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Review

Trade-Offs in Multi-Purpose Land Use under Land Degradation

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Abstract: Land provides a host of ecosystem services, of which the provisioning services are often considered paramount. As the demand for agricultural products multiplies, other ecosystem services are being degraded or lost entirely. Finding a sustainable trade-off between food production and one or more of other ecosystem services, given the variety of stakeholders, is a matter of optimizing land use in a dynamic and complex socio-ecological system. Land degradation reduces our options to meet both food demands and environmental needs. In order to illustrate this trade-off dilemma, four representative services, carbon sinks, water storage, biodiversity, and space for urbanization, are discussed here based on a review of contemporary literature that cuts across the domain of ecosystem services that are provided by land. Agricultural research will have to expand its focus from the field to the landscape level and in the process examine the cost of production that internalizes environmental costs. In some situations, the public cost of agriculture in marginal environments outweighs the private gains, even with the best technologies in place. Land use and city planners will increasingly have to address the cost of occupying productive agricultural land or the conversion of natural habitats. Landscape designs and urban planning should aim for the preservation of agricultural land and the integrated management of land resources by closing water and nutrient cycles, and by restoring biodiversity.

Keywords: agricultural land conversion; biodiversity; ecosystem services; integrated land and water resource management (ILWM); urbanization

1. Introduction

Land provides a host of ecosystem services (ESSs), of which the provisioning services are often considered paramount [1]. Food, forage, fiber, fuel, and forest products that are derived from land have sustained an ever increasing human population, but at a cost. As the demand for these products multiplies, other ESSs are being degraded or used unsustainably. According to [1], this is true for about 15 out of 24 of the ESSs that were evaluated (including 70% of regulating and cultural services).

The impact and cost of such loss in ESSs, which are essential to human survival, is difficult to fathom, as many of them have never been seriously studied [2]. It has been postulated that farmers that are profiting from their land will invest in it to keep it productive [3,4]. This is conceptually depicted in trajectory A of Figure 1, which reflects an environmental Kuznets curve (EKC).

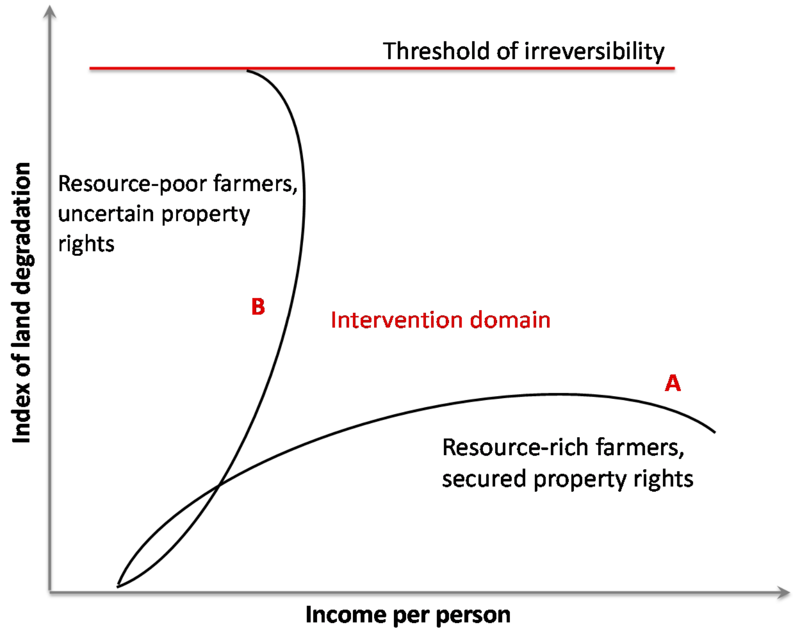

Figure 1. Land degradation as a function of income for resource-rich farmers (trajectory A) and resource-poor farmers (trajectory B).

Conversely, it is likely that farmers working lands that do not yield the necessary returns to invest in their land end up mining their soils [4] and seeing their returns diminishing over time (the B trajectory in Figure 1). They may be living on borrowed time without being fully cognizant of it [5,6], and once their land resources cross a tipping point of irreversible degradation (Figure 1), they may abandon their land at a great ecological and economic cost to the public. Other actors may be equally destructive to the land. In fact, [1] claims that the total economic value of managing natural ecosystems sustainably is at times higher than the value that is associated with the conversion of the ecosystem through clear-cut logging, farming, or other intensive use of land. The challenge in the decades to come will be to produce food and derive ESSs from land in a sustainable way.

Soils play a key role in determining the quality of land [7]. Putting land under cultivation is predicated on the removal of native vegetation, which normally goes hand in hand with a loss in soil organic matter [8], thus affecting soil productivity. This transformation may lead to a new equilibrium in soil organic matter, which might be sustainable over millennia, e.g., the rice paddies of Southeast Asia or the rice and wheat producing areas of the Nile Delta. However, there are numerous examples of cultivated land degrading, due to mismanagement or other pressures on the land (e.g., human-induced climate change, extreme natural climate oscillations) to the point that it has to be abandoned [9].

The level of disturbance that an ecosystem can sustain depends on its ecological resilience. A resilient system may recover its pre-disturbance functions without human intervention other than cessation of the management that created the disturbance [10,11]. Timely abandonment of agricultural land by shifting cultivators, for instance, allowed for repeated use of the land over time [12]. Loss of resilience can cause a system to reach a tipping-point and shift to an alternative stable state, a change known as regime shift [13–16]. Once land degradation takes hold, land loses certain intrinsic qualities or the capability to perform vital functions of both economic and ecological importance [17]. Soil salinization, alang-alang (*Imperata cylindrica*) invasion, and mangrove collapse are typical examples of regime shifts. Regime shifts can be rapid or creeping [18], and slow ones can be hard to notice and assess [5].

Environmental ecosystem functions provide a significant proportion of the ESSs that support the four pillars of food security, together with economic and social ecosystem functions. A loss of ecosystem functions will affect food and nutrition security in a myriad of ways (Figure 2).

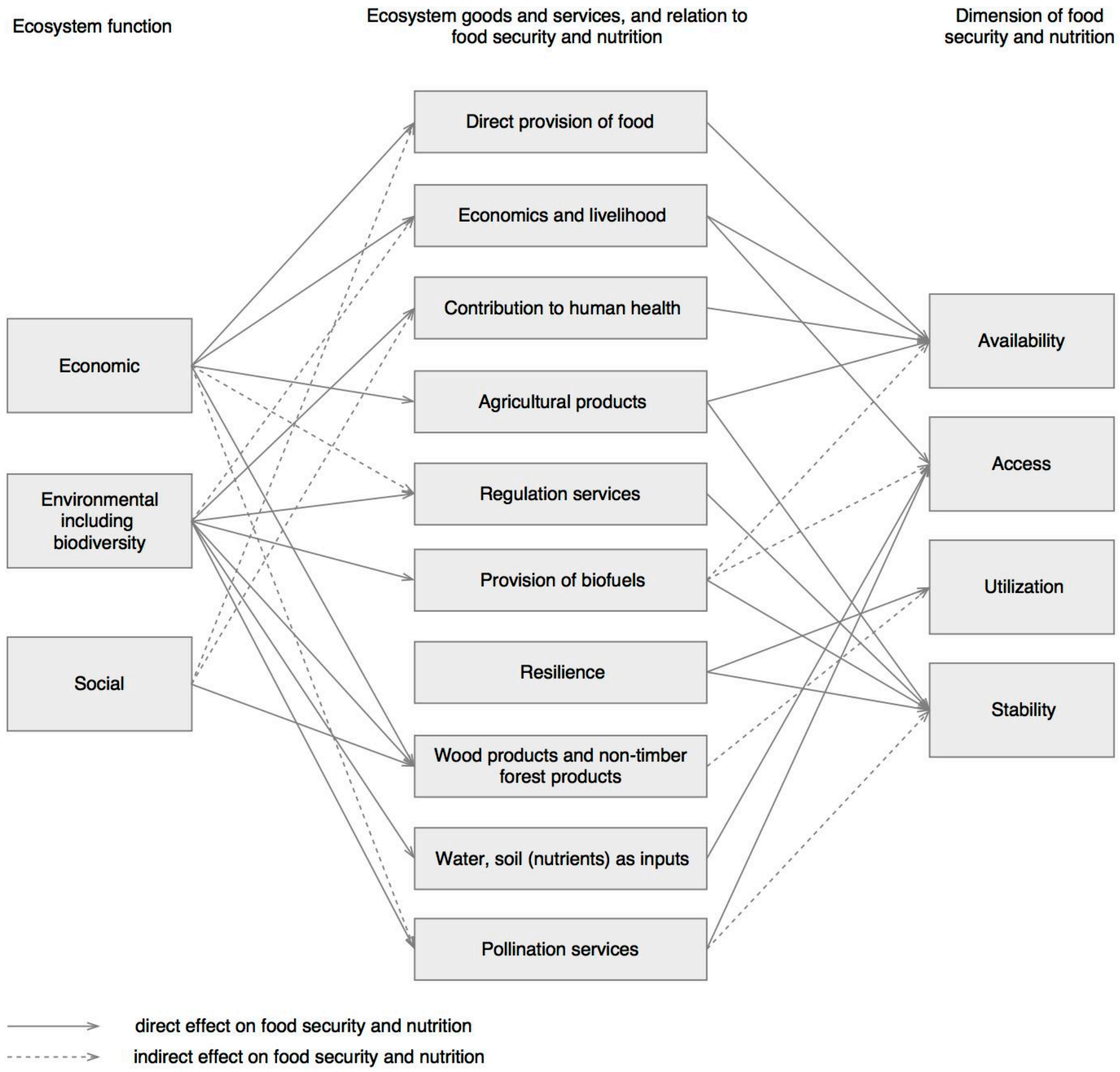

Figure 2. Links between ecosystem functions, goods and ecosystem services provided, and the four dimensions of food and nutrition security.

Given the variety of stakeholders and their interests in many of these ESSs, finding a sustainable trade-off between food production and one or more of the other ESSs is a matter of optimizing a dynamic and complex socio-ecological system [19]. The core of this argument is illustrated in Figure 3, where on the vertical axis we depict food production as a societal imperative and on the horizontal axis we show other land-derived ESSs that possess varying values for on- and off-site stakeholders. For the sake of simplicity, we depict a linear trade-off relationship, but the shape of the trade-off curve will be different for different ESSs, different contexts, and different stakeholders' valuations, as will be their substitution rates (i.e., the slope of the relationship). Finding satisfactory solutions for a simple trade-off with multiple stakeholder interests in mind is complex and this complexity increases exponentially as more ESSs are added to the mix [20].

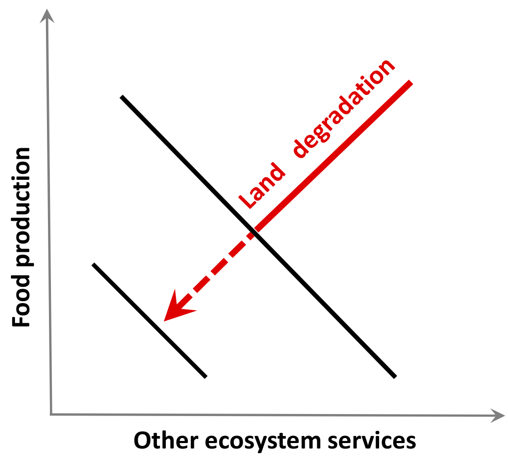

Figure 3. A simplified visualization of the key guiding principle in trade-offs between provisioning and non-provisioning ecosystem services.

2. Objective and Methodology

This paper aims to elucidate the trade-off dilemma that policy makers are confronting in addressing the needs of their various constituents. To this end, four representative ESSs, climate change mitigation, water storage, biodiversity, and space for urban infrastructure are discussed in this paper. The analysis is based on a review of contemporary literature by experts with years of experience and embedded in considerable institutional knowledge in their field of expertise. Authors undertook literature searches that were varying in their approach, ranging from selection based on expert knowledge to systematic screening to investigate the dilemmas of multi-functional land use. Such searches focused on materials that were published after 2000, the year that the ESS concept became widely accepted. The approaches were reviewed and adjusted during the joint authors' meeting on 20–21 October 2016 in Bonn, Germany.

3. Land for Food and Climate Change Mitigation

Agriculture is the prime consumer of the world's water and land resources and is an important source of greenhouse gas (GHG) emissions [21]. Land conversion to agriculture is the principal driver behind deforestation worldwide. Some 24% of GHG emissions are attributable to agriculture (13%) and land-use change (11%), both of which have indicated slight increases since 2010 and 2008, respectively [22,23]. Global emissions from land-use change and agriculture are increasing because of a growing population, accompanied by an increasing consumption of meat and dairy products, as well as the rise in the use of nitrogen fertilizers. Conversion to agricultural land presents a trade-off to society because the same land that is used for providing essential food, feed, fiber, and biofuels, could store large amounts of carbon in soils and biomass in its natural state, and thus mitigate climate change. The expansion of croplands to satisfy the needs of a growing population with changing diets along with a shift towards biofuels is causing a costly loss in carbon stocks in natural vegetation as well as soils [24]. In order to meet emission reduction targets, it is important to leverage the mitigation potential of land in combination with adapting to a changing climate [25].

Ecosystems vary widely in the amounts of carbon stored depending on soil type, species composition, relief, climate, and other biophysical features. The total amount of carbon stored in plant biomass in ecosystems globally ranges from 3 Gt in croplands to 212 Gt in tropical forests, while soil carbon stocks range from 100 Gt under temperate forests to 470 Gt under boreal forests [26]. Boreal forests and wetland biomes have the highest density of carbon storage. Soils generally hold more carbon than vegetation across biomes and account for 81% of terrestrial carbon stock at the global level (Table 1).

Table 1. Carbon stocks in vegetation and the top meter of world biome soils [26].

Biomes	Area (Million km^2)	Carbon Stocks (Gt) and Proportion in the Ecosystem (%)				
		Vegetation	Proportion (%)	Soils	Proportion (%)	Total
Tropical forests	17.6	212	49.5	216	50.5	428
Temperate forests	10.4	59	37.1	100	62.9	159
Boreal forests	13.7	88	15.7	471	84.3	559
Tropical savannas	22.5	66	20.0	264	80.0	330
Temperate grasslands	12.5	9	3.0	295	97.0	304
Deserts	45.5	8	4.0	191	96.0	199
Tundra	9.5	6	4.7	121	95.3	127
Wetlands	3.5	15	6.3	225	93.8	240
Croplands	16	3	2.3	128	97.7	131
Total	151.2	466		2011		2477
Proportion (%)		19		81		100

The carbon loss resulting from converting natural ecosystems to croplands is, on average, higher in the tropics (~120 t C ha^{-1}) than in temperate regions (~63 t C ha^{-1}), largely because tropical forests store much more aboveground biomass carbon than any other biome [24]. A trade-off analysis has shown that carbon loss per ton of crop yield in the tropics is about three times higher than in temperate regions (Figure 4).

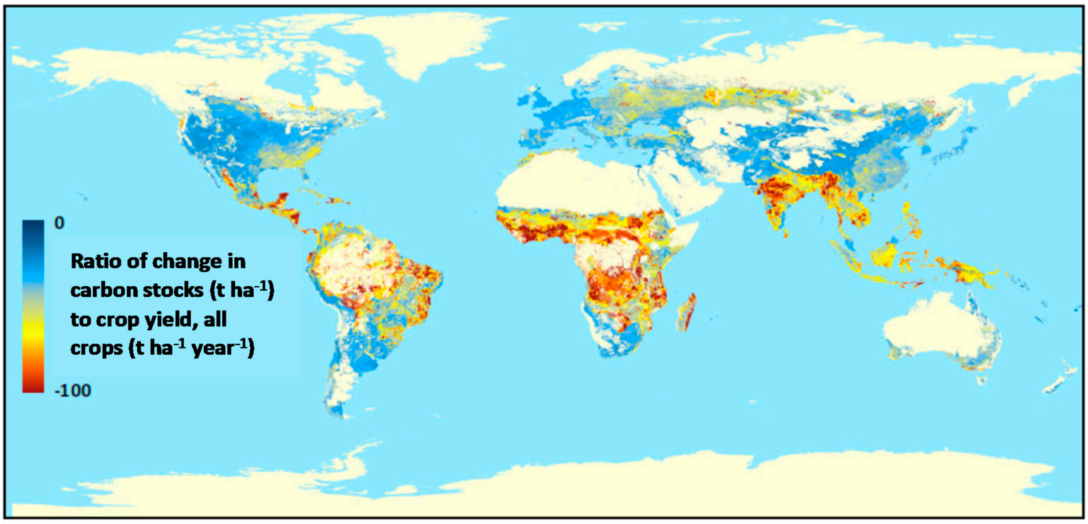

Figure 4. Trade-off index showing changes in carbon stocks per unit of annual crop production [24].

The high carbon loss per unit crop yield in the tropics results from two factors: the overall highest average carbon loss from conversion and the lowest average crop yields. Tropical peatlands are among the most carbon-rich ecosystems in the world, typically storing more than 1000 t ha^{-1} (191 Gt, or one-third of all carbon in peatlands globally [27]); preserving those peatlands would prevent a great amount of carbon emissions.

In meeting the demand for food, we rely on both the expansion and the intensification of agricultural production, as only rarely can productivity increase without land use intensification [28]. Intensification of agriculture is based on concentrated livestock production and the increasing use of fertilizer and other inputs for crops. Agricultural intensification has been an important strategy to keep up with food demand over the past 50 years, and is credited with sparing 1.1 billion ha of land and its associated carbon sinks that would have been lost if intensification options had not been available [29].

When compared to land conversion, the relative contribution of agricultural operations to CO_2 emissions in agriculture-based economies is very small–about 4%–out of which, 70% is due to energy use in fertilizer production [30]. Thus, in developing countries, the conversion of natural vegetation to farmland is the primary source of non-fossil fuel emissions. While intensification adds to the agricultural sector's GHG emissions, a central question is whether the cost of fertilizer-related CO_2 emissions due to further intensification can be justified by the carbon sequestration on agricultural land that would be released for reforestation.

According to [30], increasing fertilizer consumption in developing countries (excluding China) by 20% could lead to cereal yield increases of 5–20%, depending on the crop and region (Table 2).

Table 2. Potential carbon sequestration from reforestation of agricultural land that can be spared as a result of increasing the fertilizer use by 20% on prime land (modified from [30]; NA = data not available).

	Sub-Saharan Africa	Near East/ North Africa	East Asia	South Asia	Latin America and Caribbean	Total
Increase in cereal yield (%) from a 20% increase in the use of fertilizer						
Rice	5.1	8.7	9.8	10.0	10.7	8.9
Wheat	11.0	11.1	NA	7.4	12.2	10.4
Maize	9.9	11.3	20.0	8.3	13.2	12.5
Potential spared land area (Mha)	2.0	2.7	6.1	7.0	5.0	22.9
CO_2 emission from a 20% increase in fertilizer production (Mt)	0.37	1.20	1.90	6.54	1.85	11.9
Potential CO_2 sequestration from forest regeneration (Mt) on spared land						
Low rate (4 tCO_2 ha^{-1} yr^{-1})	8.1	10.7	24.8	28.4	20.3	92.3
High rate (9.5 tCO_2 ha^{-1} yr^{-1})	19.2	25.3	58.5	67.2	47.9	218
CO_2 balance (Mt)						
Low	7.7	9.5	22.9	21.9	18.4	80.4
High	18.8	24.1	56.6	60.8	46.1	206
Average	13.3	16.8	39.8	41.2	32.3	143

The amount of land that is set aside for reforestation because of an increase in productivity ranges from 2 Mha for Sub-Saharan Africa to 7 Mha for East Asia, while emissions from a 20% increase in fertilizer production range from 0.4 Mt to 6.5 Mt. It is noteworthy that intensification would result in carbon sequestration that more than compensates for the emissions that are associated with the production of the additional fertilizer that is required to increase yields. A 1% GHG emission rate from the additional fertilizer [31] would not materially change this balance. The CO_2 balance ranges from an average of 13 Mt CO_2 for Sub-Saharan Africa to 41 Mt CO_2 for South Asia. There is, however, a wide variation in the amount of land spared per unit of CO_2 emissions from increased fertilizer production. Due to the low usage of fertilizer, a 20% increase of fertilizer use in Sub-Saharan Africa would spare the least land among the world's regions. However, the scope for increasing fertilizer use in Africa is far in excess of 20%.

The designation of land to be targeted for sustainable intensification and for being spared or set aside for land restoration is an exercise in landscape management that requires community consensus building and concerted action. Failing to do so is a recipe for land degradation, which is a major concern in Sub-Saharan Africa [32]. More than 40% of Africa's 220 Mha of farmland is experiencing annual losses of at least 30 kg per ha of nutrients, which is equivalent to more than US$4 billion [33]. Hence, rehabilitating degraded lands in Africa by restoring soil fertility, curtailing soil erosion, and boosting water retention capacity will greatly facilitate meeting escalating food demands. This type of land management calls for a strong policy environment and community efforts to be successful.

In addition to community efforts in managing landscapes, there is an equally important role for individual farmers in minimizing their carbon footprint while producing food. Sustainable intensification by investing in soil through fertilizer and judicious use of crop residue and manure, when combined with soil conservation measures along with improved crop varieties with high genetic yield potential and nutrient use efficiency would improve food production while retaining the natural resources that are essential to sustain such productivity [34]. The adoption of sustainable intensification approaches will be required to minimize societal trade-offs in attempts to utilize land for food and CO_2 sequestration. One such strategy, conservation agriculture, including conservation tillage, has seen widespread adoption over the past decades [35,36], although it consists of a variety of approaches with varying effects [37–39]. However, sustainable intensification is not just a technological adjustment, but, according to [40], comprises of socio-economic, ecological, and genetic reinforcing pillars that must be appropriately combined and scaled up to address the challenges of food security and land degradation in the years to come.

Socio-economic factors often pose barriers to the successful adoption of sustainable intensification practices. Such barriers include the significant upfront investments and expenditures that are required to adopt some sustainable intensification technologies [41]. Inputs such as improved seeds and fertilizers need to be made available in local markets. Farmers require information and evidence about the potential benefits of adopting new technologies and must be shown their compatibility with traditional practices. Many farmers have little if any experience with the kinds of collective action that are needed for proper landscape management or the adoption of certain sustainable intensification technologies [42]. The approach that is being promoted under the term climate-smart agriculture (CSA) is seen as a viable means of sustainable land management and increasing productivity under a changing climate [43].

Climate-smart agriculture is an acknowledgment of the environmental services that a well-managed agricultural sector can provide. It aims to increase agricultural productivity in a sustainable fashion and boost incomes while building resilience and adapting to climate change, at the same time reducing GHG emissions from agriculture. CSA is context specific, evidence based, and assesses synergies and trade-offs across multiple objectives as a basis for informing and re-orienting policy in response to climate change. Scaling up will require the promotion of nation-wide CSA and sustainable intensification policies in order to increase the adoption of CSA technologies. Moreover, nations will have to make investments in CSA, build reliable private sector input markets, ensure durable access to land, be innovative, and to establish inclusive knowledge systems. Institutional arrangements set the legal framework within which sustainability and landscape management can occur. The degree of integration of various sectors and levels of government can play a large role in promoting or hindering sustainability policies [44].

4. Land for Food and the Provision of Water

Whereas the connection between water and food security has been high on the scientific and public agenda, the connections between water and land resources in the production of food, feed, fiber, and fuel, and the functioning of ecosystems are just starting to gain attention. Land cover and land use are paramount in linking the terrestrial and atmospheric compartments of the hydrological cycle. Land plays an important role in water supply including soil moisture, reservoirs and underground water storage. Land-use changes will affect these cycles and thus cause changes in water availability, quality, and management. Water is critical to food security as irrigated agriculture represents about 20% of the land under cultivation and contributes up to 40% of global food production [45]. Globally, agriculture is the largest user of water, using 70% of total groundwater and surface water withdrawals [46].

Today, the intensification of agriculture in emerging economies, such as India and China, is repeating the problems of excessive fertilization and irrigation witnessed in western agriculture. This often leads to the degradation of water resources with increased nutrients and toxins in groundwater and surface waters [47]. Thus, the degradation of water and land often occurs simultaneously, leading to a lower level of ESSs, and a reduced capacity for food production and income generation [48,49] in the long term. Efforts to secure water can be readily counterproductive if land degradation processes are not kept in check. The result might be the siltation of reservoirs with a reduced reservoir storage capacity, damaged irrigation infrastructure [50], pollution of potable water [51] or eutrophication, and low oxygen conditions in water bodies, with serious consequences for food production and human health [52]. Conversely, poor management of available water can cause serious damage to land and topsoil, as is seen in the salinization of many irrigated agricultural lands [53–55].

Quantity and quality of freshwater resources in vast areas across the globe are acutely threatened [49]. More than 60% of the world's largest rivers, which together deliver half of global water runoff to the oceans, are at least moderately threatened at their mouths, with eight rivers showing a very high threat to human water security. The sources of degradation in many of the most threatened rivers are similar for developing and industrialized countries [49]. Rivers in the United States show wide-spread degradation across 750,000 km (50%) of sampled river length where the impacts of chemical fertilizers have often spread to water systems [56]. These nutrients find their ways into lakes and deltas where they result in eutrophication with adverse impacts on aquatic habitats [57,58]. Integrated land and water management is crucial in achieving water security, while preserving other ESSs.

Water and land resources are also linked by the increasing number of large dams. Most large reservoirs today are built as multi-purpose schemes, serving energy production, irrigation, domestic supply, and flood control needs. Large dams have been built for more than 130 years, and since 2000, the construction of dams of more than 60 m in height has increased (http://icold-cigb.net/). Although their impact as effective flood control measures is being contradicted for some large rivers (e.g., [59]), particularly the dams with large storage reservoirs, have been documented to prevent the flow of nutrients and sediments, hamper fish spawning, and affect the water cycle by increasing water residence time, thus altering the ecosystems and their services [60,61]. Properly designed dams with sufficient storage, however, can be effectively integrated in sustainable ecosystem management through reducing destructive flash flows and retaining sediments on land [62]. Traditional large-storage infrastructure, such as dams, is now back on the agenda of multi-lateral donor agencies and governments of many developing countries. However, there are a number of diverse storage types, ranging from natural storage (e.g., wetlands, glaciers, soil moisture, aquifers) to various smaller structures (terraced paddies, ditches, and retention ponds; Figure 5). This 'storage continuum' often slips the attention of development organizations [63].

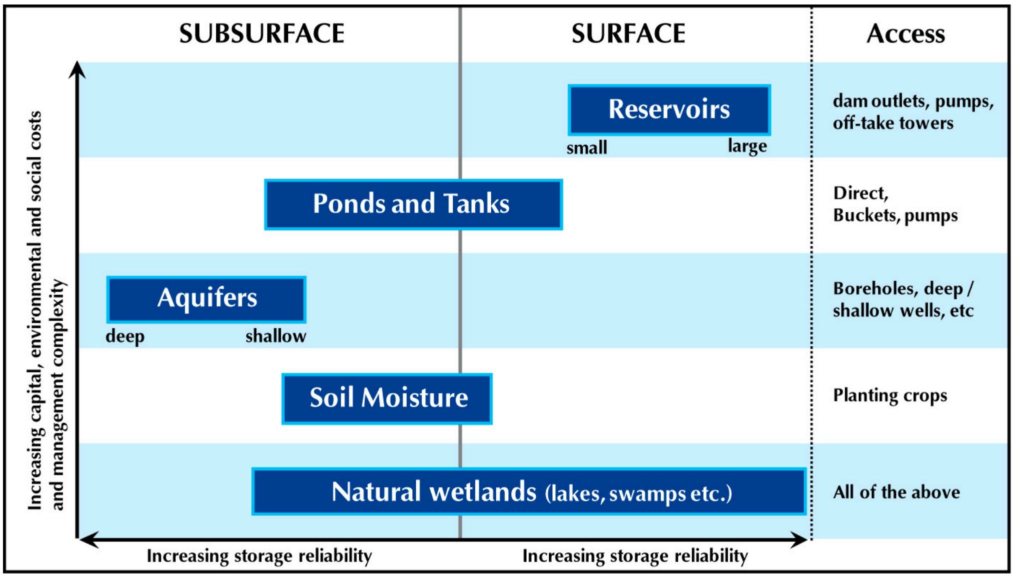

Figure 5. The continuum of water storage options [63].

An ecosystem-based management approach can bring the components of energy, food, and water into a single viewpoint or nexus, and can help to mitigate the negative trade-offs and generate co-benefits [64]. When combined with cost and benefit analyses, this approach provides strong support to land use planners and decision makers.

Nexus planning does not always lead to win-win situations. Trade-offs are often unavoidable and need to be calculated and assessed in designing optimal solutions. Taking a systems view can help to increase efficiencies and optimize production values, but value is in the eye of the beholder. For example, discussions between Nepal and India on the development of large dams in the Upper Ganges Basin have been deadlocked because India wants larger dams for energy, as well as to store water for irrigation requirements downstream, whereas Nepal argues that large dams with large reservoirs consume too much prime agricultural land [65]. Gaining efficiency in one sector can also be detrimental to other sectors. For instance, when electricity becomes cheaper, it is typically used more, which may encourage the unsustainable extraction of groundwater for irrigation [66,67]. Therefore, understanding the connections among water, land, food, and energy within a broader socio-ecological systems perspective can promote efficiency and improve the management of trade-offs. The benefits might be greater food, water, and energy security, and a more equitable distribution of such resources.

Although policy makers have been keenly aware of the challenges that are associated with managing water, land, and energy resources, few have taken their interdependence properly into account [58]. This is, in part, because in many countries, different institutions and agencies are responsible for managing agriculture, land, water, and energy, and there often is little reliance on actual data for planning. To effectively manage this nexus using an integrated approach, greater collaboration, coordination, and planning amongst the different sectors and their institutions will need to be facilitated through institutional reform and incentive mechanisms [58,68,69].

5. Land for Food and Biodiversity

The Millennium Ecosystem Assessment [1] has influenced the perception of the role that biodiversity plays in food security. The four pillars of food security, health, and nutrition (food availability; access to food; utilization of food; and, stability of food supply [70] are "inextricably linked" with the health of natural ecosystems and the biodiversity they contain [71] (Figure 2). The delivery of ESSs is dependent on a landscape, consisting of a mosaic of various ecosystem types (forests, croplands, water bodies, infrastructure, etc.) in which ecosystem functions are optimized to meet social, ecological, and economic demands. Biodiversity is a critical component of the ecological functioning of such multi-functional landscapes.

Although long considered mutually exclusive [72,73], biodiversity conservation and food security are now increasingly perceived as going hand in hand. With food security high on the current development agenda, it is imperative to understand how biodiversity can contribute to a food and nutrition-secure future. Many ecologists and conservation biologists focus on biodiversity conservation in non-agricultural ecosystems, but such a narrow focus fails to recognize the role that biodiversity plays in agricultural production [74–76]. The majority of the world's biodiversity, particularly in the tropics, resides outside of the protected areas, often in complex, multi-functional landscapes, which are managed by farmers [77–80].

Approximately 7000 plant species and several thousand animal species have been used in human history for food and medicine [81,82]. Today, only 12 plant crops and 14 animal species provide 98% of the human requirement for food. Three crops alone—wheat, rice, and maize—account for more than half of global energy consumption [81,83,84]. This increasing uniformity of agricultural production has eliminated many wild relatives of crop [85] and livestock [86] species. Moreover, three-quarters of crop genetic diversity has been lost in the past century [87]. This genetic erosion compromises food security, nutrition, and health [88], because relying on a narrow genetic base makes agricultural production vulnerable to biotic and environmental stresses, and, consequently, yield failures [83]. Most of the crop and livestock varieties that are used today are derived from their wild relatives, and the annual worth of products derived from genetic resources (including agricultural products, pharmaceuticals, and energy) is estimated at US$500 billion [89].

Biodiversity is important as a safety net during times of low agricultural production due to seasonal or cyclical food gaps or climate-induced hazards [88,90,91]. Many rural communities, particularly those that lack domesticated farm animals as sources of protein, derive 30–80% of their protein and micro-nutrient intake from bush meat [92]. Up to 80% of the population in many developing countries rely on biodiversity for primary health care [93]. Biodiversity loss has also been associated with an increase in the emergence and transmission of infectious diseases [52,94].

The inherent conflict between an ever-growing human population and finite natural resources is indeed evident in the trade-off between food production and biodiversity. By raising production efficiency through intensification, biodiversity is being reduced, and this, in turn, reduces the degree of ESSs that support production [52]. This can have dramatic consequences. Pollination is just one ESS that is provided by biodiversity, the role of which is consistently underestimated. Pollination services can be replaced by human activity only at a very high cost. Globally, the economic value of pollination of the main food crops by insects such as bees was estimated at €153 billion in 2005 [95], about 9.5% of the value of global agricultural food production of that year. A worldwide decline of pollinators is observed due to diseases, climate change, invasive species, habitat loss, and large-scale agro-industries based on the high input of chemicals [87]. Many pollinators are crop specific; their disappearance could wipe out the crop in question within a cropping period with dire consequences for the economics of crop production. New approaches that are based on understanding the plant–pollinator interplay attempt to harmonize the goals of productivity and biodiversity conservation [96].

The loss of ESSs is a concern at the field, landscape, and continental scales. Pollinators often come from forest patches in the landscape, thus providing an important ESS in cropland nearby. Losing the forest means the loss of those services if no measures are taken to accommodate the pollinators elsewhere. The role of natural habitats in biocontrol can vary dramatically depending on the type of crop, pest, predator, land management, and landscape structure [97]. Similarly, biodiversity losses upstream (e.g., tree cover loss or loss of soil function) lead to reduced ESSs downstream [98]. A landscape approach thus adds options to the basket of opportunities, which are not available when working at the field scale alone.

Biodiversity loss both within and beyond agricultural ecosystems affects food availability and choices, as well as income and wealth creation as a result of diminishing provisioning ESSs. Hence, biodiversity is not only a feature of food security (as provisioning ESS), it also affects the ability of cropland to rely on supporting ESSs from adjacent land that act to provide water and pest control. A balance has to be found in multi-functional landscapes [99]. Employing the principles of CSA [43,100] offers a variety of options that address the whole food production system, including ecosystem-based agricultural management (conservation agriculture, agroforestry, crop residue management, water harvesting, and crop diversification). Increased productivity gains within such improved systems may benefit from the feedback effects by which biodiversity raises productivity; these effects have been identified and quantified across a variety of landscapes and ecosystems [101].

Land degradation pressure reduces our options to meet food demands while conserving biodiversity (Figure 3), whereas applying CSA principles will counter land degradation and help to attain both. Degradation corresponds to moving the line in Figure 3 lower and moving restoration to higher levels. However, changes in the slope of this relationship might also be attained if intensive agriculture were to be combined with efforts to improve biodiversity.

6. Land for Food Production and for Infrastructure

Rapid urban expansion involving large-scale land use/cover change, particularly in developing countries, has become a matter of concern since urbanization drives environmental change at multiple scales [102]. According to [103], landscapes have become highly fragmented as a result of the rapid increase in the built-up areas. Landscape fragmentation, configuration, and diversity, as induced by urbanization, can significantly impair the provisions of ESSs [104]. Large-scale rural–urban migration and economic development have contributed to rapid urbanization [105,106]. For instance, Dhaka's growth in gross domestic product has played a pivotal role in the development of built-up areas in the city [107]. A study by [108] reports that whilst national policies had an indirect impact on land-use changes through the disruption of land institutions, local factors (soil fertility, local rules governing upland management) were prominent in explaining land-use change history.

Urbanization and industrialization are development trends that mostly occur spontaneously, but are at times encouraged to alleviate pressure on land in rural areas. Generally, these developments are poorly managed, leading to urban poverty and poorly planned urban expansion. At present, as much as 54% of the population dwells in cities, with 3% of the global land surface being covered by infrastructure [109], equivalent to 26% of the earth's surface actually under cultivation. Population growth and persistent urbanization and infrastructure development lead to urban encroachment onto agricultural lands, which is often seen as an unavoidable global phenomenon [110,111]. Both in China [112] and in India [113], this phenomenon is attracting increasing attention as large tracts of agricultural lands are lost in these countries due to rapidly expanding urbanization.

Urbanization results from rural push and urban pull factors. The urban pull results from the perception of rural residents that urban and industrialized regions provide significant opportunities for employment and livelihood [114]. The rural push factors drive people away from the deteriorating quality of life in rural areas [115]. Cities push their boundaries into agricultural lands, in many cases without regard for the suitability of the land for urban expansion or the loss in productive capacity. Often the best agricultural lands are appropriated with farmers trying to compensate for their land loss by taking new, often inferior, land for cultivation [116]. Governmental industrialization policies promote industrial zones at the expense of agricultural lands in peri-urban areas [117–119]. The promotion of the energy sector in many developing countries has resulted in a further significant rate of agricultural land conversion for infrastructure [120,121].

While serving as an engine of economic growth [122], the conversion of productive land to urban areas has become a stumbling block to world food security because it reduces the land that is available for food and timber production. For example, in only five years, around 1 Mha (about 5%) of arable land in Indonesia was converted to urban use to meet the increasing demands of industrial and infrastructural development [21]. The sealing of agricultural land surfaces leads to a shift in the trade-off curve in Figure 3 towards the origin when it comes to the delivery of ESSs. Moreover, urban centers tend to modify regional nutrient and water flows, causing environmental stress both in the regions of origin as well as in the areas of destination of these essential chemicals.

Finally, in many developing countries, poorly managed urban sprawl and a lack of transparent regulations regarding land rights have resulted in serious social conflicts over land. The land market in these countries also faces governance challenges, including corruption and bribery, illegal land transfer, weak service provision, and inefficient land administration [123]. Most problems associated with agricultural land conversion are related to weak land governance, lack of recognition and protection of the rights of poor farmers to land, poor land use planning (LUP), and the processes that are involved in decisions about land use [124]. It is argued here that a sustainable nexus on land for food and infrastructure can be promoted through good land governance and proper LUP. The challenge then is then to find the means to implement these plans.

Good land governance realizes and ensures the rights to enforceable claims on land via regulations ranging from national laws to local rural rules. It confers to people the ability to control, manage, transfer, or lease land and to dispose of its products [125]. Once strong governance is established for land, decision-making becomes more transparent and inclusive, and common rights through which the rule of law can be applied equally to vulnerable groups are expected to be more respected [126]. Good land governance will lead to transparent, accessible, informative, and effective rules on land, which result in judicious land conversion and development [127]. Good governance requires good monitoring. Remote sensing and geographical information systems (RS/GIS) are now able to identify settlement densification and expansion processes, and can quantify the loss of agricultural land, even when differentiated by land quality, during settlement growth.

In order to optimize the integrated use of land, different techniques have been used globally with some adjustments to account for differences in local circumstances [128]. LUP is the process of analyzing and determining land suitability of a given region for a certain use (e.g., agriculture, forest, infrastructure or recreation) and is the key to rational land allocation [124]. An important part of this process is to determine the criteria that reflect the suitability of the land for use in multi-criteria analysis. The analytical hierarchy process (AHP), as developed by [129], has become a very popular multi-criteria decision making technique that has been widely applied for preference analysis in complex and land allocation problems. It helps to structure decision problems and to assess scores that translate stakeholders' preferences into a prioritized set of objectives or alternatives [130]. The AHP can formalize public participation in decision making and increase the transparency and credibility of the processes that are involved [131]. It also simplifies complex, ill-structured problem situations by arranging the decision factors in a hierarchical structure [132]. AHP is appropriate for regional management and planning as it can accommodate conflicting, multi-dimensional, incommensurable, and incomparable set of objectives [131]. Taking sustainability into account, this technique involves the paired comparisons of socio-economic objectives that are considered to be as important as eco-political aspects [133,134]. While AHP is an important member of a general family of multi-criteria decision making, which helps to combine the information from various criteria into a single index of evaluation, RS and GIS can capture a wide range of criteria data that are derived from different multi-spatial, multi-temporal, and multi-scale sources for a time-efficient and cost-effective analysis. Accordingly, the combination of AHP with RS and GIS offers a powerful tool to deal with the complexity of LUP to optimize the ESSs that carefully planned urban landscapes can provide. Arguably, spatial multi-criteria assessment-based decision making is one of the most effective techniques for LUP and environmental planning, and for resolving the agricultural–ecological–infrastructural nexus problems that many nations are facing [135,136].

It is widely recognized that infrastructural development is desirable and will not stop. However, it is also increasingly recognized that such infrastructure does not necessarily have to take the best agricultural land and that urban development can benefit greatly from urban landscape planning, thus retaining essential ESSs that benefit the urban dweller. As portrayed in Figure 6, agricultural land conversion can be seen as a consequence of urbanization, industrialization, and infrastructure development.

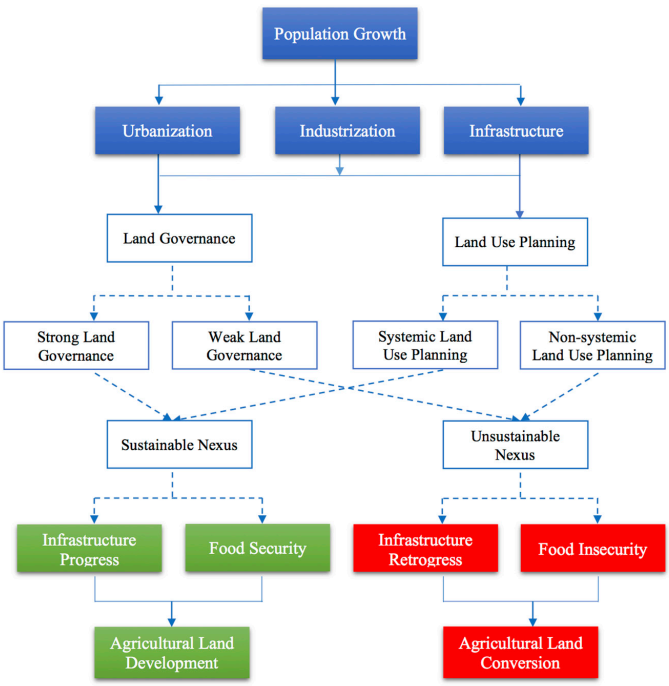

Figure 6. The management system of agricultural land conversion.

Infrastructure development has often been essential and desirable for economic growth, though it can pose a number of challenges, particularly for food security. A sustainable nexus of food and infrastructure results from systemic LUP and strong land governance. A systemic LUP can purposefully designate land for agriculture and infrastructure development. To achieve this goal, the combination of AHP with RS and GIS has repeatedly shown to assist the decision-making process.

7. Conclusions

From the experiences of the past decades, we can draw a number of lessons. Many concerns for the well-being of land are grounded in the multiple ESSs that are derived from land and their complex interaction, and the different scales at which stakeholders are demanding these services. Research on these complex socio-ecological systems is rapidly evolving with the help of modern tools, including systems modeling, big data, and geo-observation equipment. Climate-smart agriculture and conservation agriculture are options for sustainable agricultural management, but their effect is limited if they are not brought to scale and tied in with a sustainable landscape effort.

There is an increasing awareness of the need for the integrated management of land and water resources (ILWM) at the watershed and landscape levels. Land management needs to spare water and water management needs to optimize ESSs from land, while also satisfying the needs for water in multiple sectors. Keeping in mind the many purposes of these resources, ILWM should derive the optimal mix of ESSs without diminishing the resource base. Finding win-win options or the best trade-offs of land use and management based on resource endowment and stakeholder needs is a complex endeavor, requiring different forms of researcher engagement with stakeholders and the public, an effort with which the scientific community is slowly coming to terms.

Agricultural research has to expand its focus from field and plot research to landscape research, and in the process should look at the cost of production by internalizing environmental costs. In some situations, the public cost of agriculture in marginal environments outweighs the private gains, even with the best technologies in place. Land use and city planners will increasingly have to address the cost of occupying productive agricultural land or the conversion of natural habitats. There is a great need to close nutrient cycles and improve the efficiency of external inputs. Landscape designs and urban planning should aim for the conservation of resources, the restoration of biodiversity, and the optimal delivery of ESSs.

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