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Implications of agricultural transitions and urbanization for ecosystem services

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Historically, farmers and hunter-gatherers relied directly on ecosystem services, which they both exploited and enjoyed. Urban populations still rely on ecosystems, but prioritize non-ecosystem services (socioeconomic). Population growth and densification increase the scale and change the nature of both ecosystem- and non-ecosystem-service supply and demand, weakening direct feedbacks between ecosystems and societies and potentially pushing social–ecological systems into traps that can lead to collapse. The interacting and mutually reinforcing processes of technological change, population growth and urbanization contribute to over-exploitation of ecosystems through complex feedbacks that have important implications for sustainable resource use.

Contemporary research suggests that humanity is over-exploiting the environment[1], driving global climate change, eutrophication, degradation of ecosystems and biodiversity loss[2]. At the same time, the world's human population is projected to grow from 7.2 billion people to 9.6 billion by 2050 (ref. 3). Although most agro-ecosystems have coped with anthropogenic pressures[4], we cannot assume they will continue to meet our increasing demands[5]. Food-production systems are now global, with attendant benefits and risks[6]; the diversity of farmed crops is declining[7]; and environmental degradation from agriculture is widespread[8–10]. These trends are eroding the resilience of agro-ecosystems to anthropogenic perturbations such as climate change[6,11,12].

Reconciling the demands of the growing human population with ecological sustainability is increasingly difficult[13]. The Millennium Ecosystem Assessment[14] classified ecosystem goods and services (ESS) into four categories: provisioning, regulating, supporting and cultural. It also acknowledged that ecosystems can provide or contribute to disservices, such as pathogens and floods. Subsequent analyses have generally focused on single services, or on ESS as outcomes of ecosystem-focused or food-production-focused models[15–17]. The underlying drivers of ecosystem degradation are, however, economic activities that are not themselves ecosystem-focused[18] and may be separated from their own consequences by long socioeconomic supply chains[19]. ESS research has concentrated on ecosystems[20], rather than the institutional, political and socioeconomic drivers of ecological change[21]. Even the recognition that monitoring ESS requires not only ecological but also socioeconomic data is relatively recent[22] and has not yet influenced the ways in which important policies, such as international trade agreements and development goals, are designed and implemented[22,23].

Social–ecological systems are complex and adaptive, and attempts to manage them often have unintended consequences[11,24]. To manage ESS sustainably, we need to understand the trajectories of change that have produced our current situation and continue to shape it; the interactions, feedbacks and trade-offs between different services and the social–ecological interactions that produce them; and the ways in which fundamental structural changes (those that require new system models, rather than simply adjustments to existing models) occur within the ESS context. Developing this understanding requires us to connect people and ecosystems in an interdisciplinary social–ecological systems framework[25,26]. We address this challenge by proposing a simple conceptual model that shows how a systems perspective on ESS, in the context of agricultural transitions and increasing urbanization, helps to explain ecological over-exploitation.

Service shifts in agricultural transitions

In a sense, human history is the story of the great transition from hunting and gathering, through farming, to the present situation in which less than 1% of the population (in many industrialized countries) is directly employed in food production[27–29]. In Germany, for instance, the average farmer in 1950 fed 10 individuals, but in 2010 he or she was feeding 131 people[30]. Despite its importance, there have been few attempts to develop formal social–ecological models of this transition. Generic systems models of ESS are also surprisingly hard to find. Most empirical analyses apply to individual goods or services, such as water flows or climate regulation[21]. A few published studies have quantified trade-offs between different ecosystem services[31–35], but we are unaware of any formal, causal systems models that provide a broad overview of ESS across multiple categories and scales. Despite the existence of a wide range of land-cover change models[36], and a growing interest in transforming cities for greater environmental sustainability[37], the changes in service provision that are likely to happen during the transition from an agricultural society to an industrial society are poorly specified.

If a human population is stable and most of the people depend directly on ESS, the feedbacks from ESS to human well-being are clear. Many cultures have developed rules and traditions that, under normal conditions, maintain their own resource base (for example, Balinese water temples as irrigation systems[38]; the protection of sacred forests in southwest Madagascar[39]; and the release of trained eagles, once they reach 5 years old, back to the wild by the Kazakh Golden Eagle hunters of western Mongolia[40]). Although rules for natural resource management are not always effective, if a local equilibrium between resource use and human population size is maintained, a 'green loop' that avoids long-term degradation of ecosystems can be sustained.

The green loop starts to break down when human populations grow as a result of technological change that increases food supply and life expectancy. Population density and infrastructure increase as urban settlements create alternative livelihood opportunities, provide security

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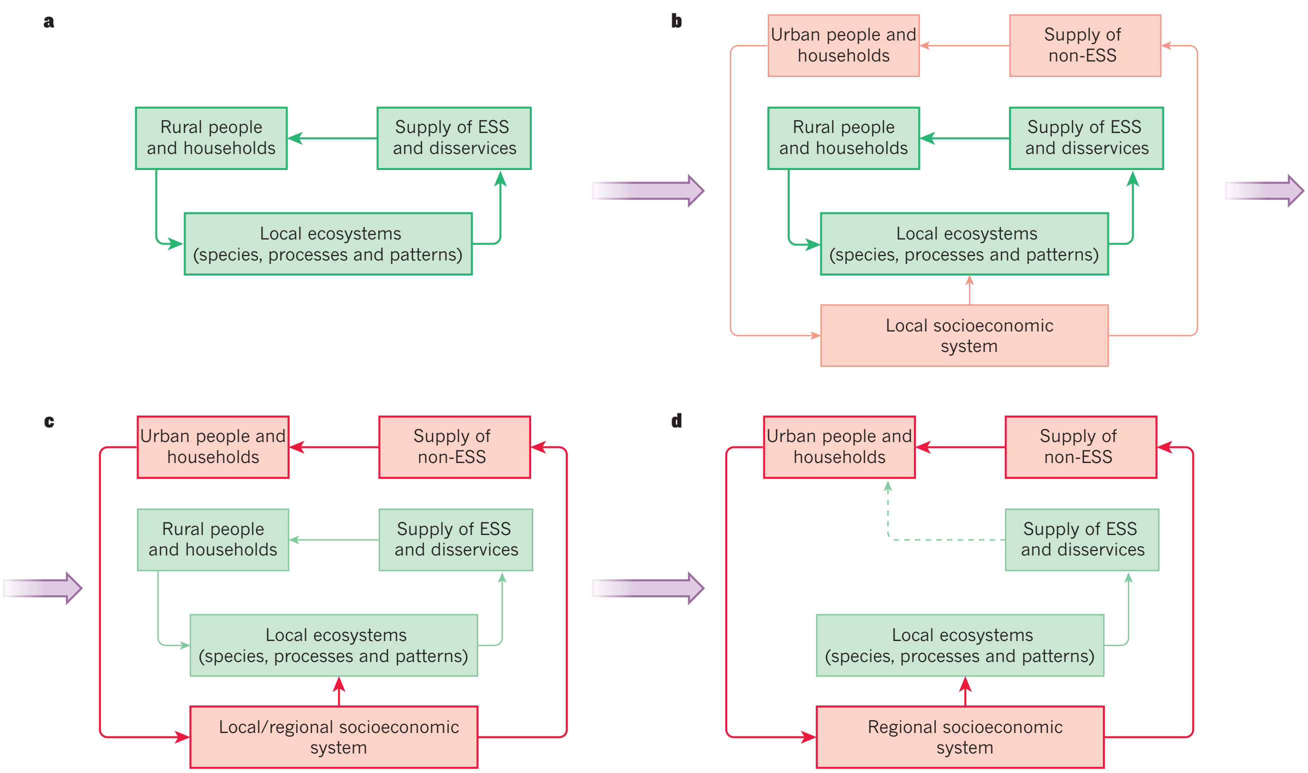

Figure 1 | The green-loop to red-loop transition. In this transition, as the population grows, the red loop overwhelms the green loop to become the dominant regime driving the use of ecosystem goods and services (ESS). **a**, In the starting green loop, rural populations manage their local ecosystems. **b**, As the population grows, a 'shadow' red loop begins to develop; changes in socioeconomic variables, such as increased demand for food, fibre and fuel, lead to greater local ecosystem impacts. **c**, The red loop gains prominence as demand for services shifts from a need for ecosystem services to a need for non-ecosystem services. **d**, As the demand for services shifts, the red loop becomes the dominant driver in the flow of ecosystem services and is accompanied by an upscaling and specialization process that results in the gradual alienation of urban people from the ecosystem; the strength of the connection between the local ecosystem and society is heavily reduced (dashed line). This can easily result in over-exploitation of ecosystems and ecological degradation.

and increase economic, social and political complexity. However, urban dwellers typically have less contact with their primary resource base[41]. Over time, the ability of local ecosystems to supply a full range of ESS to growing settlements is reduced by one or more possible causes. First, the area required to meet the needs of each family exceeds the boundaries of the area that they cultivate, and the needs of the entire population exceed the resources that they can access directly. The local ecosystem cannot produce enough food, particularly during periods of adversity. In addition, as settlements grow, the surrounding ecosystems are increasingly modified for provisioning services such as food and water, often at the expense of other kinds of ESS. Second, increasing population density makes simple forms of waste disposal impractical, necessitating technological solutions. Third, as the settlement grows the logistics of access to ESS and travel time make it impractical for each household to extract everything that it needs from the local ecosystem. This creates demands for trade, technology and infrastructure to enhance resource-use efficiency (particularly of land and water), and the need for specialized production roles (for example, farmer or blacksmith)[42]. Last, an institutional environment that enables specialization and exchange, as well as the planning and maintenance of public infrastructure, requires individuals such as administrators, merchants and law-enforcers who do not contribute directly to food production, further distancing individuals from ecosystems. As societies find solutions to these challenges, local economies and populations grow and the tasks that people perform become more specialized[42]. These changes gradually transform a system in a green loop to one in a 'red loop' (Fig. 1) as three trends unfold. First, demands for non-ESS continue to increase, resulting in changes in institutions (rules, laws, policies and customs) and governance systems as well as the construction of infrastructure (housing, roads and reservoirs). Second, urban settlement and specialization foster technological progress, which is then pursued systematically. Technological progress in agriculture, specifically, can strengthen both population growth and urbanization[43,44]. Third, because provisioning from local ecosystems can no longer meet local demand, many needs that were formerly met by local ecosystems are outsourced, resulting in an increase in the geographic extent of supply and demand (upscaling). This trend is reinforced by developments in transportation technology and the demand for foreign products (for example, spices and precious metals) by a growing and increasingly wealthy population. Thus, a gradual transition occurs from an economy based on ESS to one based on non-ESS and remote extraction. In the process, the perceived importance of ecosystems to people decreases. The proportion of people who extract goods directly from ecosystems (farmers, fishers and loggers) declines and their status might be reduced. During the transition period, which may last for decades, elements of both red and green loops coexist (Fig. 2). Typically, this increases socioeconomic diversity, spatial heterogeneity and inequity, often with the formation of spatial gradients in ecosystem service provision and socioeconomic variables related to proximity to various resources[45].

The socioeconomic dynamics that are driven by growing markets for non-ESS, together with upscaling, ongoing technological change and related acceleration of population growth, have many consequences for ESS. Society's ecological footprint grows[46]. As people's reliance on ecosystems becomes less obvious, they become less aware of ecological degradation and less concerned about it. They might also be too overwhelmed by local change to pay attention to their regional and global impacts[47]. As the connections between food production and food consumption (as well as feed and fuel production and use) become less apparent, societies unintentionally place increasing pressure on dwindling resources. In addition, the ability of people to censure others for abusing natural resources declines[48] because social interactions between producers and consumers weaken.

Once the transition from green-loop to red-loop dynamics is underway, the red loop becomes the dominant driver of societal change. Institutions and actions that conserve ESS and contribute to their sustainability must then be negotiated in new action forums[49] in which many powerful and often competing actors, such as politicians, mining corporations and manufacturing industries, push to enhance the provision of non-ESS, often at the expense of ESS. The shift from green-loop to red-loop dynamics thus underpins a gradual regime shift[24,50] in the entire social–ecological system.

Although the transition occurs gradually, the shift from a green to a red loop represents a fundamental change in system functioning that requires two different system models, rather than parameter changes within a single model. The two loops are alternate social–ecological states, each of which has reinforcing feedbacks that buffer it from change. The key slow-changing variables in the system[51] are increasing human population and population density, which create amplifying feedbacks that rapidly ratchet up the demand for ESS and non-ESS; technological change, which accelerates population growth and enables a growing proportion of people to obtain their livelihoods in ways unrelated to agriculture; and a loss of biodiversity, which can lead to eventual socioeconomic collapse.

During transition, the proportion of aggregate income obtained directly from ecosystems declines from high (green loop) to low (red loop)[52,53]. A shift occurs from high to low relative prices for basic ESS (provision of staples such as wheat, potatoes and cassava) and to higher demand for special commodities (luxury food items such as a range of fruits)[54]. The value of sustaining and regulating services also increases while the value of provisioning services declines. For example, access to electricity and fossil fuels in cities reduces the reliance on local wood-fuel production[55]. Demands for cultural services might change with peoples' perception of nature, and willingness to pay for cultural services may increase as natural landscapes become scarcer. For example, temples and shrines in heavily populated cities in Japan and Thailand have found new significance as places in which to experience nature[56]. Upscaling and increased trade in a red-loop population are not necessarily unsustainable if they lead to an equilibrium between the human population and resources at larger geographic extents.

Lock-in to a red loop need not be an 'end point'[57]. Demand for new cultural services, such as walking trails and ecotourism, could lead to a reintegration of local ESS into urban economies and politics (although ecosystems may be species-poor by the time this occurs). Concerns for human health could also lead to measures to prevent environmental degradation. Ageing and declining post-peak human populations will bring new dynamics and possibly, if sufficient biodiversity remains, the potential to return to more direct interactions with ESS. It remains unclear, however, whether efforts to 're-green' cities (for example, through urban rooftop gardens[58]) can persist as the human population continues to grow, and whether cities will become unsustainable without efforts to make them greener and more self-sufficient.

The transition from green- to red-loop dynamics occurs through feedbacks between technological change, population growth and ecosystem change. The resulting red loop has the potential to sustainably reconcile these forces by solving service supply and distribution problems. There may, however, be hurdles that prevent a successful transition and/or reduce the sustainability of the red loop. Overconsumption in the red loop and failure to regulate ecological decline can produce a 'red trap'. Rural poverty and ecological degradation in the green loop may reinforce each other, leading to a 'green trap'. In both cases, systems must reorganize or they will collapse (Fig. 3).

Tests of our model require long-term time series data for agricultural production, demography, economic developments and ecosystem change (Table 1). As a first step towards grounding the model empirically, we review evidence from three case studies: Sweden, as an example of a green-loop to red-loop transition; the Sahel, focusing

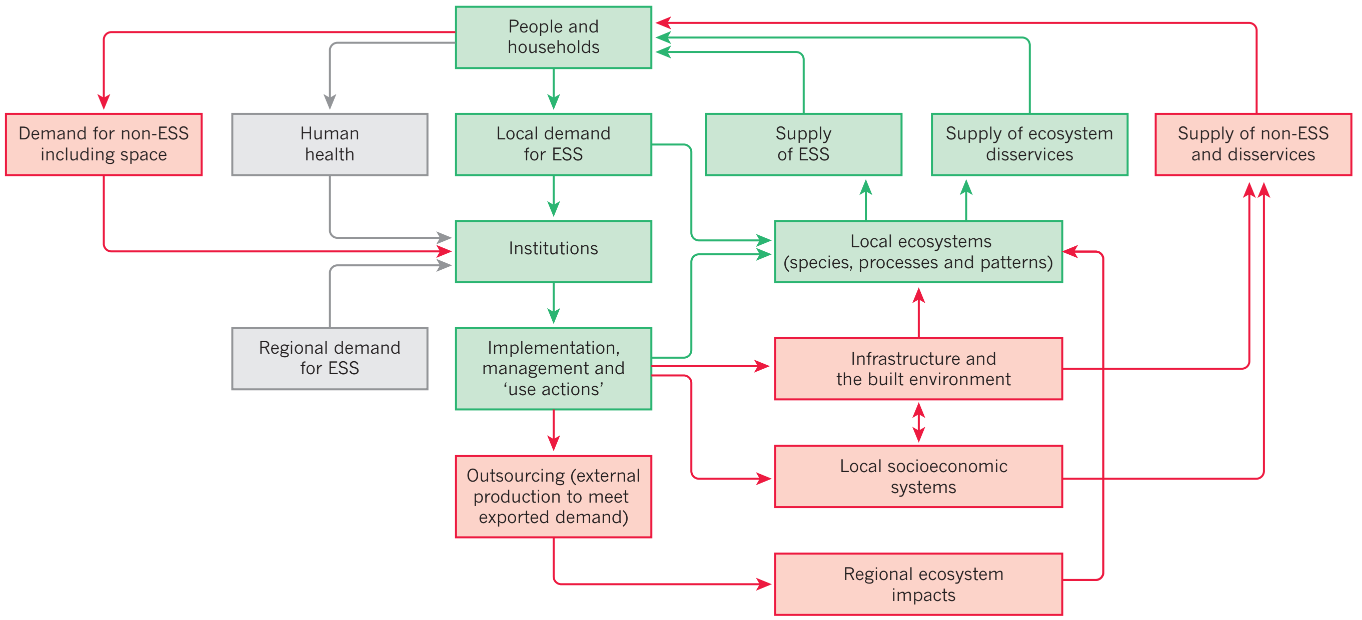

Figure 2 | Detailed interactions and feedbacks during the transitional period between green and red loops. Basic household needs create a local demand for ecosystem goods and services (ESS). This may be expressed as direct and unregulated impacts on ecosystems, or, more typically, as 'use actions' (consumptive and non-consumptive) that are governed by rules, laws, policies and customs (institutions). Among use actions, those that have the highest ecological impacts are generally those that involve direct extraction of resources (for example, logging, cultivation or water extraction). Use actions affect the provision of ESS as well as 'disservices' (pathogens, crop damage or floods). The degree to which human needs are met by ecosystem services then affects future demand, completing the loop. The direct interactions of people and ecosystems are gradually overrun by the red loop, in which the focus is non-ESS, despite the continued importance of ecosystems for the community. Ongoing local and regional impacts on ecosystems are hidden from urban dwellers by outsourcing and infrastructure development. The two 'wild card' variables (in grey), human health and regional processes, may be present in either red- or green-loop situations and may create ecological or socioeconomic surprises that can alter system dynamics.

on Niger, as an example of a green-loop to green-trap transition; and Beijing, as an example of a red-loop to red-trap transition (in the absence of an unequivocal contemporary example of a country in a red trap).

Green loop to red loop in Sweden

For more than 1,000 years, Sweden had low population levels and a dominantly agrarian lifestyle, consistent with a green-loop dynamic. It still has one of Europe's lowest population densities (around 9.5 million inhabitants; 21 people km^{-2}), but between 1750 and 1850 the population doubled and its subsequent growth was much faster[59,60]. Around 1870 to 1890, population growth triggered a switch from a green loop (or possibly even a green trap; more than 1% of the population emigrated to America every year during the 1880s[61]) to a red loop. Rapid economic development, fuelled by engineering, mining, and the steel and pulp industries as well as internal institutional changes and a growing export market, took place between 1870 and 1914 (ref. 62). Two world wars and a global recession reduced economic growth, but gross domestic product (GDP) grew rapidly after 1950 (ref. 60).

Since 1950, industries and business services have expanded, whereas agricultural production has remained relatively constant. Infrastructural assets — buildings and machinery — grew by two orders of magnitude from 69 billion year-2000 Swedish kronor in 1965 to 2.5 trillion year-2000 Swedish kronor in 2000. By contrast, employment in agriculture declined from nearly a million people in 1880 to under 50,000 in 2000, and roughly 20% of agricultural land was removed from production between 1949 and 1999 (ref. 63). Sweden managed to retain substantial natural resources through its agricultural transition. In 2013, 69% of the country was forested, 8% was used as agricultural land and only 2.8% was 'built-up'[64]. Transport infrastructure (roads, railways, harbours and airports) accounted for 40% of built-up land, with total infrastructure occupying a greater area than residential dwellings.

Advances in technologies and farming methods seem to be helping Sweden to remain sustainably within a red loop, with reductions in local environmental degradation and stable or increasing food production. According to Statistics Sweden[64], total household water withdrawals between 1995 and 2010 declined from 616,000 m^3 to 576,000 m^3 per year; and for agriculture, from 137,000 m^3 to 99,000 m^3. Nitrogen inputs into water bodies declined from 34,527 t in 1995 to 24,416 t in 2005 and for phosphorus, from 970 t to 733 t during the same period. From 1965 to 2012, the area farmed and the numbers of individual people engaged in farming strongly declined, but yields per hectare of wheat (summer and winter) increased from 6,880 kg ha^{-1} to 11,110 kg ha^{-1} and annual production more than doubled from 1,039,320 t to 2,289,300 t.

In a red loop we expect a disconnect between people and local ecosystems, with negative consequences for biodiversity and ESS. The available evidence supports this view. The greatest losses of Swedish grasslands, one of the country's most species-rich habitats, occurred before 1950 and created an extinction debt for habitat-specialized vascular plants, with species still being lost from the remaining grasslands[65]. Extensive loss of old-growth forest dates back to a 1948 policy that enabled clear-cutting and over-use of herbicides in Swedish forests. The remaining forests of high conservation value are considered too small and too fragmented to meet current forest and environmental policy goals[66]. The Swedish Environmental Protection Agency was only created in 1967, and biodiversity conservation has only been a nationally agreed objective of forest management since 1992 (ref. 66). In the Baltic Sea, the Swedish cod harvest peaked at 59,000 t in 1984, but had dropped to 16,000 t by 1993 as the fishery collapsed[67]. A review of the impacts of agricultural intensification on essential ESS in Sweden between 1950 and 1999 (ref. 63) found that most of the measures indicated a loss of ESS from the Swedish agricultural landscape. These included a 60% decline in native pollinator abundance and 46%, 33% and 14% increases in the concentrations of the heavy metals mercury, cadmium and lead, respectively.

Sweden has met many of its needs by upscaling, as predicted by our

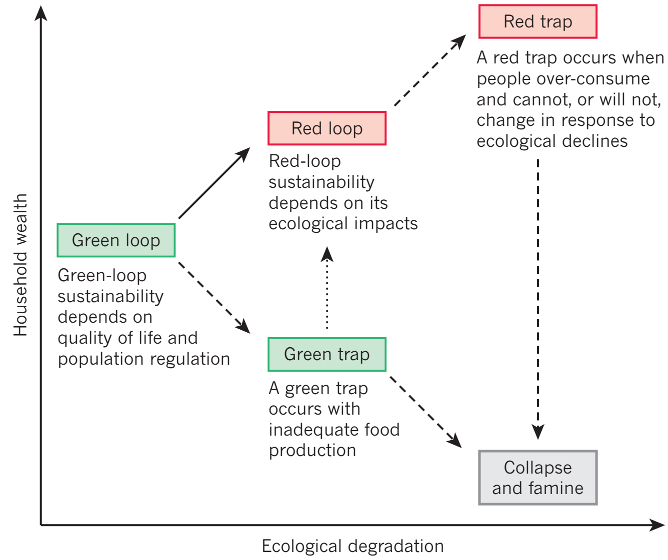

Figure 3 | States, traps and transitions along the rural to urban gradient. A typical development trajectory from an agricultural (green loop) to industrial (red loop) society involves individual households gaining wealth while some level of ecosystem degradation occurs. Depending on population growth rates and governance, societies may grow without true socioeconomic restructuring (green trap) or become rich and continue to over-exploit ecosystems (red trap). The dashed lines indicate avoidable transitions. Both traps can lead to socioeconomic collapse. One of the primary challenges of development and policy initiatives is to shift societies from a green trap to a red loop (dotted line) without heavily altering consumption patterns, thus maintaining a relatively high individual quality of life without entering a red trap.

model. The ecological footprints of large cities in the Baltic Sea region for food and timber production and waste assimilation are more than 565–1,130 times their combined area[68]. Swedish imports and exports increased sevenfold from 1975 to 2000, with unknown ecological impacts on remote locations. Internal biodiversity loss or an external limit to growth (such as climate change) may yet affect Sweden's economy[69]. We could, however, find no obvious evidence that Sweden has entered a red trap. For the moment, it is an example of a shift from a green to a red loop that first increased and then reduced the impacts of the growing human population on local ecosystems.

Green loop to green trap in the Sahel

In Niger, millennia-old, environmentally specialized societies of pastoralists, agro-pastoralists, fishermen and traders indicate the long-term adaptations of people to ecosystem limitations and opportunities. In some parts of the pre-colonial Sahel, the wealth created as a result of labour division and the inter-regional trade of gold, salt and slaves led to the formation of cultural centres such as Timbuktu and Djenné in Mali between the thirteenth and sixteenth centuries[70], proving the economic success of combined trade, regional migration and agro-pastoralism in successfully defying unpredictable rainfall. The existence of a relatively sparse rural society in the Sahel for several thousand years suggests a stable green loop.

The slave trade during the eighteenth and nineteenth centuries resulted in the loss of up to 3 million African inhabitants, affecting the workforce and cultural progress. Population recovery during the twentieth century rapidly led to a shortage of fertile land. Together with erratic rainfall, low soil fertility has, for centuries, limited the effectiveness of agricultural intensification efforts[71]. Shorter fallow periods have led to the expansion of cropping systems into ever more marginal drylands. The resulting large drop in per capita cereal production has required rapidly increasing cereal imports[72] (Fig. 4). Although between 1970 and 2012 the area of harvested cereals expanded from 2.3 million to 10 million ha, cereal imports increased from almost zero to 340,000 t (Fig. 4).

Table 1 | The main premises (both well proven and those for which the evidence is circumstantial) underpinning our model, and forms of evidence on which proof or disproof of our argument rests

Model stage, prediction or hypothesis	Evidence that would support the model	Relevant data
Relatively stable populations of low densities are maintained with an agrarian or pastoral lifestyle.	Lower population density before the formation of cities.	People per hectare before urbanization, showing evidence of stability in numbers.
Low population density is, or was, ecologically sustainable over timescales of centuries.	Low population density did not lead to degradation of ecosystem services (in addition to evidence of more than 250,000 years of human existence in Africa).	Estimates of how much land was needed for sustainability, for example, the number of hectares per household needed to maintain shifting agricultural system productively for more than 50 years, and proof that this much land was available.
Population increase leads to an increase in the number and size of cities (and/or land degradation and poverty).	Increasing urbanization, declining per capita agricultural production, declining household smallholding sizes as well as intensification as a temporary fix, or failure of agricultural production to sufficiently increase to meet demand.	City sizes, urban population demographics and urban growth rates; per capita production of key food crops; and village, farm or smallholding sizes.
In cities, the proportion of household income from agriculture drops as the society enters a red loop. The agricultural transition divides urban (red loop) and rural (green loop) people.	Differences in household income sources between rural and urban dwellers, declines in proportion of income from agriculture (as an income source) or the increasing role of non-ESS.	At the microscale, household-level data on net income and sources of income; at the macroscale, agricultural production as a proportion of GDP between urbanized and developing countries; and data on service industries and government or city expenditures.
Once in a red loop, upscaling of production systems must occur to meet the food demands of the urban population.	Upscaling, for example, greater ecological impacts on the surrounding countryside, impacts of urban demand on rural production systems and markets, and increased importance of trade.	Data on food prices, diversity and demand from city dwellers (compared with rural dwellers); rates of land conversion around cities; and per hectare production of crops in relation to market growth.
Red-loop dynamics reduce the connections of city dwellers to the countryside, fostering further ecological degradation.	Increasing rates or magnitudes of ecological impacts as urbanization levels increase, with less obvious dependency by city dwellers on provisioning ecosystem services, and increased ignorance about ecosystems (for example, where food comes from or what natural habitats really look like).	Data on land-cover change and biodiversity loss as urbanization occurs, ideally compared with a dysfunctional green-loop situation (increasing population and declining quality of life).
Existence of a green trap.	Population increase is possible without urbanization (or the total population may grow more rapidly than the urban population).	Data showing increasing rural population and declining per capita production.
Existence of a red trap.	Unsustainable consumption by wealthy societies.	Despite arguments for the existence of red traps based on archaeological data, because of global upscaling few, or no, clear-cut contemporary examples exist.
Potential for collapse.	The demonstration that collapse is possible from both green-trap and red-trap situations.	Archaeological evidence for social–ecological collapse in past civilizations, both agrarian and urbanized. Contemporary examples are harder to find because of technology and globalization.
Potential for shifting from a green trap to a red loop.	Urbanization and migration can provide a short- or intermediate-term solution to rural poverty.	Data on household incomes for societies (for example, Gini coefficients) as they go through a transition.

GDP, gross domestic product; ESS, ecosystem goods and services

These trends correspond with a shift from a green loop to a green trap, in which poor rural populations remain enmeshed in rural poverty. Apart from during the two big Sahel droughts (in the early 1970s and mid-1980s), Niger has coped with the per capita decline of its rain-fed cereal production by upscaling. In our model, this indicates a shift towards a red loop. However, the economic basis for imports was the uranium boom — recently complemented by revenues from oil and gold — which resulted in an availability of funds without the creation of a full set of economic, infrastructural and institutional assets that would characterize a red loop. The decline in demand for nuclear fuel during the 1990s therefore resulted in a food crisis and political instability.

In response to the green trap, the rural population of Niger migrated. In 1951, the urban population was 6% of the country's 3.3 million inhabitants; by 2012 it was 17% of 16.6 million[72]. As people in Niger attempt to escape the green trap, the intensive production of vegetables in urban and peri-urban agricultural systems and in irrigated gardening systems of southeastern Niger has increased; for example, onion sales in the Maradi region increased from 26,000 t in 1961 to 370,000 t in 2011 (ref. 72). Imports of staple foods, largely financed by foreign aid, have allowed the urban population and its alienation from ESS to continue to grow (upscaling based on external economic resources). Upscaling of demand without expansion of local supply has led to further neglect of the rural sector, putting additional strain on ecosystems, leading to more ecosystem degradation, and making it increasingly difficult to escape the green trap. For example, reliance on wood fuel from the marginal shrublands that formerly surrounded the cities[73] has led to the widespread loss of vegetation cover and a decline in associated regulating and supporting services.

Agricultural innovations proposed for the Sahel over the past 50 years have largely failed because food production is hampered by a combination of climatic unpredictability and political neglect[74]. A few examples from Sudano–Sahelian West Africa[75,76] indicate that agricultural intensification with positive feedback loops to ESS is possible, in principle, in this region. It depends, however, on effective local policies, risk-reducing technologies and stable market demand for commodities that support farmers' investments in agriculture (as well as curbing the present 3.9% per annum population growth rate).

Red loop to red trap in Beijing

Beijing is situated on the fertile North China Plain. It has an average annual precipitation of 578 mm and relies, for staple foods, on an intensive double cropping system of maize (corn) and wheat. Although the lack of water has limited the development of the Beijing basin area for centuries, and despite China's one-child policy, the greater metropolitan area has grown from 9 million inhabitants in 1978 to more than 17 million in 2009 (ref. 77).

Population growth, exacerbated by immigration, rapid industrialization and changes in consumer demands, has led to an ever-increasing demand for water resources. Beijing's per-capita water-storage capacity of 300 m^3 is 12.5% of China's urban average and 3% of the world's.

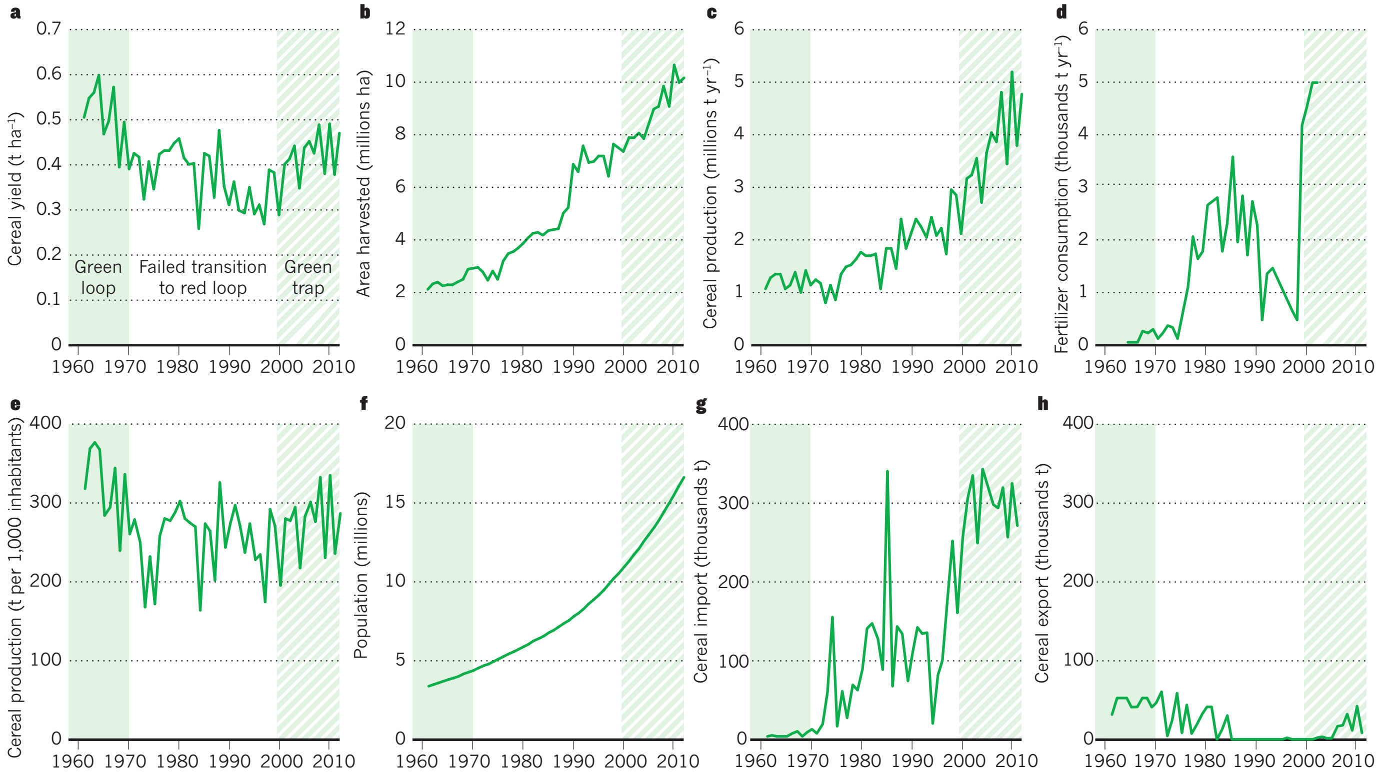

Figure 4 | Development of cereal production in Niger between 1960 and 2014. Cereal data illustrate the failed transition from a green to a red loop, and the resulting entry into a green trap. Cereal yield per hectare (a) has declined and the large expansion of the cultivated area (b) is primarily responsible for the increase in total cereal production (c), despite an overall increase in fertilizer use (d). Cereal production per 1,000 people (e) dropped slightly as the human population grew (f). This would have led to a decline in cereal availability per capita. However, since the 1990s, extensive cereal imports (g) have compensated for the shortfall, with the linked collapse of cereal exports (h).

Overuse of ESS is evident: 60% of Beijing's total water use, and 80% of its irrigation water, is fossil groundwater, which is unrenewable. Average water table levels in 2000 were 8.1 m lower than in 1980 and 12.2 m lower than in 1960 (ref. 78). In 2005, agriculture consumed 38% of the total water, for industry the value was 20%, and for municipal and residential purposes it was 39%; the latter is rapidly increasing, leading to fierce competition between these sectors[78]. Around 70% of the irrigation water in the North China Plain is wasted by evaporation, deep percolation or run-off[79]. China's central government has now implemented measures, such as the use of plastic mulching and tree-crop interplanting on large areas, to enhance water conservation.

High-intensity agricultural production in the Beijing area satisfies only 17% of city dwellers' demand for grain and 31% of their demand for vegetables[77]. Heavy environmental contamination has occurred from uncontrolled wastewater discharge into water bodies, nitrate leaching from over-fertilization, and the release of gaseous pollutants and aerosols into the atmosphere. An estimated 75% of urban residents in China live in areas in which the air quality is below the country's own standards; fine particle, emissions of sulphur dioxide and nitrogen oxides and subsequent fallout of acid rain[80] affect an even higher proportion of Beijing's population. In 1997 the nationwide death toll from air pollution was already estimated to be 300,000 people per year[81]. Annual total aerial nitrogen deposition rates in China rose from 13 kg N ha^{-1} in the 1980s to 21 kg N ha^{-1} in the 2000s, of which agricultural nitrogen sources contributed two-thirds[82]. Recent data for the Beijing area show annual total dry and wet nitrogen depositions of more than 90 kg ha^{-1} per year[83], resulting in widespread acidification of the generally well-buffered surface soils of China's croplands[84].

In recent decades, per capita income in Beijing has risen faster than the cost of living and the proportion of household income spent on food has declined. Hence, Beijing has witnessed a transition to urban lifestyles, a growing dependence of food markets on distant ESS (upscaling) and the breakage of direct feedbacks from local ecosystems to the local population. So far, upscaling seems to have been a successful strategy for dealing with a potential red-trap situation. However, it is unclear whether further development in Beijing will be sustainable given ongoing declines in ESS and human well-being[85].

General implications

Although ecosystems are the foundation on which non-ESS rest, demands by urban societies for non-ESS make the connections between humanity and ecosystems less obvious and less immediate. The social–ecological dynamics of ESS are strongly driven by the more general demands of society for non-ESS and by the changes in the scales of supply and demand, for both ESS and non-ESS, that accompany the transition from agricultural to industrial societies. The first point in particular has not been incorporated into the ESS literature.

Agricultural transitions are fundamentally linked to human population growth[86]. Growing societies that attempt to remain in a green loop will almost inevitably enter a green trap, which could result in greater biodiversity losses than a red loop[87]. Few contemporary societies exist in a green loop, and those that come closest to doing so are often socially and economically marginalized and vulnerable to external exploitation of their ecosystems[88,89]. Contemporary societies that seem to have best navigated a balance between ecological sustainability and human well-being are those, such as Sweden, that have entered a red loop without shifting exploitation to red-trap levels. The red loop has bought such societies additional time, and the best-case scenario is that socioeconomic feedbacks within the red loop (for example, declining fertility, or simply longer inter-generational times and smaller families) could reduce population growth and ecological footprints before these systems enter a red trap and collapse[90].

Scale is of critical importance here: the cumulative effect of many local or regional red loops may be a global trap, for example if their combined greenhouse-gas emissions trigger climate change. We would expect to find scale dependencies in the relative importance of different links in the model. At local extents, questions of access and infrastructure development may dominate red-loop ecological impacts. At national extents, the model may capture the basis of an economy as rural or urbanized, and upscaling can be perceived as globalization. For empirical analyses, we suggest an initial unit of analysis as the household, with aggregation of household data across a range of different spatial and temporal scales, and institutional levels.

Our model shares some elements with the environmental Kuznets curve[91,92], which suggests that indicators of environmental degradation follow an inverted U-shaped curve over the course of economic development. We do not wish to reinstate Kuznets' hypothesis, which has been criticized[92,93]; but the different pathways that we have identified explain why the environmental Kuznets curve might apply to some societies (such as those undergoing a green- to red-loop transition) and not to others (such as those that are caught in, or heading towards, red or green traps).

It remains unclear whether, how and when ecological debts incurred during industrialization will have to be repaid. Human survival depends on maintaining functional, resilient ecosystems and resulting ESS through the bottleneck of maximum human population. The loss of a crucial proportion of Earth's fauna during the next 50–100 years would be irreparable over the time frame of human existence, and future societies may struggle to live sustainably if left with unstable, depauperate life-support systems.

Our model has some parallels with existing research on traps and transformations[94–97], with many relevant details and implications that will take time to work out. It is not directly diagnostic or prescriptive but it has the potential to both explain and predict, in the context of ESS and agriculture, the creation and resolution of scale mismatches[98] and the development of various systemic syndromes (such as the retention of perverse incentives and subsidies[99], or the continued presence of destructive feedback loops that are almost impossible to break). The transition from green to red loops may also help to explain collapses in some past societies, providing a translation mode (in moving from theory to empirical, testable hypotheses) for ideas about social complexity and adaptive cycles[100]. A diversity of data-intensive, comparative case studies is needed to test and refine these ideas; developing economies and fast-growing cities should be particularly fertile grounds for further research. Ultimately, we see in these ideas the basis for a scientific framework that would explain why humanity's use of ESS is, despite our combined knowledge and expertise, rapidly approaching planetary boundaries. ■

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