frac{d}{dt}\,N(t) = rN(t)(1 - \frac{N(t)}{K}) \qquad \text{(Eq. 3)}$$

Where ***r*** = the rate of growth and K = the carrying capacity, representing the maximum population N of a given species the ecosystem can support. As N -> K, population growth asymptotically approaches zero.

Deviations from the idealized conditions can be modeled by adaptations to the sigmoid curve (and underlying equation). A drop in resource abundance at the growth limit is represented by a downward trend after a local maximum; exhaustion of resources at the growth limit would correspond to a steeply downward-sloping roll-off, expressing a rapid decline in population. Growth of a population subject to pulses of predation, or dependent on a resource process subject to periodic exogenous perturbations, would be mapped onto an oscillating growth curve, in which amplitudes and periods would indicate extent and frequency of the population-changing events.

The carrying capacity referred to is an abstraction of the maximum population that can be sustained by the resources of the environment in which it resides, or the population size at which the birth rate is equal to the rate of death. It is generally denoted as K from the German *Kapatzitätsgrenze*, or capacity limit. From the equation above, its value can be calculated algebraically by setting dN/dt equal to zero and taking the positive root. A population reaches carrying capacity as its death rate increases, and its birth rate decreases, as functions of population growth under limitation pressure (represented graphically by the second half of the logistic curve), until birth and death rates become equal, and the population enters a steady state. Variations of this versatile general model are applied across a variety of disciplines, from chemistry, to cancer research, and epidemiology (including the initial COVID 19 outbreak). straightforward application to human population growth, however, is complicated by the phenomenon of exceptional capacity to manipulate their environments.

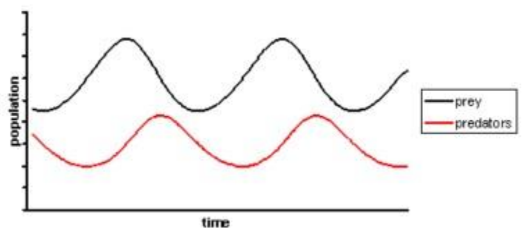


Logistic Growth

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}$$

Carrying Capacity

$$\frac{d}{dx}f(x) = f(x)\big(1 - f(x)\big)$$



Lotka-Volterra

$$\frac{dx}{dt} = \alpha x - \beta x y,$$
$$\frac{dy}{dt} = \delta x y - \gamma y,$$

Fig. 2. Logistic growth equation and graph; carrying capacity equation; Lotka-Volterra equations and a typical graph of interacting predator-prey populations.

2. Conceptual Frameworks

This investigation examines limitation pressure on human population growth in the subset of world nations most likely to be sensitive to it. Because socioeconomic systems are ecosystem subsystems, conceptualization of the social system in this context must rest upon a foundation of ecosystem theory. The holistic perspective of systems analysis is well-suited to ecosystem study, and this investigation adopts a system perspective, which encompasses complex physical and biological components. The multi-dimensional complexity of ecosystems severely challenges the human mind trying to keep track of system elements and interactions at a realistic level of detail (Beckage et al. 2011, Levins 1966). As in all sciences, ecologists develop insights by substantially simplifying, or reducing, the system under consideration, in the spirit of the apocryphal Einstein admonition to "Make everything as simple as possible, but not more so."[3]

A systems approach also allows simplification of processes into stock-and-flow processes (see Chapter 4.1), which are conveniently scalable to national ecological and socioeconomic systems. At this scale, reservoir and flow abstraction helps to focus on macro-scale parameters, eliding details of individual organisms, and even individual species. In addition, this approach frames an ecosystem and embedded socioeconomic systems one integrated system. The relationship between human societies and their host ecologies, in this framework, is one of diversion, or appropriation, of material flows from among all the possible ecological pathways to the specific path of human use. Conjugate with this species-specific appropriation of resources are its feedback effects on the growing socioeconomic system. A systems perspective thus offers the efficiency of contemplating a single, integrated system, rather than two, interacting systems, and clears away potential conceptual clutter caused by juxtaposing two systems of different types.

[3] This apocryphal quotation is itself a simplification of an excerpt of Einstein's 1933 lecture *On the Method of Theoretical Physics*," Einstein's original wording was "It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience." (Dyson 2010)

3. System Simplification

As indicated above, the eco-cum-socioeconomic system is conceptualized as one of organized, macro-scale material flows, without regard to specific behaviors of individual system elements. System boundaries are arbitrarily defined to correspond to country borders. The diverse species populations of the study ecosystem are reduced to those of producing autotroph and consuming heterotroph: autotrophic species communities are reduced to a set of 11 functional pant types (see Chapter 3.2); the heterotroph community is substantially reduced to the human population and animals raised by humans as sources of food. System energy is assumed to derive entirely from solar radiation, photosynthetically bio-processed into NPP biomass. Chemotrophic energy sources and planetary energy of formation are disregarded. Energy transfer occurs only as work, latent heat, or sensible heat; energy storage occurs as atmospheric potential energy or molecular valence bonds in biochemically reduced mass particles. Any energy flow implies a material flow, and vice versa.

The set of real ecosystem processes is reduced to emphasize biomass production and consumption (here understood in the economic rather than ecological sense; e.g., any extraction of NPP from its productive state, as in the harvesting of trees, is considered to be consumption). The insights obtained by this overall approach are heuristic, rather than fundamental; emerging predictions will be general and qualitative in nature, not specific and quantitative.

4. The Ecological Landscape with Embedded Socioeconomic Subsystem

4.1. Limitation and The Organism in Environment

It is useful by frame this study in an objective ecosystem perspective, anticipating an implicit predisposition to adopt a narrower, anthro-centric perspective. We start here, therefore, with a review of organism populations in relationship with their environments, noting some milestones in the evolution of these relationships. From this broad orientation, we then narrow our focus to the special case of human interaction with the environment.

The long-term relationship between organisms and environments is the process of evolution. Earth's biogenesis produced sequestered microenvironments inside of phospholipid satchels, in which metabolic reactions proceeded spontaneously, in ambient conditions, among materials in the immediate environment, at rates sufficient to sustain and propagate the resulting cell structure (Istrazivanja 2011). Since then, life forms have differentiated in adaptive response to the material, energetic, and competitive conditions of various environments, by means of such mechanisms as gene transfer, gene recombination, gene mutation, and genetic drift. Environmental conditions are therefore fundamental to the origin of living organisms and substantially determinative of the specific characteristics of different organism types (Stearns et al. 2005).

Populations of cells operate on the microscopic scale as massively parallel material processing units. They take up material and energy from their environment, use the latter to reorganize the former, and vent material not retained in the organism back into the environment (Alberts et al. 2015). By amending both the material composition and organization of their environments, organism populations, therefore, propagate in an interactive relationship with them. This interaction drives evolution of the entire ecosystem, under Tansley's definition (1935). This recursive effect of organism action to the abiotic environment evolving at geological time scales, once biologically inhabited, enter a state of relative flux, forming a temporally moving frontier of environmental conditions. Organisms residing in a specific location must continuously adapt to conditions changing in this manner. As the local ecosystem changes, it generates a shifting 'adjacent possible' for biological innovation in the new combination of physical and ecological conditions (Beckage et al. 2011).

The reorganization of environmental material by single cell organisms over several hundred million years, causing the so-called oxygen catastrophe (Lyons et al. 2014), was a landmark change in the adjacent possible of terrestrial ecosystem. It amended atmosphere and hydrosphere composition, re-reset the terrestrial greenhouse effect, and dramatically increased ambient oxidative potential at the Earth's surface (Holland 2006). These changes created the preconditions necessary for emergence of aerobic organisms. Whole taxa were extinguished by the toxicity of atmospheric free oxygen during the event, but the altered environment radically increased the scale of metabolic energy available to organisms by means of respiratory metabolic processes, laying a foundation for the subsequent bio-innovation of multi-cell organisms later in the Proterozoic eon (Sperling et al. 2013).

Biological adaptation to an ever-shifting adjacent possible is the causal basis for multi-dimensional species diversification. It has progressed from the inception of prokaryote species to endosymbiotic eukaryotes, and from simple multi-cell organisms to life forms of increasing size, complexity, and organization. Regardless of the extent of this diversification, every living cell must take in certain materials from the local environment, together with sufficient energy (often embodied in the substrate material composition) to arrange and rearrange them (Alberts et al. 2015).

The first law of thermodynamics dictates that a population of organisms cannot grow beyond an aggregate biomass stock correlating to the quantities of essential materials available in the local environment (Himmelblau et al. 2004). This constraint is the fundamental basis for ecological limitation, discussed above, which constrains growing populations, once the local inventory of essential materials is depleted. Limitation can equally affect a resident population in steady state, if the rate of resource regeneration slows, causing reduction of the available inventory, and attendant reduction of the steady state population. An extreme paleontological example of the latter case is the series of large-scale extinctions during the Phanerozoic eon, in which changes in environmental conditions reduced or eliminated access to essential factors for large numbers of species (Whiteside et al. 2016).

4.2. Feedback Effects to Socioeconomic Growth under Limitation

Every consumer population exists in relationship with a sustaining producer community, including human populations (Branding et al. 1998). Humans are only viable in groups; human propagation and maintenance require sufficient ecosystem production to support socially-organized groups. In the case of national units, as well, reliable supply of environmental goods and services is essential. Even Singapore (2021 population: 5,453,699), which imports most of its food and wood products (World Bank/WITS 2022), requires that these goods be produced in an ecosystem somewhere. Food security, a function of ecosystem productivity, is therefore fundamental to the integrity of social organization. The socioeconomic response to food deficiency is the onset of the Malthusian effects referred to previously, which intensify existential competition within society to an extent that may disrupt social organization, compounding peril to the population.

Population growth increases socioeconomic capture of environmental resources, if consumption per individual is constant or increasing. Under conditions of strict limitation, such an increase should eventually generate negative feedback to the socioeconomic system, as modeled by the logistics equation. If socioeconomic consumption greatly exceeds the rate of available ecosystem production, socioeconomic system population overshoot may occur, causing ecosystem collapse, followed by socioeconomic collapse, in keeping with the *LTG* BAU scenarios cited in Chapter 1.

Changes in ecosystem conditions or exogenous perturbations are a second pathway to an overshoot-and-collapse trajectory, but abruptly reducing ecosystem production below the level necessary to sustain its embedded socioeconomic community. An ecosystem already under stress from consumption pressure would be predictably less robust to such external disruption. Conversely, a socioeconomic population imposing substantial consumption pressure on available ecosystem resources should be increasingly sensitive to variations in ecosystem production. A combination of increasing ecosystem sensitivity to changes in exogenous conditions, and socioeconomic sensitivity to changes in ecosystem productivity, indicates tightening eco-socioeconomic coupling, which may degrade into a self-amplifying feedback loop, if the effects to net population growth lag behind those to ecosystem production.

Negative feedback effects of increasing population density regulate the net population growth of most species, limiting population to a size that can be sustained by the local ecosystem in steady state. Socioeconomic system growth is distinctive, however, because the effect of this regulating mechanism on human populations is irregular. Humans have demonstrated a unique capacity to alleviate local ecosystem limitation pressure by a variety of actions, including importation of ecosystem resources from remote sources and invention of cultivation techniques to enhance local productivity (von der Goltz et al 2020). By ameliorating local limitation effects, however, human populations can become highly leveraged with respect to the inherent productive potential of their host ecosystem. In such cases, a disruption of the ecosystem resource foundation may cause a disproportionate or catastrophic disruption to the socioeconomic system, as disintegrating social organization compounds the severity of initial Malthusian effects.

Because humans have demonstrated an exceptional capacity to alleviate limitation, socioeconomic populations densities may vary, relative to their ecosystem resource bases, on the basis of cultural characteristics and technological developmental. Societies that have mastered so-called green revolution technology, for example, may exercise an agricultural production efficiency many times that of societies lacking this capability. Austria in the second half of the 20th century reduced the extent of land used for agriculture to a fraction of its previous extent, while generating ample production to ensure a comfortable level of food security for its population (Haberl et al. 2001) By contrast, national populations lacking productive agrarian techniques may struggle within the limitation imposed by the carrying capacity of the arable land at their disposal, or else become dependent on international assistance contributions to meet their needs for sustenance (Fader et. al 2013, see also Chapter 1.2).

5. The Nation as Study Unit

Any examination of humans in ecosystem context must consider humans in social groups, not individually, because the individual human is not viable in realistic scenarios. Humans' phenotypical attributes and abilities confers species viability only as members of social-organized groups*. This study investigates the durable relationship between socioeconomic communities and the ecosystem in which they reside on large local scales.

The study unit study used is the nation-state, a well-defined social unit that connects a spatially-defined ecosystem to an embedded socioeconomic subsystem. Social units defined by tribal allegiance, shared language, proximity, small-scale administrative unit, may be ideally-suited to anthropological and sociological research. The aims of this study require measurements of material flow and flow ratios at the scale of substantial populations, where significance of individual members of ecosystem and socioeconomic communities is insignificant, and reasonably uniform measurements can be across numerous units.

In addition, contemporary nation-state boundaries are substantially rigid and immobile (subject to intermittent exceptions). Both human population and ecosystem production can be defined by reference to stable, delimited terrain extents, with relatively constant boundaries over decadal time periods. International transfer of socioeconomic material is extensively monitored and recorded, from human migration to agricultural products and commodities. Since at least 1961, descriptive statistics have been collected and maintained according to standard procedures established by international administrative institutions established after the global socioeconomic spasm of World War II.

5.1. Characteristics

No single, authoritative definition of the nation-state is universally accepted, although general, working definitions are ubiquitous. It is useful, therefore, survey key characteristics and context of the nation-state, both in the modern international system, as well as its specific significance in this investigation. A state is a centrally administered, territorially-defined social unit imposing internally-consistent rule sets on a permanent resident population. States may comprise terrain as small as a single city, as in the case of Monaco (2.02 km^2, 38,000 citizens) or Singapore (728.6 km^2, 5,043,600 citizens), or large land masses under unified administration, as in the case of Russia (17,098,246 km^2, 143,759,445 citizens) and China (9,596,961 km^2, 1,412,600,000 citizens. The United States of America (3,796,742 km^2, 331,893,745 citizens) is a superstate, in which individual state administrative regimes and rule sets may vary significantly within the subsuming envelope of a federal code of law. National population densities range from 21,055 km^{-2} (Macau) to 2 km^{-2} (Western Sahara, Mongolia). The number of states in the modern international system is contested, because of disagreements about country status and independence, but United Nations membership of 193 (with two observer states) is a benchmark (UNSD 2022).

The state eco-socioeconomic unit entails several benefits for this study, in which the scale of resolution is focused on resource flows at scales of gigatons, and information about individuals or smaller social units is elided. National-scale data used in this study comprise arrays of land use and harvesting statistics, as well as indicators related to socioeconomic health, nutrition, trade, and international assistance. The generally stable state boundaries (see below) spatially delimit the fixed extent of a national ecosystem, as well as a national population that is substantially immobile across borders, in normal conditions. The disadvantage of some breadth of sampling error from one country to another is acceptable in this context.

5.2. Historical Survey

The modern nation state emerged out of the processes of social evolution, beginning with permanent settlements established in the neolithic period, comprising, *en route*, tribal social organization, city-based civilizations, regional feudal systems, and empires. Over the period of state evolution, socioeconomic populations have grown exponentially (subject to intermittent interruptions) at local, regional, and global scales, and humans have occupied progressively more territory.

Prior to World War II (WWII), the international system was characterized by large administrative asymmetries, especially within colonial empires, in which colonies were subordinate to imperial states, and the status of independent, autonomous state was irregular (Brown 2018). Borders were also mutable in response to conflict and conquest*. Recent examples include the border between southwestern France and Germany, which was relocated eastwards and westwards across Alsace several time between the late 19th century and the end of WWII*; Poland's borders were eliminated prior to the WWII and then reconstituted several hundred kilometers to west at the war's end (Poland|Britannica 2022). Similar inter-state conditions prevailed in other regions, and many contemporary national boundaries did not exist prior to the world wards, after which they were imposed by imperial authorities*.

Following WWII, international conventions nominally guaranteed countries' inherent right to self-determination, and delegitimized coerced border changes (UN Charter|UN 2022). The doctrine of mutually-assured destruction emerged after the invention of nuclear explosive devices, characterizing the global peril should future wars entrain nuclear powers into direct conflict. The prospect of comprehensive devastation compelled the so-called superpowers to police local and regional cross-border conflicts, and to conduct their own conflicts through proxy states, in order to avoid direct confrontation. Because of this regulation of international conflict by the superpowers and their allies, even the most intense and sustained wars, such as those in Korea and Vietnam, have been geographically contained, relative to previous wars of the 19th and 20th centuries, especially the two world wars.

Global and regional international institutions were established concurrently with the post-WWII international conventions, to help regulate international conflict, by setting normative standards and providing international military resources to police border conflicts (UN Charter|UN 2022). In addition to formalizing and policing international behavior, they promoted cooperation in economic development assistance and country administrative capacity - including the statistical standards governing the collection of data for this study (USND 2022; FAOSTAT 2022).

5.3. State Function, Fragility, and Failure

The posited working definition of state function is the promotion of overall socioeconomic welfare at levels constant or increasing, relative to those previously prevailing*. The functioning state regulates resource availability, at least minimally, as well as social relations, and border integrity. It also safeguards physical security at levels generally acceptable to the national population. Acceptable norms of resource availability and physical security vary from country to country, on the basis of numerous factors, including baseline precedent, cultural value systems, and political organization.

Thinking on state fragility and failure derive from that of state function. In the present context, they are useful in considering social responses to changes in environmental conditions, especially those affecting resource availability. The term *failed state* appeared in a white paper developed by the U.S. Agency for International Development (USAID 2006). The notional idea was linked to severe consequences for domestic populations, and, potentially, neighboring nations, caused by cessation of state function. The suicide attacks launched from Afghanistan on the U.S. on September 11, 2001, was the initial impetus for the USAID study, and the paper was a validation of development assistance in terms of national security policy, aimed at forestalling state failure and attendant international disturbance. The idea of the failed state idea was subsequently adopted by academic researchers in international studies, and elaborated by the Institute for Peace (US Institute for Peace 2022) in 2007 to arrive the term *fragile state*.[4]

The consequences of state fragility and failure are illustrated in Chapter 1. Domestically, state failure implies unregulated competition among national residents for limited resources. Extreme examples of recent state failure include Rwanda and Sudan, where such unregulated competition has grossly disrupted endemic social organization, causing casualties, displacement, and emigration on large scales. Disruption of social organization, moreover, compounds national resource scarcity, causing failure of cooperative activity, which undercuts efficiency of production and distribution. The international consequences of state failure include regional perturbation and possible function disturbance by large-scale migration, increasing effective population and competition for resources in the receiving states, or by conflict spillover*. As in the case of international attacks on Kenya and the United States international effects may also extend beyond the limits of a failed state's own region.

5.4. Country Criteria and Selection

Laboratory control conditions are obviously elusive for an investigation of national ecosystems and populations. In the present case, countries were selected using to criteria designed to

[4] The IP developed a fragile state index (FSI), published annually, which ranks countries according to an index formulated on the basis of their stability and resilience characteristics. The lower the index score assigned to a country, the greater that state's sensitivity to perturbations that may disturb the state-level social organization sufficiently to disrupt it and precipitate failure.

control for characteristics tending to ameliorate potential socioeconomic limitation by finite ecosystem resource abundances. Variation among study countries in these dimensions is incorporated into the analysis and interpretation of results. These criteria comprised:

- Landlocked countries without direct access to marine sources of ecosystem productivity (pelagic fish, etc.).
- Agrarian economies, in which more that 60% of gross domestic product is derived from agricultural activity, without the capacity to export manufactured goods at large scales.
- Low levels of manufactured agricultural inputs (artificial fertilizer, pesticides, agricultural machinery) over the study period, which would tend to alleviate potential limitation.

The countries selected using these criteria are:

- Bolivia
- Central African Republic
- Chad
- Democratic Republic of Congo
- Laos
- Mongolia
- Rwanda
- Uganda

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Chapter 3 Environmental Limitation of Socioeconomic System at National Scale

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1. Introduction

1.1. Population Growth under Limiting Conditions

The concept of ecological carrying capacity is a commonplace in environmental sciences. Life forms are dissipative structures that move material from the environment into a sequestered spatial domain, regulate its oxidization, and eject disorganized material. A fraction of this material is retained by the organism, and the energy released during oxidation is channeled to organize this retained material for the organism's maintenance and reproduction. A limited number of available terrestrial materials are suitable for use in these processes and, in any terrestrial locality, the abundances of these materials will also be limited, particularly those in an energized, reduced state, suitable for metabolic oxidation. The local abundance of any of these essential materials sets a limit on the number of dependent organisms living simultaneously in that environment (Alberts et al. 2008). The history of biosphere evolution is, in part, one of sequential, accumulating innovations enabling organisms to sustain metabolic activity in the varying material circumstances of different environments (Stearns 2005). The limit on population growth of a particular species imposed by finite material abundances, and prevailing environmental conditions, is the ecosystem's carrying capacity for that species. The principles of limitation and carrying capacity apply at all organism scales, from prokaryote bacteria and eukaryote megafauna.

Population growth is regulated is by the mechanism of intensifying competition, as exponential rates of reproduction exceed the rate of additional resource acquisition, generally algebraic, at best, causing resources per capita to decrease from previous levels. These circumstances lead to the onset and progressive increase of so-called Malthusian effects (ME) among the population, as insufficiency of the limiting resources causes increasing rates of malnutrition, vulnerability to disease vectors, starvation, and, potentially, violent conflict. In these conditions, birth rates taper while death rates increase. Expressing this development in game theory terms, competition in negative sum conditions modify the previous structure of risk and reward outcomes from one incentivizing cooperation over defection to one incentivizing defection over cooperation. The introduction to this study illustrates the incidence and practical significance of ecosystem limitation passed through to socioeconomic populations in the modern world system.

1.2 Sustainability Science

Sustainability science emerged as an identified research field at the beginning of the 21st century, in response to the growing need for a scientific understanding of the effects of the human population on finite ecosystem resources (Clark 2007, Kates et al. 2001, Komiyama et al 2006). Its antecedents include such social policy programs as sustainable development, put forward by the World Commission on Environment and Development in 1986 (Glasby 1995, Keeble, 1988, Komiyama et al. 2006). On the environmental science side, foundational work included research into the material basis of ecological-socioeconomic interaction, such as early analysis of primary production capture globally by human societies (Vitousek et al. 1986, Wright 1990).

The interdisciplinary approach applied integrates conceptualizations of socioeconomic and ecological system dynamics to focus on interactions between these two system types (Bettencourt et. al 2011, Manning 2013, Ness 2007, Waggoner et al. 2002). Research in this field is defined by the problems addressed rather than their academic disciplines of the researchers. By bringing theory together with practice, sustainability scientists aim to develop actionable knowledge (Mauser et al. 2013, Wiek et al 2012), focusing on both qualitative and quantitative system parameters (Abson et al. 2017). The intersection of global processes with the eco-socioeconomic conditions of specific regions and localities necessitates integration of research at all spatial scales (Termorshuizen et al. 2009, Swart et al. 2004). Because of characteristics of natural systems, sustainability science must deal with complex, often irreversible system responses (Ostrom 2007, Rammel et al. 2007).

Sustainability scientists have responded to demand for models to assess the long-term effects of growth in human population and consumption on social development and environmental processes (Schulter et al. 2011, Walker 2004). Effects of excessive ecosystem stress include depletion of natural capital, diminished recycling and regeneration rates, and biodiversity loss through species extinction (Abson 2014). Extreme socioeconomic stress can cause malnutrition, disease, and conflict (Hsiang 2013 and 2014, Zhang et al. 2011). Sustainability science seeks to assess limits of system stability and resilience (Brand 2007, Briske et al. 2010, Carpenter et al., 2011, Turner et al. 2003), identifying which parameters have significant effects on the resilience or fragility of a system's response to change (Fath et al., 2015, Kates et al. 2001, Lima et al. 2011).

Measurement is fundamental to scientific research, providing the basis for both prediction and verification of system relationships (Witkovsky et al 2020). Measurement of ecological productivity poses special difficulties, because of the ensemble and variability of biotic production vectors and supporting physical processes. Scientific responses to this challenge comprise (1) field sample measurements scaled from plot- to ecosystem level, (2) modeling of net primary productivity (NPP) from remote sensing measurements of radiation absorption by plants; and (3) biogeochemical model-based simulation based on land cover and environmental conditions (Cleveland et al, 2015). Biogeochemical dynamic global vegetation models (DGVM) simulate productivity at planetary scale typically integrate modules representing soil quality, latitudinal placement, climate and weather conditions, plant types, and other variables. Two DGVMs commonly used to estimate ecological productivity are the Community Land Model (CLM) DGVM (Levis et al. 2004) and elaborations of the Lund-Potsdam-Jenna (LPJ) DGVM (Sitch et al. 2003).

Social parameters are defined by a large community of universities, government agencies, and international organizations. For cross-national comparisons, international organizations, such as the United Nations and World Bank (as well as regional development banks) are useful, because of their internationally-standardized data collection and statistical processing procedures (UNSD, Data Programs (World Bank), FAOSTAT) and large data bases. Non-governmental institutions with specialized interests also develop social measurements corresponding to their particular focus, such as the Fragile States Index (Fragile States Index), generally using raw data collected by one of the aforementioned organizations.

Sustainability scientist have developed innovative parameters conceived specifically to indicate characteristics of ecological and socioeconomic system. The ecological footprint was developed in the early 1990s (Rees et al. 1992) toe estimate the natural capital replacement rate, or biocapacity, of localities and regions, and places them in perspective with the consumption of resident human societies. This idea has been adopted by a substantial number of researchers to analyze the impact of social units from university campuses (Cetin et al. 2021) to continents (Zakari 2022). In 2003, an international non-governmental research organization was founded that monitors international consumption and environmental conditions, maintaining annual so-called National Footprint and Biocapacity Accounts and related public services (Footprint Network 2022). The concept of planetary boundaries (Rockstrom 2009) is distinct from the ecological footprint framework, but overlaps it, defining ten boundaries in 10 dimensions for the environmental byproducts of socioeconomic activity.

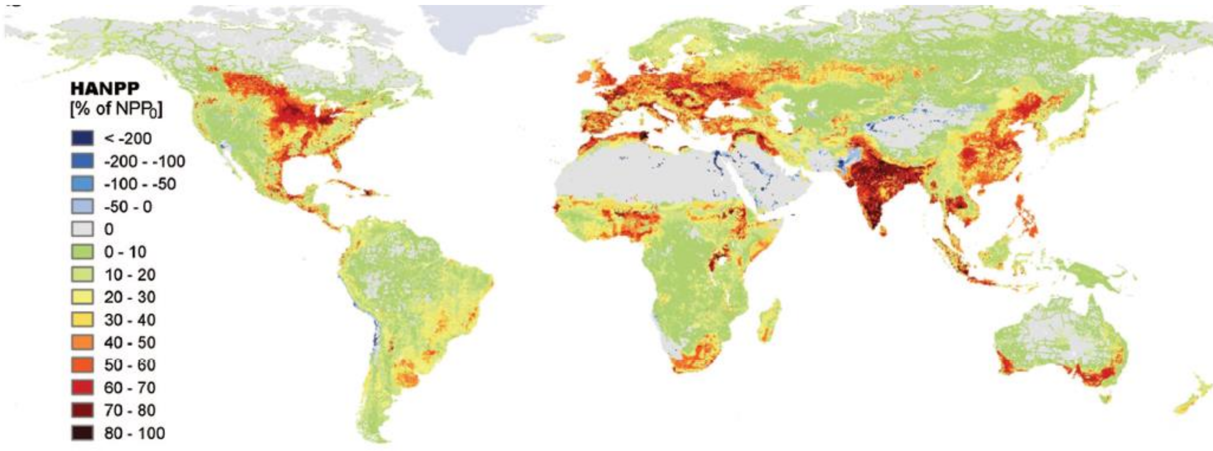


Fig. 1. Global HANPP as a Percentage of Potential NPP (Haberl et al 2007). Color coding shows the estimated percentage of total ecosystem NPP appropriated by socioeconomic populations. Percentages greater than %100 indicate land surface on which primary productivity has been boosted beyond its normal potential by factor inputs, use of agricultural capital, and advanced agrarian technology.

Haberl (1997) developed human appropriation of net primary productivity (HANPP), building on previous analyses by Vitousek et al. (1986) and Wright (1990), and elaborated by Rojstaczer (2001). This approach estimates the potential net primary productivity (NPP) of a surface area unaffected by human habitation, and contrasts it with actual NPP, subject to socioeconomic effects. HANPP is the difference between the potential and actual NPP and serves as a proxy for aggregate human loading of ecosystem goods and services.

> "It determines the amount of energy available for transfer from plants to other levels in the trophic webs in ecosystems. HANPP not only reduces the amount of energy available to other species, it also influences biodiversity, water flows, carbon flows between vegetation and atmosphere, energy flows within food webs, and the provision of ecosystem services." (Haberl et al. 2007).

Haberl et al. subsequently further developed the HANPP to account for transfers of HANPP traded across national borders (2014). The 'human appropriation' framework of socioeconomic resource capture has also been transferred to use of fresh water (Postal et al. 1996, Weiss et al. 2009).

The combined effects of undernourishment, disease, and conflict will tend to bring national population growth to zero over time, by the Malthusian mechanisms of scarcity feedback, unless limitation can be alleviated by trade, efficiency increase or emigration. A population that adapts rapidly and continuously to changes in local resource abundances may, following the logistic growth model, converge monotonically to an equilibrium level within ecosystem resource limits. Delays in adaptation, however, promote a population growth rate exceeding that of the limiting factor, that may cause overshoot and resource decline, followed by collapse of both resource and population (Meadows 1972). Changes in exogenous conditions can bring about the same effects, by disrupting ecosystem processes, lowering productivity, and imposing unprecedented limits on autotrophic production, including socioeconomic production. In the case of an ecosystem hosting an immobile human population nearing the sustainability limit of its endemic ecosystem, causing the same pattern of population overshoot and collapse.

1.3 Study Purpose and Expected Results

Kates discussed the aim of sustainability science to generate ‘actionable knowledge’ (2001). Socioeconomic action at the international scale to address resource deficiencies, and their effects, at regional or local scales, as an international public administration function. In this system, institutions exogenous to the populations experiencing deficiencies direct resources to these populations through the mechanism of national governments. The United States Agency for International Development (USAID) is the world’s largest donor institution distributing such resources, with a 2021 budget of $41 billion (USAID 2022). The United Nations Development Programme is the largest multi-lateral institution, distributing $4.2 billion within a self-proclaimed strategic framework of sustainable devlopment goals and indicators (UNDP). The distribution of assistance resources on this scale represents one end user group of the actionable knowledge generated by sustainability science. In the context outlined here and in the preceding chapters, therefore, acknowleding the essential role played by national-scale administration, narrowing the focus of socioeconomic sustainability to the national scale is a useful contribution to the understanding of limitation dynamics, within the ambit of sustainability science, including practical responses to deleterious limitation effects

In this investigation, I test for evidence of ecosystem limitation of national socioeconomic population, in countries with agrarian economies, functioning at near-constant agricultural efficiency, and constrained access to exogenous sources of NPP from marine ecosystem sources. In socioeconomic systems functioning under these conditions, inhabited by mature populations of long residence, informed observer would expect a population growing exponentially under constant limitation, *ceteris paribus*, eventually to be regulated by the negative feedback effects of increasing competition for environmental resources, causing resource abundance per individual to decrease, and intensifying Malthusian effects.

Calculation of a uniform, quantified human carrying capacity is impractical, because of variation in cultural norms and population distributions. In this study, a qualitative application of the logistic growth modal is adopted. Population increase accompanied by increasing HANPP per capita over a period of observation is not constrained by ecosystem resource limitation during that period; in these circumstances, nationally-available resource abundances exceed the populations' requirements. Constant or decreasing HANPP per capita over the same period, by contrast, indicates that the socioeconomic population is at or beyond the flexion point in the conceptual logistics curve, indicating the onset or progression of resource limitation. With the onset of limitation, Malthusian indicators of limitation pressure should be observable in the form of public health measures of nutrition and deficiency-related health effects.

Alternatively, if evidence of limitation is present, but no accompanying Malthusian effects are discerned, the observer would expect to find evidence of alleviation in the form of NPP 'leakage' *into* the system from exogenous sources, such as net food imports or improvements to endogenous HANPP efficiency. Efficiency improvement, in turn, can be achieved by acquiring agricultural capital or applying of agrarian technology. The former requires importation of manufactured goods from outside the national system, and the latter, in most cases, requires importation of processed inputs, such as artificial fertilizer and pesticides, and, often, an extended habituation period (Boyd 2013). Imports of HANPP products and manufactured agricultural inputs rely on accumulation of foreign exchange reserves either by trade for endogenous goods, or grants of assistance from international donors. In cases where alleviation of national socioeconomic limitation is observed, therefore, an observer would expect to find corresponding accumulations of foreign exchange currencies from one of these sources.

Objective: Assess presence or absence of ecosystem limitation effects on socioeconomic population national units highly reliant on NPP and derived goods from within the national territory.

Question 1

In these conditions, is the ecosystem resource availability per individual increasing?

Question 2

Where resource availability per individual is not increasing, is there evidence of Malthusian effects, or, alternatively, of conditions that would alleviate the effects of limitation pressure?

Fig. 2. Chapter objective and study questions.

2. Methods

2.1. Conceptual Approach

This section offers an overview of the conceptual framework applied, the system under examination, data sources, and processing techniques. In general, a systems orientation is applied in this investigation, stopping short of a formal stock-and-flow analysis, which is undertaken in Chapter 4.

The system type is the ecosystem, as defined by Arthur Tansley (1935), comprising both abiotic and biotic elements within an arbitrarily-defined spatial area. The subject here is the relationship between country-scale, whole ecosystem and the socioeconomic population nested within it. This study focuses on flows of material between system and subsystem, but the analytic perspectives adopted for each are asymmetrical. The ecosystem is viewed etically (adopting an outside view) that objectifies system elements and is convenient for unitized quantification. The socioeconomic subsystems, on the other hand, are examined emically (adopting an inside view) in which the subjective experience of country populations are considered, facilitating qualitative evaluations of observed changes in system parameters. The neologism eco-socioeconomic system is used occasionally to emphasize the ecosystem nesting and dependency of the socioeconomic system, when considering its aspects separately.

2.2. Study Unit

The system unit examined is the national ecosystem, bounded at the surface by generally accepted international political boundaries. Focus is on the dynamic relationship between the whole ecosystem and one of its subsystems, *viz*. the human-specific socioeconomic system. The socioeconomic system comprises humans and environmental material placed or displaced by them within the spatial boundaries of the corresponding ecosystem. The socioeconomic system is a dependent subsystem of the ecosystem; the ecosystem is the local environment of the socioeconomic system and determines its proximate exogenous conditions. (A detailed rationale for taking the nation-state as the study unit for this investigation is presented in Chapter 2.6.)

Ecosystem function is understood to be the emergent pattern of material and energy flow through the ecosystem, which develops and supports the systems biomass stock and replacement rate. This function therefore comprises physical processes, such atmospheric carbon partial pressure, and water cycling, as well as biological processes, such as material uptake, photosynthetic conversion of solar irradiance, and metabolic oxidation of consumed substrate (Albert et al. 2008). The perspective adopted in this study simplifies the numerous processes aggregated in ecosystem function by focusing substantially on NPP. Implicit is the idea that NPP, at the scale of the study unit, is an effective proxy for overall ecosystem function, specifically in the context of ecosystem-socioeconomic interaction. Autotrophic displacement and reorganization of environmental material proceed along numerous productivity vectors which are simplified in the model simulations of NPP simulations to a limited number of plant functional types (Schaphoff et al. 2018a). The analysis disregards ecosystem secondary production, except for humans and their supervised livestock, to concentrate attention on the relationship between ecosystem and SE subsystem.

The key parameter employed in this study to indicate the flow of material and energy between system and subsystem HANPP. HANPP represents the difference between potential biomass in an ecosystem without a human SE subsystem and the same ecosystem with an embedded socioeconomic system. It thus quantifies the effect on overall ecosystem function imposed by human-directed land use and consumption. The variable is an evolution of analytic frameworks previously advanced by Wright (1990), Vitousek et al. (1997), Rojstaczer (2001), and Imhoff (2004). The early work with this concept was developed and elaborated by Austrian and

German research team at the beginning of the 20th century (Haberl 1997, Haberl et al. 2003, Haberl et al. 2007, Erb et al. 2009).

2.3. Socioeconomic Subsystem

15. By analogy to ecosystem function, socioeconomic function is understood to be human activity directing flows of ecosystem goods and services that sustain essential structures and processes. Individual humans rely on social organization for survival, and the development and elaboration of social groups has made humans a uniquely successful mammalian species. The socioeconomic macro-metabolism is distinctive feature of contemporary society, comprising work and socioeconomic production derived from combustion of biomass and geo-processed, paleo-photosynthetic material (Krausman 2013) The macro-metabolism plays a significant role in socioeconomic-ecosystem interaction, multiplying the socioeconomic effect on ecosystem per population member many times, relative to that of species with comparable individual metabolisms.

2.4. Country Selection

Table 1. Selection criteria and list of countries examined in the study.

CRITERIA	COUNTRIES SELECTED
Purpose	➢Bolivia
Select countries with maximally constrained access to sources of NPP and derived goods from beyond spatial extent of national borders.	➢Central African Republic ➢Chad
➢Landlocked	➢Democratic Republic of Congo
➢Agrarian economy, low manufacturing base	➢Laos
➢Low artificial fertilizer use	➢Mongolia
➢Low irrigation	➢Unganda
	➢Rwanda

Researchers cannot impose laboratory conditions on national ecosystems and populations. Some control over the degrees of freedom of variation in ecosystem limitation of national socioeconomic population is exercised, however, by applying criteria to select countries for this study. Landlocked countries lack free access to exogenous sources of NPP-derived products in the form of marine ecosystem productivity. Countries with agrarian economies, and correspondingly small manufacturing sectors, have limited means of earning foreign exchange, which constrains both their access to other exogenous sources through trade, to means of rapid agricultural efficiency improvement.

Table 2. Plant functional types used in LPJmL4 DGVM simulation of NPP_0 (Boneau et al. 2007, Schaphoff et al. 2018a, Sitch et al. 2003)

Tropical broadleaved evergreen tree	TrBE
Tropical broadleaved raingreen tree	TrBR
Temperate needle-leaved evergreen tree	TeNE
Temperate broadleaved evergreen tree	TeBE
Temperate broadleaved summergreen tree	TeBS
Boreal needle-leaved evergreen tree	BoNE
Boreal broadleaved summergreen tree	BoBS
Boreal needle-leaved summergreen tree	BoNS
Tropical herbaceous	TrH
Temperate herbaceous	TeH
Polar herbaceous	PoH

2.5. DGVM Model

Table 3. Biophysical process equations used in the LPJmL DGVM to simulate soil and litter carbon pools. The full inventory of process equations used in the model is presented in Appendix 3a (Schaphoff et al. 2018a, *Supplement*)

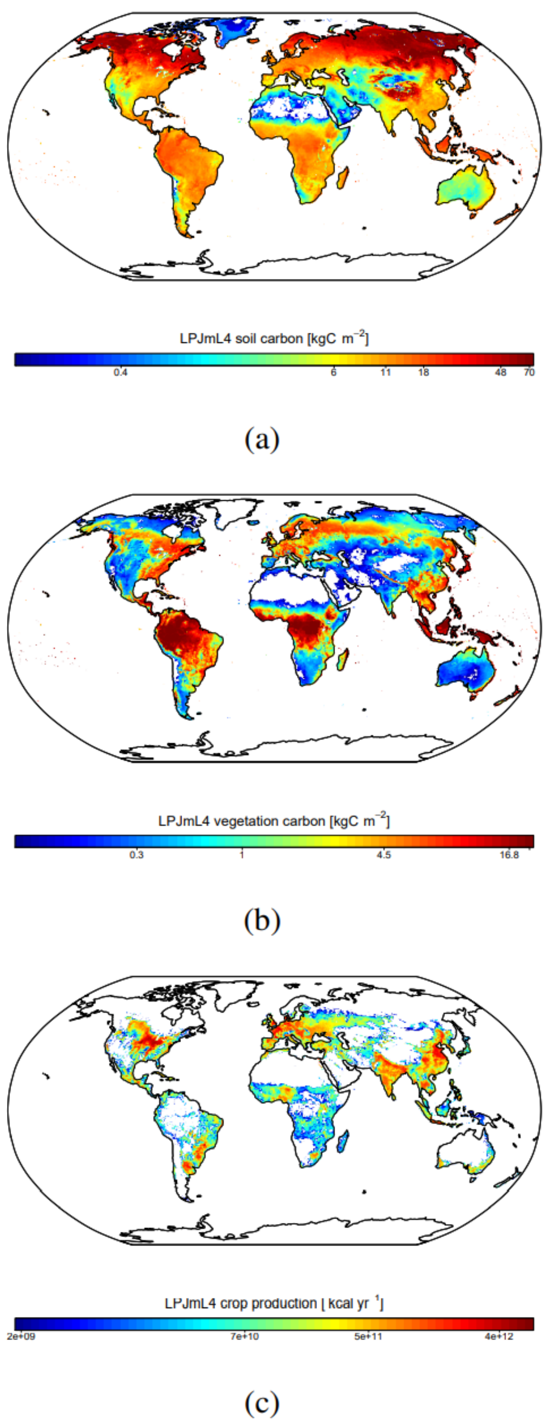
heterotrophic respiration	R_h	$\mathrm{gC\,m^{-2}\,day^{-1}}$	$R_h = R_{h,\mathrm{litter}} + R_{h,\mathrm{fastSoil}} + R_{h,\mathrm{slowSoil}}$
carbon pool size of soil or litter per layer	C_l	$\mathrm{gC\,m^{-2}\,layer^{-1}}$	$\frac{dC_{(l)}}{dt} = -k_{(l)} \cdot C_{(l)}$
decomposition rates for litter	k	$\mathrm{a^{-1}\,layer^{-1}}$	$k_{(l,p)} = \frac{1}{\tau_{10_{(p)}}} \cdot g(T_{\mathrm{soil}}) \cdot f(\theta)$
mean residence time	τ_{10}	a	
soil volume fraction of the layer	θ		
fraction of soil organic carbon per layer	Cf_l		$\mathrm{Cf}_{(l)} = 10^{k_{\mathrm{soc}} \cdot \log_{10}(d_{(l)})}$
relative share of the layer l	$d_{(l)}$		
soil layer depth	k_{soc}	mm	
total amount of soil carbon	$C_{s_{\mathrm{total}}}$	gC	$C_{(l)} = \sum_{\mathrm{PFT}=1}^{n_{PFT}} d_{(l)}^{k_{\mathrm{soc}_{\mathrm{PFT}}}} \cdot C_{s_{\mathrm{total}}}$
mean annual decomposition rate	k_{mean}	$\mathrm{gC\,a^{-1}}$	
mean decomposition rate for each PFT	$k_{\mathrm{mean_{PFT}}}$		$k_{\mathrm{mean_{PFT}}} = \sum_{l=1}^{n_{\mathrm{soil}}} (k_{\mathrm{mean}_{(l)}} \cdot \mathrm{Cf}_{(l,\mathrm{PFT})})$
annual carbon shift rates	C_{shift}	$\mathrm{a^{-1}}$	$C_{\mathrm{shift}_{(l,\mathrm{PFT})}} = \frac{Cf_{(l,\mathrm{PFT})} \cdot k_{\mathrm{mean}_{(l)}}}{k_{\mathrm{mean_{PFT}}}}$
infiltration rate of rain water into the soil	infil	mm	$\mathrm{infil} = \mathrm{Pr} \cdot \sqrt{1 - \frac{\mathrm{SW}_{(0)} - \mathrm{WPW}_{(0)}}{W_{\mathrm{sat}_{(0)}} - \mathrm{WPW}_{(0)}}}$

Ecosystem productivity estimates used in this study are products of model simulations conducted by the LPJmL4 DGVM, an evolved, downstream development of the Lund-Potsdam-Jenna DGVM developed in 2003 (Sitch), incorporating improvements to water balance simulation (Gerten et al. 2004) and plant functional types (Bondeau et al. 2007, Sitch et al. 2003; Table 3). The LPJmL4 dynamic global vegetation model (DGVM), used here to estimate country-scale NPP, simulates ecosystem processes using environmental data taken from numerous sources (Table 5), and processing them using a stock-and-flow process model (Fig. 4), applying mathematically-simulated biophysical processes (Table 4). A detailed description of LPJmL4 design and operation was published 2018 (Schaphoff et al. 2018a), together with an extensive evaluation of output quality (2018b). Earlier versions of this model were employed to generate ecosystem productivity data in more than 90 published studies between 2007 and 2017.

Table 4. Environmental data inputs incorporated in the LPJmL DGVM productivity output.

Input variables	Description	References
Precipitation	GPCC Full Data Reanalysis Version 7.0	Becker et al. (2013)
Temperature	CRU TS version 3.23	Harris et al. (2014); University of East Anglia Climatic Research Unit; Harris (2015)
Net downward long-wave radiation	ERA-Interim	Dee et al. (2011)
Shortwave downward radiation	ERA-Interim	Dee et al. (2011)
Number of wet days per months	synthetically derived	New et al. (2000)
Wind speed	NCEP re-analysis data	NOAA-CIRES Climate Diagnostics Center, Kalnay et al. (1996))
Landuse	MIRCA2000+ (see Fader et al. (2010))	Portmann et al. (2010); Monfreda et al. (2008); Siebert et al. (2015); Monfreda et al. (2008)
Soil texture	Harmonized World Soil Database (HWSD)	FAO/IIASA/ISRIC/ISSCAS/JRC (2012); Nachtergaele et al. (2009)
Drainage direction map	Topological Network (STN-30)	Vorosmarty and Fekete (2011)
Water reservoirs	GRanD database	Lehner et al. (2011)
Lakes	natural lakes	Lehner and Döll (2004)
Atmospheric CO_2 concentrations	NOAA/ESRL	Tans and Keeling (2015)

Model developers published global output data sets in NetCDF format, at monthly timesteps and 0.5 degree resolution, (Schaphoff et al. 2018c). For this study, global model output of potential NPP (NPP_0), generated by the standard model configuration, was replicated, using QGIS software. The global data was then masked by individual country shapefiles (DIVA-GIS) to acquire country-level, grid-scale NPP_0 values. The LPJmL DGVM estimates values for a number of ecosystem parameters in addition to NPP_0 (Figs. 2 and 3), including gross primary productivity, carbon stock, soil carbon, and burned carbon emissions.



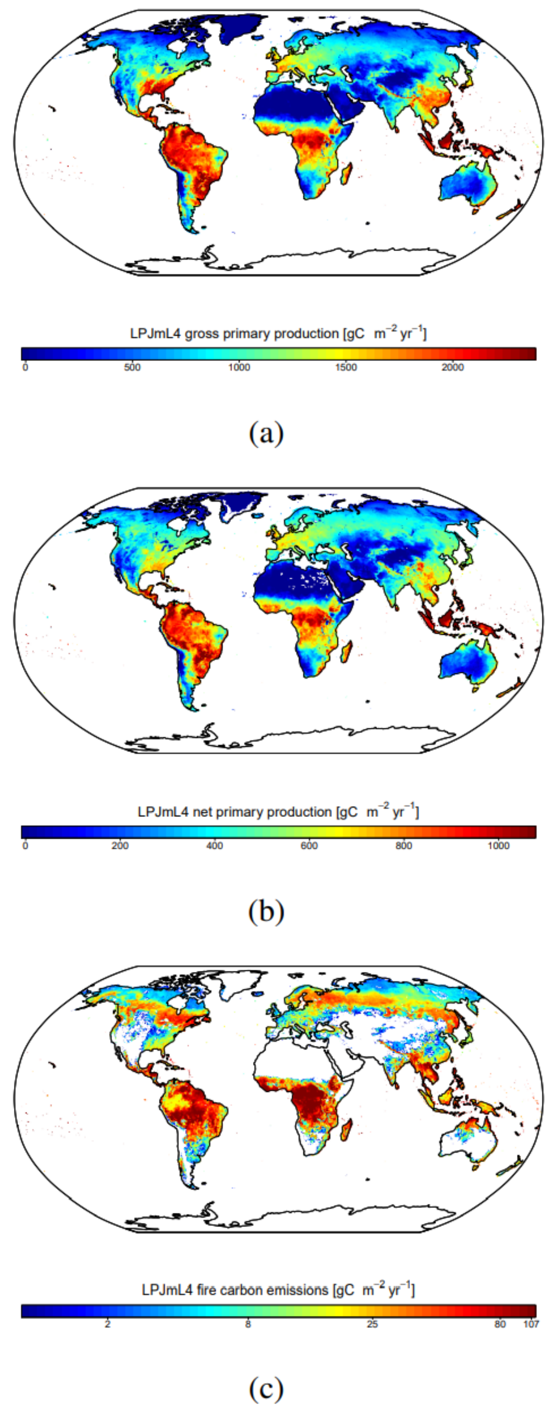


Fig. 3. LPJmL4 global-scale, color-coded mapping of model output for (a) soil carbon, (b) vegetation carbon pool, and (c) cumulative crop production. Values are averaged over the period 1996–2005. Value scale is logarithmic (Schaphoff et al. 2018a).

Fig. 4. LPJmL4 mapping of (a) annual GPP, (b) NPP, and (c) fire carbon emissions (c). Values are averaged over the period 1996–2005. Value scale is logarithmic (Schaphoff et al. 2018a).

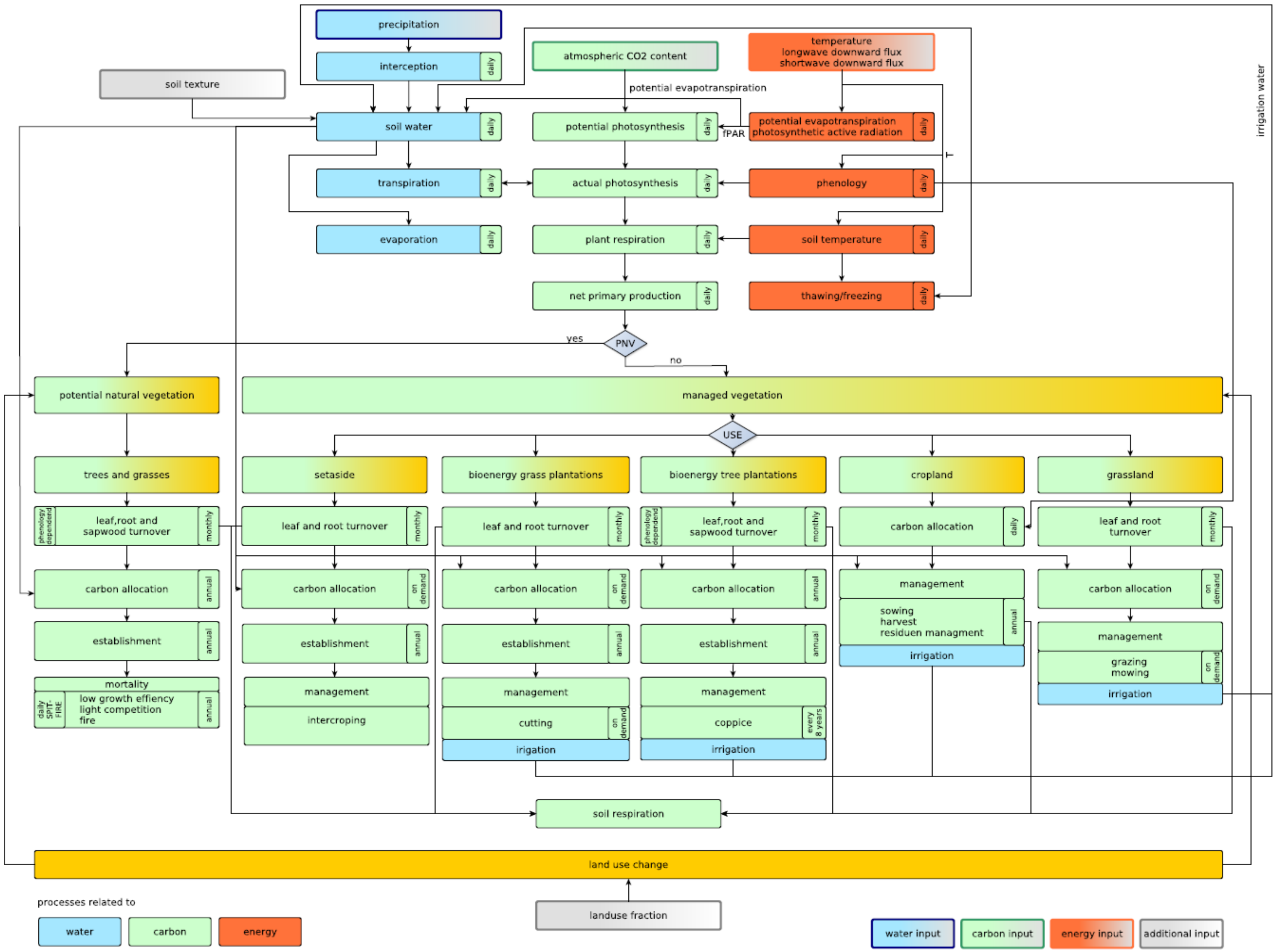
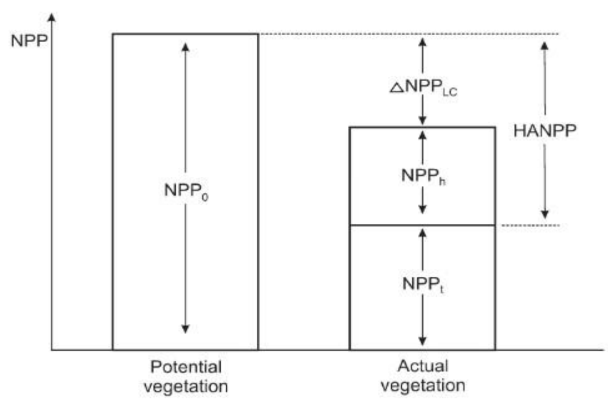


Fig. 5. LPJmL4 DGVM process flow chart (Schaphoff et al. 2018b); potential natural vegetation (PNV) is equivalent to potential net primary productivity (NPP_0) in the study

2.6. Computation of HANPP

HANPP connects the ecosystem and socioeconomic system and provides the empirical means for monitoring energy and material exchange. Analytically, HANPP is calculated by adding the NPP displaced by SE land use (ΔNPP_{LC}) and harvested biomass (NPP_h). Alternatively, it can be calculated as the difference between potential NPP (NPP_0) and the actual vegetation (NPP_t or NPP_{act}). Fig. 5 illustrates both methods.



Human Appropriation of N Primary Productivity (HANPP)

(from Erb et al. 2009)

$$HANPP = \Delta NPP_{LC} + NPP_h = NPP_0 - NPP_t$$

NPP = Net Primary Productivity
NPP_0 = Potential NPP
NPP_{LC} = NPP Displaced by Land Use
NPP_h = Harvested NPP
NPP_t = Residual NPP $_0$

Fig. 6. Calculation of HANPP (from Erb et al. 2009)

Calculation of HANPP here combines modeling output, incorporating environmental data, as well as country productivity and consumption data recorded by the FAO. The FAO compiles data collected by member countries following an internationally standardized methodology, providing technical assistance to member countries to build their statistical collection and analysis capacities. Details, definitions, and standards for the collection of each data category are presented in the institutional resource center (FAOSTAT).

Biomass units are calculated as metric tons of carbon, assuming a general carbon content of 0.5 times total biomass dry weight (Haberl 1997). Calculation of ΔNPP_{LC} is the sum of NPP_0 displaced by artificial surfaces, such as infrastructure and built areas, plus the NPP_0 displaced by anthropogenic fires, plus the NPP_0 displaced by annual crop cultivation. The following computational steps were taken for each year and country.

- Annual NPP_0 is estimated by LPJmL4 simulation for each year and country masked using GIS software to associate results with specific countries.
- Artificial surface area is taken from the FAOSTAT compilation of country statistics.
- Anthropogenic fire is estimated as the total biomass burned per year per biome (FAOSTAT 2021) and country multiplied by a factor specific to region and country estimating the fraction of total fires started by human action, adopted from Haberl et al. 2007 (*Supplementary Materials*).
- Annual crops are assumed to be destroyed at harvest, causing 100% displacement of NPP_0 for arable land. The NPP_0 displacement is calculated as average of the top quartile of productive land within the country, because crops are planted in fertile land, comprising favorable soil, precipitation, temperature, and exposure.

NPP_h is calculated as the sum of the carbon content of harvested permanent crops, wood harvested for lumber and fuel, together with associated tree waste material (bark, below-ground mass), and pasture grazed by husbanded animals. The following computation steps were taken for each year and country:

- Permanent crop dry mass rate is calculated by multiplying harvested weight statistics, taken from FAO compilations, by standard, crop-specific water content ratios published by the U.S. Department of Agriculture. •
- Lumber and fuel wood harvest quantities are compiled by the FAO in units of volume. Dry weight is calculated by standard estimates of wood densities specific to tree type and region, adopted from Haberl et al. 2007 (*Supplementary Materials*). Associated waste and belowground leavings are estimated using standard ratios specific to region, tree type, and wood use, adopted from the same source.
- Grazed biomass is estimated as total demand for animal fodder net of fodder. The balance of demand remaining is assumed to be met by pasture grazing. Fodder demand is calculated as estimated daily food intake per head per day by large animals (horses, cattle, sheep), including provision for milk production, summed over a year. Fodder demand for pigs, chickens, and egg production is estimated according to processed product mass per years (both following Haberl et al 2007). Non-pasture fodder supply is calculated as the sum of commercial fodder (such as oil cakes) sold at market and non-market fodder crops (such as green corn) or crop by-products (e.g., molasses), included fodder fractions of crop residues (edible plant waste, such as some roots and greens),

following Haberl et al 2007. Fodder dry mass weights are estimated using published water content fractions. Grass consumed to meet remaining fodder demand is assumed to have approximately the same water content as leafy annual crops.

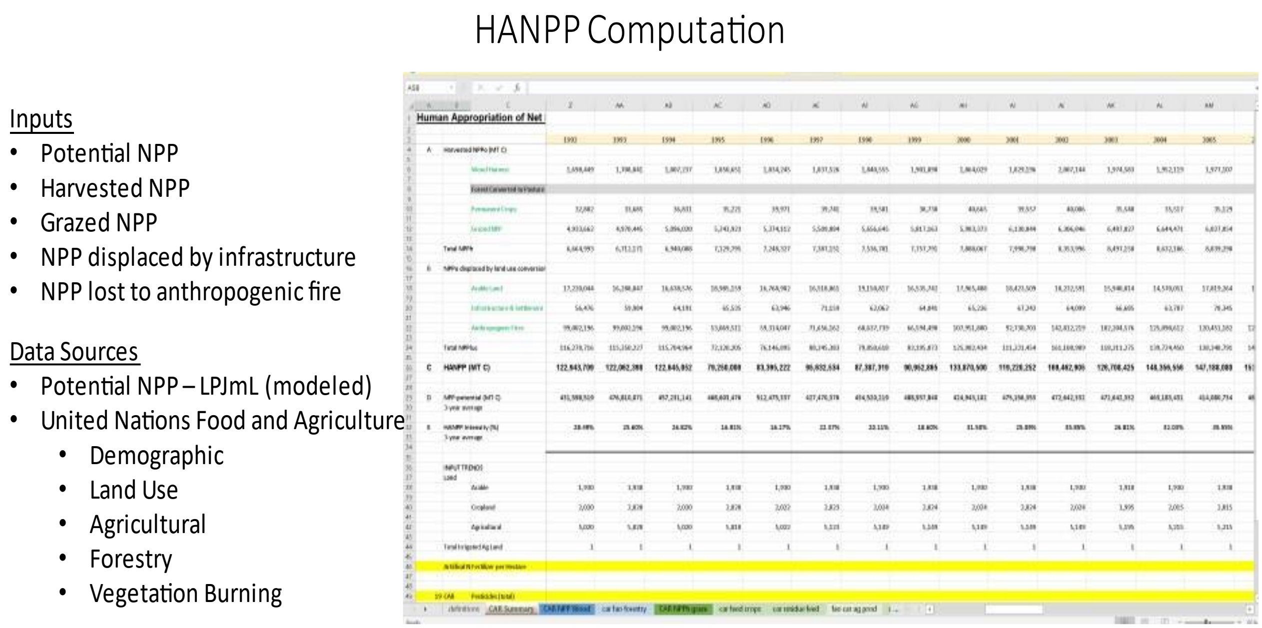


Fig. 7. Complete HANPP computation workbooks for each country in the study are attached in Appendix 3b.

3 Results

3.1 NPP_0 HANPP

Values for the variables HANPP, HANPP intensity, potential NPP, and HANPP per capita were computed for the period 1992 to 2010, together with linear trendlines for each time series, calculated using least-square regression analysis of annual values. HANPP Intensity is the proportion of NPP_0 appropriated for socioeconomic use. Results are summarized here in tabular for (time series graphs are presented in Appendix 3c, computation and data for HANPP, HANPP

Intensity, and HANPP per capita, together with LPJmL4 DGVM estimation of NPP_0, are presented in Appendix 3b. Population growth time series graphs for all eight countries are displayed in Figure 7; growth rates during this period are positive for all countries.

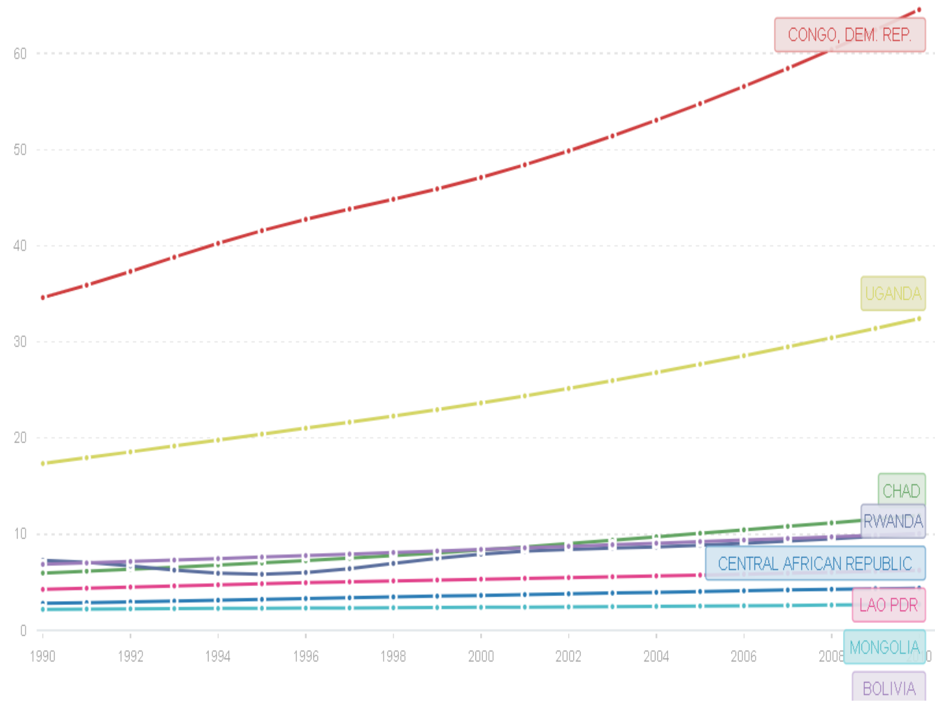


Fig.8. Population growth from 1990 to 2010 is flat in Bolivia, monotonically increasing in Chad, Uganda, Bolivia, Mongolia, the DRC, the CAR and Laos, while varying in Rwanda and the DRC. Rwanda's population declined in the mid-1990s because of civil conflict and attendant disruption of normal socioeconomic processes. (United Nations 2019)

The slopes of the trendlines indicate the net increase or decrease in each of these variables over the time period examined. Trendline slopes for these four variables are compiled in Table 6.

Table 5. Trendline slope sign for the eight study countries for NPPo, HANPP, and HANPP intensity.

Country	NPP_0 Trend Slope	HANPP Trend Slope	HANPP Intensity Trend Slope	NPP_0 per Capita	HANPP per Capita
Bolivia	+	+	+	+	+
CAF	-	+	+	-	-
Chad	-	+	+	-	0
DRC	+	+	+	-	-
Laos	+	+	+	-	0
Mongolia	-	-	-	-	-
Rwanda	+	+	+	-	-
Uganda	-	+	+	-	-

The NPP_0 trend provides a background of change in general primary productivity conditions, which offers context for the increase or decrease in the HANPP variables over this period. Country NPP_0 trends increase over the 18-year study period in Bolivia, DRC, Laos, and Rwanda, and decrease in CAF, Chad, Mongolia, and Uganda. All increases and decreases are at average annual rates of less than 1%. There is, therefore, no consistent pattern across all countries with respect to this variable. Mongolia's NPP_0 decreases most rapidly, followed by Uganda and Chad, while NPP_0 in the Central African Republic is nearly constant. Bolivia's NPP_0 increases most rapidly, whereas Laos, and Rwanda, and the DRC all increase only slightly. NPP_0 values are estimated by the LPJmL DGVM described in section 3.2. The most dynamic data inputs into the LPJmL model are climatic, *viz*., precipitation amount and time distribution, net insolation, and temperature, which are, therefore, the main drivers of the relatively modest multi-year changes in NPP_0.

The HANPP trend over the same period is positive for all the countries except Mongolia. Its slope is steepest in the DRC, followed by the Central Africa Republic and Bolivia, then by Chad, Uganda, Laos, and Rwanda (Appendix 3c).

3.2 HANPP Intensification and HANPP per Capita

Table 6. Trendline slope sign for the eight study countries for HANPP, HANPP intensity, and HANPP per capita.

Resource Availability
HANPP
HANPP intensity
HANPP per capita

- **Extraction** increased in all countries, except Mongolia:
  - in absolute terms, and
  - as a percentage of potential NPP.
- **Scarcity** increased in all countries except Chad, where it remained Constant.

NPP Appropriation	Change from 1992 to 2010		
	HANPP	HANPP/NPPo	HANPP/Cap
Bolivia	Increase	Increase	Increase
Central Africa Republic	Increase	Increase	Decrease
Chad	Increase	Increase	Constant
Dem. Rep. Congo	Increase	Increase	Decrease
Laos	Increase	Increase	Constant
Mongolia	Decrease	Decrease	Decrease
Rwanda	Increase	Increase	Decrease
Uganda	Increase	Increase	Decrease

HANPP and HANPP Intensity increase over this time period in every country except Mongolia. The greatest intensification occurred in Uganda, followed by Rwanda and Chad. Following are the Central African Republic, Bolivia, Laos, DRC, and Mongolia, where intensification is nearly constant (Appendix 3c). Mongolia is anomaly.

HANPP per capita increases in Bolivia, remains constant in Laos and Chad, and decreases in the other countries. The reduction is greatest in Mongolia and the DRC, and more modest in Uganda, Rwanda, and CAR (Appendix 3c).

4. Discussion

4.1 NPP_0 and NPP_0 per Capita

Modeled NPP_0 varies by irregularly among the eight study countries by less than 1% annually (Fig. 1). Because the most dynamic inputs into the LPJmL4 DGVM are those related to climate and weather, and interannual changes in potential productivity are reasonably ascribed to yearly variation in precipitation, cloud cover, and temperature. Significance variation in NPP_0 could indicate changes in the environmental conditions controlling ecosystem primary productivity in the absence of direct socioeconomic intervention. The moderate changes indicated here, increasing in four of the countries and decreasing in the other four, fail to indicate significant changes in these background conditions. Relatively large deviations from the mean occurred in the fourth quarter of the period in four of the eight countries, Bolivia, Chad, Uganda, and Laos, may indicate accumulating effect of global climate change (GCC). GCC is beyond the scope of this study, however, except tangentially. The observed decrease in NPP_0 per capita is a simple mathematical artifact of population growth in a context of relatively stable ecosystem productivity conditions.

4.2 HANPP, HANPP Intensity, and HANPP per Capita

Increases in HANPP and HANPP intensification, viewed together, indicate expansion of socioeconomic resource capture, both absolutely and as a proportion of total available NPP – here observed in all the study countries except Mongolia. These increases are consistent with expectations for resource demand that grows with the growing populations. Figures 8 and 9 partly corroborate this expansion, showing increases in the endogenous agricultural inputs of arable land and water, by means of irrigation.

Land Equipped for Irrigation (1,000 hectares)

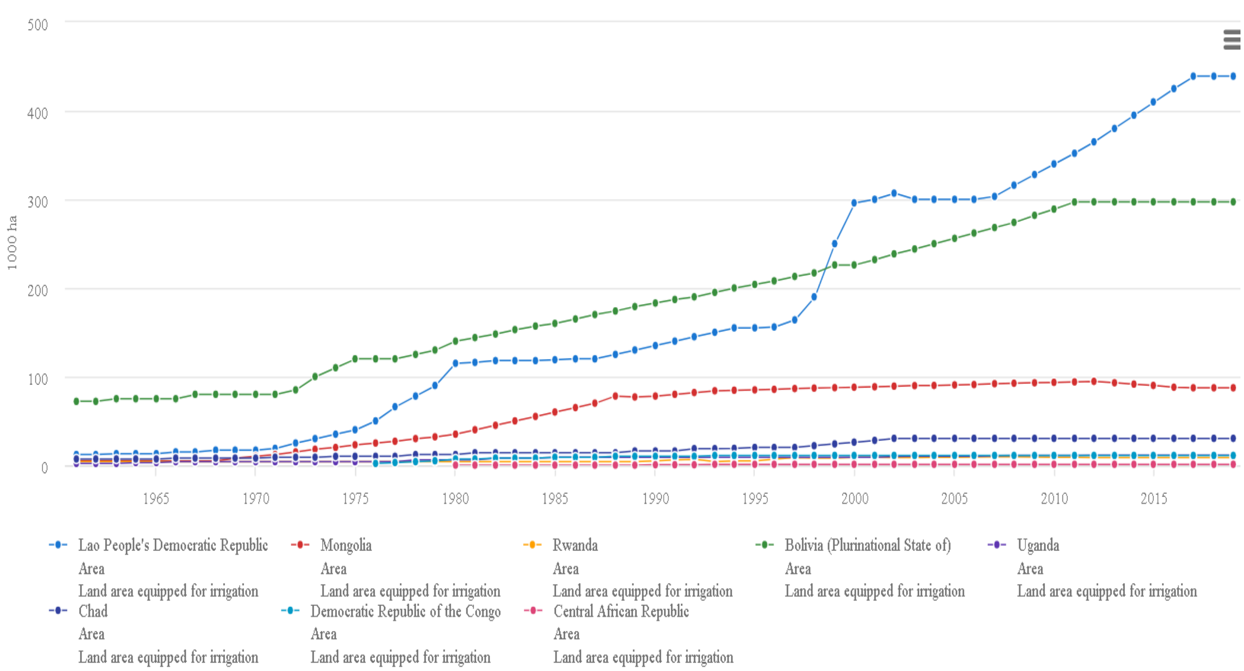


Fig.9. Bolivia, Laos, and Mongolia increased the extent of land equipped for irrigation substantially, indicating local water surpluses within their national ecosystems that is available for redirection to locations of agricultural production. Chad achieved a more modest increase by irrigation drawn from Lake Chad (World Bank 2022).

The concurrent decrease in HANPP per capita in Mongolia, the DRC, Uganda, Rwanda, and the CAR, indicates marginal resource capture rates lagging behind population growth rates, despite increases in capture of photosynthetic product. In Chad and Laos, the marginal rate of resource capture is just keeping pace. These results are consistent with expectation that national populations in countries with agrarian economies, operating at low efficiencies, should encounter limitation imposed by the limited productive potential of the national ecosystem.

Endogenous HANPP Inputs: Arable Land (hectares)

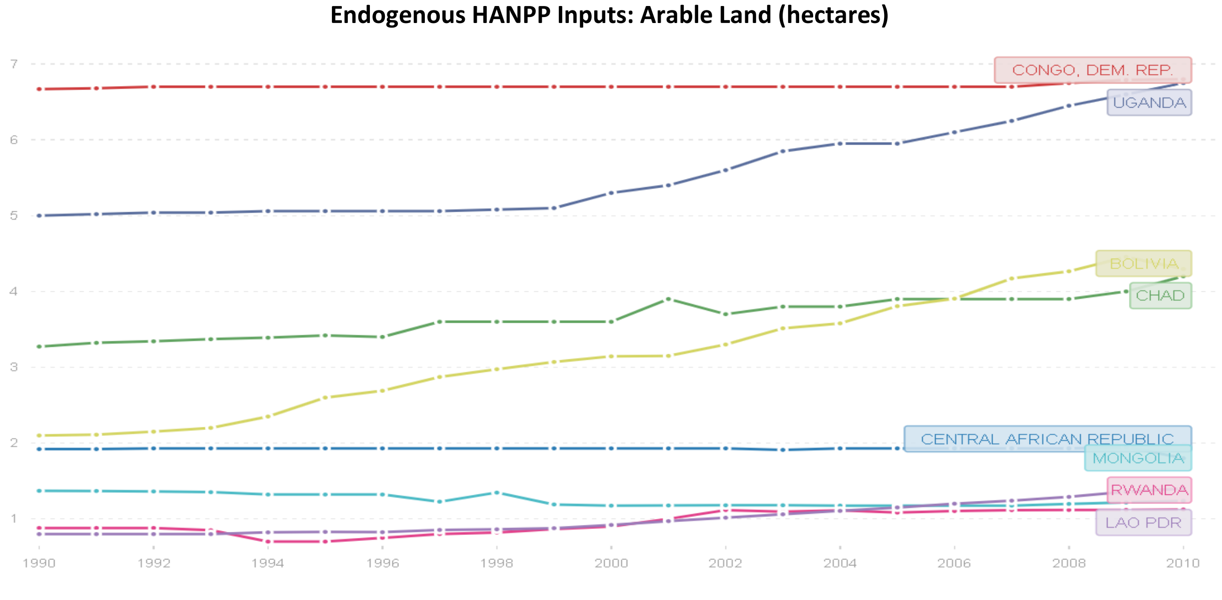


Fig. 10. Arable land in Uganda and Bolivia by more than 1,000,000 hectares between 1990 and 2010. Laos, Rwanda, and Chad by smaller amounts. Mongolia, the CAR, and the DRC remained approximately constant (World Bank 2022).

Resource capture per person exceeds the rate of population increases only in Bolivia. This result is consistent with expectations for national populations free of the effects of limitation imposed by finite ecosystem resources and process rates. Conditions protecting this socioeconomic populations from limitation effects are discussed below.

4.3 Limitation Effects

In general, we expect to discern so-called Malthusian effects in socioeconomic populations encountering limitation, manifested as decreasing indicators of social welfare in the dimensions of nutrition and health. In a country exhibiting evidence of limitation, but not of socioeconomic welfare decline, we expect to find identifiable alleviation mechanisms that, in effect, counteract the limitation pressure imposed by the finite ecosystem productivity resources. Seven countries in the study show evidence of limitation onset or progression; Bolivia alone does not.

4.3.1 Food Security and Nutrition

Table 7: Selected Health and Nutrition Indicators

Health and Nutrition Indicators	Nutritional Adequacy	Agricultural Production Index	Infant Deaths	Maternal Deaths
Bolivia	Increasing	Increasing	Decreasing	Decreasing
Central Africa Republic	Decreasing	Constant	Increasing	Constant
Chad	Increasing	Constant	Increasing	Increasing
Dem. Rep. Congo	Decreasing	Decreasing	Increasing	Decreasing
Laos	Increasing	Increasing	Decreasing	Decreasing
Mongolia	Increasing	Decreasing	Decreasing	Decreasing
Rwanda	Decreasing	Increasing	Decreasing	Decreasing
Uganda	No Data	Decreasing	Decreasing	Constant

Food production is a fundamental element of HANPP, and food security is an indicator of socioeconomic welfare, implying approximately constant or increasing availability of food per individual. Agricultural Production per Capita and Prevalence of Malnutrition are food security indicators (Table 8).

Agricultural production per capita (Fig. 10) varied among the eight countries over the study period. It declined in Mongolia, Uganda, and the DRC, increased in Bolivia, Laos, and Rwanda, and remained nearly constant CAR and Chad. Because HANPP per capita declined for Laos and Rwanda, this decline agricultural productivity is contrary to expectation, unless mechanisms of alleviating limitation and its effects can be identified. Country alleviations are discussed in section 4.5 below.

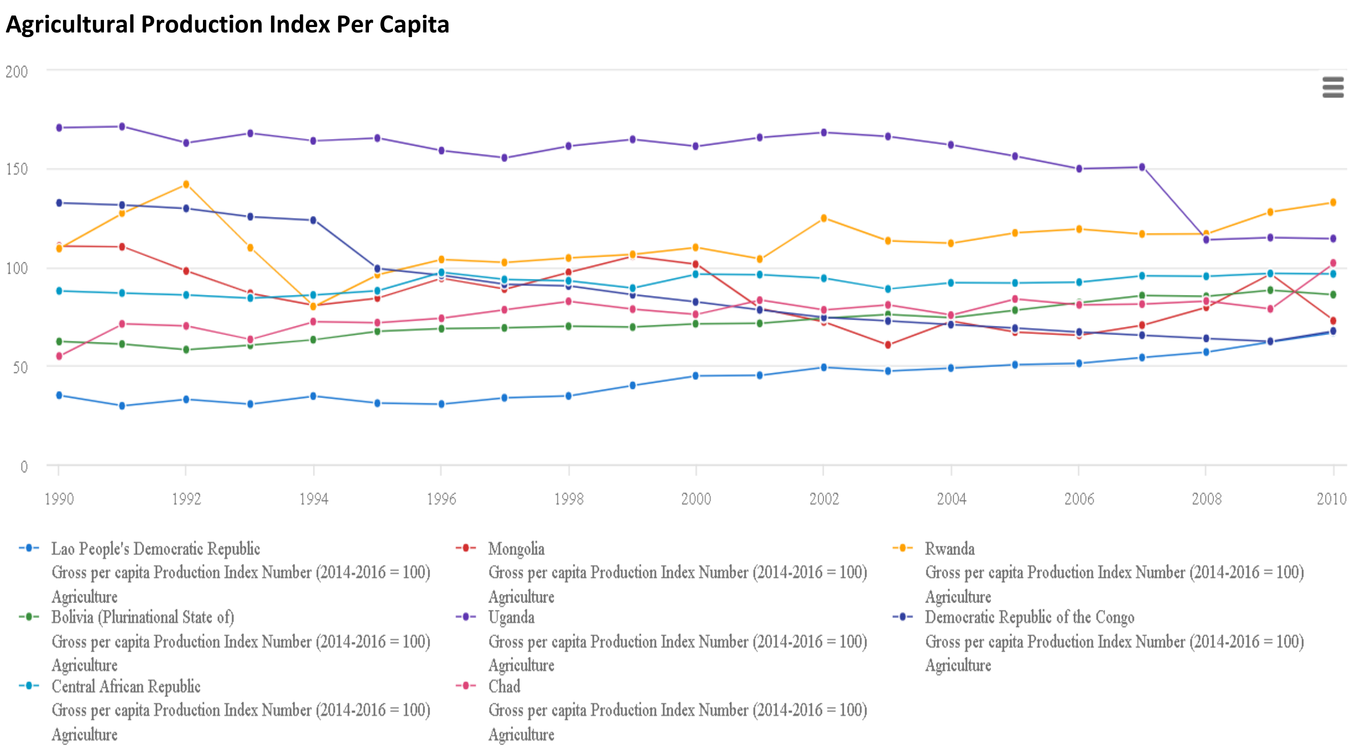


Fig. 11. Uganda, the DRC, and Mongolia trend downward over the period, while monotonically increasing for Bolivia and Laos. For Chad, it is increasing from 2003, after a 'double-dip' decline in previous years. In Rwanda and the CAR, average production was relatively stable, with Rwanda showing some fluctuations (World Bank 2021).

Prevalence of undernourishment (Fig. 11) is a lagging indicator of limitation pressure. It increased in Rwanda, the CAR, and the DRC from 2002 and 2019 and declined in the remaining countries (data before 2002 is unavailable; no data is available for Uganda). Constant or increasing undernourishment would be expected in all countries except Bolivia, because of declining or constant HANPP per capita, unless mechanisms of alleviating limitation and its effects can be identified (section 4.5).

Prevalence of Undernourishment (% of population).

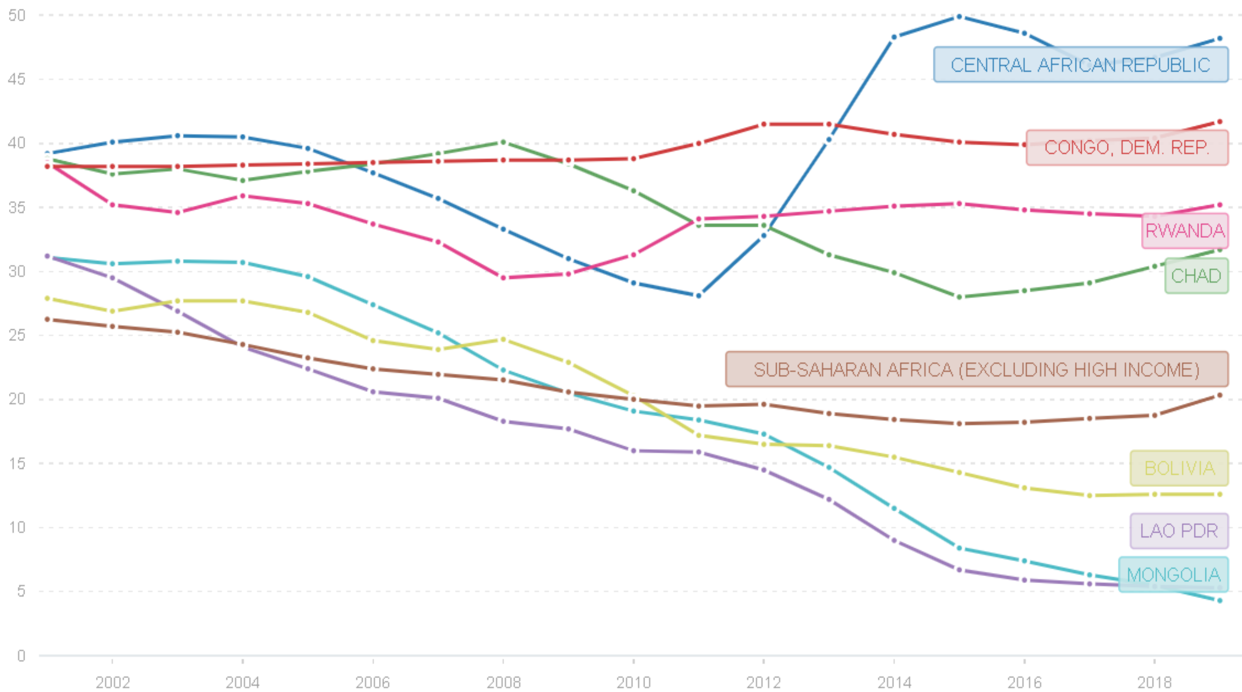


Fig. 12. Increasing prevalence of undernourishment is statistically indicated in only two countries: Rwanda and the DRC. By the end of 2019, however, six of the eight study countries show increasing prevalence of undernourishment sustained over periods of three or more years (World Bank 2021; Data for this variable is only available from 2000).

4.4 Public Health

A population's aggregate state of health is a downstream indicator of limitation pressure, because undernourishment causes disease, thereby increasing mortality rates among vulnerable demographic groups. Here we see increases in infant mortality (Fig. 12) in the CAR, Chad, and the DRC. Deaths increased through 1999 in Uganda and Rwanda before declining subsequently. Infant deaths in Mongolia fell from an already low level by about three quarters, while Bolivia and Laos declined steadily over the period.

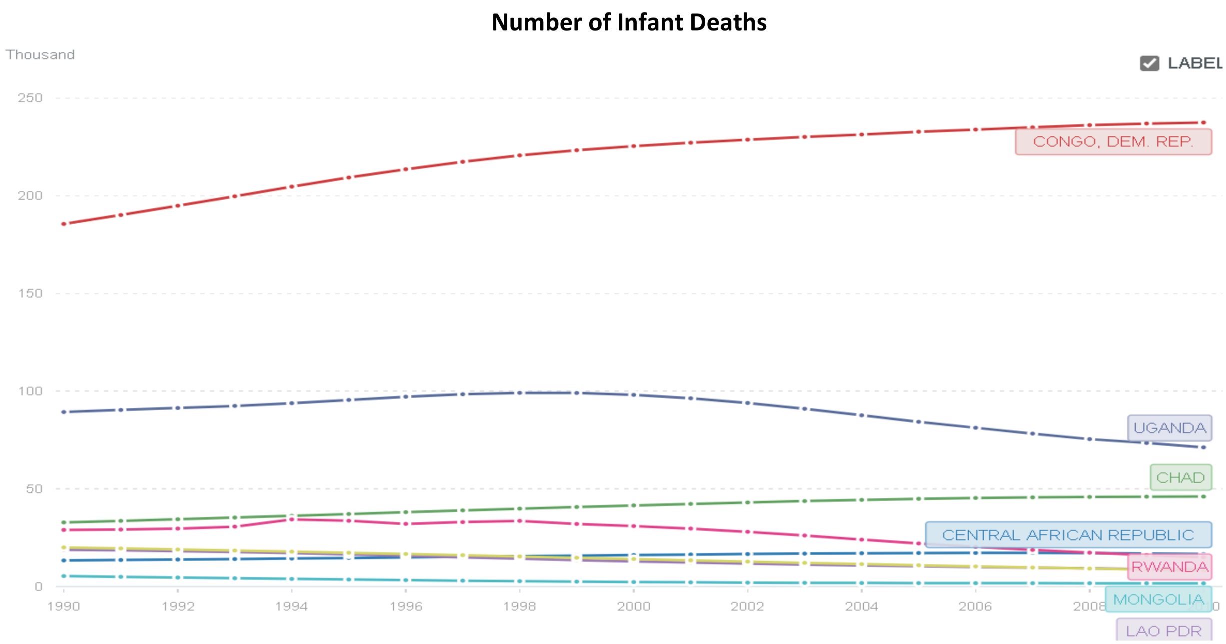


Fig. 13. During the period from 1990 to 2010, infant deaths worldwide diminished by approximately 40%. Infant deaths increased monotonically in Chad and the CAR, and in Chad and Rwanda after initial declines. No data is available for Bolivia. (World Bank 2021).

Maternal deaths (Fig. 13) increased in Chad, but decline in the DRC, Uganda and the CAR by 6%, 7%, and 15%, respectively, compared to an average decline of 40% worldwide.

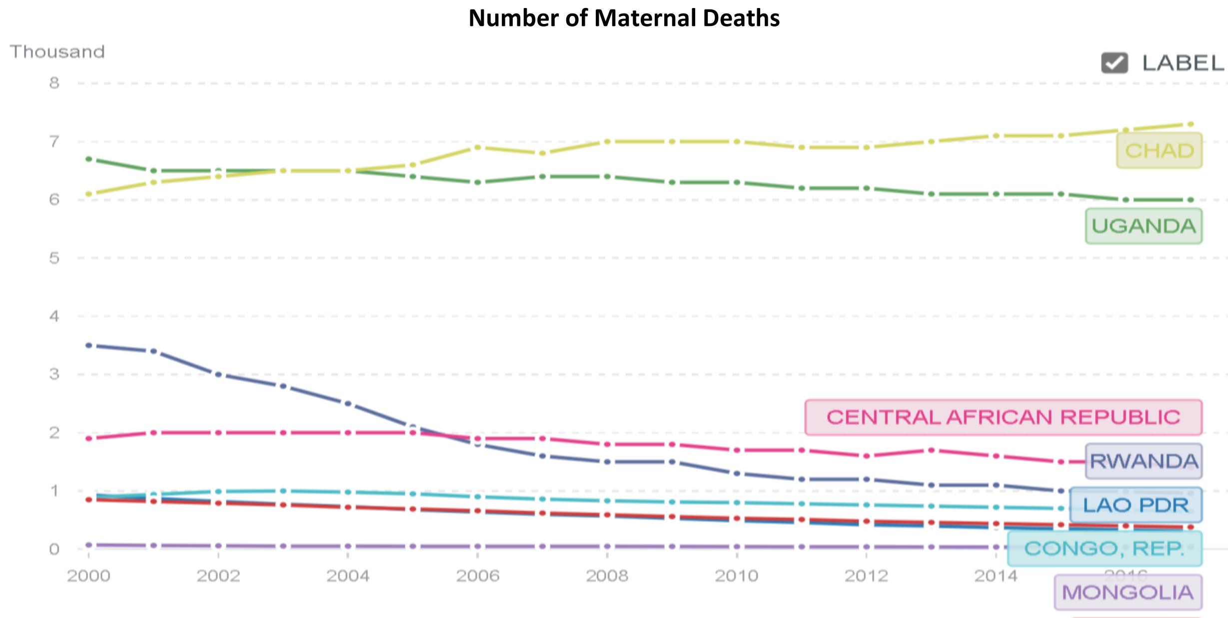


Fig. 14. Maternal death increase over the ten-year period from 2000 to 2017 in Chad while fluctuating in Uganda for a net 7.5% decrease, the CAR for a net 15.7% decrease. In Laos, Mongolia, Bolivia, and Rwanda, maternal death rates declined by more than 40%. Data is available from 2000, except for Uganda (World Bank 2021).

4.5 Ameliorations of Limitation Pressure

Table 8. Allevation Mechanisms

Limitation Alleviation	ExportableGoods	Increasing International Assistance	Agriculural Input Increases	HANPP Efficiency Measures	Food and Factor Imports
Bolivia	**Tin, Lithium, Natural Gas**	No	Cropland Extensification	Fertilzation, Irrigation	Yes
Central Africa Republic	No	No	No	No	No
Chad	No	Yes	Cropland Extensification	No	Yes
Dem. Rep. Congo	Cobalt, Diamonds, Minerals, Manufacture	Yes	No	No	Yes
Laos	**Surplus Crops, Manufacture**	No	Cropland Extensification	Irrigation	No
Mongolia	**Mineral Ores**	No	No	Yes	Yes
Rwanda	No	Yes	Cropland Extensification	Fertilzation, irrigation	Yes
Uganda	Manufacture	Yes	Cropland Extensification	No	Yes

HANPP analysis indicated actual or impending limitation pressure on the socioeconomic populations of seven of the study countries; evidence of limitation was absent in Bolivia only.

Of the seven countries in which limitation was indicated, no evidence appeared in Laos and Mongolia of the expected limitation pressure effects, in terms of food security or public health, while only modest effects were indicated in Uganda and Rwanda. Evidence of more severe limitation effects was discerned in CAR, Chad, and the DRC. Are there mechanisms of alleviation operating in the cases where limitation effects are absent or light, which enable these countries to eschew limitation effects, despite the evident limitation imposed by their endemic resource base?

National socioeconomic systems may adopt a combination of strategies to ameliorate the effects of HANPP limitation on the population. One such strategy is to increase endogenous inputs to agricultural production, such as arable land and water, as displayed above (Figs. 7 and 8). A second is to increase domestic HANPP by improving production efficiency, in particular agricultural NPP (NPP_{ag}), by introducing agricultural capital, supplying factors otherwise constraining crop productivity, such as plant nutrients, and measures to suppress pest competition for HANPP. Agricultural machinery is an example of agricultural capital, artificial fertilizers of factor inputs, and pesticides of competition suppression. A third strategy is importation of HANPP captured in locations beyond the spatial boundary of the national ecosystem.

Socioeconomic population limitation occurs when the rate of population growth exceeds that of HANPP. In the general case, endogenous inputs in limiting circumstances are already being brought into NPP_{ag} productive processes as expeditiously as possible, given the capabilities of the country in question, without causing an alleviation effect. An exception to this case may occur if technological or organizational methods can be introduced into nation HANPP systems, which that have not previously enjoyed their benefits, without substantial capital inputs from foreign sources. The success demonstrated by Bolivia, Laos, and (temporarily) Chad, where extension of irrigation allowed corresponding increases in arable land, is an example of this kind of advance.

The second and third strategies noted here require importation of goods from outsides sources: agricultural capital or manufactured inputs in order to increase efficiency of domestic productivity; or HANPP-derived products to ameliorate deficits in domestic HANPP. Importation of goods requires means of payment for those goods, in the form of foreign exchange reserves. Counties accumulate foreign exchange either through sale of goods domestically produced, or in the form of official aid[5] from bilateral or multilateral donor agencies, such as the UNDP, USAID, or international development banks. Countries with agrarian economies have, by definition, small manufacturing sectors, which constrains foreign exchange earnings from the sale of manufactured goods. These countries should only be able to import significant quantities of HANPP, or manufactured agricultural inputs, if they produce large agricultural-silvicultural surpluses, if they are recipients of substantial official aid, or if they have access to another kind of tradable good, such as extractable mineral or energy resources.

[5] Official aid is defined by the United Nations as aid from national or international governmental agencies, in contrast to assistance from foundations, non-governmental organizations, religious organizations, or other sources.

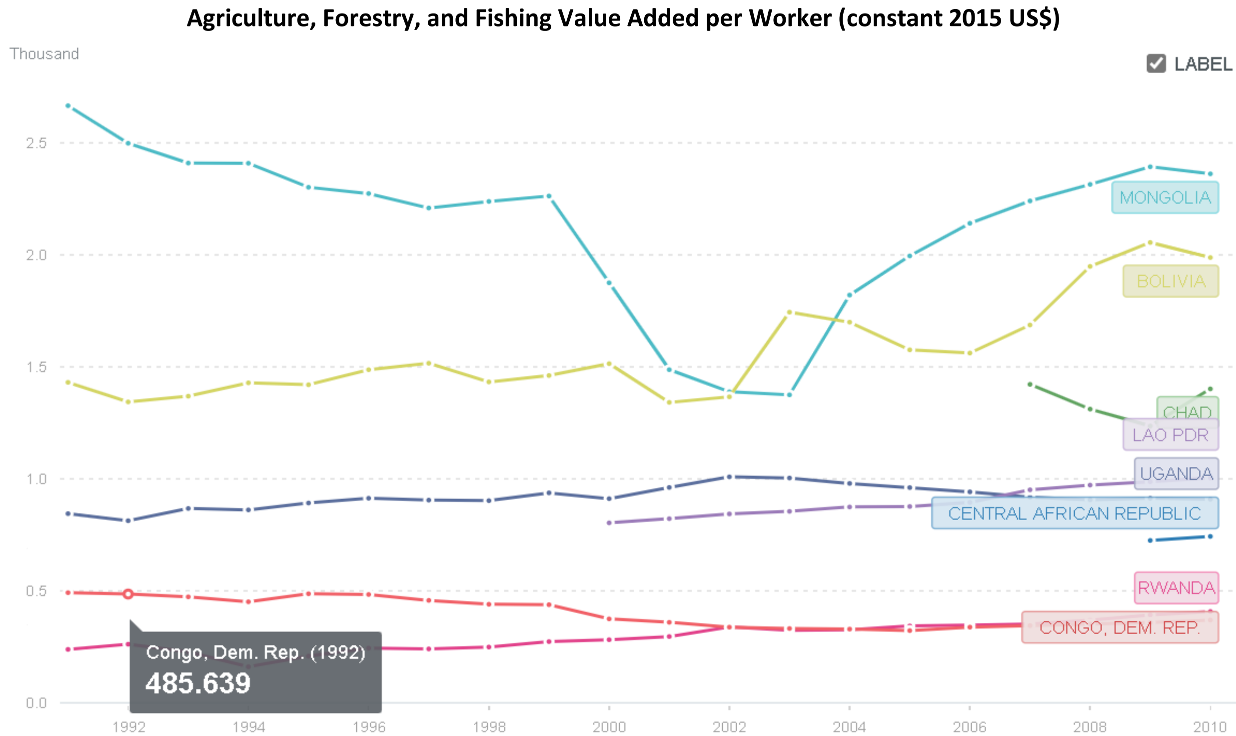


Fig. 15. Average change over the period is generally neutral, except for Bolivia, where it increases and Mongolia, where it decreases. Note that Bolivia's increase correlates to its increases in irrigated land and use of fertilizer (World Bank 2021; data is incomplete for the CAR and unavailable for Laos).

4.5.1 Alleviation by Increasing Efficiency

HANPP value-added per sector worker (Fig. 14), and cereal yield per unit land input (Fig. 15), are indicators of efficiency. Value added per worker increased in Bolivia, Laos, Mongolia and Rwanda over the study period, while declining in the DRC and remaining approximately constant in the CAR and Uganda. Uniquely in Mongolia value added declined steeply from 1990 to 2003, and increased steeply from 2003 to 2010. Cereal yield per hectare increased significantly over the period in Bolivia, Mongolia, Laos, Uganda, and Rwanda, with little net change over the period for the CAR, Chad, and the DRC. In Mongolia and Rwanda, yield decreased in the first half of the period, before increasing rapidly in the second half.

Cereal Yield (kg per hectare)

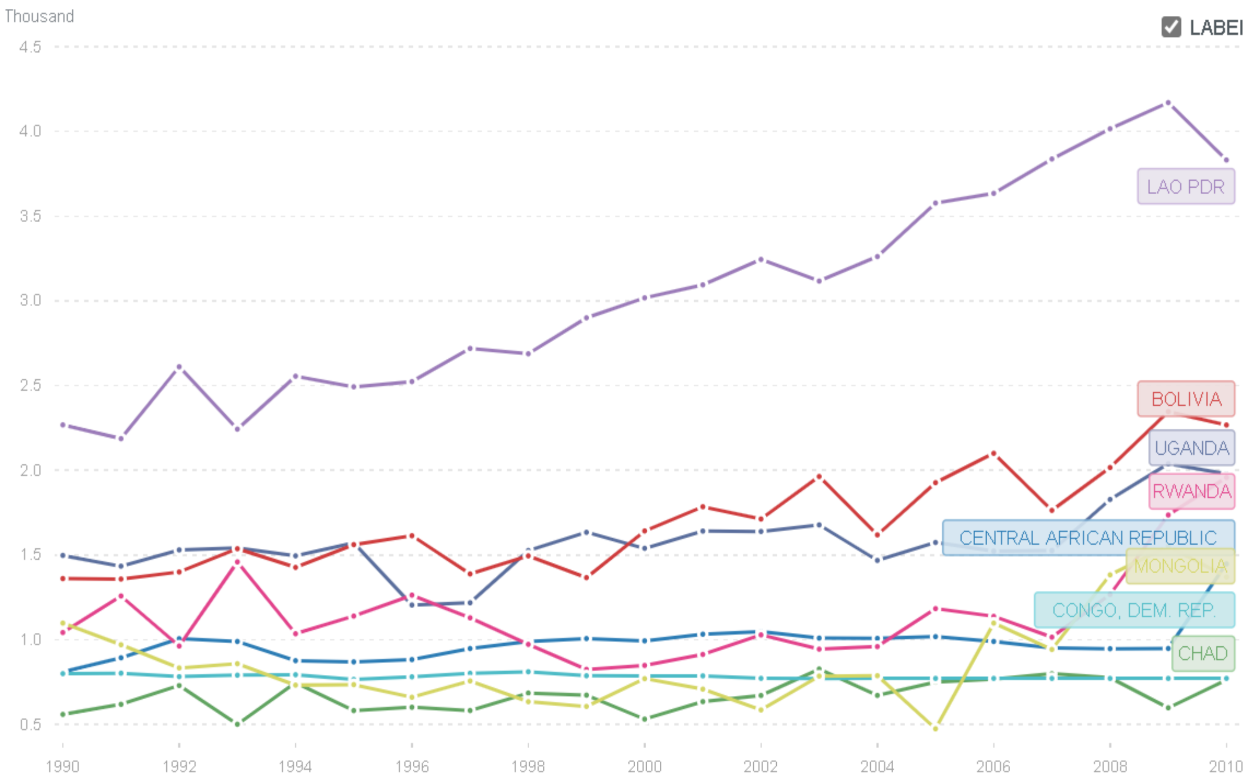


Fig 16. Cereal yield per hectare increases over this period for Laos, Bolivia, Uganda, Rwanda, and Mongolia. Yield remains roughly constant for Chad, the DRC and the CAR, with a discontinuous uptick in 2010.

The efficiency increases indicated in Bolivia, Mongolia, Uganda, and Rwanda approximately coincide with increases in application of artificial fertilizer, and imported productivity factor input (Fig. 16). The coordination between fertilizer use and efficiency indications is most apparent in Mongolia, where fertilizer application decreased abruptly after the 1992 dissolution of the Soviet Union, previously Mongolia's largest trade partner and a source of artificial fertilizer.

Fertilizer Use (kg per hectare of arable land)

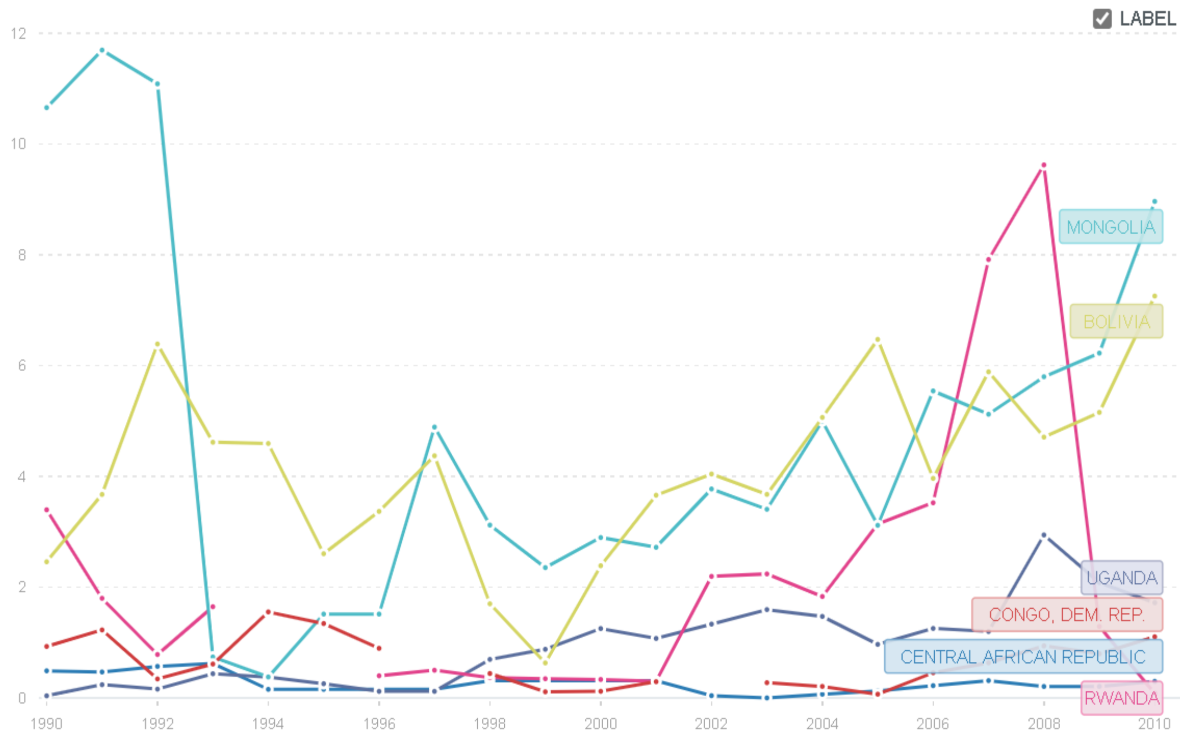


Fig. 17. The CAR and DRC show little or no change during this period, while Uganda and Rwanda show a trend of increasing application from about 2000 on, although they both decline sharply at the end of the period. Bolivia's and Mongolia's use first decreases and then increases to around 8 kg per hectare at the end of the series. Mongolia's use declines sharply after1992, coinciding with to the breakup of the Soviet Union in 1991. Data not available for Laos and Chad (World Bank 2022).

4.5.2 Alleviation by Importing HANPP from Exogenous Sources

Net food imports and cereal import dependency are indicators of HANPP deficit alleviation through the mechanism of importing HANPP from outside national boundaries (cereal import dependency is the ratio of net cereal imports to overall cereal supply). Net food imports (Fig. 17) increased in Bolivia and Mongolia over the entire period, in Uganda during the second quarter and in Chad and Rwanda during the final quarter. In CAR net food imports remained approximately constant and in Laos they declined into negative magnitudes, indicating that Laos was generating enough surplus HANPP to became a net food exporter. (Net food export data for the DRC is unavailable.)

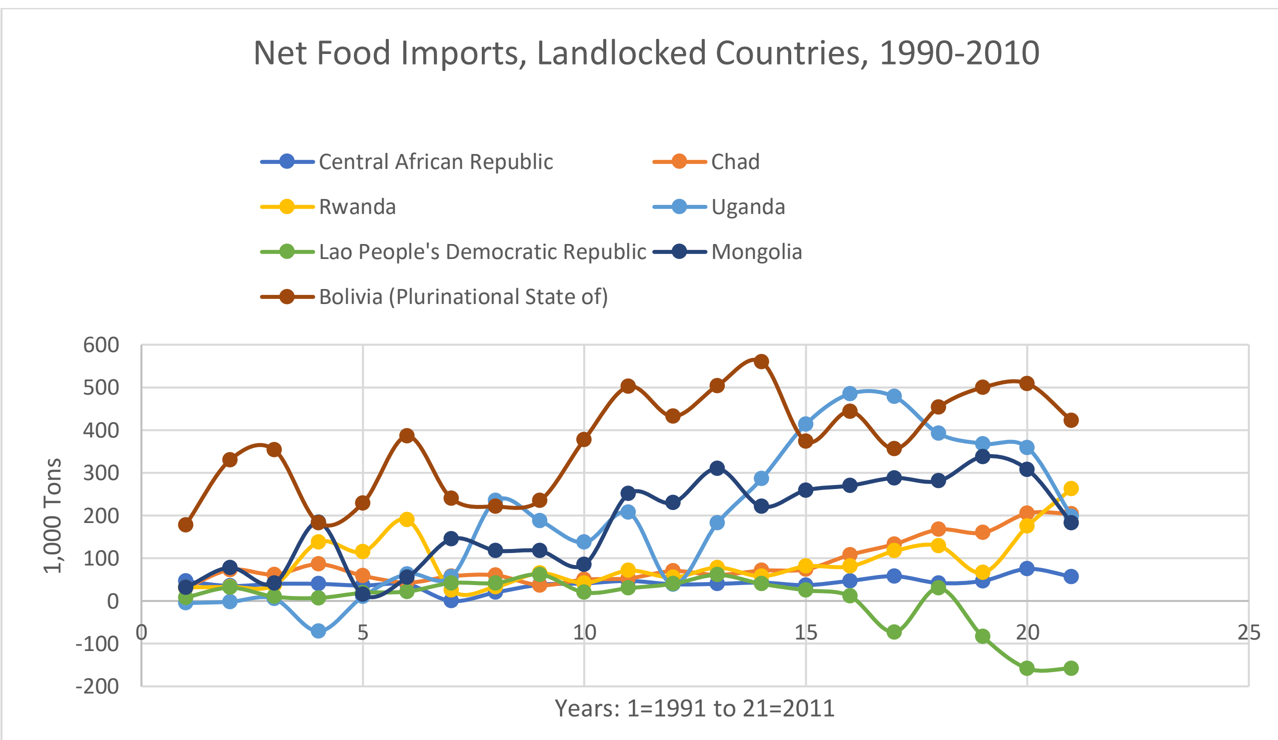


Fig. 18. Imports increase over period shown for all countries, except Laos, which becomes a net exporter after 2006. They decrease for Mongolia, Uganda, and Bolivia between 2005 and 2010. (Based on data from FAOSTAT, 2021; data unavailable for Democratic Republic of Congo)

4.5.3 Means of Payment for Imports

Alleviation of socioeconomic limitation by mechanisms requiring importation of HANPP-derived goods, agricultural capital, or productivity factor inputs should be possible only when the importing countries control foreign currency reserves necessary to pay for them. Six of the eight study countries are observed to be either directly importing HANPP or factor inputs contributing to efficiency of domestic agricultural efficiency. Is the apparent operation of this mechanism in these countries corroborated by evidence of means of payment?

Means of payment is in evidence for each of the importing countries. Mongolia began to develop extensive mineral extraction resources in the early 2000s (Mongolia 2022, Mining 2022), allowing it to import sufficient food and efficiency enhancements to forego some of its previous domestic agricultural production (Fig. 10). Bolivia has exported extracted tin and fossil fuel products from before the beginning of the study period (Bolivia 2022), in keeping with the lack of evidence of any limitation pressure during this period, and has used this import capacity to improved agricultural production efficiency (Figs. 14 and 15), while also increasing its endogenous land inputs through expansion of irrigated terrain. Laos commanded adequate water resources to increase domestic HANPP sufficiently through irrigation (Fig. 8) and become a net exporter of HANPP. Laos's cereal yield efficiency increased nearly 100% during this period, as well, and it may have used revenues from sales of surplus crops to import productivity inputs. Chad's modest sales of domestic oil reserves provided means of payment for small increases in food imports from 2006-2010 (Chad 2022).

Official aid flows to Uganda and Rwanda increased during the second half of the period corresponding to the increases of food imports during the same period. Despite an anomalous, large increase in official assistance to the DRC between 2002 and 2004, and a sustained relative increase in assistance subsequently, neither labor efficiency nor crop yield increased there. This study stops short of examining the effects of social organization on socioeconomic system function, but organizational causes may account for the lack of alleviation response in DRC to means of importing HANPP and efficiency improvement inputs.

Official Development Assistance Received (constant US$)

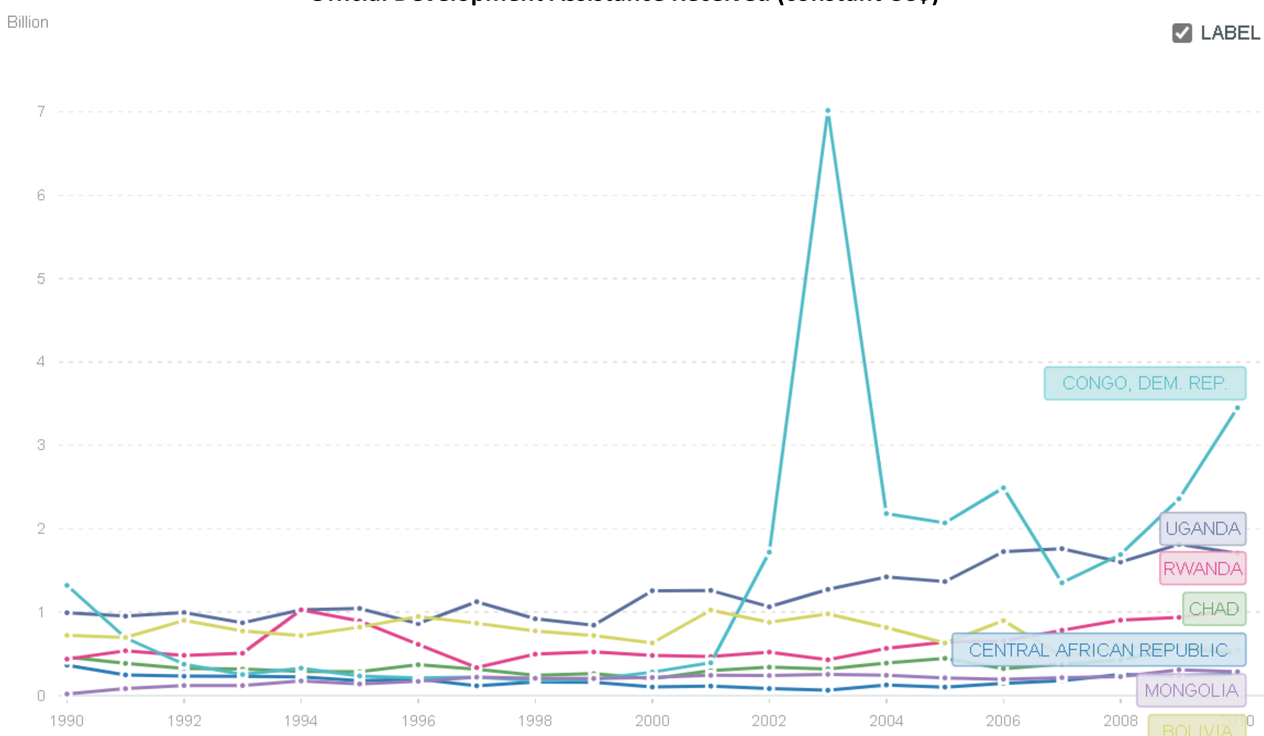


Fig. 19. Official aid increased for over the period for Rwanda, Uganda, and the DRC, with roughly stable assistance flows for the other study countries. Uganda's assistance flow fluctuates sharply between 2002 and 2007 (World Bank 2021; data for Laos is not available).

4.6 Summary

Constant and decreasing HANPP data are evidence of impending or active socioeconomic limitation by national ecosystem resources in each of the eight study countries, except Bolivia. Food security and health indicators of limitation were substantially absent in Laos and Mongolia (the decrease in Mongolian agricultural production (Fig. 10) offset by HANPP imports (Fig. 17)), and moderately present in Uganda and Rwanda. Evidence of limitation was strong in the CAR, Chad, and the DRC.

The five countries showing no or only moderate signs of limitation (including Bolivia) commanded one or more of three alleviation mechanisms. Bolivia and Laos were able to increase endogenous inputs to agricultural productivity by extending irrigation to create more arable lands (Figs. 8 and 9). Bolivia, Mongolia, Rwanda, and Uganda also increased efficiency of agricultural production (Figs. 14 and 15) by importing artificial fertilizer (Fig. 16). (Laos also increased efficiency, possibly by means of input importation, as well, but fertilizer data is unavailable for Laos.) Bolivia, Chad, Mongolia, Rwanda, and Uganda also directly imported HANPP-derived goods (food importation data for the DRC is unavailable) – Chad only modestly so at the end of the study period. Laos produced and sold surplus agricultural goods.

Evidence of alleviation by the mechanism of importing productivity inputs and HANPP-derived goods is strengthened by associated evidence of means of payment in the importing countries, in the form of foreign reserve earnings or donations of official aid. In the study countries, Bolivia, Mongolia, and Chad earned foreign exchange by sales of exported mineral and fossil fuel resources, and Laos by sales of exported surplus crop production. The DRC, Rwanda, and Uganda were recipients of increasing levels of official international assistance – albeit to little apparent effect in the DRC. No evidence of alleviation, or means of alleviation, is discerned in the CAR alone, the country in this sample showing the most effects of severe socioeconomic limitation by national ecosystem resources.

5. Conclusion

Objective: Assess presence or absence of ecosystem limitation effects on socioeconomic population n ational units highly reliant on NPP and derived goods from within the national territory.

Question 1

In these conditions, is the ecosystem resource availability per individual increasing?

- Ecosystem resource availability per capita is constant in two of the eight countries studied (Chad and Laos) and decreasing in four (CAR, DRC, Rwanda, and Uganda.
- Ecosystem resource availability per capita is increasing in Mongolia and Bolivia.

Question 2

Where resource availability per individual is not increasing, is there evidence of Malthusian effects, or, alternatively, of conditions that would alleviate the effects of limitation pressure?

- Evidence of limitation effects is seen in Chad and the CAR.
- Sources of limitation pressure alleviation are present in the DRC, Laos, Rwanda, and Uganda (as well as Mongolia and Laos).

Table 19. Objective and Questions

Eight countries were selected for examination on the basis of constrained access to NPP-derived products from outside sources, agrarian economies, and modest application of techniques to improve crop production efficiency. The countries were tested for indications of impending or operational limitation, based on the 18-years trends of HANPP per resident in growing populations. Evidence of limitation was discovered in six of the eight countries, absence of limitation in two of the countries. Of these six countries, indication of Malthusian effects was discerned in malnutrition and maternal death statistics for two. In the other four countries, as well as the two countries not experience limitation pressure, sources of limitation alleviation pressure were identified.

An extensive body of literature has been developed using the HANPP parameter since its introduction as a research tool (Haberl 1997). Calculations of HANPP for individual nations or subnational units have used country-specific historical records (Chen et al. 2015, Kastner 2009, Krausman et al. 2012, Fetzel et al. 2014, Zhang et al. 2011) to estimate background NPP_0, NPP_h, NPP_{luc}, and the other component sub-variables. HANPP computation using uniform international data sources and model output has been generally limited to examination of global and inter-regional analyses (Haberl et. al 2007 and 2011, Imhoff et al. 2004, Krausman et al. 2009 and 2013). This study brings together the internationally-standardized productivity data and LPJmL DGVM output, used in these global and regional analysis, to estimate HANPP for individual countries, as part of an international comparative study. The results are presented in the context of sustainability science generating 'actionable knowledge' (Kates 2001) that can support practical responses to actual eco-socioeconomic development issues. Applications of this research providing input into policy formulation governing the rational blend and allocation of scarce international assistance resources among competing priorities, helping to accurately assess risks of population growth and ecosystem stress under varying conditions of limitation, in a period of rapidly changing environmental conditions.

Potential improvements are available to future investigators working on questions similar to those examined here. The time range here was determined by availability of interoperable national data on biomass burning and infrastructure land use. Alternate estimation procedures for these variables could extend the length of the HANPP and related time series, generating more interesting and powerful results. In addition, rapid advances are being made in fine-grained modeling of surface productivity on the basis of remote sensing data (Phalke et al. 2020). These results should be examined as means of improving the precision and accuracy of HANPP estimation, and its applicability as a measure of material flow between ecological and socioeconomic systems. With respect to social indicators and detection of deleterious social effects of exceeding endemic primary productivity resources, careful examination of the relationship between short-term improvements in public health and their lagging effects of population-ecosystem dynamics may be useful, because of the potential for declining death rates to accelerate population growth in sensitive national ecosystems.

Future research directions indicated by this study and its results include examination of changes in ecosystem sensitivity to perturbation under conditions of national population convergence to the sustainability limits of their ecosystem productivity. This study has intentionally stopped short of considering climate change effects on national ecosystems, but it is understood in the environmental science community that increases in radiatively active gas partial pressures are modifying some regional climate conditions which, in turn, perturbs local ecosystem conditions.

What is the effect of unregulated HANPP on the decay rate of ecosystem resilience and recovery from such perturbations?

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Chapter 4: Dynamic Analysis of System Behavior

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1. Introduction

1.1. Socio-economic Growth under Limitation

In contemporary society, national borders impede mobility in pursuit of non-adjacent ecosystem resources, reversion to nomadic hunting strategies is not viable, and cross-border raiding is impractical in most cases. If consumption of local ecosystem resources exceeds their rate of generation, scarcity must either be endured or alleviated. Endurance generally means a Malthusian reduction of population lowering net birth rates (births minus deaths) or population displacement and emigration, both of which imply disturbance of inertial social organization and function. Alleviation is generally sought by either increasing primary production efficiency or importing surpluses of NPP-derived goods from abroad. Increasing agricultural efficiency requires local mastery of agrarian technological advances. Import of NPP-derived goods or efficiency-boosting imports requires local command of tradable goods or services, e.g., commodity surpluses (mineral or organic) and industrial production, or reliable flows of official international assistance.

Chapter 3 provided evidence and analysis showing instances of socioeconomic limitation by finite ecosystem resources, despite a general superabundance of NPP-derived production at the meta-population scale. As indicated above, countries confronted by impending or ongoing ecosystem limitation face intensifying Malthusian effects, the outcomes of which are problematic and undesirable. The dynamics of socioeconomic subsystems embedded in mature ecosystems is a focus of research interest, especially where neither alleviation strategy is available, because of humanitarian issues caused by scarcity, as well as the potential risk posed to international security by disruption of national social organization. A substantial body of work has been generated examining historical cases of socioeconomic instability and collapse under conditions of increasing ecosystem limitation pressure (see Chapter 3.1).

Chapter 4 explores the dynamics of spatially-delimited ecosystems burdened by growing human populations, assessing the risk to socioeconomic subsystem sustainability under of increasing perturbation by ecosystem-imposed limitation pressure. It examines national-scale socioeconomic trajectories, as populations grow under limitation pressure imposed by ecosystem resources. In these circumstances, standard population growth models predict a transition from a regime of relatively continuous, monotonic growth to one of turbulence, in socioeconomic terms, where growth rate may change rapidly with potentially disruptive effect. The present investigation compares projected system evolution under inertial conditions ('business as usual, or BAU), with evolution under modified conditions, in which the modifications represent either discretionary changes, reflecting policy choices, or changes imposed by the system's environment.

1.2. Abstract System Conceptualization

Prediction of system evolution is an evolved characteristic of many living organisms: predators, for example, are adept at directing their paths of pursuit to intersect with the flight paths of their prey. In human social evolution, successful prediction of system behavior was long interpreted as knowledge revealed to an individual by a supernatural agent (The Holy Bible 1950). Galileo's study of pendulums in the 15th century (Newton 2009) is a milestone event marking the formalized representation of dynamic physical systems in terms empirically-verifiable units, which can be generalized to families of systems sharing similar essential features with different dimensional specifics. Isaac Newton, born in the year of Galileo's death, invented differential calculus[6] (Cohen et al. 2002) in his effort to calculate the movement of astronomical bodies in gravitational orbit. The Lagrangian reformulation of further generalized classical mechanical conceptualization of physical systems (Campanelli et al. 2021), deriving the concept of system action, enabling analysis of complicated, deterministic systems comprising large numbers of point-particles.

Boltzman's 19th-century investigation of the heat-motion relationships (thermodynamics) yielded the statistical mechanics methodology for probabilistic reconciliation of aggregated micro-system behavior with correlated macro-system behavior (Uffink 2004). Poincaré developed geometric methods of qualitative systems analysis (Charpontier et al. 2010, Poincaré

[6] Independently discovered by Gottfried Leibnitz in 1684 (*Gottfried Wilhelm Leibnitz* 2022).

2017). Early in the 20th century, Einstein's relativistic interpretation of mass behavior at very high speeds further extended the reach of abstract conceptual representation and analysis. The development of quantum mechanics and field theory, based on research by (again) Einstein, Plank, Bohr, Schrodinger, Heisenberg, and others (Kragh 1999), combined analytic techniques from statistical mechanics with the Hamiltonian re-formulation of Lagrangian classical mechanics to conceptualize sub-atomic dynamics in terms of probability densities. Much recent research emphasizes development of techniques for modeling and analysis of complex and chaotic systems (Strogatz 2015).

Analogous conceptualization of living systems has lagged that for physical systems by centuries. Individual biological cells eluded human ability to observe and describe until the proto-microscopy developed by van Leuwenhook (Dyer 2008), whose life span roughly coincided with Newton's. A series of conceptual syntheses since then laid the foundation for a detailed understanding of cellular processes, including the 18th-century synthesis of Mendel's theory of plant genetics with Darwin's evolutionary conjecture, and the 20th-century synthesis of genetics with biochemistry, creating the field of molecular biology (MIT 2004). Advances in microscopy, combined with improving understanding of the cell-scale chemical reactions, enabled such breakthroughs as the DNA-RNA phenotype replication mechanisms and genome organization, based on Crick's "central dogma" of molecular biology (Watson 1980). Biologists now command the capacity for very fine-grained process replication, which is implicit in the emerging technologies of protein-folding simulation (Calloway 2020) and individual gene replacement, based on genetic palindromic repetition (CRSPR) (Israeli et al. 2022).

Researchers have largely explored modeling and simulation of system-scale biological processes by transferring conceptual and analytic techniques developed previously in the study of physical systems. Living systems are complex, even at the scale of a single, prokaryotic cell, which comprises very large numbers of components interacting according to the fundamental physical principles governing mass and force (Voet et al. 2004). This complexity is progressively compounded as living systems increase in scale: from aggregates of functionally-uniform cells, as in a prokaryote colonies and slime molds, to the organized aggregates of functionally-heterogenous cells in plants and animals, to so-called super-organisms. Because of this complexity, together with the large number of biological species, and the potential for ontically-open system evolution, expectations of modeled replication of system behavior differ qualitatively from those for physical systems (Nielson et al. 2011, Jorgensen et al. 2001). Substantial loss of lower-level system information through simplification is accepted perforce (Levins 1996), limiting the power of ecological generalizations, based on time and space invariance, relative to those in the physical sciences.

Ecology compounds the complexity of this hierarchy of biological organisms even further, by mixing species in spatial proximity. This irreducible complexity has promoted extensive use of modeling approaches to understand ecological phenomena at in terms of intermediate elements and motivations, rather than fundamental ones. Early ecological conceptualizations included the community succession approaches of Clements (1916) and Gleason (1926), and analysis of such biophysical processes as stream oxygen balance (Streeter et al., 1925). Population studies and analysis of dynamics were formalized by Alfred Lotka (1910, 1956) in the Lotka-Volterra equations[7] of species interactions. Shugart (1998) enumerates a partial list of modeling approaches, comprising finite-state automata, dynamical systems with state variable representations, and compartment models with material flow, which is elaborated by Jorgensen et al. (2001) into a full taxonomy of ecological model types.

Tansley defined the ecosystem in 1935 as the "basic units of nature," comprising both biological and abiotic elements of an arbitrarily delimited spatial domain (alternately formulated by Lindeman (1942) and Morowitz, 1968). The emphasis of this formulation on the ecological *system* defines a perspective more holistic than that previously adopted, focusing on aggregate-level properties, where characteristics of individual elements of the system are relevant, but not dominant. Use of models in this context is a necessary scientific technique, taking into account the complexity, layering, and systemic properties of the phenomena under examination (Jorgensen et al. 2001, Levins 1996). Jorgenson discusses at length the general outlines of an iterative process that alternates between reductive analysis of system elements and synthetic, modeled simulations of whole system behavior. H. T. Odum's study Silver Springs in Florida (1957) is an early example of an explicitly system-level examination, which focused on the flow of energy through the defined ecosystem, adapting conceptual techniques from electronics (circuit diagrams) and chemical engineering (Sankey diagrams). Odum codified his

[7] Independently published by Vito Volterra in 1926 (Goel 1971).

approach in *Introduction to Systems Ecology* (1983), the first textbook of ecosystem ecology, which presented a formalized ‘energy circuit language.” In this work, he set out basic concepts for ecological analysis, including a discussion of ‘embodied energy,’ which formed the basis for eventual introduction of the term ‘emergy’ denoting the accumulated sum of exergy from lower-hierarchy, upstream system elements, which are implicit in the mass-energy composition of a higher-level, downstream ecosystem element. He also appropriated the term ‘feedback,’ first used in electronics and later applied to systems contexts during WWII cybernetics research into fire control systems (Bateson 1972), to denote certain eco-system process regulating patterns.

Ecosystem study through model-based analysis proliferated at the end of the 20th century, as experience and theoretical insight accumulated, and computational power increased. The palate of conceptual approaches grew to include agent-based models, simulating growths of populations of individual ecosystem elements from prescribed initial conditions; a family of landscape models, comprising homogenous, spatially-interactive, and mosaic landscapes; up to general circulation models of global-scale atmosphere-surface interaction and dynamics (Shugart 1998, Jorgensen 2001 et al.). The range of system process focus comprises biogeochemical processes, trophic interaction, population dynamics, energy-mass flows, and thermodynamics (Prigogine, 1961 and Jorgenson, 2001), among others. The examination of ecosystems in juxtaposition with ‘coupled’ socioeconomic subsystems, currently topical, was presaged by (again) the prolific H.T. Odum in *Environment, Power, and Society* (1971, 2007), where he extended and elaborated ecosystem energy flow synthesis to global scale, emphasizing the human socioeconomic subsystem embedded in it. Sustainability science (Kates et al. 2001) is a 21st century offshoot of ecosystem-socioeconomic subsystem study that examines"… [E]merging models and conceptualizations that integrate the Earth system, human development, and sustainability," together with other related issues.

Natural system modeling, as described here, entails several key concepts, *viz*., qualitative vs. quantitative results, system complexity, linearity vs. non-linearity, and stability. Richard Levins's influential paper on model building (1966) addresses the first these issues in the specific context population biology, but in terms sufficiently general to apply broadly. Levins describes ecological modeling as simplified representations of a system that retain the essential features necessary to solve a specific problem. He asserts that it is impossible to maximize generality, realism, and precision simultaneously, and recommends sacrificing the former to maximize the latter two when developing ecosystem models. Distinguishing between theorizing and modeling, he takes the position that precision is only necessary for testing hypotheses when theorizing. Modeling for system insight and understanding often focuses on long-run, qualitative results, Levins writes, satisfying predictions expressed as inequalities to meet heuristic criteria. In part, this approach is prescribed by the irreducible complexity of natural systems, which interdicts results in terms of fundamental physical concepts, limiting their explanatory reference framework, instead, to intermediary system elements, which are subject to flux. The Inherent complexity of ecological systems requires each parameter to be selected as "a many-to-one transformation of lower-level phenomena … [w]herein lies its power, but also its source of imprecision." This imprecision emerges from omission of factors with small effects, vagueness about the exact form of mathematical functions, and loss of information about lower-level events (the ‘many-to-one transformation’).

System linearity concerns whether the system conforms to the property of superposition (Clugston 1998), which states, in essence, that an operation performed on a linear system has the equivalent effect as the aggregation of the same operation performed separately on each of the system parts. Its significance is twofold. One is the validity of experimental procedures using certain input functions, especially the family of singularity functions (Shugart 1998). Second, stability tests for linear systems are not identical with those for non-linear systems. System stability is defined as decay of perturbation effect to zero (or some arbitrarily small range) as time approaches infinity (Strogatz 2015). Linear (and linearized) systems can be tested for stability heuristically, e.g., conservation of stock material in a compartment model, or formally, applying Routh-Hurwitz criteria, for example using a ‘loop analysis’ (Levins 1974, Justus 2004), to determine if perturbation decay goes to zero, without analytically solving system equations. Alternatively, Lyapunov stability denotes system output response to perturbation within a certain range that remains bounded by a correlated output range. A further development of the idea of system stability is structural stability (Arnol’d et al. 1988), which relates to perturbation of a system, rather than initial conditions. A system is structurally stable if an arbitrarily small perturbation to the system does not affect the configuration of system elements, within small ranges.

4.1.3. Stock-and-Flow Modeling of Socioeconomic Systems in Limiting Environments

Stock-and-flow system analysis have been applied as a modeling technique for examining socioeconomic populations in circumstances of ecosystem limitation since at least 1998 - nearly coinciding with the declaration of sustainability science as a discipline (Kates 2001, see Chapter 3.1). Brander et al. (1998) adapted the Lotka-Volterra (L-V) predator-prey equations to represent the consumer-producer dynamics of the Rapani society resident on Easter Island from ca. 400 CE.

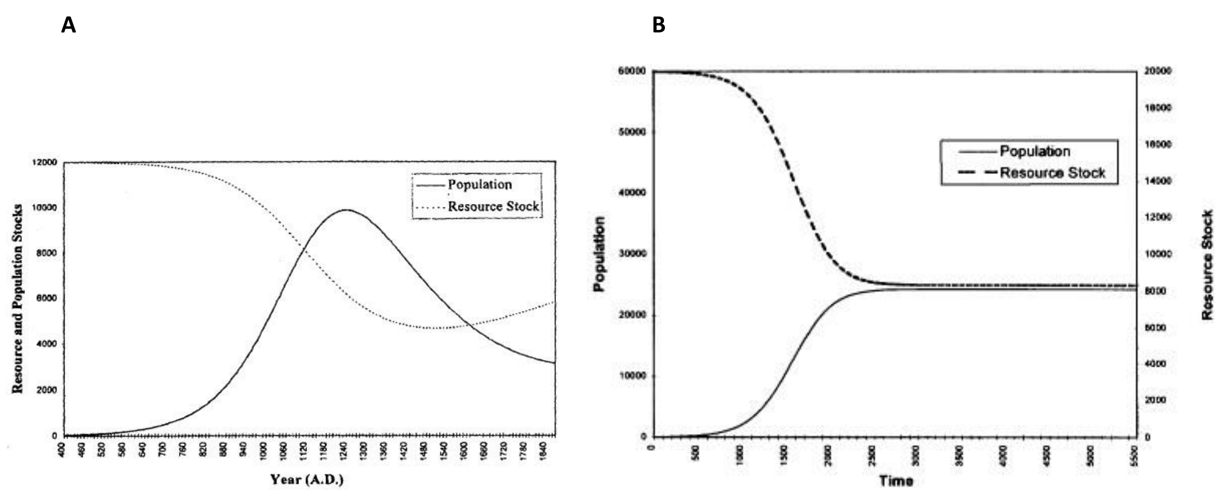


Fig. 1. Two scenarios of the modified Lotka-Volterra equations employed by Brander et al. (1998) to analyze the trajectory of Easter Island ecosystem evolution under the pressure of Rapuni socioeconomic residence and consumption. (A) represents a population overshoot scenario illustrating Branders interpretation of actual events, calculating that the socioeconomic rate of consumption overwhelmed the rate of essential primary production, depleting and ultimately exhausting the resource capital base accumulated prior to Rapuni immigration. (B) represents a socioeconomic system converging asymptotically to the carrying capacity of its host ecosystem. In Brander's analysis, this trajectory of system evolution represents the general pattern of socioeconomic adaptation to environmental conditions on other Polynesian islands, based on evidence that the rate of primary production on Easter Island was atypically slow among the island population of this archipelago. Not the differing vertical axis scale configurations in the two diagrams.

The model simulation showed exponential growth rate of the socioeconomic population, and attendant consumption of primary production, exceeding the rate of essential resource regeneration. The island's previously-accumulated stock of this productivity vector, a species of Palm tree, was depleted and eventually exhausted. A time path graph of the Rapuni population supported by island resources (Fig. 1A), shows an overshoot-and-collapse pattern, consistent with the documented abrupt decline in the Rapuni population on Easter Island to about 2,000, from a peak of about 10,000 *ca*. 1200 CE (echoing that of the *LTG* BAU scenarios observed in Chapter 1). Brander attributed the incidence of this pattern here to an atypically slow rate of resource regeneration, specific to the endemic palm tree species. Because of this slow regeneration rate, the attritional adaptation of Rapuni population growth to its available resource base lagged behind the rate of resource depletion, causing, in turn, population overshoot. In this analysis, the analog tree species on other Polynesian islands regenerated at a faster rate, and the embedded socioeconomic population growth rates slowed gradually until they came into equilibrium with the rate of ecosystem regeneration. This pattern of consumer-producer interaction is illustrated in Fig. 1B, where population converges asymptotically to the sustainable rate of resource productivity.

Good et. al (2009) disputed this conclusion, after modifying the Brander model to included social welfare functions, and concluded that institutional resource management would not have prevented the outcome. Other studies (Basener et al. 2011) have proposed modifications to the initial analysis, e.g., by positing incidence of invasive rate species, which were instrumental in the overconsumption of island resources. Among studies of non-insular historical civilizations, Good et al. (2009) examined the evolution of Sumerian, Mayan, and Anasazi societies, each of which succumbed to a process of population diffusion & loss of corporate identity over relatively short time spans. They adopted the Lotka-Volterra equations, following Brander's precedent, adding the etic (inside-view) parameters of utility and harvesting effort, to find that ultimate collapse had been inevitable in each of these cases, under the given socioeconomic and limitation conditions.

This chapter develops a stock-and-flow, system dynamics model of the ecosystem-socioeconomic relationship, related to those in cited studies by Brander (1998), Good (2009), and Meadows (1972), to examine 21st-century national societies subject to increasing resource limitation, as evidence emerges that continuous population growth is coming under limitation pressure imposed by the local (in this case, national) ecosystem resource base. In contrast to Easter Island, the circumstances imposing relative isolation on the societies studied here are political and economic, rather than geographic, and thus susceptible of political and economic amelioration. In contrast to the global scale analysis of the *Limits to Growth*, the objectives of this chapter address actual policy responses to potentially critical situations in near-real time.

Objective: In limited national systems, assess future system behavior by simulating national-scale ecosystem dynamics with an embedded, mature socioeconomic population.

Question 1

What is the trajectory of a growing socioeconomic system, appropriating a progressively greater proportion of local ecosystem primary production, without capacity to increase production of NPP-derived goods or to supplement existing productions with imports of such goods

Question 2

Which system variables, within socioeconomic control, should be effective in alleviating limitation effects of finite ecosystem resources to embedded socioeconomic populations?

Fig. 2. Chapter 4 objectives and research questions.

2. Methods

2.1. Systems Dynamics Analysis

The general objective of systems dynamics modeling is to provide a learning tool for policy-makers to improve their understanding of the long-term dynamic behavior of the system they are trying to manage, and as a decision support tool for examining outcomes of various available policy choices (Elsawah et al. 2017). This approach focuses on the system's endogenous structure as the primary determinant of dynamic behavior, including responses to disturbances and policy changes. Developed by J.W. Forrester for analysis of industrial and urban systems (1961, 1969), The *Limits to Growth* study (Meadows 1972) is an early application of this technique to examine eco-socioeconomic sustainability. System dynamics modelling has since been used repeatedly to analyze socioeconomic integration with ecological systems: Gastelum et al. (2009) developed a basin ecosystem to model interacting socioeconomic, ecosystem, and hydrological systems, for example; Vugteven et al. (2015) applied system dynamics techniques to assess coastal region eco-socioeconomic indicators, and Uehara et al. (2012) developed a generalized system dynamics model of adaptive population and resource dynamics.

The system dynamics approach emphasizes a holistic, systems perspective along a continuum from events to behaviors to structure. The implicit assumption that the principal drivers of system behavior are endogenous implies that exogenous perturbations have the effect of triggering or resetting the system. A system dynamics model also promotes a conceptual understanding of the system before it is modelled quantitatively with stock and flow computation. Finally, the modeling diagrams and corresponding graphical expression make system dynamics models intuitive to grasp and, therefore, effective as communication tools.

The modeling process starts with definition of the system boundary, here the set of elements and interactions that represent the system in suitably reduced form. The researcher then formulates a dynamic hypothesis, representing the top-level system conceptualization, expressed in the form of a causal loop diagram. This technique emphasizes the mechanism of balancing and reinforcing feedbacks effects, which are often inherent in complex natural systems. The loop diagrams are translated into series of Stock and Flow

- Boundary (System Components)
- Causal Loop Diagram
- Stock-Flow Diagram
- Verification

Fig. 3. System dynamics modeling steps

Diagrams, which map causal relationships on to a virtual system of reservoirs and regulated material flows, computing the outcomes of stock accumulations and depletions in response to varying initial values and flow rates. The investigator then runs the model evaluate performance and assess sensitivity of system behavior to changes in parameters or subsystems. Typically, the tested model is used to simulate a menu of policy options.

2.2. System Characteristics

The system analyzed here is that introduced in chapter 2 and closely examined in Chapter 3, *viz.*, the global ecosystem, comprising the aggregate of terrestrial ecosystem parcels bound by a national political frontier, including an embedded socioeconomic subsystem. Depending on specific national circumstances and location, the national ecosystem may be ecologically relatively homogenous, as in the Central African Republic (CAR), which is contained within an encompassing tropical semi-arid region. Alternatively, it may comprise segments of differing ecological character, like Chad (examined subsequently), which straddles desert tropical, temperate, and tropical semi-arid zones. As described in Chapter 3, the national ecosystems examined here are relatively isolated from marine resources, with agrarian economies at low, approximately constant management intensity, and show diminishing national HANPP per capita.

A B

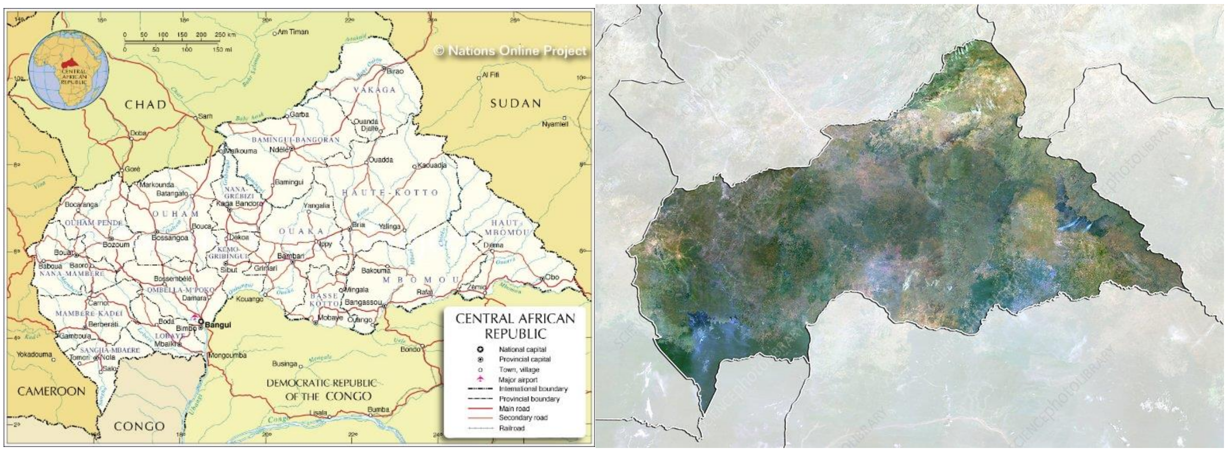


Fig. 4. The Central African Republic: (A) administrative (Nationsonline 2022) and (B) terrain (Planetobserver 2022), showing the country in continental context, with details of socioeconomic spatial organization, waterways, and landcover.

A B

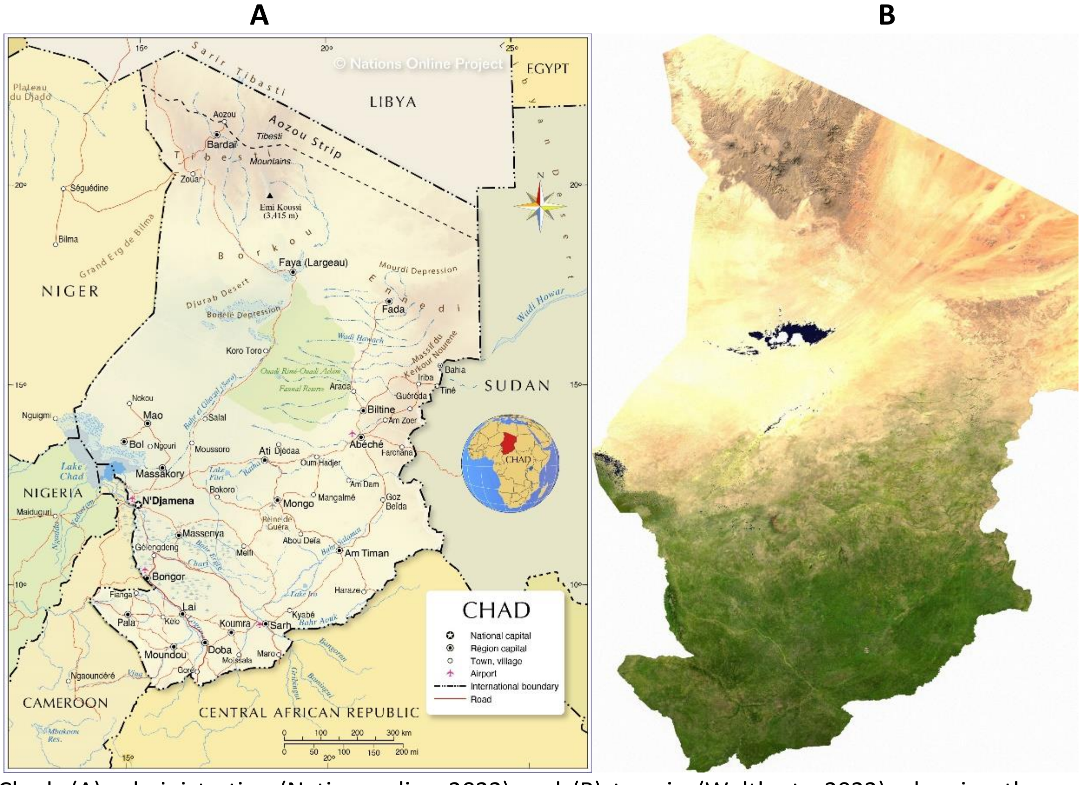


Fig. 5. Chad: (A) administrative (Nationsonline 2022) and (B) terrain (Weltkarte 2022), showing the country in continental context, with details of socioeconomic spatial organization, waterways, and landcover.

Table 2. Model boundary of system components, classified. A full table of boundary elements is presented in Appendix 4A, tabulated with equations, properties, units, and annotations.

System Component	**Component Type**
Adult_Population(t)	Stock
Child_Population(t)	Stock
Crop_Yield(t)	Stock
Cropland_Area(t)	Stock
Adult_Deaths	Flow
Births	Flow
Crop_Yield_Change	Flow
Cropland_Change	Flow
Infant_Deaths	Flow
Maturation	Flow
Food_Consumption_per_Cap	Converter
Actual_Birth_Rate	Converter
Actual_Death_Rate	Converter
Actual_Food_Available_Per_Capita	Converter
Annual_Food_Demand	Converter
Effect_of_Food_Available_on_Birth	Converter
Effect_of_Food_Available_on_Death_Rate	Converter
Food_Available	Converter
Food_Consumption	Converter
Initial_Birth_Rate	Converter
Initial_Death_Rate	Converter
Initial_Food_Available_Per_Cap	Converter
Maturation_Delay	Converter
Net_Growth	Converter
Normal_Food_per_Capita	Converter
Required_Cropland_Area	Converter
Cropland_Demand	Converter
Total_Arable_Land	Converter
Cropland_Supply	Converter
Total_Population	Converter
Yield_Efficiency_Change	Converter

2.4. Boundary

The model boundary is conceptual and enumerates all the system elements to be included in the model. Stocks are reservoirs subject to accumulation and depletion. Flows are flows into and out of the reservoirs. Convertors are system elements that regulate flow rates. The model comprises two sectors, 31 variables, four stocks, six flows, 21 converters, eight constants, and 18 equations (model statistics, equations, and run-time specifications are presented in Appendix 4A).

2.5. Dynamic Conceptualization

System understanding and top-level conceptualization is developed as a causal loop diagram (CLD). The CLD shows system components in relation with each other, emphasizing the interactive, often cyclical nature of system processes, including feedback links,

2.6 Model Structure

The model structure is developed as a stock-and-flow diagram (Figs. 7 and 8), building on the CLD (Fig. 6) represented as a configuration of stocks and flows initialized using the values shown above in Table 1. The stock and flow diagrams are composed of stocks (squares), flows (valves), and convertors (circles). As the system evolves, initial stock values change by the net flow rate in or out, and flow rates, in turn, are regulated by conversion effects.

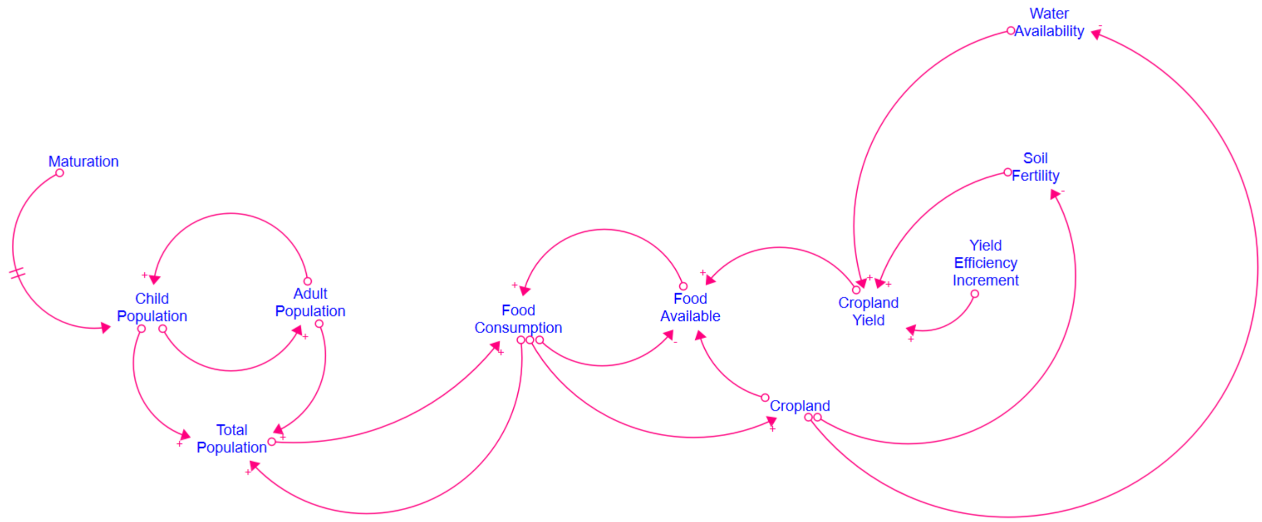


Fig. 6. Modal causal loop diagram, illustrating the top-level system dynamics conceptualization, showing key system components in relation with each other, emphasizing the interactive, often cyclical nature of system processes, including feedback links.

2.7. Model Initialization

Initial parameter values are presented below in Table 2.

Table 2. Model Boundary with Initial parameter values for the CAR and Chad. Other model parameter values are derived from these values, according to the enumerated equations shown in Appendix 4A.

Component	Initial Quantity: CAR	Initial Quantity: Chad	Units	Source
Initial Adult Population	1,571,774	3,220,158	Persons	World Bank
Initial Child Population	1,234,967	2,734,098	Persons	World Bank
Initial Birth Rate	42 per 1,000	50 per 1,000	unitless	World Bank
Initial Death Rate	17 per 1,000	19 per 1,000	unitless	World Bank
Cereal Consumption per Capita	31	99	Kg/year	FAO
Maturation Delay	16	16	Years	Assumed
Arable Land Area	1,800,000	3,273,000	Ha	FAO
Cropland Area	1,800,000	3,273,000	Ha	FAO
Initial Crop Yield	48.3	179.3	Kg/Ha	FAO
Yield Efficiency Increment	8.675 kg/Cap	10.16 kg/Cap	Kg/Cap	Inferred

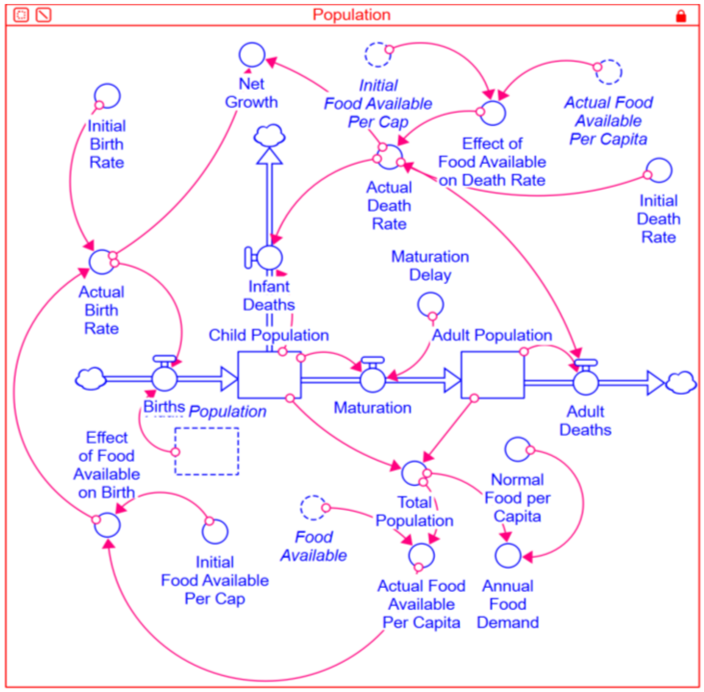


Fig. 7. Stock-flow diagram of the system dynamics model population sub-sector, which programs calculation of population changes in response to food consumption and availability, from initial conditions shown in Table 2. This sector interacts with the model agriculture sector (Fig. 8) to simulate demand and limitation feedback effects between food production and population growth.

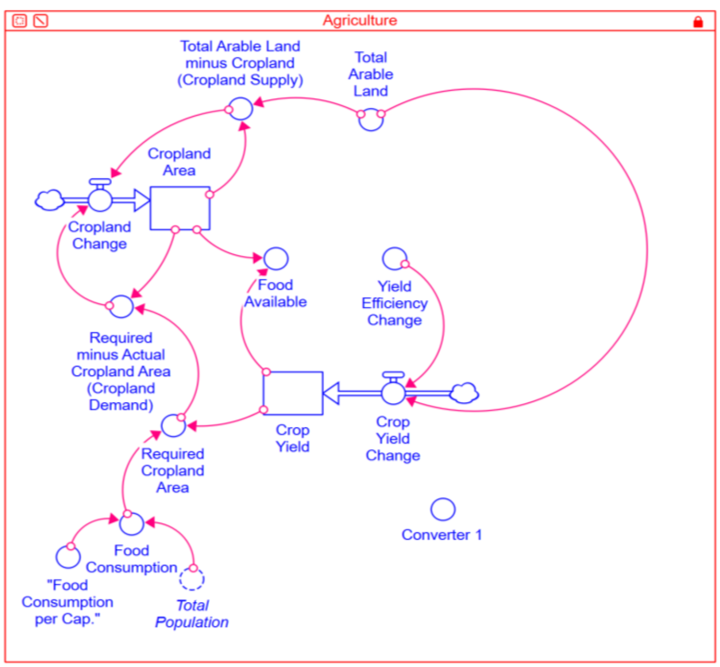


Fig. 8. Stock-flow diagram of the system dynamics model agricultural sub-sector, which programs calculation of changes in agricultural production in response to socioeconomic population demand, from initial conditions shown in Table 2. This sector interacts with the model population sector (Fig. 7) to simulate demand and limitation feedback effects between food production and population growth

2.8. Coefficient of Determination

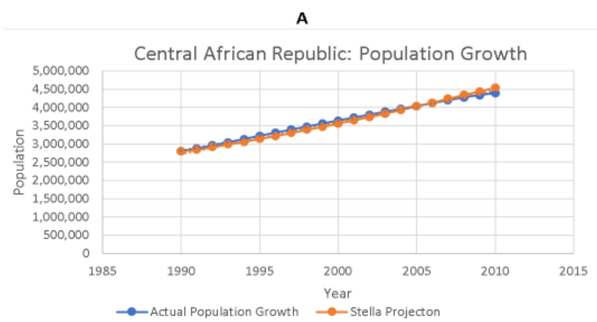
The coefficient of determination was calculated for key parameter projected values, relative to actual values, to test the realism of the former, using the formula:

$$R^2 = \frac{Cov\ (Y_{sim} - Y_{obs})}{\sigma Y_{sim} \sigma Y_{obs}}$$

The coefficient of determination summarizes the agreement between modeled and observed values and therefore serves as a measure of the goodness of fit. An R^2 value of 1 indicates a perfect fit between observations and model output; a value of 0 indicates no agreement.

3. Results

3.1 Coefficient of Determination



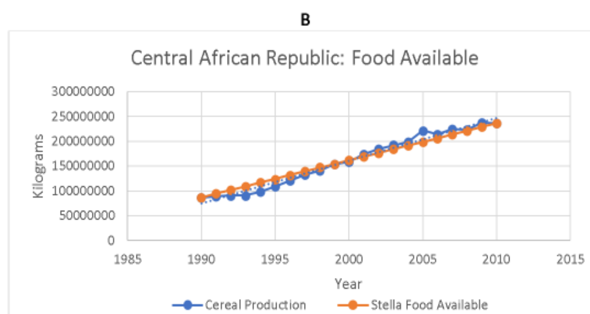


Fig. 9. Comparisons of simulated (orange) and observed (black) data time series in the Central African Republic, showing (A) population growth (R2 = 0.9821) and (B) food available (R^2 = 0.9809) for the 20-year period from 1990 to 2010, with similar trends, shapes, and value ranges, indicating good model calibration.

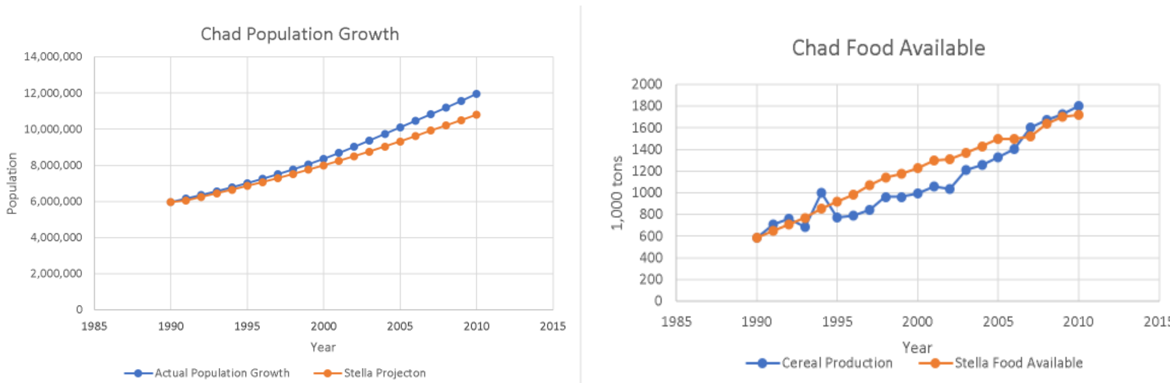


Fig. 10. Comparisons of simulated (orange) and observed (black) data time series in Chad, showing (A) population growth (R^2 = 0.9875) and (B) food available (R^2 = 0.8712) over the 20-year period from 1990 to 2010, with similar trends, shapes, and value ranges, indicating good model calibration.

3.2 Business as Usual Simulation

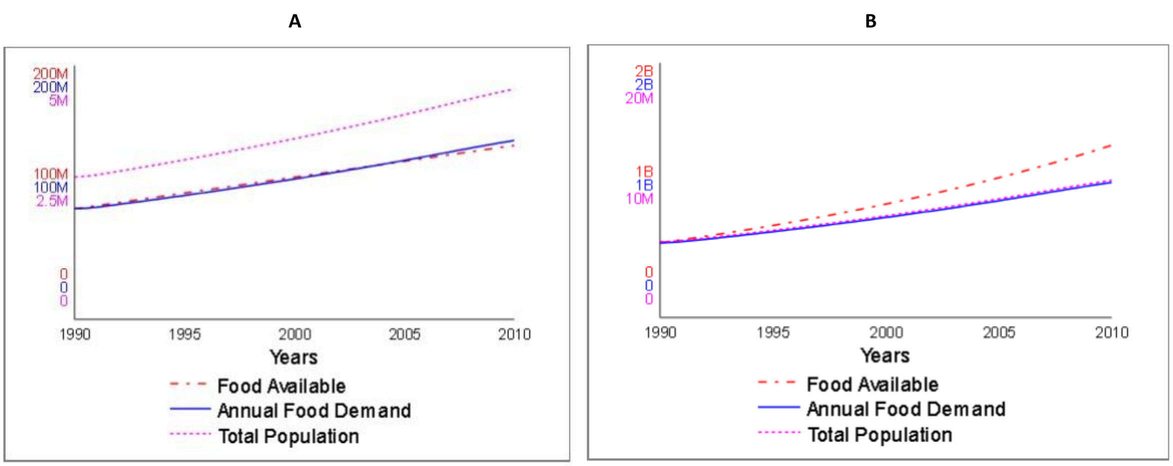


Fig. 11. Illustrative 'business as usual' trajectory simulations for (A) the Central African Republic (CAR) and (B) Chad from 1990 to 2010. Note the different scale for Total Population. In this example, Food Available in CAR is barely keeping pace with Annual Food Demand. In Chad, by contrast, Food Available is growing annually faster than Annual Food Demand.

4. Discussion

4.1 Coefficient of Determination

The R^2 values for the modeled output, vis-à-vis FAO data, were:

- Central African Republic
  - Population Growth: 0.9821
  - Food Available: 0.9809
- Chad
  - Population Growth: 0.9875
  - Food Available: 0.8712

All of the R^2 values are between 0.8 and 1, indicating a good model calibration and fit with the observed data.

4.2 Simulation of Country Population and Food Trajectories

Central African Republic

Baseline model run (business as usual scenario) projects food production and food demand through the end of 2010. Here we see production delivering just enough food to support the growing population. Arable land inputs have been essentially constant for more than a decade suggesting that land amenable to cultivation with prevailing farming techniques is all being used. There is a small interannual decline in forest land concurrently, but, according to the data, that land is not being converted to cultivation.

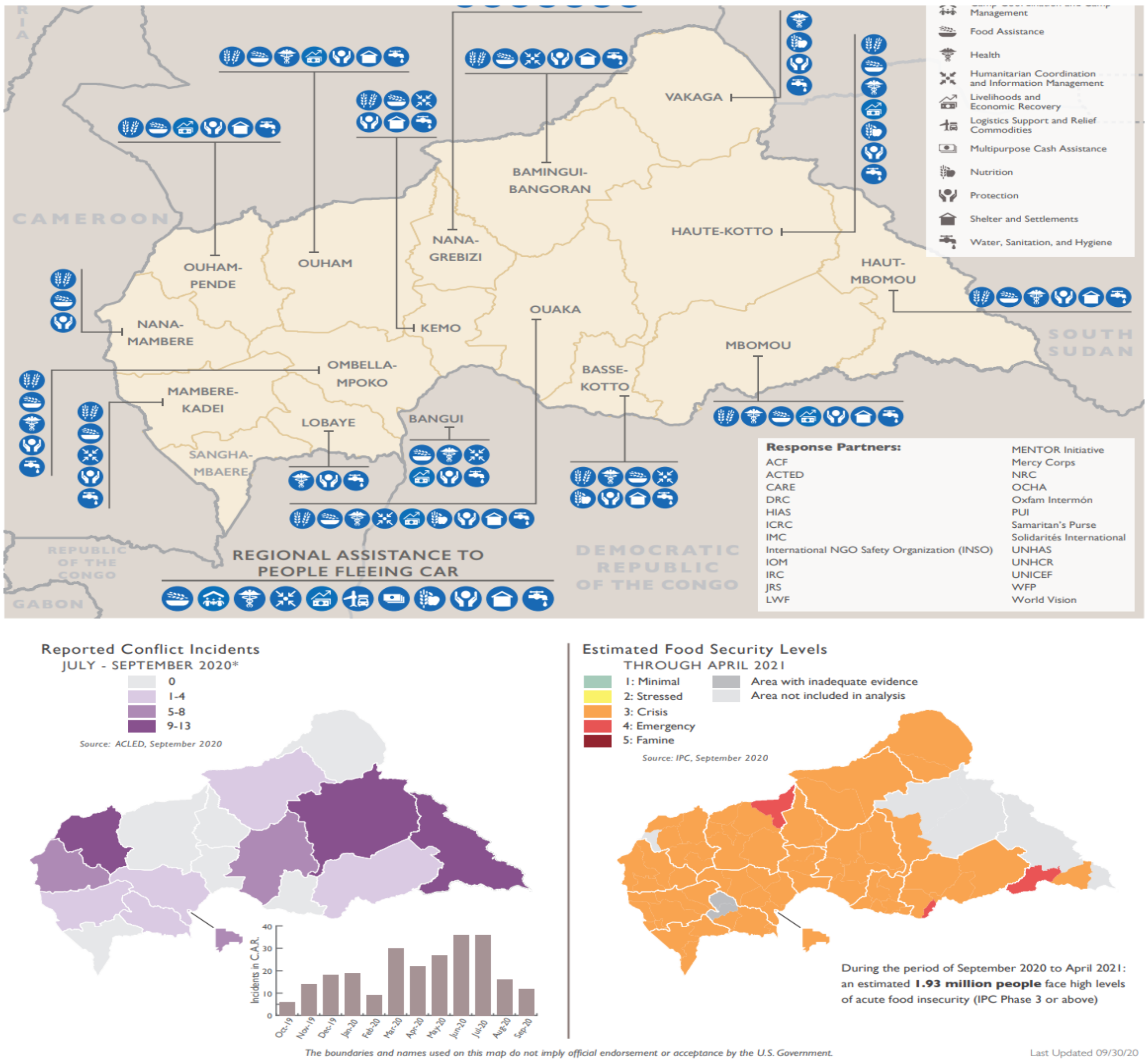


Fig. 11. Color-coded maps indicating he Central African Republic in potentially fragile national conditions. The top map shows combinations of assistance being funded by the United States Agency for International Development (USAID) in the individual CAR provinces. The lower left map shows instances of conflict in the three-month period from July to September, 2020, and the lower right map indicates assessment of food security in each province, showing 16 provinces in crisis status and three in emergency status (USAID, 2020).

The model implies a sensitive, precarious position for the CAR, in which small changes in any one of several dimensions could cause a resource deficit, relative to population consumption. A sustained deficit would intensify competition for available resources. Civil war broke out in the

CAR in 2004 and the country suffered drought conditions from 2010, which substantially increased the extent of water-limited land. When the level of harvested NPP is just keeping pace with population growth, the ecosystem and socioeconomic subsystem become tightly coupled, as discussed in Chapter 2, so that even modest perturbations to the latter are likely to pass through to the former. The CAR is now viewed as a country substantially in crises, and the focus of assistance efforts by such international agencies as USAID and FAO (Fig. 11).

Chad

Food production in Chad exceeded the rate of population growth and the correlated increase in annual food production. This outcome is consistent with the increase over this period in the extent of arable land, thus providing a direct input to existing agricultural production, which correlates to a monotonic increase in area under cereal crops over the period. Data on irrigated land extent is unavailable for Chad, but, considering the presence of Lake Chad, a substantial freshwater source, and absence of increase in fertilizer use, irrigation is the likely mechanism of amelioration. The increase in HANPP per capita implied by greater abundances of foodstuffs is offset by decrease in anthropogenic burning of vegetation, which decreased by more than four million metric tons carbon equivalent, or about 15%. Chad has been experiencing violent domestic and cross-border conflict since at least 2006, and the chief source of enduring conflict has been antagonism by international raiders and terrorist organization, including Boko Haram, operating regionally. In this instance, HANPP analysis threw up a false positive indication of possible limitation onset, which, upon closer examination using the system dynamics model, proved to be unsupported.

5. Conclusion

5.1 Study Context, Characteristics, Conclusions

This study aligns within the broad category of sustainability studies examining the long-term viability of social units in environments with finite resources and inelastic material processing rates. A large number socioeconomic sustainability studies have been conducted at Global (see chapter 1.2), regional (Graymore et al. 2010, Marquart-Pyatt 2015), ecosystem (Santibanez-Aguascalientes et al. 2021, Bian et al. 2021), and even locality scales. Relatively few are conducted at the scale of the individual nation and most of these concentrate on large, super states (Peters et al. 2016, Yue et al. 2008). The studies on this topic are broadly subsumed within the new discipline of sustainability science (Kates 2001, see chapter 3), or its precursors, in which environmental science concepts and methods are applied to understanding natural processes, as these relate to continuity of ecosystem size, scale, or function under socioeconomic encumbrance. Sustainability studies frequently adopt systems perspectives and conceptualize material flows between ecosystem and supported socioeconomic system as specially-formulated parameters, such as ecological footprint (Fang et al. 2015) and HANPPP (Haberl 1997, see also chapter 3.2).

Within this category, the present study incorporates several distinctive features. It compares socioeconomic sustainability at national scale, employing HANPP data calculated for eight individual, mid-sized countries with agrarian economies. This study also examines exclusively countries selected for characteristics that tend to control their access to sources of NPP-derived goods, *viz*., geographic isolation from non-terrestrial sources, economic isolation from international sources, and relatively static domestic agricultural production capacity. The study eclectically combines methodological techniques in pursuit of its objective, including national-scale HANPP calculated in the preceding chapter. To this data it applies a system dynamics modeling analysis to simulate system evolution under a scenarios representing so-called business-as-usual conditions. The system dynamics analysis has the advantage of being relatively intuitive and easy to explain, bringing communications utility to its already demonstrated value as an analytic tool.

Objective: In limited national systems, assess future system behavior by simulating national-scale ecosystem dynamics with an embedded, mature socioeconomic population.

Question 1

What is the trajectory of a growing socioeconomic system, appropriating a progressively greater proportion of local ecosystem primary production, without capacity to increase production of NPP-derived goods or to supplement existing productions with imports of such goods.

- The expected trajectory is towards intensifying scarcity of essential resources, especially food, causing increasing competition within the population.

Question 2

Which system variables, within socioeconomic control, should be effective in alleviating limitation effects of finite ecosystem resources to embedded socioeconomic populations?

- A fulsome response should address short term limitation effects promptly with direct aid, while simultaneously supplying technical expertise and inputs to improve domestic agricultural efficiency, and long-term technical assistance aiming at self-sufficiency based on combined domestic production and international trade.

Fig. 12. Chapter 4 objectives and research questions.

5.2. Applications

The model analysis presented in this study offers potentially support to formulation of international assistance activity aimed at designing balanced and effective aid packages to fragile states. Its systems perspective of interrelated dynamics between key elements facilitates analysis of coordinated interventions designed to increase local sustainability. Assistance aimed at optimizing sustainability in the cases like those examined here may need to consider a diverse collection of individual initiatives which only make sense when viewed together holistically, such as:

- Stopgap assistance in the form of grants, food aid to reduce the peril of humanitarian crises.
- Technical assistance in low-input improvements to agricultural practices, related to seed selection, manuring, pest control, and distribution, to durably increase domestic agricultural efficiency and food security in the short-term.
- Grant aid and in-kind agricultural efficiency inputs, to further augment agricultural production capacity, anticipating future trade and importation capacity.
- Technical assistance in economic development, entrepreneurship, and financial capacity, in part to build a foundation for eventual, reliable importation of food and agricultural inputs, without sliding into a long-term state of national dependency.
- Technical assistance in public health, balancing measures that reduce loss of life to disease with family planning options that empower families with respect to their futures and families.

Because aid assistance is, in effect, a form of international public administration, the analyses and conclusions developed here may also be adaptable to domestic public administration problems, and scalable, with adaptations, to socioeconomic administration at regional scales.

5.3. Improvements

As noted, this investigation combines methods of eco-socioeconomic material flow observation with systems dynamics modeling in a fresh approach that brings HANPP methodology to country-level sustainability analysis and harnesses it for use as policy assessment tool. Several improvements are available for future similar studies. NPP data quality may be improved by blending DGVM output with estimation algorithms based on remote sensing data, as sensing data and analysis continue to advance rapidly(…). With adequate budget resources, in-country workshops with representatives from government, workers involved in HANPP activities, and scientists, ground-truthing model and algorithm calibrations, would probably improve accuracy of model input, and incorporating human practices in policy implementation from the same groups could improve selection and accuracy of projection outcomes (…). Finally, developing an index of limitation based on indicators of productivity and material 'leakage' across national borders would facilitate exploration of possible correlations with socioeconomic welfare indicators, opening a perspective on generalizable limitation – socioeconomic effect relationships.

Some caveats attend the use of any model, the one developed here not excepted. Because of data and time constraints, persistent scrutiny is needed to be sure that data, context, and issues have been represented in correct proportion to their significance. Transference of this model to other countries and regions, therefore, should be performed judiciously, with reasonable deliberation over what specific changes are apt and what their significance will be to simulation outcomes.

5.4. Additional Research

An obvious follow-on research step building on the model development and analysis developed here would be to conduct a series of policy experiments, initiating a schedule of forcings in the model using parameters representing the effects of system interventions within the ambit of public administration and international assistance agencies. An illustrative schedule of possible such interventions is presented here, together with expected qualitative effects on population, internal competition for resources, and international dependency,

- Material Assistance
    - Food aid -> population neutral, competition negative, dependency positive
    - PP production inputs -> population neutral, competition negative, dependency positive
- Technical Assistance
    - Agriculture -> population neutral, competition negative, dependency negative
    - Non-ag economic -> population neutral, competition negative, dependency negative
    - public health
        - disease -> population negative, dependency neutral
        - reproduction -> population negative, dependency neutral

This project fits into the currently topical research area of ecological-social system interactions. Downstream research related to this project could include development of additional system dynamics model modules to simulated networked interactions among individual country models, to examine material flow dynamics between countries subject to varying conditions and limitation pressures, would bring international trade and dependency effects within the ambit of examination.

The investigation of Fader et al. (2013) of global-scale spatial decoupling of agricultural production and consumption, provides a sound foundation for simulations on regional scales, at least. Fader's work could also be a jumping-off point for an assessment of country risk caused by international dependency for NPP-derived goods and services. An elaboration of model development aligned with this research direction could be applied to assess the potential effects of perturbations to the international, trade-based distribution of HANPP, caused by events like the 2022 Russian invasion, on the growing network of import-dependent countries (Fader et al. 2013).

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Chapter 5: Conclusion

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1. Overview

1.1 Topic, Scope, and Focus

This investigation examines the socioeconomic effects of ecosystem limitation of human populations, within geopolitical state borders. Its purpose (Chapter 1.1) is to:

- *assess the incidence of national-scale ecosystem limitation of socioeconomic populations;*
- *assess relative effectiveness of possible policy interventions to alleviate the deleterious socioeconomic effects of limitation.*

The study combines recently-developed methods of ecological-socioeconomic material flow observation with systems dynamics simulation modeling in a fresh, distinctive way. In the process, it brings HANPP methodology to country-level sustainability analysis, harnesses it for use as an assessment tool for national scale assistance policy. In addition to the research aim of this study, its results will also contribute to the kit of observational, analytical, and conceptual tools available to researchers, while providing evidence-based insights to policymakers confronting decisions about allocation of scarce resources.

It first tests for evidence of ecosystem-sourced socioeconomic limitation in national units by examining eight potentially limited countries with agrarian economies, near constant agricultural efficiency, and constrained access to exogenous sources of NPP, including imported NPP-derived products and marine net ecosystem productivity. Methodology previously developed to calculate human appropriation of net primary productivity (HANPP) is applied over an 18-year period. HANPP is a parameter of ecological-socioeconomic material flow developed at the end of the 20th century and elaborated over the subsequent decades.

1.2 Conclusions

The objective and research questions of this stage of the investigation (Chapter 3.1) were:

Objective: Assess existence of socioeconomic limitation by ecosystem resources in nations dependent on NPP and derived goods from local sources (within national territory).

1. *In these conditions, is the ecosystem resource availability per individual increasing?*

    - Ecosystem resource availability per capita is constant in two of the eight countries studied (Chad and Laos) and decreasing in four (CAR, DRC, Rwanda, and Uganda.
    - Ecosystem resource availability per capita is increasing in Mongolia and Bolivia.

2. *Where resource availability per individual is not increasing, is there evidence of Malthusian effects, or, alternatively, of conditions that would alleviate the effects of limitation pressure?*

    - Evidence of limitation effects is seen in Chad and the CAR.
    - Sources of limitation pressure alleviation are present in the DRC, Laos, Rwanda, and Uganda (as well as Mongolia and Laos).

The second stage of the investigation applies system dynamics methodology and tools to simulate the interaction of consumption and production and qualitatively assess its effects on the dynamic relationship between ecological and socioeconomic systems. The objective and research questions of this stage of the investigation (Chapter 4.1) were:

Objective: In limited national systems, assess future system behavior by simulating national-scale ecosystem dynamics with an embedded, mature socioeconomic population.

1. *What is the trajectory of a growing socioeconomic system, appropriating a progressively greater proportion of local ecosystem primary production, without capacity to increase production of NPP-derived goods or to supplement existing productions with imports of such goods?*

- The expected trajectory is towards intensifying scarcity of essential resources, especially food, causing increasing competition within the population.

2. *Which system variables, within SS control, should be effective in alleviating limitation effects of finite ecosystem resources to embedded socioeconomic populations?*
    - A fulsome response should address short term limitation effects promptly with direct aid, while simultaneously supplying technical expertise and inputs to improve domestic agricultural efficiency, and long-term technical assistance aiming at self-sufficiency based on combined domestic production and international trade.

2. Significance

Limitation effects are geopolitically unevenly distributed: development and application of advanced agricultural technologies has provided superabundances of NPP-derived goods in many countries, but some countries are experiencing limitation and the onset of harmful limitation effects. The advantages of policy intervention to support normal social function, compared with restoration of orderly function to a disrupted socioeconomic unit, are obvious. Social organization is an important element of agricultural efficiency. Once a society drifts into violent conflict based on competition for resources, this social element of production efficiency is undermined, potentially setting off a self-amplifying causal loop, in which violence begets scarcity, which begets more violence. Disruption of social organization at the national scale can kick off this deleterious positive feedback Contemplating the illustrative examples of historical and contemporary socioeconomic disruption, caused by scarcity, capacity for early detection of limiting conditions, and preemptive amelioration, is valuable.

The research conducted here develops a methodological basis for anticipating national ecosystem limitation of socioeconomic welfare, by monitoring national-scale HANPP. It thereby contributes to capacity, within the international assistance community, to deliver timely, policy interventions, aimed at forestalling potentially disruptive intensification. Applying system dynamics modeling to national-scale HANPP processes helps to create a holistic, eco-socioeconomic perspective. Adopting this perspective can aid administrators to design balanced assistance policies, combining food assistance to bridge acute deficits in agricultural productivity, with technical assistance and inputs supporting improvements in agricultural production efficiency. Long-term technical assistance can then contribute to broad-based economic development, working towards a foundation for self-sufficiency in essential materials, eschewing chronic dependency.

This investigation also supports the idea that environmental resource management is a high-priority, long-term component of sustained social welfare, both in national and international contexts. The significance of a robustly functioning national ecosystem is multi-dimensional, often indirect, and complex. It ultimately forms part of the foundation for realizing national potential. At super-national scale, an aggregate of robustly-functioning ecosystem promotes regional socioeconomic welfare, and indirectly diminishes the likelihood of international instability caused by migration and cross-border conflict spillover. As the human population continues to grow, therefore, environmental resource management should increasingly be a primary focus of policy attention. For these reasons, assistance and training in environmental and natural resource management is a significant element of balanced aid packages.

The strategic importance of fossil fuel use in the context of socioeconomic sustainability is also implied. Energy generation by and chemical processing of petroleum products provide essential inputs to numerous mechanisms for alleviating potential limitation effects to local populations, such as fuel for machinery operation and fertilizer manufacture, or an ingredient in agricultural chemical production. In addition, it is widely recognized that the waste products of fossil fuel use also threaten to undermine continuity of environmental conditions for ecosystem productivity changing regional and local climate conditions that regulate potential primary productivity. This combination of short-term dependency and long-run toxic response creates a problematic dilemma for socioeconomic populations in general, but especially for those now near the threshold of limitation.

3. Applications

In addition to the specific application illustrated in this study, the approach outlined can contribute to detection of potential national-scale socioeconomic limitation sensitivity, on the one hand, and developing preventative, multi-dimensional policy responses on the other. This application potentially has versatile applications in the realm of ‘actionable knowledge’ (Kates 2001), if incorporate, for example, into national and regional scale early warning systems, like the USAID-funded Famine Early Warning System (Famine). Official assistance is, in effect, a form of international public administration, so the analyses and conclusions developed here may also be scalable to sub-national, domestic public administration uses, on the one hand, and to coordinated, supernational administration at regional scales.

With reasonable modifications, this approach can also play a role in assessing vulnerabilities of national populations potentially subject to future limitation pressure, forestalled temporarily by command of one or more alleviation mechanisms, under varying scenarios of international trade dynamics. As the more countries become increasingly dependent on importation of NPP-derived goods (Fader et al. 2013), assessment of country risk in these circumstances becomes more valuable. The effects now on international food supplies caused by the 2022 Russian invasion of Ukraine illustrate this point vividly.

4. Features and Improvements

HANPP is a holistic variable that encourages systemic thinking about ecological-socioeconomic system interaction, defining a continuous perspective of resource flow, with uniform parameters for the system and subsystem. This perspective correctly places human social organizations as subsystems operating within a subsuming framework of ecosystems processes. This view helps the researcher to see ecosystem function changes that are caused by increasing human diversion of its productivity, as feedback effects to an embedded socioeconomic subsystem of its own activity. It is also easy discern a direct relationship between diminishing ecosystem robustness to disturbance, or post-disturbance resilience, and socioeconomic system sensitivity (Haberl et al. 2014).

The uncertain precision and accuracy of the data underlying HANPP computation, however, can constrain its application, especially as the size of the study unit diminishes. Government collection of statistics, algorithmic processing of remotely sense reflectance data, and DGVM estimates, based on climatic and soil data, are the three main sources of this data. The first incorporates variations in government statistical capacity among nations, despite the envelope of uniform standards promulgated by the FAO internationally. The second is limited by the difficulty of calibrating data analysis to surface conditions varying among locations. The second and third are subject to the inherent limitation of algorithmic interpretations of complex systems.

Improving the accuracy of eco-socioeconomic material flow measurement should improve the quality of sustainability studies in general, and extend the scale range of their application to increasingly fine-grained ecosystem units. Remote sensing data is already folded into elements of the data used here (e.g., FAO land use statistics are based partly on MODIS data), and some

HANPP-based research already incorporates satellite data in ways not contemplated within the Haberl computation model. (Zhang et al. 2019, Zhang et al. 2015) the ever-improving data and algorithmic analysis provided by remote sensing platforms (e.g., Phalke et al 2020) could be a fertile source of improvement to HANPP calculation, to benefit of the sustainability science community.

System dynamics analysis also a systems-friendly tool – as its name suggests. Its focus on causal loops and feedback is suited to examination of non-linear systems. Because it emphasizes pattern analysis, it is adaptable to large-scale system overviews, especially when precise and accurate measurement are elusive. Attempts to present finely-detailed quantitative results in these circumstances may imply a more fundamental understanding of the system under examination that is actually available (Levins 1966). The same qualities that make system dynamics analysis effective in a suitable context, however, undermine its effectiveness when the aim is precise causation and a detailed understanding of relationships between system components. Future work in this field would benefit by complementing high-level SD pattern analysis with other tools for close and detailed analysis of subsystems of special interest.

Choice of the nation as the study unit for this project is explained in detail in Chapter 2.6. It has unique characteristics, as the large-scale social unit under approximately uniform internal administration. The wide range of variation among characteristics of different nations, however, as well as in their interrelationships, severely limits the ability to develop conclusions about them, especially when the specific traits of their resident socioeconomic communities. In the case of this study, reasonable attempts to control for a set of several parameters nevertheless resulted in a group that was heterogenous with respect to closure to outside sources of NPP-derived products, as well as pace and character of development based on endogenous resources. Applying the overlay of a state-organization typology, as discussed below, could help optimize selection of individual countries for comparison in multi-national investigations.

5. Downstream Research

A potentially important research dimension, presaged above, is the nuanced role played by fossil-fuel consumption in the sustainability of fragile socioeconomic systems. On the one hand, energy and energy-related inputs are implicit in the use of agricultural input factors to increase production efficiency, notably artificial fertilizer, agricultural machinery, and pesticides. A nation becomes ‘petroleum limited’ when an adequate domestic food supply becomes reliant on exogenous the fossil fuel input into the manufacture of these inputs, or the fueling of agricultural capital. The robustness to perturbation of a petroleum-limited country is sensitive changes in the availability and cost of petroleum products, in addition to environmental conditions as precipitation and soil quality. Simultaneously, ongoing widespread use of fossil fuels potential imperils the agricultural productivity of the same social units through the mechanism of climate change, increasing water and land limitation by changing exogenous conditions. In the latter regard, the role played by climate change-induced drought in disrupting large-scale social organization is well-documented (see Chapters 1.2 and 3.1). For these reasons, applied research into developing and entraining renewable energy sources, specifically tailored to agricultural use, could be highly beneficial.

This study has explicitly precluded details of cultural and social organization regimes from the scope of its analyses. Different societies respond differently to similar stimuli, however, and work towards a typology of social organization, for use in assessing correlation between (a) socioeconomic response to variability in ecosystem function and (b) downstream appropriation of NPP, could be beneficial in formulating assistance approaches to specific countries approaching crises. Acemoglu et al. (2012) laid a cornerstone for this focus in *Why Nations Fail*, which posits a fundamental distinction between nations in which resources and authority are highly concentrated ('centralized') among a small number of agents, and those in which they are held diffusely within the governed society ('inclusive'). The authors argue that this distinction is correlated with effectiveness of resource use and responses to exogenous disturbances of the socioeconomic system. Combining these ideas with conceptual approaches adopted from social sciences, such as prisoners' dilemma risk-reward matrixes and Nash-point equilibria may help researches conceptualize appropriate parameters of social organization and integrate them with ecological ones.

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