

Systems Thinking for Sustainability

Illustrated by the Application to Soil Erosion and Food Security

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Abstract: A sustainability framework based on nested adaptive socio-ecological systems is used to analyse historical examples of soil erosion and its implications for food production and security for a growing population. While there are examples of innovation in agriculture to address food availability, there are also cases of inadequate social responses leading to famine. The analysis highlights the value of considering these issues in a framework of linked biophysical and socio-economic systems. The socio-economic system generates management interventions to resolve biophysical limitations such as soil depletion on food production. The socio-economic system is also responsible when there are inadequate social responses. Currently, the biophysical system produces enough food to feed the world population. However, food distribution through the socio-economic system results in increasing numbers of undernourished people. Biophysical system modelling indicates that unless major changes are made to the current world system, overshoot because of resource depletion will lead to system collapse within the 21st century. To develop sustainability strategies, we need to analyse the socio-economic response to this biophysical vulnerability. A socio-ecological analysis also indicates that perspectives based on power relations that govern real-world decision making rather than sustainability interventions to address food security, need to be incorporated.

Keywords: food production and security | linked biophysical and socio-economic systems | nested adaptive socio-ecological systems | soil erosion and depletion | sustainability strategies

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Significance and Public Understanding: Making the concept of sustainability operational is a challenge for society. One important example is soil erosion and food security. Throughout human history there has been degradation of our soil resources upon which food production depends. Even though the world produces enough food to feed the current world population there are many who are undernourished or cannot afford a healthy diet. This paper provides a system framework for understanding the biophysical and socio-economic processes and their interactions to address the issues of land degradation and food security. Historical examples are provided to illustrate the framework. The framework provides policy makers with the basis for identifying management interactions to address biophysical limitations of food production and social responses to food security. Even though the world produces enough food to feed the current world population, many are undernourished or cannot afford a healthy diet. This paper provides a framework for understanding land degradation and food security as a system. Historical examples are provided to illustrate the framework. The framework helps policy makers address limitations of food production and develop appropriate responses to food security.

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1. Introduction

An ongoing debate in sustainable management is between the Malthusian view that population growth locks humanity into an endless cycle in which population outstrips the capacity of the land to feed people (1), and the Godwinian view that scientific progress promises endless prosperity and ongoing advance in material well-being (2). This paper provides a framework to consider the management of soil erosion and food production as a socio-ecological system. Both Malthusian pessimism and Godwinian optimism are components but the framework demonstrates a greater complexity than these two conflicting views. The framework highlights the significance of societal choices for developing and implementing interventions to ensure food production while maintaining the natural resource base upon which food production is dependent.

The paper describes the sustainability framework based on nested adaptive socio-ecological systems and places the framework within the context of DSRP. This is followed by applying this framework to issues of soil erosion and food production using historical examples to illustrate key issues. Biophysical processes of the impact of agriculture on soil erosion, and the implications of land use intensification for land productivity are then presented. Attention shifts to development of social responses to reduced land productivity from intensive land use. One set of responses are interventions into biophysical system to address soil loss and land degradation. However, there can also be changes in the socio-economic system, in particular, changes in institutional arrangements for managing natural resources, social responses in areas beyond the affected resource base, and social responses to adjust to the degraded resource base. Finally, there is the possibility of famine when social responses are inadequate or inappropriate to address reduced land productivity. Findings of this analysis of historical examples are then discussed, followed by examining the current world food situation and scenarios for food sustainability in the future. The paper concludes that the sustainability framework based on nested adaptive socio-ecological systems provides a way of integrating the multiple perspectives on food production and the resource base upon which food production depends.

2. Sustainability Framework

Nested adaptive systems analysis provides a framework for developing sustainability strategies with seven major elements: (i) the adaptive cycle which defines the system response to disturbance; (ii) nesting of adaptive cycles to link systems operating at different spatial and time scales; (iii) socio-ecological systems as linked socio-economic and biophysical systems; (iv) failure pathways that can lead to system collapse; (v) critical variables and their thresholds leading to collapse; (vi) management interventions to address failure pathways; and (vii) sustainability strategies as a combination of interventions to achieve sustainable outcomes (3).

A. The Adaptive Cycle. The adaptive cycle describes how an ecological or social system can be sustained in obtaining resources for its survival, and its ability to accommodate disturbance and recover (4). There are four phases: (i) exploitation – use or harvesting of resources; (ii) accumulation – storage of material or energy in the system; (iii) release – disturbance

of the system; (iv) reorganisation – restructuring of the system after disturbance (Figure 1)*. The adaptive cycle can be sustained if the resources continue to be available and the system can recover from disturbance. Otherwise, the system may shift to an alternative (degraded) system.

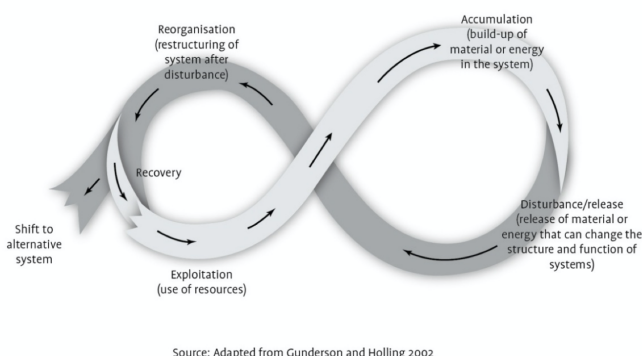


Fig. 1. The adaptive cycle (adapted from Gunderson and Holling. (4))

B. Nested Adaptive Systems. Sustainable management issues often involve multiple spatial and time scales that are linked. Figure 2 shows the example of the relationship between catchment erosion and loss of river channel capacity from sediment deposition, based on the experience of the Yellow River in North China. The catchment adaptive cycle is: (i) exploitation – intensive deforestation and cultivation in Shanxi province; (ii) accumulation – large areas of hillslope soil vulnerable to erosion; (iii) disturbance/release – intense storms erode the soil surface; and (iv) reorganisation – soil profile degraded. There is then (v) the link between spatial scales – sediment transported by the river. The riverbed adaptive cycle is (vi) exploitation – sediment deposition in the riverbed as river slope flattens; resulting in (vii) accumulation – sediment accumulation in the riverbed; leading to (viii) disturbance/release – reduced channel capacity and increased flooding; which the floodplain residents attempted to address by (ix) reorganisation – raising dykes to increase channel capacity. However, this also meant (x) system failure – with catastrophic flooding when the dykes failed. A more sustainable intervention would be (xi) land remediation to reduce erosion.

C. Socio-Ecological Systems. Socio-ecological systems are linked socio-economic and biophysical systems. This highlights four generic sustainability issues: (i) capacity of a natural system to be sustained; (ii) impact of human activity on the natural system; (iii) contribution of natural systems to human activity; and (iv) capacity of the socio-economic system to be sustained (Figure 3). In this context, maintaining soil profiles with respect to the processes of weathering and erosion is an example of a sustainability issue type 1 (biophysical system maintenance). The impact of agriculture on erosion rates is an example of a type 2 issue (socio-economic impact on the biophysical environment). Ecosystem services, such as food production are a positive expression of a type 3 issue (biophysical impact on socio-economic systems) while environmental disasters, like droughts and hurricanes, are a negative

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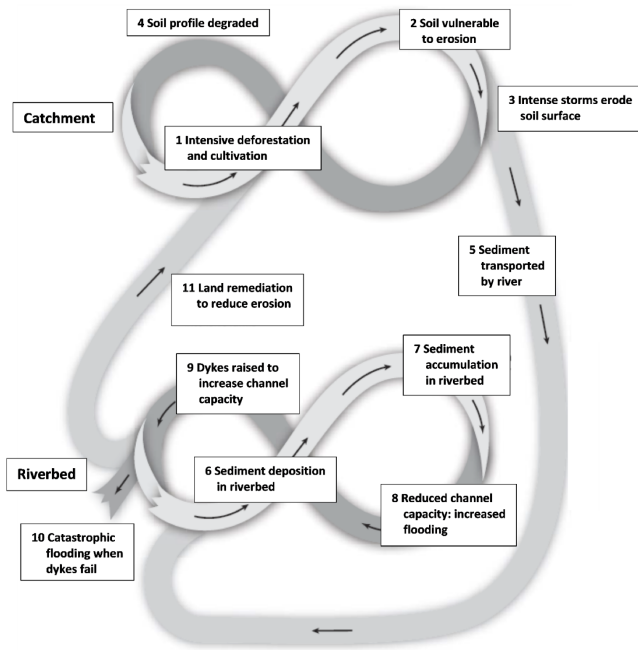


Fig. 2. Catchment erosion and loss of river channel capacity from sediment deposition as nested adaptive system.

Table 1. Categorisation of failure pathways by type of sustainability issue and geographic scale.

Geographic Scale	Type 1: Biophysical maintenance	Type 2: Socio-economic impact on biophysical	Type 3: Biophysical impact on socio-economic	Type 4: Socio-economic maintenance
Region	Climate variability	Climate change	New technology changing social relationships	Conflict: External intrusion Integration: Loss of trade networks
Society	Cumulative depletion of natural resources	Cumulative environmental degradation	Natural disasters	Conflict: Internal warfare Integration: Diminishing marginal productivity
Individual	Local natural resource depletion	Local environmental degradation	Disease	Individual commitment to society

impact. Developing appropriate institutional arrangements for managing human affairs is an example of a type 4 issue (socio-economic system maintenance).

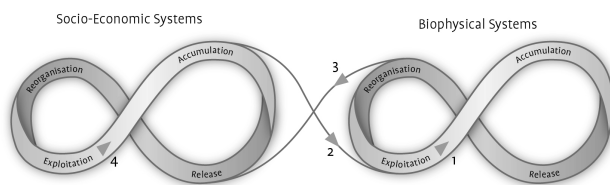


Fig. 3. Socio-ecological systems as linked socio-economic and biophysical systems (Jenkins (5)).

D. Failure Pathways. For a society and its natural resource base, theorists like Tainter (6), Diamond (7), and Webster (8) have identified failure pathways for societal collapse, which can be classified in terms of the four types of sustainability issues (3) as shown in Table 1. Three geographical levels are considered: (i) one at the level of the society under consideration; (ii) a lower level at the scale of the individual within society; and (iii) a higher level of the broader region in which society operates.

At the societal scale, failure pathways comprise cumulative depletion of natural resources (in relation to biophysical system maintenance), cumulative environmental degradation (in relation to socio-economic development impacts on the biophysical environment), natural disasters (in relation to the biophysical system impact on society), and two pathways relating to socio-economic system maintenance: one concerned with managing societal conflict, i.e. internal warfare, the

other concerned with achieving effective social integration, i.e. diminishing marginal productivity.

At the regional scale, pathways relate to climate variability (natural climate variations in the biophysical system), climate change (man-induced climate changes, i.e. socio-economic impacts on the biophysical system), introduction of new technology that changes social relationships (a biophysical impact on society), and two pathways relating to socio-economic system maintenance: external conflict (external intrusion), and loss of trade networks.

At the individual level, there are local depletion of natural resources (related to biophysical system maintenance), local environmental degradation (from local development impacts on the environment), disease (from the biophysical environment affecting individuals), and individual commitment to society (relating to how strongly an individual feels connected with society).

E. Critical Variables. Key properties of adaptive cycles relating to their sustainability are: (i) potential for resources to be available through use or harvesting; (ii) connectedness in terms of the nature and degree of links between processes; and (iii) resilience in relation to the capacity of a system to absorb disturbance and still retain its basic function and structure. These properties change throughout the adaptive cycle. In the exploitation phase, potential and connectedness are initially low but growing, while with resources available, this growth phase has high resilience. In the accumulation phase, there is high potential and connectedness. However, high resource use and the need to maintain connections makes the system vulnerable to disturbance, i.e., it has low resilience. In the release phase, after a disturbance there is a loss of potential and declining connectedness. In this destabilised phase resilience is low. When plotted in three dimensions, the variation in

properties throughout the adaptive cycle creates a Lissajous figure pattern (4).

Using the catchment erosion and river channel capacity example from above, river channel flow capacity is a critical variable in terms of resilience - the capacity of the river system to absorb high river flows without flooding. With sediment deposition in the exploitation phase, flow capacity of the channel starts at its maximum but is reduced making the river system more vulnerable to flooding as sediment accumulates. After a flood, riverbank failure further reduces the resilience of the channel to flooding.

F. Management Interventions. Management interventions in the biophysical system can be developed for each phase of the adaptive cycle. These have been derived from the stewardship strategies of Chapin, Kofanis and Folke (9): (i) reducing pressure on the resource in the exploitation phase; (ii) addressing legacy issues of accumulated changes in the past in the accumulation phase; (iii) increasing the resilience of the system in the disturbance/release phase; and (iv) rehabilitating adverse effects on the system for the reorganisation phase (Figure 4).

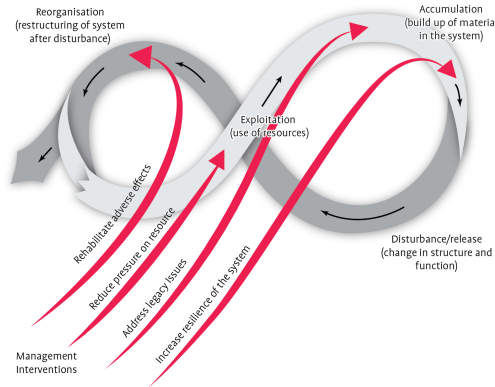


Fig. 4. Management interventions for each phase of the adaptive cycle (3).

G. Sustainability Strategies. A socio-economic adaptive cycle can be constructed for developing management interventions for formulating a sustainability strategy: (i) use of human, technical and financial resources being applied to addressing a resource management issue (i.e. exploitation phase); (ii) accumulation of knowledge, social, cultural and economic capital to develop integrated approaches to sustainable strategies (i.e. accumulation phase); (iii) formulation of new approaches to management that change existing practices (i.e. disturbance/release phase); and (iv) development of new social systems to implement new approaches to management (i.e. reorganisation phase). New social systems can lead to adopting management interventions leading to a sustainability strategy. However, failure to adopt appropriate interventions will lead to inadequate actions to achieve sustainability (Figure 5).

H. Relationship to DSRP. This section places the nested adaptive system framework in the DSRP structure of Cabrera (10–15). In terms of “Distinctions”, the main distinctions are between socio-economic and biophysical systems, and between the different spatial (or temporal) scales forming the nested

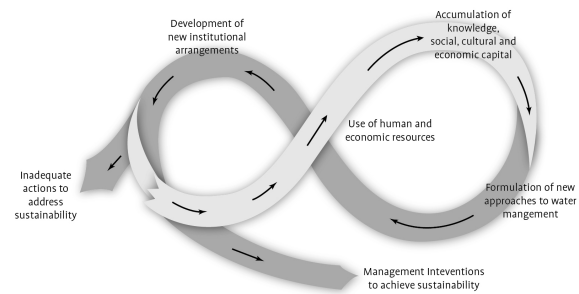


Fig. 5. Socio-economic system framework to develop management interventions for a sustainability strategy (3).

adaptive system. In terms of “Systems”, the adaptive cycle is the key basis for defining the parts of the nested adaptive systems framework. In terms of “Relationships”, the cross linkages of the impact of the socio-economic system on the biophysical system and the impact of the biophysical system are the significant relationships, together with the linkages between the different spatial (or temporal) scales in the nested system of adaptive cycles. Lastly, in terms of “Perspective”, a sustainability perspective is the basis of the framework.

This placement of the nested adaptive systems framework in the DSRP structure can be shown diagrammatically. Figure 6 shows the minimum viable concept of a system that underpins the DSRP structure with a distinction of at least two parts that are connected by a relationship within a whole system being considered from a particular perspective (16). Figure 7 shows the same system concept using the information content of the nested adaptive system framework: the linkage of socio-economic and biophysical systems with the impacts of one on the other within a nested system from a sustainability perspective.

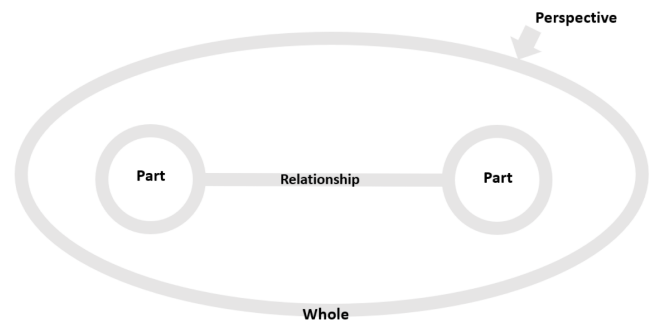


Fig. 6. The Minimum Viable Concept of a System (16).

DSRP defines an “atomic structure” for systems thinking of identity-other Distinctions, part-whole Systems, action-reaction Relationships, and point-view Perspectives (10–15). These provide the basis for “molecular structures” that are combinations of atomic structures. For the sustainability framework, the adaptive cycle, which distinguishes four phases (i.e., exploitation, accumulation, disturbance, and recovery)

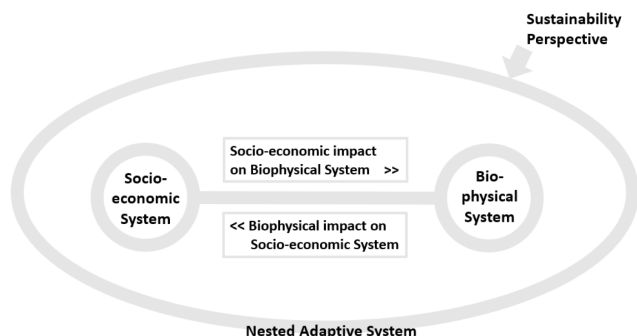


Fig. 7. Nested Adaptive System Framework in DSRP Structure.

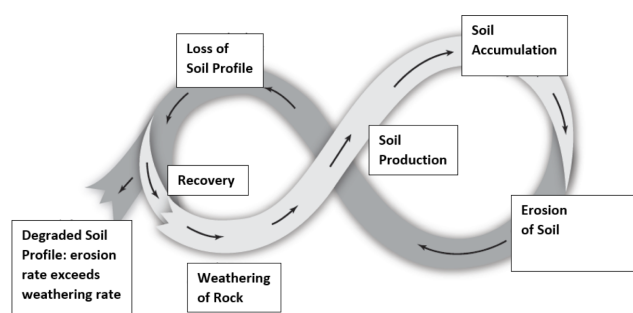


Fig. 8. Adaptive Cycle of Weathering and Erosion.

and their relationship to define whether a subsystem is sustainable, is a fundamental molecular structure or “jig” in the DSRP terminology. DSRP also contains “compound structures” which are more complex derivations of atomic and molecular structures. The combination of linked adaptive cycles to form a nested adaptive system is the compound structure underpinning the sustainability framework.

3. Application to Soil Erosion and Food Production

A. Upland Weathering and Soil Erosion. In soil erosion, there is a fundamental difference between floodplains where annual flooding refreshes mineral soils, and upland soils where soil depths reflect the relationship between erosion of surface soil and soil production through weathering of underlying rock. Over time, hillslope soils tend to evolve toward a balance between erosion and soil production, developing a characteristic soil thickness for that location depending on soil properties, ground slope, vegetation, rainfall amount and intensity, and geologic setting. There is a sustainable rate of erosion (the geological erosion rate)– the rate at which soil in a particular environment would erode under native vegetation and would match the rate of soil production. The geological erosion rates are low in gently sloping lowland landscapes (less than 0.0001 to 0.01 mm/a). For moderate gradient hillslopes of soil-mantled terrain geological erosion rates range from 0.001 to 1 mm/a. Steep alpine topography has higher rates varying from 0.1 to more than 10 mm/a (17).

The process of weathering and erosion can be shown as an adaptive cycle (Figure 8). Weathering of rock represents the exploitation phase leading to soil formation which accumulates to deepen the soil profile (the accumulation phase). Soil erosion is a disturbance event releasing soil from the surface leading to loss of soil profile (the disturbance/release phase). The reorganisation phase can either lead to recovery of the soil profile through further weathering of rock, or to a degraded soil profile if erosion rates exceed soil production rate.

However, agricultural practices increase rates of erosion. Montgomery’s analysis compared measured erosion rates under conventional agriculture and background rates (Figure 9)[†], indicating a ten to hundred-fold increase in erosion because

of agricultural practices. It also shows that geologic rates of erosion for sustainable soil profiles are well below the United States Department of Agriculture values for tolerable soil loss. For the adaptive cycle for weathering and erosion, agriculture represents an external disturbance increasing erosion rates (in the disturbance-release phase) and soil profile loss (in the reorganisation phase). This increases the likelihood of degradation (Figure 10).

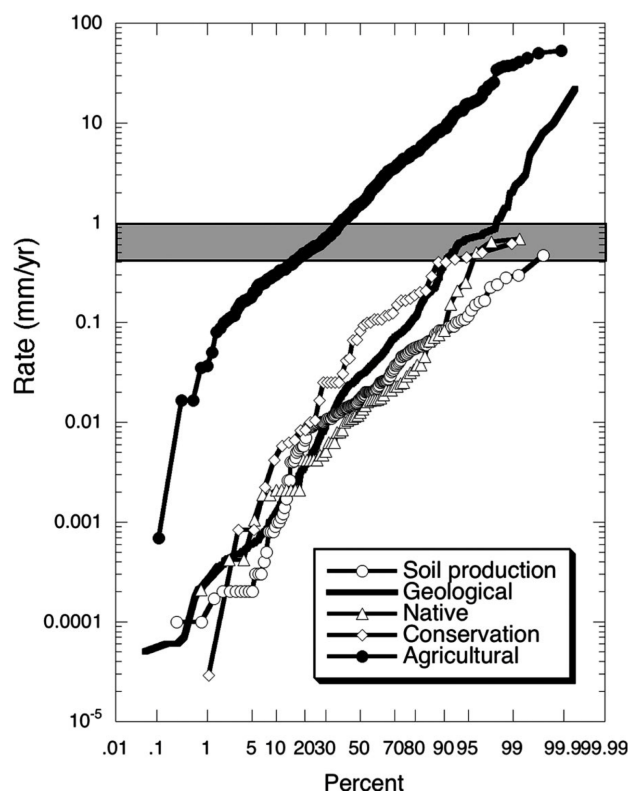


Fig. 9. Measured Erosion Rates under Conventional Agriculture and Background Rates.

B. Sustaining Soil Profiles for Food Production. Montgomery sets out what he sees as a common story line for the history of many civilisations:

“Initially, agriculture in fertile valley bottoms allowed populations to grow to the point where they came to rely on farming sloping land. Geologically rapid

[†] Probability plots of rates of soil erosion from agricultural fields under conventional (e.g., tillage) and conservation agriculture (e.g., terracing and no-till methods), with erosion rates from areas and plots under native vegetation, rates of soil production, and geologic rates of erosion (a composite distribution of the data for cratons, soil-mantled landscapes, and alpine areas). Shaded area represents range of USDA soil loss tolerance (T) values (0.4–1.0 mm/y) were used to define tolerable soil loss. (Source: Montgomery (17)) Copyright (2007) National Academy of Sciences, U.S.A.

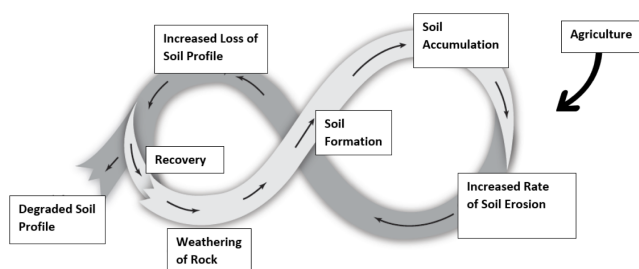


Fig. 10. Impact of Agriculture on Adaptive Cycle of Weathering and Erosion.

erosion of hillslope soils followed when vegetation clearing and sustained tilling exposed bare soil to rainfall and runoff. During subsequent centuries, nutrient depletion or soil loss from increasingly intensive farming stressed local populations as crop yields declined and new land was unavailable. Eventually, soil degradation translated into inadequate agricultural capacity to support a burgeoning population, predisposing whole civilizations to failure” (Montgomery (18):5-6).

Dotterweich (19) provides a conceptual model highlighting a similar sequence. Starting from natural conditions, for most land surfaces there are stable systems of soil development driven by natural processes associated with geology, topography, geomorphology, vegetation, soils, hydrology, and climate. With land clearing and agriculture, land use intensification accelerates destabilisation making the system vulnerable to increased soil erosion from anthropogenic-driven processes. This can occur through slow gradual denigration or punctuated events triggering catastrophic changes. Land productivity declines and may lead to abandonment of agricultural usage. After abandonment, naturally driven processes will then dominate.

This model can be represented as an adaptive cycle (Figure 11). The exploitation phase is from increasing food production to support population growth leading to an accumulation phase of increased land use and land use intensification. Destabilisation is the disturbance/release phase leading to increased soil erosion from both slow changes or more catastrophic punctuated changes. In the reorganisation phase, there is reduced soil fertility leading to crop failure. This results in a degraded system with reduced land productivity, or, abandonment allowing for restabilization and recovery through the return of vegetation cover (afforestation) reducing erosion.

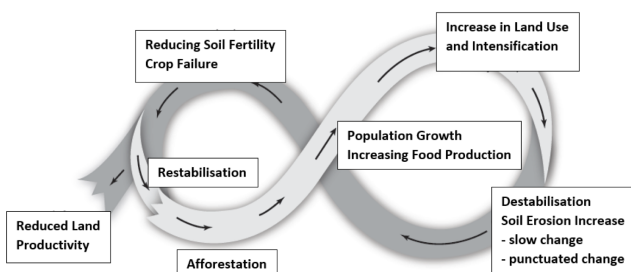


Fig. 11. Adaptive Cycle of Land Use Intensification.

Montgomery provides case studies such as ancient Greece

and around the Mediterranean, where cycles of agricultural clearing and erosion associated with population growth gave way to migration, population decline and renewed soil formation. Archaeological surveys around Lago di Monterosi near Rome shows intensive human activity from about the 2nd century BC. Prior to that, erosion rates estimated from lake sediments, were 2-3 cm per 1000 years and thereafter an average of 20 cm per 1000 years (20). By the time of Christ, decline in agricultural production around Rome led to importation of grain from Egypt and North Africa to feed Rome. Many of northern Italy’s fields lay fallow until the eleventh century. Soil loss over 200 years took around 1000 years to recover. Increased cultivation then supported prosperous medieval cities but also led again to increased erosion (18).

C. Framework for Developing Social Responses. Biophysical processes associated with land use intensification leading to reduced land productivity (Figure 11) can be linked to socio-economic processes for developing social responses to reduced land productivity. Figure 12 sets out the framework for developing social responses. The initial phase requires using human and economic resources to address the impacts of reduced land productivity (exploitation phase) and to accumulate knowledge about land productivity to build social, cultural and economic capital (accumulation phase) to formulate new approaches to land productivity (disturbance phase) that leads to reorganisation of social systems for food production and distribution (reorganisation phase). Three reorganisation pathways are identified: (i) social responses that change the socio-economic system; (ii) management interventions to the biophysical system to address reduced land productivity, and (iii) inadequate actions leading to famine. These three pathways are not mutually exclusive, e.g., management interventions in the biophysical system may involve institutional changes in the socio-economic system for their successful implementation.

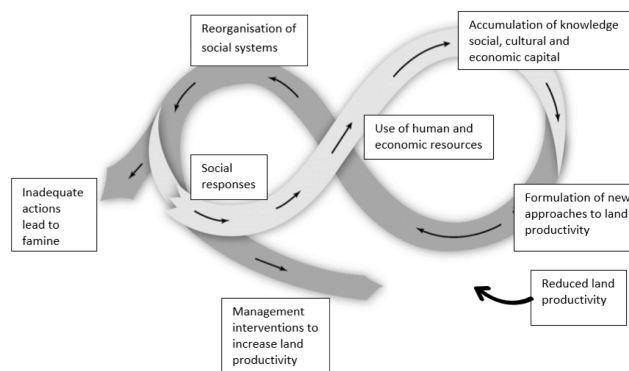


Fig. 12. Framework for Developing Management Interventions to Achieve Sustainability.

The historical formulation of new approaches to land productivity is well described by De Fries (21). Her version of the adaptive cycle is “ratchet, hatchet, pivot”. New approaches to increased food production (ratchets) allow more people. However, when an innovation reaches its limit there is an obstacle (a hatchet) to providing more food. A new way of using nature’s resources (a pivot) is found for providing more people with food.

DeFries (21), drawing on Danish economist Boserup (22), argues that human ingenuity finds “pivots” for “ratchets”. Human culture provides the ingenuity. Cumulative learning gives rise to cultures, that can adapt to changing conditions that might otherwise spell calamity, and to human-made institutional arrangements that can implement these changes.

DeFries identifies key pivots that have supported increased food production, such as, domestication of wild grains leading to the shift from humans as hunter-gatherers to farmers, crop rotations to increase land productivity, addition of phosphorus and nitrogen to increase soil fertility, and the Green Revolution with high-yielding rust-resistant plant breeds as well as artificial fertilisers, herbicides and pesticides. DeFries also notes that “ingenuity has brought humanity back from the brink of overshoot time and again, this history does not ensure the same will occur in the future” (DeFries (21):14).

D. Biophysical Interventions. One reorganisation pathway to address declining land productivity is introducing interventions to the biophysical system. Interventions can be identified for each phase of the adaptive cycle (Figure 13): (i) interventions to increase productivity (exploration phase); (ii) measures to address land deficiencies (accumulation phase); (iii) actions to increase resilience to erosion (disturbance/release phase); and, (iv) interventions for land reclamation (reorganisation phase).

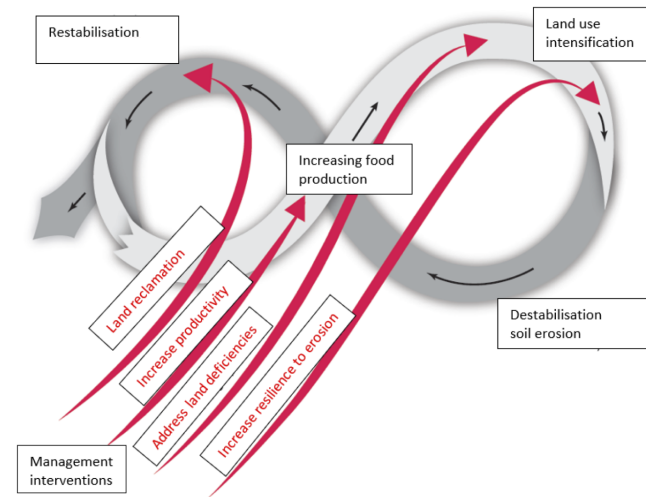


Fig. 13. Management Interventions for Each Phase of the Biophysical System.

D.1. Increase Productivity. For the exploitation phase, a traditional way of increasing productivity is increasing the area under cultivation. Montgomery describes early European agriculture in southern Bulgaria around 5300BC. Agriculture spread from arable soils in valley bottoms into forest soils on steeper slopes. However, expansion into marginal hillslope lands increased vulnerability to erosion. Irrigation has also been a means of increasing productivity. Upland erosion in the Zagros Mountains led agricultural communities to cultivate lowland areas with inadequate rainfall to grow crops. This led to building canals to irrigate the area between the Tigris and Euphrates Rivers of the Sumerian civilisation in Mesopotamia. By 4500BC, the fertile land in Mesopotamia was under cultivation. However, salinization led to reduced productivity and then decline in political influence of the Sumerian civilization.

Introduction of the plough in Mesopotamia had allowed greater food production from farming land. Ploughs have enabled expansion of agriculture throughout the world. Invention of the steel plough enabled cultivation of the American prairies thick turf soils. However, ploughed areas, especially on sloping lands have led to increased rates of erosion (18).

D.2. Address Land Deficiencies. In the accumulation phase, it has been in addressing land deficiencies (the negative side of “accumulation”) that improved land productivity has been achieved. Addition of manure to improve soil fertility was an early innovation. Montgomery (18) notes the transfer of progressive European practices to Pennsylvania by German and Dutch immigrants. He also cites the increased crop yields in England between the Middle Ages and Industrial Revolution that were achieved by introducing clover and other nitrogen-fixing plants into crop rotations. One of the significant innovations was Liebig’s discovery that plant growth was limited by the element in shortest supply relative to a plant’s needs. This led to the intervention of adding artificial fertilisers containing nitrogen and phosphorus.

D.3. Increase Resilience to Erosion. For the disturbance/release phase, there have been interventions to reduce the potential for erosion. Montgomery (18) gives the example of cover crops, where using grass as a permanent cover on sloping land reduces erosion by intercepting and absorbing rainfall impact and by keeping the ground more porous for precipitation to infiltrate the soil surface rather than causing runoff over the soil surface. There are also changes in ploughing practice. Contour ploughing can retain rainfall rather than channelling runoff downhill and causing gulying. There are no-till methods that reduce direct disturbance of the soil. Another approach is to reduce the effects of slope on the potential for erosion. Farmers in Peru’s Colca Valley built terraces to control erosion in cultivated areas that have been in place for fifteen centuries. They maintain soil horizons around a metre thicker than that of nearby uncultivated areas.

D.4. Land Reclamation. Slash-and-burn agriculture relied upon natural recovery processes for a return of land productivity. In Mayan agriculture a patch of jungle was cleared and then burnt. Ash from burning cleared forest provided fertiliser for the soil and guaranteed good crops for a few years after which fertility of nutrient-poor tropical soil fell rapidly. Cleared patches could not be farmed for long before being abandoned to the jungle to restore soil fertility. Slash-and-burn worked well while population density remained low and there was enough land for farmers to move their fields every few years.

Terra preta is a management intervention to create a soil profile for sustainable agriculture. In contrast to slash-and-burn agriculture, Amazonians stirred charcoal into the soil and then used their fields as composting grounds. With almost twice the organic matter as adjacent soils, terra preta retains nutrients better and has more soil microorganisms. Archaeological investigations using radiocarbon dating showed that sites had been occupied for about two thousand years (18).

E. Changes in Institutional Arrangements. Adoption of new approaches can lead to reorganising institutional arrangements to facilitate their implementation. Introduction of irrigation systems in Mesopotamia required technical expertise and organisational control that was not needed for dryland farming.

This required administrators to manage water and land resources, and surplus food enabled non-farming activities such as administrators, priests, soldiers, and artisans to develop. Wittfogel (23) argued that development of successful irrigation schemes depended on developing a bureaucratic hierarchy. Irrigation schemes require division of labour as well as cooperation on a large scale to be effective. The Angkor civilisation (9-14th centuries) is an example of an “hydraulic society” (24). A complex system of river diversions, barays (storage reservoirs) and irrigation channels facilitated additional rice harvests.

However, others have compared irrigating societies where there was extensive ethnographic information or organisational analysis and found there were alternative ways of organising irrigation and irrigators (25) (26). The extensive review of institutional arrangements by Ostrom (27) for common pool resources like water indicated that self-managed communities are associated with long-term sustainable management of resources. Water management for irrigated rice production in Bali is an example of collaborative governance at different spatial scales. It is a nested system of management based on water temples. Temples provide the connection between productive groups and catchment hydrology for irrigation. There is a sequence of community rituals linked to the schedule of cropping defined by a complex calendar (tika) to coordinate farmers’ activities with the cropping cycle (28).

As discussed by Lees (29), while irrigation has the potential to increase resource productivity, this does not mean that there are not adverse consequences or that changes will be successfully managed. Development can create winners but also create losers, such as those displaced by development activities or where livelihoods are disrupted. Environmental degradation can occur, for example, siltation and salinization in Mesopotamia (30). Development implementation can be poorly designed and managed leading to technical or distributional failure. Lees cites the relatively long canal systems of the Hohokam where differences between upstream and downstream users are considered to have had significant economic and political implications.

Montgomery (18) provides two examples where institutional arrangements for agriculture were designed for short-term profit rather than long-term retention of soil profiles. The first was the decline of Roman agriculture. The countryside around Rome had fed the growing metropolis until late in the third century BC. By AD 395, large areas of Campagna (the rural area around Rome) had been abandoned. Soil exhaustion and erosion had depopulated the countryside. The place of innumerable small farms was taken by extraordinarily large estates (latifundia) owned by city-dwelling landlords. This left large tracts of land in the hands of overseers using slave labour growing cash crops such as olives and grapes on degraded soils.

The second was growing tobacco in the American South. Tobacco was the most profitable crop that could be exported to Britain. However, the method of growing triggered severe soil degradation and erosion. After five years of tobacco cultivation the ground was too depleted to grow anything. New land was constantly being cleared and old land abandoned. Plantation owners did not work the land. Overseers and tenant farmers who were paid a percentage of the crop were incentivized to maximize each year’s harvest rather than maintain soil fertility. Slavery was also critical to the export-oriented cash-crop monoculture throughout the South. The institutional

arrangements of absentee landlords, hired overseers, and forced labour provided no incentive to invest in maintaining soil fertility. Rather, they shaped land-use patterns that favoured mining soil fertility and the soil itself.

F. Social Responses. To address the issue of reduced productivity of its natural resource base, societies can look beyond the affected area to maintain its food production. Such social responses include conquering other areas and using its resource base, migrating to other areas, or importing food from other areas. For all these responses the affected area remains degraded with only the slow processes of natural recovery available for regeneration. Historical examples of such social responses from the Roman Empire, North America and Europe are discussed below.

There are also social responses where societies adjust to the degraded resource base. The islands of Mangaia and Tikopia provide stark contrasts in human adaptation to the realities of a finite resource base (31).

F.1. Social Responses Beyond the Affected Natural Resource Base.

In the early period of the Roman Empire the countryside around Rome was famous for its wheat. However, decline in grain production from land degradation led to seeking grain from elsewhere. Province by province was conquered by Rome to feed its increasing population within the city. Nevertheless, province by province was turned into desert from greater exploitation of the conquered land leading to soil exhaustion. The regions included Sicily, Sardinia, northwest Africa, and Spain. This led to depopulation of the countryside due to the loss of soil fertility. Exhaustion of Roman soil was a contributing factor to the decline and fall of the empire (32).

In the American South, as soil fertility declined along the coast from tobacco cultivation, farmers moved inland. Emigrant planters continued their destructive farming practices in the new western lands. By the early 1900s they left behind more than five million acres of formerly cultivated land in the South which lay idle because of detrimental effects of soil erosion. However, the new lands of the semi-arid High Plains from Nebraska to Texas were vulnerable to erosion after ploughing broke the protective surface sod. Initially soil loss was relatively slow but still ten times soil formation rate. In the 1930s, a series of windstorms created dense dust clouds and sand dunes. Barren desert had replaced the short-grass prairie. More than three million people left the plains in the 1930s with about three-quarters of a million displaced farmers heading further west (18).

In post-medieval Europe, the initial response to rising population was to bring more marginal land into agricultural production. From the 18th century, European countries used the agricultural potential of their colonies to provide cheap imported food. By the end of the 19th century many European nations depended on imported food to feed their populations. Between 1820 and 1930, about 50 million people left Europe. Europe solved its perennial hunger problem by importing food and exporting people (18).

F.2. Social Responses Within the Affected Resource Base. The initial history of the two Pacific Islands of Mangaia and Tikopia was similar. During the first millennium of human occupation, there was forest clearance and burning, increased erosion and depletion of native fauna. On Mangaia, the social response was

one of internal warfare where the dominant tribe controlled highly productive river flats while the other social groups were relegated to inferior limestone terrain. Whereas on Tikopia, a new agronomic system of arboriculture was developed where plants mimic the multi-level diversity of the tropical rainforest. Furthermore, there was a system of population control so that the population size did not exceed the carrying capacity of the food supply (18).

On Mangaia, there was a change from shifting cultivation on deforested and eroding hillslopes to irrigated cultivation of taro in valley bottoms with alluvial soils. However, irrigated lands represented no more than two per cent of the island's land area. By the late 18th century, irrigated areas were the coveted spoils of intertribal warfare and were surrounded by habitation terraces and temple sites. Defeated social groups were consigned to limestone terrain where cultivation was limited to pockets between karst pinnacles. Hereditary chieftainship became less important than rule by force, and the paramount ruler was the one who could defeat opponents and control the irrigated area (31).

On Tikopia, the system of arboriculture comprised an upper canopy of economic trees (such as coconut, breadfruit, sago, and various fruit and nut trees) which protected and shaded a lower canopy of edible aroid tubers, yams, and other crops. Protein was from reef and open sea fishing and collecting. To limit the population to the carrying capacity of the island, mechanisms such as celibacy, prevention of inception, abortion, infanticide, and forced emigration were practised. It is interesting to note that when Christian missionaries prevented the more stringent of these measures, the population increased beyond the carrying capacity and when a cyclone struck damaging crops famine resulted. Relief supplies were needed. Land grants on other islands enabled many Tikopia to live elsewhere so that a sustainable population could be maintained on Tikopia (31).

G. Famine. When land productivity is insufficient to feed the population or when reorganisation of social systems provides an inadequate response to food availability, famine is the likely outcome. The example of North China is discussed below. There are also historical examples where social responses aggravated food availability problems making the famine worse.

G.1. History of Famine in North China (1630 to 1950). North China has been especially prone to famine. In the late 17th and 18th century there was a population explosion in China from 150 to 300 million people. This led people in North China to expand cultivation into mountain lands due to population pressure as well as famines in the deltas and alluvial plains. Accelerated erosion reduced aggregate productive capacity of land areas making them more vulnerable to crop failure, and increased silting of rivers making floodplain areas more vulnerable to flooding (33).

There had been a major famine in North China in 1630-31 at the time of the Ming dynasty collapse. As described by Li (34), the Qing dynasty (1644-1912) played a significant role in ensuring food availability to the population through affecting population movements, distributing resources among regions, regulating land and water use, and controlling grain circulation. However, population pressure eventually rendered ineffective the power of the Qing state for interventions. Famine was avoided until 1876-79 (with about 10 million deaths) when

the Qing bureaucratic structure was still intact but could not draw upon the same level of financial resources it had fifty to one hundred years earlier.

Occurrence of drought in 1920-21 led to famine in northern provinces, but mortality was limited to about half a million people with the availability of rail transport and international relief supplies of food. Another drought in 1928-31 had a greater mortality (around 3 million) because internal political conflict cut off rail supply lines. Famine in 1943 in Henan province was largely due to military exigencies. There were ample grain supplies in neighbouring provinces, but these were not permitted to be transported into Henan (34).

This history of famine in Northern China illustrates that where effective intervention can occur famine can be managed. However, when intervention is not possible, famine can ensue.

G.2. Social Responses That Aggravate Famine. The outcome of famine is not only because of the decline in food availability whether by erosion, drought, or plant disease but also because of the social response to the situation. Keneally (35) describes the circumstances around several famines including the Irish famine that began in 1845 initiated by potato blight, and famine in Bengal in 1943-4 triggered by a combination of cyclones, tsunami inundating rice fields with saltwater, and fungal disease. Keneally explains how ideology, government mindsets, racial preconceptions and administrative incompetence were ultimately more lethal than the crop losses.

In the Irish famine, the British government took the view, based on the theory of political economy of John Stuart Mill and Adam Smith, that government intervention was inappropriate and that market forces through trade rather than government relief was the appropriate response. Furthermore, the British government position was influenced by Malthus that the Irish calamity was inevitable due to overpopulation. In addition, there was the view that famine was God's providence to teach the Irish a lesson and should not be mitigated. So, while Irish peasants starved, corn grown on estates of Irish landlords was still exported to Britain. Also, import tariffs on corn were still in place after the Napoleonic War so importing grain to Ireland was not viable.

The Bengal famine commenced in WW2 when the Japanese had overrun Burma and were threatening India. British policy permitted Indian provincial governments to retain all food produced within their borders and refused to export it to other parts of India. Maximum prices for wheat were imposed but this meant grain dealers retained their wheat in their warehouses and waited for a higher price. "Famine codes" designed in the 19th century to bring special systems of relief into play were not invoked. The British War Cabinet introduced a Rice Denial scheme to buy up Bengali rice to make it unavailable to the advancing Japanese. Boats in Bengal were also confiscated to deny Japanese access; however, this meant grain transport was impeded. These responses increased the adverse effects of the Bengal famine.

These examples show that government responses can aggravate rather than alleviate the social problems associated reduced food production from land degradation and adverse events. This can result in societal failure and unsustainable outcomes.

4. World Food Situation

A. Current World Food Situation. It is also important to consider the cumulative effects of land degradation and food production at the global scale. The regional considerations discussed above are linked to the global scale as part of a nested adaptive system.

With current world food production, technically there is enough food being produced to feed everyone. However, 690 million people (8.9%) were undernourished in 2019. The number affected by hunger in the world continues to increase: in 2019 there were 60 million more undernourished people compared to 2014. The world is not on track to achieve the UN Sustainable Development Goal 2.1 target of Zero Hunger by 2030. If recent trends continue, the number of people affected by hunger would surpass 840 million by 2030 (36).

Food production in developed countries is predominantly industrialized with significant investment in farm equipment and fertilisers. In less developed countries there is predominantly subsistence farming. Trade is a major tool to bring food security to an estimated 800 million people in the world that remain chronically undernourished. Many countries depend on access to international markets to supplement their inadequate food supplies (37). However, more than 1.5 billion people cannot afford a diet that meets the required levels of essential nutrients and over 3 billion people cannot even afford the cheapest healthy diet (36). The less developed countries cannot afford to buy food at prices charged by developed countries, nor can farmers in less developed countries afford high costs of farm inputs such as seeds, fertiliser and machinery needed to increase their food production.

Food aid is therefore important to address market failure. There are a variety of international agencies in food security and nutrition, such as the World Food Programme (WFP) which provides emergency response and food aid, the World Bank which provides project and sector financing to less developed countries, and, non-government organisations and private foundations. The WFP provided food assistance to nearly 90 million people in 83 countries to victims of conflict, drought, floods, earthquakes, hurricanes, crop failures, and pandemics (38). However, as noted by one expert during the Global Financial Crisis, current institutional arrangements and the interactions among them, do not seem able to handle either the broad nutrition challenges that have persisted for decades or the immediate challenge of food security amidst the economic crisis (39).

The complex nature of dealing with hunger and malnutrition is reflected in the list of contributing factors identified by the Committee on World Food Security (40). This list includes unsustainable resource use and ecosystem degradation that were the initial focus of this paper. The list also includes: governance matters, such as inadequate institutional structures, inadequate political commitment, war and conflict; economics and production issues, such as inadequate growth in agricultural production, poverty, insufficient access to technology, and inadequate infrastructure; demographic and social concerns, such as population growth, inadequate social protection systems, and low levels of education and literacy; climate and environmental problems, such as climate change and disaster preparedness. These are examples of the range of failure pathways that need to be reflected in a sustainability framework.

B. System Dynamics and Future World Situation. While current food production may be sufficient to feed the current world population, there are concerns about future world food availability. One of the first attempts to consider the biophysical systems relating to population and food production at a global scale was undertaken for *The Limits to Growth* studies using system dynamics (41). As well as population and food production, other key subsystems included industrial output, pollution levels and resource availability.

The modelling analyzed several scenarios. The first was a “standard” world model which assumed no major change in physical, economic, or social relationships that have historically governed the development of the world system. This scenario led to overshoot because of non-renewable resource depletion leading to system collapse. Assuming no major change in the present system, population and industrial growth would stop within the 21st century at the latest.

Other scenarios were analyzed that assumed increased resource reserves, reduced pollution generation, increased agricultural productivity or greater birth control, but all ended in crises of overuse of land reducing food production, severe resource depletion, or increased pollution. The authors concluded that application of technology to resource depletion, increased pollution, and food shortages does not address the essential problem of exponential growth in a finite and complex system.

A “stabilized” world scenario was then generated to constrain exponential growth with negative feedback loops and to weaken the positive loops that generate growth. This produced an equilibrium state sustainable far into the future. However, if changes were delayed until the year 2000, the equilibrium state was no longer sustainable: levels of population and industrial capital created food and resource shortages before 2100 (41).

The results of *The Limits to Growth* analyses have been heavily criticized, particularly by economists because of the ability to find substitutes for depleted resources. Nordhaus was critical that no attempt was made to estimate the behavioural equations economically. Using the Cobb-Douglas production function to represent technological possibilities for substitution, Nordhaus calculates that technological growth must exceed 0.25% per year to overcome the growth drag from resource exhaustion and diminishing returns. He argues that because historical rates of total factor productivity in developed countries have been of the order of 1-2%, this is sufficient to offset resource exhaustion and diminishing returns (42).

Other commentators like Lomborg and Rubin (43), argue that after 30 years the most dire forecasts have failed to come true. Citing Nordhaus, they argue the weakness of the assumption in *The Limits to Growth* that the planet has finite essential resources for which there are no substitutes. Furthermore, the sustainability limit is not a static ceiling but is expanded by human invention and technological progress. They contend that instead of focusing on limits to growth, humanity would be better served by focusing on corruption, barriers to trade, and war as the real threats to growth and prosperity.

However, Turner undertook a comparison of historical data for 1970-2000 with scenarios presented in *The Limits to Growth*. Contrary to Lomborg and Rubin’s statement, Turner’s analysis

showed that the 30 years of historical data compare favourably with the “standard” world model. For example, the comparison of food per capita indicated about a 5% difference between observed and modelled data; furthermore, observed food per capita showed signs of diminished growth similar to the “standard” world model simulation (44).

Furthermore, a World Bank study for its Long-Term Growth Model included the average total factor productivity (TFP) for the 21 high income OECD countries that have been members for 40 years. Average TFP growth rates are positive during 1985-94 and 1994-2004, i.e., 0.7 to 0.9%, slightly below Nordhaus’s historical range of 1 to 2%. More significantly for 2004-14, average TFP growth rates were negative, i.e., -0.2 to -0.4% (45) thus confounding Nordhaus’s argument.

In relation to Lomborg and Rubin’s criticism about focusing on corruption, barriers to trade, and war, the authors of *The Limits to Growth* acknowledge that their analysis focused principally on the planet’s physical limits of depletable natural resources and finite capacity to absorb emissions. They also acknowledge that in the real world there are many other kinds of limits, including managerial and social ones. While some of these limits are reflected in historical model coefficients, the computer model has no war, no labour strikes, no terrorism (41).

Thus, contrary to the criticisms of *The Limits to Growth* analysis, the “standard” world model scenario is a good reflection of reality. However, as indicated by the authors, their analysis focused on physical limits and did not address social side-effects. Therefore, criticisms that the analysis does not address economic behaviour and consider social responses are valid.

In terms of the failure pathways identified in the sustainability framework of this paper, *The Limits to Growth* analysis only addresses “cumulative depletion of natural resources” and “cumulative environmental degradation” failure pathways at the world scale. The analysis does not address other failure pathways relating to external conflict, loss of trade networks, internal conflict, diminishing marginal productivity, technology changes to social relationships, natural disasters, or disease.

Neither do the scenarios relating to technological changes or stabilisation identify what interventions might be, nor how the assumed changes can be identified. In terms of the sustainability framework of this paper, *The Limits to Growth* analyses only consider the biophysical system not the socio-economic system.

As shown in historical examples relating to soil erosion and fertility depletion, both biophysical and socio-economic systems need to be considered. Also as indicated in the current situation around food availability, there is enough food being produced to feed the world’s population, but the inadequate institutional arrangements and social responses mean that malnourishment is increasing rather than reducing. For analysing the future, methods of system dynamics are incredibly valuable in identifying likely outcomes of system changes. However, *The Limits to Growth* studies only address biophysical outcomes. There is a need for similar analyses to identify likely socio-economic outcomes.

C. Paradigm Shift to Socio-Ecological Systems. Increasing food production has been a key focus of food security policy, such as the Green Revolution after WWII. Interventions to facilitate feeding the 9 billion people expected by the middle

of the century include: (i) closing the yield gap, i.e., raising actual yields to best possible yields; (ii) increasing production limits through improved crop and livestock breeds; (iii) reducing food waste through avoiding spoilage of harvested produce and reducing food thrown away; (iv) changing diets by reducing meat and dairy intake; and (v) expanding aquaculture (46).

Others have also recognised that while increasing food production, the environmental footprint of agriculture must be reduced. This includes reducing greenhouse gas emissions, reducing biodiversity loss from increasing agricultural land use, reducing water pollution from agricultural intensification and reducing water use for irrigation (47).

There has also been the addition of socio-economic considerations in sustainable production. The main challenges being seen as: (i) having an adaptive and resilient food system in both biophysical aspects (such as preserving biodiversity, maintaining healthy soil systems, and maintaining buffering capacity in water bodies), and socio-economic aspects (such as transferring knowledge, developing organisational capacity, and eliminating poverty cycles); (ii) ensuring a supply of nutritious food for all; (iii) limiting impacts of food production, consumption, and disposal to be within planetary boundaries; and (iv) ensuring food systems support livelihoods and well-being of people (48).

A different perspective is the concept of food sovereignty which argues that hunger is not merely a matter of food availability and quality but also there are political aspects of harnessing equity and justice within food systems (49). Taking a socio-ecological system perspective, Oteros-Rozas et al (50) undertook a multivariate analysis of indicators of food sovereignty and enlarged the data to include demographic and economic indicators, social well-being indicators, and environmental sustainability indicators to investigate the relationship between them.

From a principal components analysis, they identified five groups of countries in relation to food:

- Landgrabbed and undernourished: agricultural exporters but food importers, from eastern, middle and western Africa. Despite their large exports of agricultural products and the largest imports of food, undernutrition remains a constraint in these African countries.
- Diverse intensive producers of crops: mostly from Asia and western South America. Countries, such as China and India, have high population densities and intensive production but are characterised by high food deficit with low energy and protein intake.
- Least ecologically wealthy and landgrabbers: from northern Africa and the Middle East. These countries have low biocapacity for food production and are low in sources of renewable water. They are reliant on food imports and landgrabbing (i.e., wealthy companies investing in agricultural land in poor countries for commercial use).
- Intensive food producers and exporters: from Oceania, North America, and eastern South America. These countries are major food exporters, have high food consumption and large ecological footprints.
- Overnourished agricultural importers: mostly in Europe. There are high population densities and despite intensive

agriculture, they have a biocapacity deficit and are the largest importers of agricultural products.

Food sovereignty highlights the asymmetry of power relations in food. Food tends to flow to money and power not toward hunger. Wealthy countries are importing cheap food and exporting environmental degradation, with overconsumption and high food wastage. Also, there is landgrabbing from African countries (50).

This global analysis from a socio-ecological perspective reflects the regional analysis in the earlier part of the paper. Food importation and landgrabbing represent social responses by richer countries beyond their own natural resource base. Furthermore, they are social responses that aggravate famine in the most vulnerable countries.

5. Conclusion

A. Application of Sustainability Framework. The sustainability framework based on nested adaptive socio-ecological systems and illustrated with historical examples demonstrates the complexity of managing soil erosion and food production to meet the demands of increasing population. Depiction of the linked biophysical and socio-economic system is shown in Figure 14.

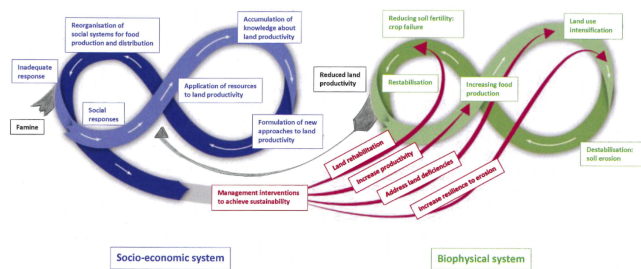


Fig. 14. Sustainability Framework for Managing Land Productivity in relation to Famine.

Increasing food production to meet increased food requirements of an increased population leads to land use intensification. However, this is destabilized by soil erosion and depletion. While there is a limited potential for restabilization by natural recovery, this is often exceeded causing reduced land productivity. This prompts the use of human and economic resources to accumulate knowledge to formulate new approaches to increasing land productivity for food production. For the new approaches to be implemented as management interventions involves the reorganisation of social systems, in particular, the changes to institutional arrangements to facilitate the intervention, and the social responses to enable the changes associated with the intervention. Inadequate or inappropriate social responses mean that insufficient food production is achieved resulting in famine.

Some of the interesting features of the sustainability framework are that it includes the Malthusian concern of population increase and food supply and the Godwinian ingenuity in achieving increased food production. Historical examples indicate that while innovation can occur (such as irrigation in Mesopotamia), there are also cases where innovative approaches were not devised to address underlying biophysical system failure (such as soil erosion in the Roman empire).

Rather, socio-economic reorganisations, such as conquering the food producing lands of others, are adopted as the means to feed an increasing population.

Furthermore, historical examples show not only that institutional changes can occur to enable increased food production (e.g., the administrative changes in Mesopotamia to facilitate irrigation), but also inappropriate institutional arrangements can be maintained (e.g., short term profit maximisation of tobacco production in the American South because there was no incentive for absentee landlords, hired overseers and forced labour to maintain soil fertility).

The framework also highlights the possibility of systemic failure if there are inadequate management interventions or inadequate social responses. The example of North China, an area prone to food production shortages due to drought and soil loss, avoided famine when the Qing dynasty was effective but incurred famine when government intervention was not possible. Furthermore, social responses can aggravate food production shortages leading to more severe famine, such as the Irish famine where the response was based on market forces, and the Bengal famine with a response based on military defence. Also, religious values in relation to certain population controls resulted in famine in Tikopia.

B. Relationship to DSRP Structure.

B.1. Perspectives. A significant issue in the analysis of historical examples of soil erosion and its implications for food production in a sustainability framework is the issues of “perspectives”. The sustainability framework includes the Malthusian perspective of population increase outstripping food supply (in the biophysical system) and the Godwinian perspective of ingenuity in achieving increased food production (in the socio-economic system).

However, it is clear from the social responses that alternative perspectives to sustainability can determine the interventions adopted. Short-term profit maximisation can override sustainable land management as in tobacco production in the American South. Allowing market forces to drive outcomes rather than government intervention led to famine in Ireland. Denial of access to food to advancing Japanese troops from a security perspective led to the Bengal famine. A Christian perspective on what are appropriate population control measures undermined Tikopia’s sustainable management of population. The food sovereignty perspective demonstrated that food distribution is driven by wealth and power rather than management of hunger.

B.2. Changes in Critical Thinking. The evolution of policy in managing food availability demonstrates the changes in critical thinking to address the issue. The focus on increased productivity has dominated the historical thinking on addressing the provision of sufficient food for an increasing population. From the 1970s, after studies like *The Limits to Growth* at the global scale and like Montgomery’s analysis at the bioregional scale, there has been an increasing emphasis on the biophysical limits (especially environmental limits) of increased intensification of food production.

More recently, the social responses and institutional arrangements for food availability have led to the analysis of soil erosion and food production as a socio-ecological system. DSRP also highlights the need to be cognisant of different perspectives to sustainability in real world decision making.

B.3. Four Waves of System Thinking. Four waves of system thinking have been defined: (i) hard systems, such as system dynamics; (ii) soft systems, such as soft system methodology; (iii) critical systems, such as systemic interventions; and (iv) universality/diversity systems, such as DSRP (11). In this paper, *The Limits to Growth* studies of physical limits using system dynamics are an example of the first wave. While subject to criticism of not accounting for human response, the review of biophysical predictions thirty years later showed a good reflection of reality. The *ratchet/hatchet/pivot* approach of DeFries which provides a qualitative model of human ingenuity for increasing food production, is an example of the second wave. The sustainability framework described in this paper with its focus on systemic intervention is an example of the third wave. The discussion on perspectives above demonstrates the generic value of DSRP thinking (an example of the fourth wave) where explanations of decisions in reality, required consideration of alternative perspectives to sustainability.

C. Closing Comments. Analysis of soil erosion and food production as well as the commentary on the current world situation on food security highlights that a sustainability framework needs to consider more than biophysical systems analysis to understand issues around famine occurrence. The sustainability framework proposed in this paper considers sustainability management as linked biophysical and socio-economic systems. To address unsustainable biophysical practices requires a socio-economic system capable of generating and implementing management interventions to deliver sustainable outcomes. Historical examples indicate that this does not always occur, and famine can result. The current food situation indicates that while sufficient food is produced to feed the current world population, a significant proportion are malnourished, and that number is increasing. Analyses of future biophysical scenarios indicate that there are constraints from depletion of natural resources, land availability and cumulative environmental degradation: interventions for stabilization are needed. Socio-ecological analysis also show the significance of the asymmetry of wealth and power. Sustainability strategies are required that address both biophysical and socioeconomic systems as well as the linkages between them.

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