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Economics of sustainable land management

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Degradation of soil and land resources is a critical global problem. It is widespread not only in drylands and cropped areas, but in most agro-ecologies and biomes around the world. Unless addressed, it may undermine global food security and negatively affect the livelihoods of billions of people, especially of the poor. Addressing land degradation requires public, community and private actions informed and supported by evidence-based research. The current paper reviews the recent economic literature on land degradation and improvement with the purpose of highlighting major new insights and continuing gaps. Drawing conclusions from the recent research under the Economics of Land Degradation (ELD) Initiative, we find that action against land degradation has considerably higher economic, environmental and social returns than inaction. The drivers of land degradation are numerous and often context-specific, so addressing them requires targeting not some individual driver in isolation, but through comprehensive and mutually consistent packages of policy actions. We suggest the following conceptual, methodological and empirical areas for future research on economics of land degradation. Firstly, more interdisciplinary conceptual frameworks are required to connect land degradation and other intricately related issues such as climate change, water scarcity, loss of biodiversity, energy and food security. In this regard, Water-Energy-Food Security (WEF) Nexus concept can be highly useful as one of such nexus platforms for future trans-disciplinary research on economics of land degradation. Secondly, more rigorous methodologies are needed on the incorporation of the value of ecosystem services into economic calculations. Finally, there is a need for empirical studies tracing the dynamic economic and social impacts of land degradation across scales: from household to global level.

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Introduction

Well-functioning land ecosystems, providing their services in undiminished manner, are essential for food security and poverty reduction [1•]. These land ecosystems services consist of provisional ones (e.g., food, fiber, feed, biomass), but also supporting, regulating and cultural services (e.g., water purification, carbon sequestration) [2,3••]. However, the values of many supporting, regulating and cultural ecosystem services are usually not considered in the decisions by landusers, policymakers and other economic agents, since most of them do not have tangible market prices [4,5]. Nevertheless, these ecosystem services are essential for human existence, omitting them from our decision making frameworks undervalues land and leads to its degradation, resulting in losses to human wellbeing [6,7••,8••]. More tangibly, land degradation reduces the provisional goods and services derived from land. It is manifested through lower crop and livestock productivity and production, with potentially negative social and economic implications, especially in the context of growing populations and increasing demands for food, feed and diversifying uses of biomass, projected climatic and other environmental changes. All this makes land degradation unacceptable [9], in fact, at the global level, land degradation is no longer affordable: a fertile land is already a scarce commodity and has become an investment asset class with growing attraction, with spillover effects on food, feed, energy, water and financial markets in this interconnected and globalized world [5].

There is a critical need for preventing and reversing land degradation, including through land rehabilitation and restoration [9]. Land degradation has occurred on about 30% of global land area since early 1980s [10••], while land improvement has occurred only on about 3% of the global land area during the same period [10••]. The drivers of land degradation are numerous and often have context-specific characteristics. The same factor could have contradicting effects on land degradation depending on its interactions with other socio-economic and institutional factors [11]. For example, in some cases, higher levels of poverty may lead to land degradation due to inability of landusers to invest into sustainable land management. However, in some other contexts, poverty was not found to lead to land degradation since poorer households have higher dependence on land for their livelihoods and thus are more incentivized to manage it sustainably [11]. Such a heterogeneity of impacts requires adapting policy actions to local conditions. In this regard, policy frameworks for action against land degradation, though already present in many countries, too often remain ineffective [3••], due to various contradictions and inconsistencies, which makes even more important that such action frameworks against land degradation need to be evidence-driven [5,12].

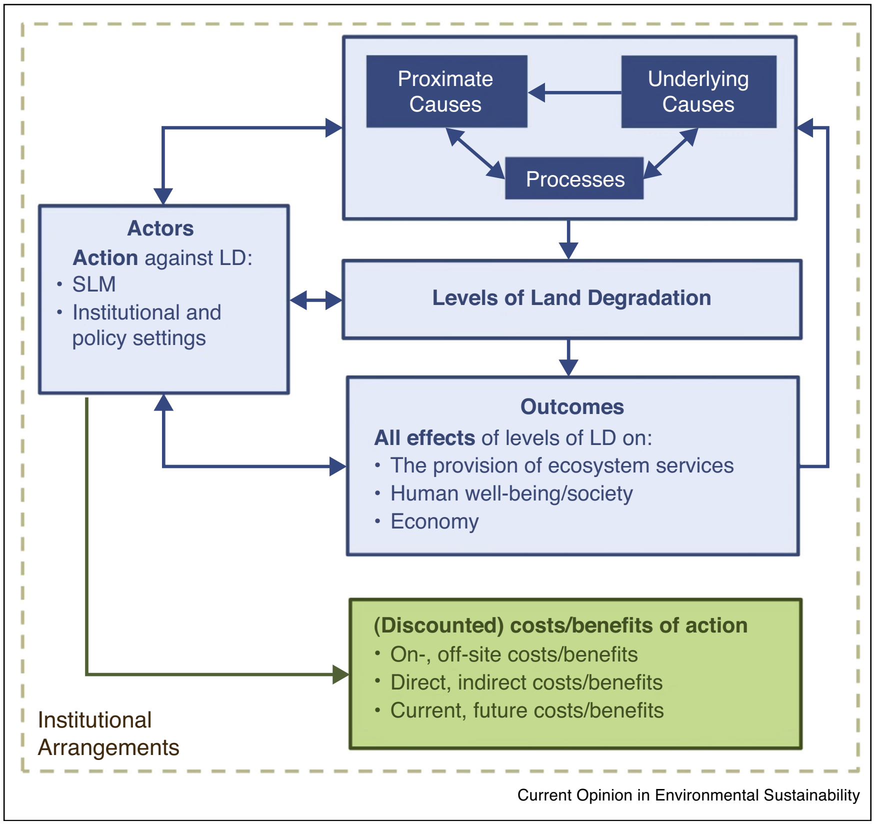
The objective of the current paper is to review the recent advances in economic literature on land degradation. In doing so, the paper seeks to answer three research questions: (1) what are the costs of land degradation at the global and regional levels, and how do the costs of action against land degradation compare with the costs of inaction?, (2) what are the new insights on the drivers of land degradation and on its socio-economic impacts?, and (3) what are the major continuing gaps in economic studies of land degradation?

Conceptual framings

Land is a terrestrial ecosystem consisting of flora, fauna, hydrological processes, providing numerous ecological goods and services to human beings [13]. Land degradation is a long-term loss of these terrestrial ecosystem goods and services [2]. These definitions call for a comprehensive approach in evaluating the costs of land degradation, including both short-term and long-term, direct and indirect, on-site and off-site benefits of sustainable land management, and comparing them with the corresponding costs of land degradation[11]. Another key element of these definitions is that they put the loss of utility to humans resulting from land degradation as their central feature.

Being comprehensive, thus, means adopting the Total Economic Value (TEV) approach [14,3••]. The TEV approach seeks to capture the value of both direct and indirect ecosystem goods and services, hence, going beyond the common monetary values of direct provisioning services only [15]. The TEV approach is based on the neoclassical welfare economics, with its roots in utilitarianism, whereby the values of ecosystem services are determined based on the degree that they satisfy individual preferences [16]. Adopting such an approach is also conceptually consistent with the definitions of land degradation by The United Nations Convention to Combat Desertification (UNCCD) and Millennium Ecosystem Assessment (MEA) cited earlier. The Economics of Land Degradation (ELD) conceptual framework (Figure 1; [11]) provides an example of the application of TEV thinking in economic evaluations of the costs of land degradation.

Figure 1



Conceptual framework for economics of land degradation.*Source*: Adapted from Ref. [11].

The ELD conceptual framework divides the causes of land degradation into proximate and underlying, which interact with each other to result in different levels of land degradation [11]. Proximate causes of land degradation consist of biophysical factors and unsustainable land management practices [11]. The underlying causes of land degradation are institutional, socio-economic and policy factors such as population density, poverty, land tenure security and property rights, access to markets and extension, agricultural subsidies and taxes [11].

The arrows in the conceptual framework (Figure 1) stand for the causal relationships among various components of the framework. Quite often, these causal relationships are reflexive, requiring that economic analyses properly account for the corresponding endogeneities.

Inaction against land degradation would lead to continued land degradation and increases over time in its associated economic, social and environmental costs. However, action against land degradation also involves costs, including resources devoted for addressing land degradation which can no longer be used for other purposes [5].

As indicated earlier, most services provided by ecosystems do not have market prices. As a result, leading to substantial negative or positive externalities. However, the ecosystem services should be considered as capital assets, or natural capital [17•,7••]. This natural capital should be properly valuated as any other form of capital assets [6]. However, the natural capital is also different from other forms of capital. The stream of returns from natural capital, in this case, the provision of ecosystem services, cannot be fully privatized. Thus, land degradation has substantial environmental externalities associated with the losses in the natural capital borne by the whole society. The standard 'polluter pays' principle may not be appropriate in many instances of land degradation, when landusers responsible for land degradation are poor agricultural or pastoralist households who cannot afford compensating the society for incurred losses in land ecosystem services. Therefore, more incentivizing approaches such as Payments For Ecosystem Services (PES) might be more effective in promoting sustainable land management [18]. However, instituting PES schemes to compensate for the safeguarded ecosystem services can be highly challenging for many land covers and uses, not least because the available methods to measure the types, flows and values of ecosystem services under different land covers and uses remain highly limited. Although there are various methods to evaluate ecosystem services [3••,7••,19,20], attributing economic values to ecosystem services is challenging, due to many unknowns and actual measurement constraints [3••]. The valuation of the natural capital, therefore, should evaluate alternative options, for example, land degradation vs. its sustainable management, then compare the costs and benefits for each alternative, including their long-term effects [6]. However, valuation of ecosystem services presents with numerous challenges, due to local and often subjective nature of valuations, resulting in their variability [21], which poses significant challenges in the estimations and comparisons of the costs of land degradation.

The ELD framework attaches a high importance to identifying and understanding the institutional arrangements, such as land tenure, farm sizes, governance mechanisms for common pool land resources, availability of extension services, affecting land management in order to devise sustainable and efficient responses to land degradation [11]. This also involves understanding the roles and motivations of key stakeholders, such as land users, landowners, governmental authorities, industries, and consumers. Understanding such stakeholder relationships facilitates developing more effective sustainable land management measures by bridging common interests and mitigating potential divergences [11].

Since households do not take their decisions about land management in isolation from their decisions on water management, energy access, alternative livelihood options, health and education investments, costs and benefits of actions against land degradation would need to be evaluated taking all these relevant dimensions into account, within inter-connected nexus frameworks [22]. The Water–Energy–Food (WEF) Security Nexus is such an integrated approach which necessitates the full evaluation of the tradeoffs and synergies between inter-connected livelihood activities by households and their effect on land management [23••]. The WEF Nexus can serve as a basis for the conceptual enrichment of the ELD framework. However, blending the ELD framework with the WEF Nexus framework may also pose conceptual challenges. The ELD framework, as indicated earlier, is based on neo-classical economics seeking to maximize individual utility, whereas the WEF Nexus framework originates from institutional economics, with emphasis on minimizing the transaction costs, negative externalities and systemic tradeoffs between the Nexus components, rather than maximizing the performance of one specific sector [22]. Moreover, at the household level, both of these economic approaches would necessitate a shift from the current resource-based view of the Nexus to people-based understanding of the Nexus, that is, seeking the achievement of progress in the people-oriented outcomes such as, for example, food security and poverty reduction, rather than minimizing the resource use or environmental footprints. Similarly, at the macro-level, the feasibility and impacts of national investments into sustainable land management need to be evaluated through a Nexus lens, where the major purpose may not necessarily be to achieve 'zero land degradation' [24], irrespective of water, energy, health and sanitation, and other equally important domains of sustainable development, but to optimize the entire system functioning, by minimizing the transaction costs and negative externalities, and seeking to maximize aggregate social welfare. This is because various Nexus components, such as land, water, energy and food systems interact with each other through complex trade-offs and synergies. Investments that promote synergies among these Nexus components are likely to have higher levels of economic returns. To illustrate, investments into afforestation of sloping areas could reduce soil erosion and the corresponding losses of ecosystem services, but also can limit the siltation of rivers and water reservoirs, saving on the costs of their cleaning [25]. Moreover, such afforestation initiatives could also reduce the instances of landslides which negatively affect peoples' lives and infrastructures.

Economic assessments of land degradation

The drivers of land degradation

The drivers of land degradation are numerous, complex and interrelated [26]. Therefore, identification of the important drivers of land degradation and, by extension, of the factors catalyzing sustainable land management and land improvement, is crucial for national and international efforts to reduce, and optimally, prevent land degradation, incentivize land restoration and rehabilitation.

Following the ELD conceptual framework, we categorize the drivers of land degradation into proximate and underlying. The effects of proximate drivers of land degradation, such as topography, climate, and soil characteristics are much better understood [27] and there is a broad consensus about their causal mechanisms. For example, steeper slopes are more vulnerable to water-induced soil erosion [28,29], or soils with high silt content are naturally more prone to degradation [30]. There are also a big number of available sustainable land management (SLM) technologies developed to address soil and land degradation [31,32].

However, there is an on-going debate on the role of various underlying drivers of land degradation [3,5] and also on the reasons why many of the existing SLM technologies are not adopted by landusers (e.g. [25,26]). For instance, some well-known points of debate on the drivers of land degradation include whether higher population causes land degradation [33–35], or leads to SLM [36]; whether poverty is the driver of land degradation [37–39], or not [40]; would higher market access lead to SLM [41,42], or to land degradation [43]. Mirzabaev *et al.* [44], using newly available datasets at global level on land degradation hotspots [10••], and various socioeconomic and institutional indicators, find that the causal patterns of individual drivers of land degradation vary across geographic locations. Similar conclusions are also reached by [3••,4]. At the same time, clustering countries of the world by similar institutional, economic and technical characteristics [44], find that the effects of the drivers of land degradation may follow some generalizable patterns within the clusters. For example, SLM is positively associated with land tenure security, especially in middle-income and advanced economies, and less so in lower income countries, where lack of secure land tenure is not associated with unsustainable land management [44]. Secure land tenure may provide with additional benefits and opportunities with relatively well-functioning markets, including output, input and financial markets. Where they do not function well or are very thin, secure land tenure may have much less effect on SLM [44]. Population pressure may not lead to land degradation if public policies provide for increases in non-farm jobs [45]. Higher population may induce agricultural innovations and lead to wider use of labor-intensive sustainable land management practices. Better rule of law may lead to sustainable land management in lower income countries, whereas the effects of further improved rule of law in more advanced economies seem non-significant, potentially due to non-linearities at higher levels [44].

Methodological challenges in studying the drivers of land degradation

There are several methodological aspects influencing the outcomes of the analyses of land degradation drivers. These are the scales of analyses (e.g. global pixel level, or at the level of administrative divisions, or at household level), the methodologies applied and the nature of the dependent variable standing for land degradation or sustainable land management. To illustrate, [42,44] conduct global level analyses of the drivers of land degradation using broadly the same set of explanatory variables, considering the same time period between 1982 and 2006, and in both cases their dependent variables are obtained from the Normalized Difference Vegetation Index (NDVI) from the Global Inventory Modeling and Mapping Studies (GIMMS) [46]. However, [42] use the values of the NDVI directly as given in the NDVI database, while [44] use these values after processing by [10••], who remove from the NDVI values potential biases emanating from rainfall dynamics, atmospheric and chemical fertilization[3]. The results obtained by the two studies, consequently, have significant divergences due to the substantial differences between their dependent variables in identification of degraded areas.

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[3] Le *et al.* [10] do this by, first, identifying statistically significant trend in NDVI time series between 1982 and 2006, followed by masking of the pixels where NDVI changes are correlated with and are likely to be driven by rainfall dynamics rather than anthropogenic unsustainable management. After removal of the effect of rainfall dynamics, Le *et al.* [10] also mask the pixels indicating pristine areas with insignificant human intervention, where NDVI increases are likely to have occurred due to atmospheric fertilization [47]. Finally, the areas with chemical fertilizer application (e.g. as input in crop production) but with neutral NDVI dynamics are delineated as having a potential risk of being degraded.

With all its imperfections as a proxy for land degradation, NDVI still serves as a valuable and globally available indicator and can be relevant in global pixel-level studies [10••]. However, at the household level, finding and compiling the right dependent variable on land degradation status in the farmer plots could be quite challenging. One option for constructing the household/plot level indicator of land degradation is to ask the households to self-report the quality of their land, usually following some Likert scale options. This approach, however, could be challenged by measurement errors/biases and also could be endogenous with other household characteristics, where finding instrumental variables to appropriately account for endogeneity in such settings is usually quite challenging. An alternative, and arguably, less bias-prone approach, is to collect information from the households on whether they use sustainable land management practices, the number and intensity of their use, and based on this, construct a dependent variable standing for SLM use. Whatever factor negatively influences SLM use is, then, considered to be driving land degradation [48,49]. Of course, in this approach as well, the issues of reverse causalities need to be carefully accounted for. In general, we note that although there have been numerous studies on the drivers of land degradation, there is still a broad lack of quantitatively rigorous methodologies properly accounting for all the potential biases such as omitted variables, endogeneity, and employing adequate estimation methods depending on the data characteristics. A potential third option at household level is to measure the actual plot level soil quality for each household. However, presently it is quite costly to be widely implemented in household surveys. In this context, the development of remote sensing capacities and techniques that would allow for direct measurement of plot-level soil quality characteristics based on satellite data could revolutionize land degradation research.

So depending on the datasets, methodologies, timeframes and locations, the conclusions reached on the drivers of land degradation have been quite diverse and often contradicting. It is likely that such diversity and contradictions will remain in future studies, since these contradictions may simply be reflecting the diverging and context-dependent causal interplays of factors affecting land management [44]. On the other hand, such diversity of results also implies that for addressing land degradation major drivers of land degradation and their interactions need to be considered jointly and addressed through consistent policy and technological packages. For empirical analyses of land degradation, it would point at the need to explicitly model nonlinearities and interactions between the variables, and to address potential biases emanating from omitted variables and reverse causalities.

The costs and impacts of land degradation

There are a number of studies estimating the costs of land degradation at the global level (cf. [50] for a review, Table 1). In these estimates, the costs of land degradation range from US$ 18 billion to US$ 9.4 trillion annually[4] [50]. Two reasons can explain this large variation. Firstly, this is due to differences in methodological approaches. Secondly, some studies evaluate fewer number of biomes, while others cover all major biomes [50].

Dregne and Chou [51], using the productivity loss approach, estimated that the global cost of cropland and grassland degradation at US$ 55 billion. Using loss of carbon sink as a proxy of land degradation [52], estimated the global cost of deforestation of tropical forests and rainforests was about US$43–63 billion. Using replacement costs of cleaning silted up reservoirs, loss of hydroelectric power and reduction in irrigated production, [53] found the annual global cost of siltation of water reservoirs to be about $18 billion. Costanza et al. [8••] used the Total Economic Value (TEV) approach and estimated that the net annual cost of degradation of terrestrial ecosystem services to be about 9.9 trillion USD, with a major share of the loss coming from wetlands degradation. The net loss of terrestrial ecosystem services was about 9.4 trillion USD, but the gross loss was 13.4 trillion USD, of which wetlands loss accounts for 74% and the remaining loss is accounted for by losses in tropical forests [8••].

Nkonya *et al.* [50], in their estimates of the global costs of land degradation, use remotely sensed data on the land use and cover changes (LUCC) from higher valued biomes to lower valued biomes between 2001 and 2009. Then, they attach to these changes the values of the terrestrial ecosystem services from the Economics of Ecosystems and Biodiversity (TEEB) database [54••]. Adding the estimated costs of cropland and rangeland degradation to the costs of degradation due to LUCC, [50] find that the annual costs of land degradation are equal to about 295 billion USD. The global community bears 62% of the land degradation costs, while the local land users where biomes are located bear the remaining 38%. [50]. In other words, private costs of land degradation represent a minor share of the total costs, with the bigger share of cost of land degradation being borne by the global community [50].

Regionally, [50] find that Sub-Saharan Africa accounts for the largest share of land degradation costs (about 68 bln USD annually, or 25% of the global total), followed by Latin America and Caribbean (about 60 bln USD), and North Africa and Middle East (about 30 bln USD). A new contribution of [50] is that they estimate not only the costs of land degradation but also compare it with the costs of action to address land degradation. They find that the cost of taking action against land degradation is lower than the cost of inaction even when one considers only the first six

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[4] All reported cost estimates are brought to constant 2007 USD values.

Table 1

Estimates of global annual costs of land degradation (in constant billion USD for 2007)

Author(s)	Annual costs of land degradation	Locations/biomes	Ecosystem services	Methodology
Dregne and Chou [51]	55	Cropland and grassland	Provisioning	Cost–benefit analysis of on-site loss of productivity
Chiabai *et al.* [68]	277	Forests	Provisioning, recreation and passive use services, carbon sequestration	Simulation of net present value of forest ecosystem services between 2000 and 2050
Trivedi *et al.* [52]	41–63	Tropical rainforest	Carbon sequestration	Literature review
Basson [53]	18	Water reservoirs	Soil erosion control	Cost–benefit analysis of off-site costs of soil erosion
UNCCD [55]	685	Terrestrial biomes	Direct and indirect	Literature review
Costanza *et al.* [8••]	9400	Terrestrial biomes	Direct and indirect	Benefit transfer approach applying TEV approach and TEEB database (changes between 1997 and 2011)
Nkonya *et al.* [50]	295	Terrestrial biomes	Direct and indirect	Benefit transfer approach applying TEV approach and TEEB database (based on land use and land cover changes between 2001 and 2009); crop simulation modeling for crops. For livestock, statistical models used to determine grassland productivity and its impact on livestock productivity

Source: Adapted from Ref. [50].

years of upfront investments and maintenance costs [50]. Globally, the returns to investments in actions against land degradation are at least twice the cost of inaction in the first six years. However, when one takes into account a 30-year planning horizon, the returns are five dollars per every dollar invested in action against land degradation [50].

Although there have been numerous country studies estimating the costs of land degradation and evaluating the costs and benefits of applying some specific sustainable land management practices (cf. [3••] for a review), most of these studies have considered only certain types of costs, for example, only losses due to lower crop productivity resulting from land degradation, while overlooking a wide range of other costs. The ELD conceptual framework presented earlier, and applied in [50], has been also used for conducting a dozen of country case studies around the world, providing with more comprehensive and up-to-date estimates of the costs of land degradation in these selected countries of the world [56••]. To illustrate, Ref. [48] find that the annual costs of land degradation are about 2.5 bln USD in Tanzania and 0.3 bln in Malawi, representing about 15% and 10% of their respective Gross Domestic Products (GDP) in 2007. The costs of action against land degradation are found to be lower than the costs of inaction by about 4.3 times and 3.8 times over a 30-year horizon in Malawi and Tanzania, respectively [48]. Similarly, the total annual costs of land degradation in Central Asia, including Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, are found to be about 6 bln USD [49]. The poorest countries of the region, Kyrgyzstan and Tajikistan, are losing about 10% equivalent of their GDP annually to land degradation. The costs of action against land degradation are found to be about 5 times lower than the costs of inaction in Central Asia [49].

The costs of land degradation due to losses in ecosystem services of land are the obvious first order impacts of land degradation. However, despite a broad agreement that land degradation may have severe negative impacts on the livelihoods and food security, of especially poor households [57], there have been few studies quantitatively tracing the impacts of land degradation on poverty levels, incomes and food security of different categories of households. For example, Diao and Sarpong [58], using an economy-wide, multimarket model for Ghana, indicate that land degradation reduces agricultural incomes in the country by 4.2 billion USD between 2006 and 2015 and increases the national poverty rate by 5.4% at the end of the period. Applying SLM practices, on the other hand, would generate an aggregate economic benefit of 6.4 billion USD during the same period, and also reduce poverty [58].

Summarizing, despite some major differences in applied methodologies, the recent literature indicates that the costs of land degradation at the global level are very high, necessitating action against land degradation [8••,50]. The costs of action are often several times lower than those of inaction [50]. However, in spite of these high returns on investments to address land degradation, land degradation is persisting, with inadequate levels of investments in sustainable land management — especially in low income countries where its impacts on the poor is most severe. There may be three reasons for this, which need to be adequately addressed to incentivize more investments into SLM. Firstly, as we have seen, the social costs of land degradation are higher than private costs, by almost two times at the global level [50], whereas the investments into SLM are often required from private landusers, who include only the private costs of land degradation into their action calculations. Secondly, though in some instances, the private costs of land degradation alone may even be higher than the costs of inaction [3••], however, even in such cases, many land users may be constrained in their actions by lack of knowledge of sustainable land management practices, access to markets and other barriers to SLM which need to be addressed by public policy. Finally, even when landusers are well aware that the direct costs of land degradation (in terms of lower provisional goods and services) are higher than the costs of actions to address it, they may still rationally opt for inaction considering potentially higher returns from investing their resources extracted from land to other areas with even higher returns (e.g. their children's education). At the current stage, there are basically no studies in the literature tracing the tradeoffs of such competing investment options faced by agricultural households. In such contexts, since the largest share of cost of land degradation is borne by the global community, both global and national policies and investments are needed to minimize the negative externalities of land degradation, often by incentivizing sustainable land management, including through payment for ecosystem services and other mechanisms which will support sustainable land management practices.

Discussion

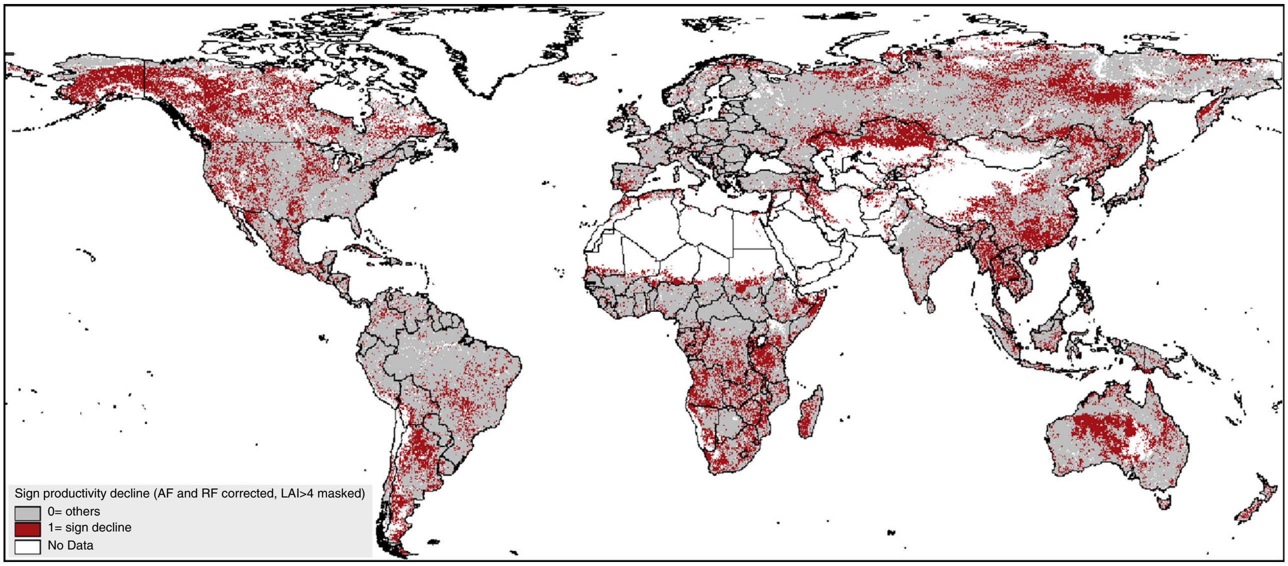
Most of the past economic studies on land degradation tended to ignore the complexity of land degradation impacts and have focused on simpler relationships, such as, for example, soil erosion and its impact on crop yields [3••,15,59]. Recent developments in remote sensing, crop simulation and other wide-ranging global datasets, including on the values of ecosystems [54••], can help address more rigorously such complex relationship of land degradation. Yet this requires overcoming some empirical challenges such as measurement and valuation of losses in ecosystem services due to land degradation, where depending on the valuation method used, there may be substantial ranges in the estimates of the same ecosystem services [60,61].

Despite extensive past research on the drivers of land degradation (cf. [5] for a review), there are continuing contradictions on the role of various factors in causing or preventing land degradation. What has crystalized, though, there are no clear-cut cause and effect relationships operating similarly across all the different settings, but the same factor may exhibit varying causal patterns depending on its interactions with other context-specific drivers of land degradation. This calls for more localized studies of land degradation: land degradation is, of course, a global problem, but its drivers are often local, the actions to address it are also local, hence its diagnostic should also be based on local studies. Localized studies would also allow for more accurately accounting for the characteristics of each landscape. Local landscapes determine not only proximate drivers of land degradation such as biophysical factors, but also may influence some underlying drivers such as access to markets (e.g. mountainous areas vs plain areas). Such local studies are needed not only for identifying the drivers of land degradation, but also tracing its impacts on livelihoods and food security. The latter area of research strongly lacks studies which rigorously trace the dynamic socio-economic impacts of land degradation across scales, form global to household levels, including national and landscape/watershed scales. Although every publication on land degradation emphasizes that land degradation has negative impacts on poverty and food security, however, there are, in fact, few studies which actually measure these impacts.

Institutional settings and governance structures strongly influence land management outcomes by providing with incentives or disincentives for adopting sustainable land management practices [62]. Decentralization of governance structures have been shown to lead to better management of forest resources [63]. Improving government effectiveness and rule of law has been found to be positively related with sustainable land management [3••], especially in cases where such improvements occur from previously low levels.

In order to address land degradation and also to evaluate the progress made in addressing land degradation, the global community and national governments need to have up-to-date and accurate maps of land degradation at various scales. Over the last couple of decades, the increasing availability and active use of remotely sensed satellite data have enabled to significantly improve the accuracy of land degradation mapping efforts. However, much more needs to be done. The estimates of the global extent of land degradation vary substantially [3••]. The reason for such variations are in the diversity of methods and datasets applied. As we have shown above, the same dataset on NDVI, but processed differently, could result on opposite conclusions about the location and severity of land degradation. So much more investments are needed into observation and monitoring systems to collect relevant data [64,65], but also into research for methodological breakthroughs in more

Figure 2



Areas with significant biomass productivity decline between 1982 and 2006.
Source: Adapted from Ref. [10••].

accurate and robust identification and mapping of land degradation at various scales, from global down to plot level.

Moreover, the past paradigms that land degradation is a problem of only drylands, mostly manifesting itself through desertification, are no longer valid. Several studies, using very different, and even contradictory methods, nevertheless, agree that land degradation is occurring all across the world, in all biomes and agro-ecologies ([66,10••], Figure 2). This renewed paradigm about the nature and extent of land degradation requires adapted global leadership, supported with much more active use of up-to-date evidence-based science. In this regard, a stronger integration of sustainable soil and land management among the Sustainable Development Goals (SDGs) could be instrumental in giving the impetus for global and national actions to address land degradation.

Furthermore, land degradation is only one of many interconnected problems affecting landusers and communities around the world. When making decisions about land, landusers and households simultaneously take into account many other factors, such as water use, availability of non-farm jobs, changing weather and climate patterns, access to energy, ensuring the food security of their families and so on. Hence, addressing land degradation in isolation from other such areas of households' activities may often result in unintended consequences and misallocation of resources.

In terms of research, what is needed is to view land degradation more comprehensively through a so-called Nexus vision, and seek joint solutions, mitigate tradeoffs and stimulate synergies with other areas of household activities. This calls for more trans-disciplinary research, joint modeling efforts bridging scales and sectors. Analyzing such a complex issue as land degradation can benefit immensely from innovative combinations of multiple trans-disciplinary data sources, such as, for example, socio-economic surveys, soil analyses, crop modeling and remote sensing, as well as local knowledge [67]. More active involvement of landusers themselves in data collection on the land quality and land management practices through use of information and communication technologies ('citizen science'), such as collecting geo-referenced land quality self-reports through mobile phone networks, may dramatically push forward the future research on land degradation.

Conclusions

The costs of land degradation are substantial and the costs of action to address land degradation are often several times lower than those of inaction. In spite of these high returns on investments in sustainable land management, land degradation is persisting, with inadequate levels of investments in sustainable land management. There are two reasons for this, which need to be adequately addressed to incentivize more investments into SLM. First, as we have seen, the social costs of land degradation are higher than private costs, whereas the investments into SLM are often required from private land users, who include only the private costs of land degradation in their action calculations. Secondly, even in cases when the private costs of land degradation may be higher than the costs of inaction, many land users may be constrained in their actions by lack of knowledge of sustainable land management practices, access to markets and other barriers to SLM. Since land degradation is a global and national ''public bad'', policies and investments are needed to minimize the negative externalities of land degradation, for instance by subsidizing sustainable land management. The opportunity cost of taking action are main drivers that contribute to inaction in many countries. Strategies should be developed that give incentives to better manage lands and reward those who practice sustainable land management. The Payment for Ecosystem Services (PES) mechanisms that saw large investments in carbon markets should be given a new impetus to address the loss of ecosystem services through Land Use/Cover Change (LUCC) which accounts for the largest cost of land degradation. Allowing landusers to internalize some of the positive externalities created by sustainable land management through PES schemes may be key to achieving a 'land degradation neutral' world.

There is a need for much stronger emphasis on addressing land degradation in international and national investment programs. A strong representation of sustainable land management in the Sustainable Development Goals could provide with a crucial impetus for sustainable land management. Moreover, attainment of many other sustainable development goals, such as poverty reduction and food security, would be undermined if land degradation is not addressed.

The research on economics of land degradation need to be increasingly based on more comprehensive transdisciplinary conceptual frameworks, such as Water–Energy–Food (WEF) Security Nexus, also accounting not only for direct costs of land degradation, but also for the losses in the ecosystem services due to land degradation. However, this also necessitates further methodological advances in the valuation of ecosystem services. Finally, there is a need for more studies quantifying the impacts of land degradation on poverty and food security which also identify these impacts across various scales.

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