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Prioritizing land for investments based on short- and long-term land potential and degradation risk: A strategic approach

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ABSTRACT

The response hierarchy of “Avoid > reduce > reverse” is increasingly acknowledged as the best strategy for prioritizing actions designed to address land degradation at hectare to national scales. This hierarchy is based on the assumption that the economic return on investment (ROI) will usually be higher for actions that help avoid degradation than for those required to restore already degraded land. While a useful first step, the hierarchy fails to account for how differences in land potential, defined as its potential to sustainably generate ecosystem services, may affect the ROI of actions at each level of the response hierarchy. The objective of this paper is to present a strategy for improving ROI at the landscape scale and above by systematically applying a more holistic understanding of land potential to the identification and prioritization of land investments. This objective is addressed in three sections. The first section explains how the potential *short- and long-term resistance and resilience* of the land can be used together with its potential productivity to prioritize actions designed to avoid, reduce and reverse degradation. In the second section we explain how this prioritization can be further optimized based on an understanding of *degradation risk* as indicated by the land’s potential to generate relatively high short-term profits under management systems that are likely to increase degradation, or result in degradation of restored land. This potential, and land managers’ perception of it, depend on a wide variety of factors including markets, infrastructure, and access to technology. Together these first two sections provide a framework for increasing ROI, while reducing the risk of failure at hectare to national scales. In the final section we briefly describe the Land-Potential Knowledge System (LandPKS), a modular mobile app that makes it possible for virtually anyone with a smartphone to make the land potential determinations necessary to apply the framework described in the first two sections.

1. Introduction

Investors seek low risk and high rates of return on their investments (ROI). Individuals and institutions seeking to invest in projects that will have a positive impact on land degradation neutrality (LDN) (Chasek et al., 2014; Cowie et al., 2018) have four options for increasing their economic ROI. The first two options are based on the “Avoid > Reduce > Reverse” response hierarchy (Cowie et al., 2018), while the third and fourth build on this hierarchy. The first is to focus exclusively on strategies, such as sustainable intensification, designed to *avoid* or *reduce* degradation of relatively undegraded lands. The second is to invest in *reversing* degradation by restoring or rehabilitating degraded lands (Cowie et al., 2018). The third is to apply an integrated, portfolio approach where the projected ROI of all three strategies (avoid, reduce, reverse) is compared across the landscape or region of interest. The fourth option is to monetize ecosystem services in addition to commodity production to increase income generation (Quatrini and Crossman, 2018). This final option can be applied to projects based on any or all four of the strategies.

The strategies for determining ROI for land management investments require an understanding of the ability of land to support particular types and amounts of ecosystem services, and its potential to

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Abbreviations: IRP, International Resource Panel; LDN, land degradation neutrality; NPV, net present value; ROI, return on investment; UNCCD, United Nations Convention to Combat Desertification; UNEP, United Nations Environment Program

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resist and recover from degradation. This ability can vary widely with soil type, degradation extent, and other factors. An understanding of land potential can contribute to increased short- and long-term economic ROI for the four options mentioned above.

The objective of this paper is to present a strategy for increasing both short- and long-term economic ROI by systematically applying a more holistic understanding of land potential to the identification and prioritization of land investments. First, we describe how the potential short- and long-term resistance and resilience of the land can be used to prioritize actions designed to avoid, reduce and reverse degradation. Second, we explore how management strategies can be further optimized based on an understanding of degradation risk. Lastly, we present the Land-Potential Knowledge System (LandPKS), a modular mobile app that makes it possible for virtually anyone with a mobile phone to make the land potential determinations necessary to apply the framework described in the first two sections.

1.1. Land potential – concepts and definitions

Evaluating the potential of land to *sustainably* support the generation of ecosystem services requires understanding both its current potential to generate these services, and its capacity to resist and recover from degradation.

Land's potential to generate provisioning services including agricultural production is relatively well understood (Millennium Ecosystem Assessment, 2005). This potential is reflected in land suitability evaluation systems, which are used to help determine which crops are likely to grow well under a particular set of soil and climate conditions (UNEP, 2016). Sophisticated crop-specific systems may even use models to predict potential production under a range of input and management scenarios (Bergez et al., 2010). These predictions can be integrated with information on infrastructure and markets to predict short-term ROI. They are often inadequate for long-term ROI projections, however, as they fail to consider land degradation (Turner et al., 2016).

The capacity of land to resist and recover from degradation is often referred to as resilience (O'Connell et al., 2015). In this paper we treat resistance and recovery potential separately for two reasons. First, the properties and processes associated with resistance and recovery, and the required management actions, are quite distinct. For example, a fire break can provide fire resistance to a landscape by altering processes associated with the spread of fire, but after land has burned a completely different set of processes (e.g. plant establishment) and management actions must be considered for its recovery (resilience). Second, the timing of management interventions required to increase degradation resistance, and the rate and extent of recovery, can be very different (Seybold et al., 1999).

We also distinguish between relatively long- and short-term potential (UNEP, 2016). Long-term land potential depends on the relatively static or inherent properties of the land. These include but are not limited to slope, landscape position, soil depth, soil texture and mineralogy, and climate. Short-term land potential is its potential at a particular moment in time. It depends on both the long-term potential together with relatively dynamic soil properties (i.e. those that typically change in response to management) and weather. The range of variability in short-term potential is generally constrained by long-term potential. However, short-term potential can exceed long-term potential if inputs have been added or the landscape has been modified. For example, soil organic matter content can be increased beyond that occurring under natural conditions by importing crop residues or manure, which can increase nutrient availability, infiltration rates, and plant-available water holding capacity. Landscape modification may include construction of terraces or installation of a tile drainage system. Degradation, through nutrient depletion or soil compaction for example, can reduce short-term potential. While useful for land use planning and management, the distinction between both long- and short-term potential, and the properties and processes associated with each, is ultimately an arbitrary one as they vary continuously in both space and time.

Finally, the authors of this paper respect the diversity of views on how the recovery of degraded land is defined and determined. The framework presented can be applied to nearly all definitions of recovery. However, the reader may assume that all uses of the term "restoration" include "restoration and rehabilitation". This is consistent with the publication describing the "scientific conceptual framework for land degradation" (Cowie et al., 2018).

1.2. Mismatches between land use and land potential results in land degradation

A mismatch between land use and its potential to support ecosystem services can lead to degradation in several ways. Degradation of agricultural production and other ecosystem services is caused *directly* where land use *exceeds* the long-term sustainable potential (Pacheco et al., 2018). This may be caused by a variety of processes, such as overgrazing of rangelands, or cultivation of steeply sloping lands. Degradation can also be caused *indirectly* where agricultural land is managed *below* its potential, resulting in the unnecessary conversion of additional land to agriculture (UNEP, 2016). Where effectively implemented, sustainable intensification of underutilized land can simultaneously avoid both degradation of the already converted lands, and conversion of additional land (Lal, 2019). This approach is currently being pursued by organizations that are taking a more holistic approach to closing the "yield gap" than simply increasing inputs (Tilman et al., 2011).

2. Section I: Investment prioritization based on biophysical land potential

This section explores how the ROI for the four investment options introduced above can be improved based on an understanding of biophysical land potential. One practical tool for assessing the biophysical potential of the land, the LandPKS mobile app, will be discussed in detail in Section 3.

2.1. Option 1: relatively undegraded land (AVOID/REDUCE)

Where much of the land is relatively undegraded, the highest ROI on land degradation investments is generally achieved by avoiding degradation through the adoption of practices, such as erosion control measures, specifically designed to avoid future declines in annual returns (Cowie et al., 2018). Where this is not possible, reducing land degradation can reduce the costs and/or time required for recovery to occur. The first step for prioritizing investments is to identify the land uses and management systems that are likely to cause degradation of different types of land in the target area. The second step is to evaluate the resistance and resilience of each land type (Fig. 1). The closer the land is to the origins of Figs. 1a-c (low resistance and resilience), the higher the priority for avoiding land uses and management systems likely to result in degradation. Alternatively, land that is both relatively resistant and resilient to degradation (upper right quadrants) may be dedicated to uses and management likely to result in greater degradation pressure.

This 2 dimensional analysis can be expanded by considering the potential value of the land, reflected in potential production gradient from low in Fig. 1a to high in Fig. 1c. Land with relatively high potential production that has both low degradation resistance and resilience should usually receive the highest priority for investments designed to avoid degradation.

Fig. 1. Prioritization of land for degradation avoidance vs. reduction based on its resistance (x axis) resilience (y axis) and potential production from low (a) to high (c).

2.2. Option 2: previously degraded land (RESTORE)

Recovery, including restoration and rehabilitation, of degraded land is generally less cost-effective than avoiding or reducing degradation of relatively undegraded land (Cowie et al., 2018). Areas where recovery investments are justified include those with a high potential production of ecosystem services, where there is little or no land left to protect from degradation (a geographic constraint on investments), and when the funding source explicitly restricts activities to recovery efforts. Fig. 2 provides a guide for locating candidate land for recovery investments based on two criteria: recovery cost and the probability that the restored or rehabilitated condition will persist. For example, gully restoration areas where the upper watershed has also been rehabilitated are generally more likely to persist than where the upper watershed continues to generate high amounts of rapid runoff. The highest rates of return on investment are likely to be found in the lower left quadrants of Fig. 2a-c, where restoration costs are low and persistence is high.

This 2-dimensional analysis can also be extended by considering a potential production gradient from low (2a) to high (2c). As above, higher value land will generally generate a higher return on investment, though this analysis must be further qualified by the absolute increase in the value generated by the restoration or rehabilitation investment. This increase in value per unit investment depends in part on the resistance of the degraded state to restoration, which is related to restoration cost, with highest ROI in areas with the lowest restoration resistance.

2.3. Option 3. landscape management including relatively undegraded and degraded lands (AVOID/REDUCE/RESTORE)

The highest ROI based on a biophysical analysis of land potential is likely to be realized where interventions designed to avoid, reduce and reverse degradation are allocated across the entire landscape. Where possible this analysis should include potential spatial interactions among landscape units (Rappaport et al., 2015). Effective implementation of LDN strategies is predicated on planning for spatial processes that operate at the landscape-scale. Thus, in addition to an analysis of resilience thresholds (e.g., low, intermediate, high) (Tambosi et al., 2014), prioritization for avoiding, reducing, or reversing degradation to a particular land type must also consider the following: (1) the types of ecosystem services it provides within a landscape, (2) the relative importance and rarity of those services, and (3) the feasibility that interventions will result in persistent enhancement of land-based natural capital (Rappaport et al., 2015). For example, in dryland areas, prioritizing restoration of springs or other water sources will likely support a number of important ecosystem services.

2.4. Option 4. Monetize ecosystem services

Economic ROI can be increased by monetizing the ecosystem services other than commodity production that the undegraded, restored or rehabilitated land provides (Quatrini and Crossman, 2018). This has two benefits for the predicted ROI. The obvious one is an immediate increase in income where income from commodity production also

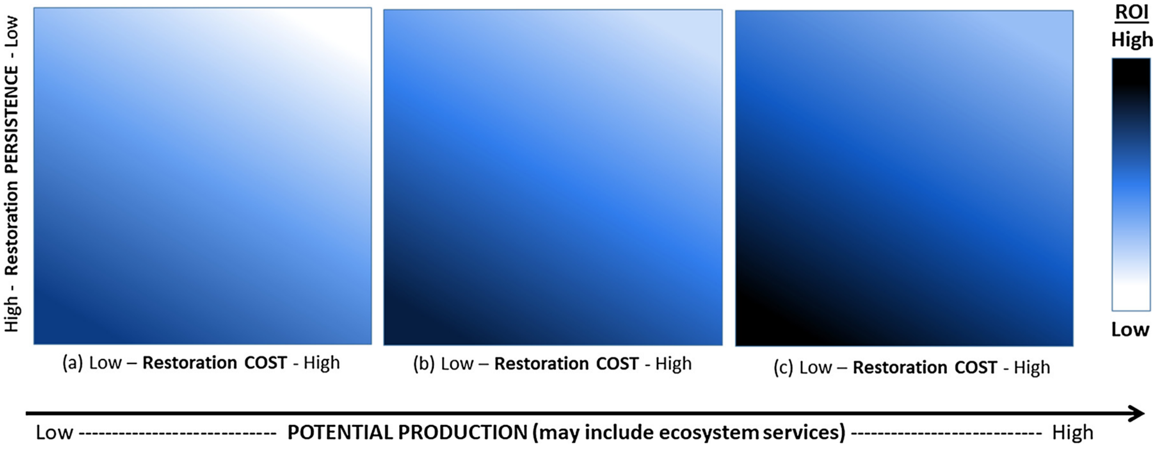

Fig. 2. Return on investments (ROI) in restoration or rehabilitation as a function of restoration cost (x axis), persistence (resistance + resilience of recovered system – y axis), and potential production from low (a) to high (c).

increases, remains stable, or declines by an amount less than that provided by payments for ecosystem services. For example, culturally-based ecosystem services such as agritourism can increase on-farm income while commodity production remains stable. A potentially more significant benefit, however, is that diversifying income from land can increase long-term income stability. For example, ranchers can often also manage their land for wildlife species, thus increasing their income though hunting or wildlife viewing concessions. This can effectively reduce the discount rate that is applied, particularly where a stable, long-term income is anticipated. A lower discount rate results in a higher net present value of investments in restoration or rehabilitation, or the establishment of a perennial crop (for avoiding or reducing degradation). Monetization of ecosystem services is a rapidly growing field of research, debate and action and a number of resources are available, such as The Economics of Ecosystems & Biodiversity website (http://www.teebweb.org/).

2.5. *Risk – the missing factor*

The four options discussed above also require an understanding of the risk of failing to meet objectives associated with changes in land use or management. For both Option 1 (Avoid/Reduce) and Option 2 (Reverse) failure often results from a lack of understanding of current and future anthropogenic pressures on the land, resulting in a poorly defined risk profile. One of the advantages of Option 3 (Avoid/Reduce + Reverse) is that it requires investors to consider the entire landscape before deciding where and how to allocate resources. These issues have been explored in depth for the intersection of climate risk and agricultural development (Schlenker and Lobell, 2010). Option 4 further mitigates risk in the previous scenarios by monetizing the value of ecosystem services present in undegraded lands, rather than dismissing them as economic externalities.

3. Section 2: Refining prioritization (Options 1–3 above) based on RISK of future conversion to a degrading land use or management system

The first section is based entirely on a biophysical analysis of how land potential is likely to affect ROI for LDN investments. Ultimately, however, the long-term success of LDN investments depends on the social-ecological systems within which they are made (Okpara et al., 2018). In particular, successful LDN investments require that both the real or perceived net present value (NPV) of undegraded or restored land exceed that of land use and management systems that will degrade it. Predicting which parts of the landscape have the highest degradation risk requires an understanding of real and perceived discount rates as influenced by markets for agricultural and other land-based commodities and/or ecosystem services. Over longer time scales, the potentially disruptive impacts of new technologies may shift the real or perceived NPV in ways that cannot be predicted in advance. Changes in any of these factors can alter the relative value and long-term predictability of actions to limit degradation of previously undegraded or restored land, resulting in a shift from the situation illustrated in Fig. 3a, where the economic incentives for degradation are low and limited to small areas, to 3c, where there are overwhelming economic incentives to manage the land in ways that results in potentially irreversible degradation. Also see Box 1 for details and examples.

In the absence of regulation or incentives, land conversion in a landscape or region usually ends when it is not profitable to convert the remaining (generally lower-productivity) lands. Incentives include the US’s Conservation Reserve Program, and the “wetlands conservation” and “sodsaver” and protection of highly erodible land provisions of the US Farm Bill (Stubbs, 2014).

It is worth noting, however, that land degradation does not only occur for economic benefit but also for political, cultural, or other socio-political reasons. For example, land may be degraded to plant a specific crop that is not matched to the potential of the land but is the staple food for the area. Additionally, land tenure systems are often highly political and degradation can occur when marginalized groups of people only have access to marginal lands.

These factors can also cause rapid shifts from Fig. 3a to 3c, associated with increases in the socioeconomic value placed on local food production and/or declines in resilience, which can cause the two curves in Fig. 3a to invert. These shifts can be caused by immigration, weather-, conflict- or currency exchange-rate driven food shortages or price increases, or changes in land ownership. For example, migration driven by drought- or land-degradation-related food shortages or by conflict in one part of a country can contribute to migration of agriculturalists to less resilient lands in another part of the country.

Scenario analyses can help determine if the area being considered for LDN investments is likely to shift to conditions where degradation pressures are likely to be particularly strong. Where this is the case, generating a positive long-term ROI on LDN investments must usually be supported by public subsidies, regulations, the development of alternative markets, or the development and implementation of cost-effective soil conservation technologies.

4. Section 3. Practical determination of land potential and determination of ROI

Rapid and effective land evaluation is critical to achieving LDN and increasing ROI. Evaluation of land potential is the first step in determining whether or not land is degraded as it establishes the reference (undegraded state) based on soil, climate and topography. This information, together with current vegetation, is also needed to determine resistance and resilience. For example, resilience is generally higher for land on more gentle slopes with neutral pH, loamy soil textures, and moderate to high precipitation because nutrient and water availability necessary for plant establishment and growth is relatively higher than for other types of land (UNEP, 2016; Herrick et al., 2013). Factors affecting resistance to soil erosion, compaction, nutrient depletion and other forms of degradation are relatively well understood (Brady and Weil, 2008). Information on soil, climate and topography is also necessary to determine the ROI, including investment cost, and the magnitude and persistence of the impact (Figs. 1 and 2).

Frameworks and tools for evaluating land potential were reviewed by the International Resource Panel (UNEP, 2016). More recently, the Food and Agriculture Organization established a website that provides access to a wide variety of land resource planning tools: http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/en/.

Here we briefly highlight one of these tools that was recently enhanced to facilitate site-specific determinations of land potential by non-specialists. The Land-Potential Knowledge System (LandPKS) mobile app also allows users to easily record much of the information necessary to determine the ROI, including management and restoration inputs and activities (for determining costs), and the magnitude and persistence of the impact. These data can then be used for the assessment of possible future investments to predict the persistence of similar types of land (for Fig. 2).

The *LandInfo* module of the LandPKS app was developed to help put information about land potential, including climate, soil, and vegetation characteristics, into the hands of land managers, land use planners, and investors globally (Herrick et al., 2013; landpotential.org). The new (~March 2019) *LandManagement* module is used to record inputs and management actions to support determinations of investment costs, while the *LandCover* and new (~April 2019) *SoilHealth* modules are used to monitor the response of the land over time to support determinations of impact and persistence.

The *LandInfo* module of LandPKS allows non-soil scientists to determine slope and soil texture, and to identify other potentially limiting factors. This information is used to automatically determine the Land

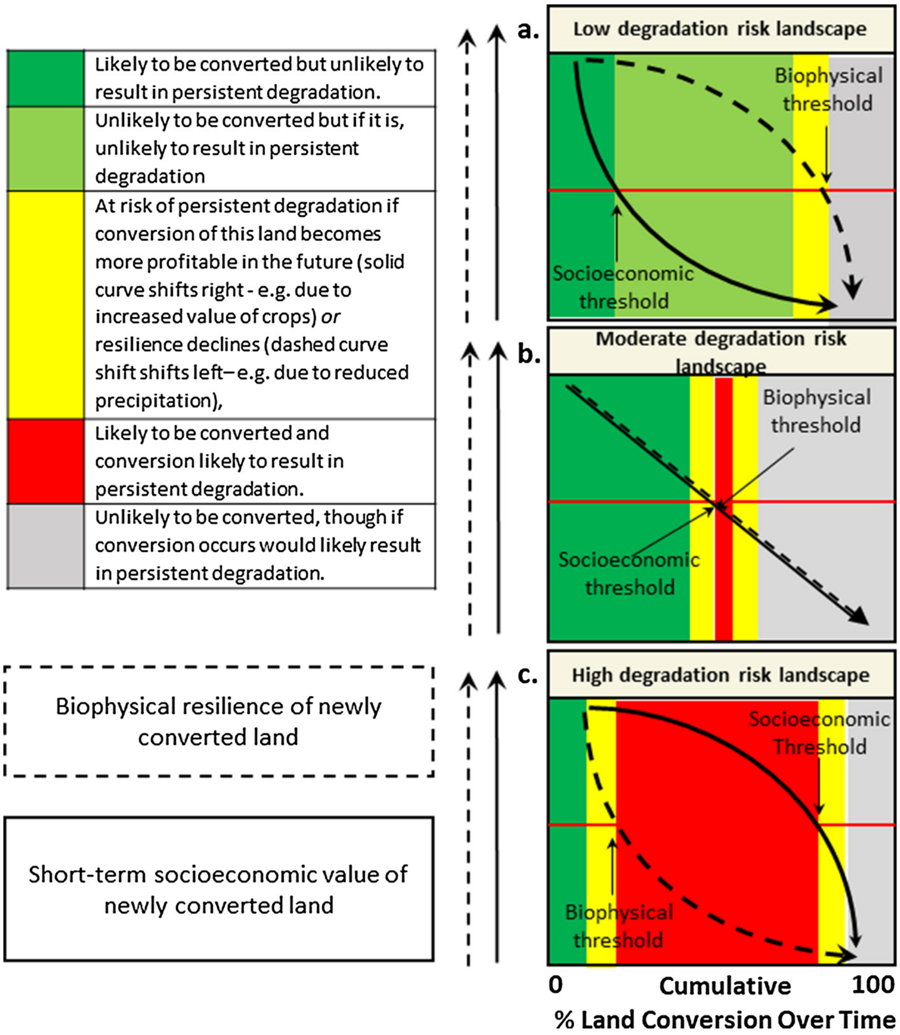

Fig. 3. Predicted proportion of a landscape or region (red) where (i) land conversion is likely based on its value for agricultural production, and (ii) that conversion is likely to result in degradation that cannot be easily reversed by restoration or remediation. Analysis based on the relationship between socioeconomic (low economic value of land conversion) and biophysical (persistent degradation from land conversion) thresholds as less productive and resilient parts of the landscape (X axis) are considered for conversion. Landscapes dominated by land with low socioeconomic value and high biophysical resilience (a) are less likely to be degraded than those with high proportions of land with high socioeconomic value and low resilience (c) (Adapted and modified from Herrick et al., 2012).

Box 1

A brief, non-comprehensive explanation of major factors that affect the relationships shown in Fig. 3.

A brief, non-comprehensive explanation of major factors that affect the relationships shown in Fig. 3. More detailed explanations are by Tilahun et al. (2018) and other recent publications of the Economics of Land Degradation (ELD) Initiative (www.eld-initiative.org/).

Discount rates. The discount rate is defined here as the rate at which individuals discount future income relative to current income. Higher discount rates can be generated by a number of factors, including extreme poverty (value of producing food to survive this year far exceeds possible value of producing food next year), and uncertainty, particularly including uncertainty of land tenure (Southgate, 1990). Secure land tenure has been shown to dramatically increase sustainable land management in a number of countries including China where in one study "farmers' likelihood of adopting straw retention were almost cut in half on rented plots compared to their owned plots" (Gao et al., 2018).

Markets for agricultural and other land-based commodities. Dramatic increases in farm-gate prices (what the farmer typically receives if they don't transport their crops to market) for crops can create opportunities for short-term profits that can rapidly shift a landscape from the situation described on Fig. 3a to c. This may result from increased market prices, improved infrastructure, or more efficient and transparent markets, for example driven by the increased dissemination of market price information through mobile phones.

Disruptive impacts of new technologies. New technologies can often simultaneously increase the rate of degradation and its profitability, particularly when combined with high crop prices. A particularly compelling example is the expansion of quinoa into the plains of the southern Bolivian altiplano. This was facilitated by the introduction of mechanized tillage and high prices for quinoa driven by the export market. This in turn resulted in the extensive conversion of native rangeland to bi-annual cropping, and the subsequent exposure of soils to extensive wind erosion (Chelleri et al., 2016).

Ecosystem services. Development of ecosystem service markets that pay landowners for non-commodity value generated by their land can significantly increase both the short- and long-term value of land degradation avoidance and reduction. The 2005 Millennium Ecosystem Assessment distinguishes four categories of ecosystem services: 1. Supporting services (primary production, pollination, nutrient recycling, etc.), 2. Provisioning services (food, water, energy, etc.), 3. Regulating services (climate regulation, purification of water and air, pest and disease control, etc.), and 4. Cultural services (spiritual, recreation, science and education, etc.). Many of these different types of ecosystem services can and do have existing markets and monetary value.

Capability Class using a globalized version of the system originally developed by the USDA in the 1950's, and subsequently adapted and applied globally (USDA-NRCS, 2007; Dent and Dalal-Clayton, 2014). While much less detailed than other land evaluation systems, the simplicity of the Land Capability Classification system has facilitated its adoption and application to a wide variety of different policy requirements (Dent and Dalal-Clayton, 2014). The module also automatically calculates plant-available water-holding capacity and infiltration capacity at different soil organic matter contents, which are particularly important determinants of land potential in drylands. The *Land-Management* module was developed to allow farmers, restorationists and other land managers quickly document inputs, management actions and rainfall. The *LandCover* app continues to be widely used as a rapid soil surface and vegetation monitoring tool. The default protocol requires just a one-meter long stick with five marks, and 20 min to collect all of the data necessary for the app to automatically calculate cover and, if desired, several indicators of vegetation structure and density (e.g. for plant establishment). Finally, the *SoilHealth* module includes simple observable indicators of soil health and soil erosion. Future versions will allow users to integrate laboratory data.

Summary outputs, including interpretations, for all of the modules are being continuously updated and expanded. Increased access to the app is also being supported by the addition of language options and the inclusion of many language-independent graphics.

In northern Kenya, LandPKS was found to be an effective tool for evaluating rangeland restoration success, and facilitating retrospective restoration analyses by properly matching treatment and control sites based on land potential information (Kimiti et al., 2017; Kimiti, 2017). The utility of LandPKS has also been demonstrated where restoration outcomes, from areas with differing land potential, are used to help identify locations on the landscape where these strategies are more likely to be successful. In northern New Mexico, researchers are working with public and private land managers to use information derived from LandPKS and other site-specific information to identify locations that have high risk of soil loss and therefore high risk of degradation.

Detailed ecological land classification information systems, including "ecological site descriptions", have been developed in the United States and Mongolia as means to identify and communicate specific changes in management and restoration strategies that vary with land potential (i.e., among ecological sites; Bestelmeyer et al., 2017). State-and-transition models are used to prioritize management investments based on the likelihood of recovery from degraded ecological states, captured in descriptions of ecological thresholds. These decision support tools have been focused primarily on rangeland, but are currently being expanded in the United States to work across multiple land uses and highlight tradeoffs among land uses based on production and non-production ecosystem services.

5. Conclusions

Changes in land use and management can avoid, reduce or reverse land degradation. This paper provides a framework for optimizing these investments based on an understanding of how land varies in its potential productivity, and its resistance and resilience to degradation. This framework can be used to increase the economic return on investment, while contributing to the achievement of SDG 15.3, land degradation neutrality. The predictive value of this framework can be improved by integrating an analysis of risk, particularly in areas where rapid and potentially unsustainable changes in land use are occurring. Had this analysis been applied to the central Great Plains of the United States during the early 1900's, the Dust Bowl and resulting mass internal migration (Steinbeck, 1992) may have been avoided.

We suggest that for investors seeking to maximize their impact on LDN may wish to consider one or more of the following strategies.

(1) Target avoidance and reduction investments to low-resilience landscapes where the short-term socioeconomic value of land conversion is currently high (Fig. 3c).
(2) Create a "rapid response" fund that targets low-resilience landscape where the socioeconomic value of land conversion is likely to increase in the future (shifts from Fig. 3a to c), "while ensuring that any resulting increased pressure on moderate and high-resilience lands does not result in their degradation (e.g. through a shift in the short-term socioeconomic value curves in (solid lines in 3a and 3b) to the right)."
(3) Support policies that minimize the risk of increasing profitability of these low-resilience landscapes (shifts from Fig. 3a to c).

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References

Bergez, J.E., Colbach, N., Crespo, O., Garcia, F., Jeuffroy, M.H., Justes, E., Loyce, C., Munier-Jolain, N., Sadok, W., 2010. Designing crop management systems by simulation. Eur. J. Agron. 32, 3–9.

Bestelmeyer, B.T., Ash, A., Brown, J.R., Densambuu, B., Fernández-Giménez, M., Johanson, J., Levi, M., Lopez, D., Peinetti, R., Rumpff, L., Shaver, P., 2017. State and transition models: theory, applications, and challenges. In: Briske, D.D. (Ed.), Rangeland Systems: Processes, Management and Challenges. Springer International Publishing, Cham., New York, NY, pp. 303–345.

Brady, N.C., Weil, R.R., 2008. The Nature and Properties of Soils, 14th edition. Pearson, Upper Saddle River, New Jersey, pp. 965.

Chasek, P., Safriel, U., Shikongo, S., Fuhrman, V.F., 2014. Operationalizing Zero Net Land Degradation: the next stage in international efforts to combat desertification? J. Arid Environ. 112, 5–13.

Chelleri, L., Minucci, G., Skrimizea, E., 2016. Does community resilience decrease social–ecological vulnerability? Adaptation pathways trade-off in the Bolivian Altiplano? Reg. Environ. Change 16 (8), 2229–2241.

Cowie, A.L., Orr, B.J., Sanchez, V.M.C., Chasek, P., Crossman, N.D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G.I., Minelli, S., Tengberg, A.E., 2018. Land in balance: the scientific conceptual framework for Land Degradation Neutrality. Environ. Sci. Policy 79, 25–35.

Dent, D., Dalal-Clayton, B., 2014. International Institute for Environment and Development, LondonMeeting the Need for Land Resources Information in the 21st Century—or Not: State-of-the Art Review, Environmental Governance Series No. 8, April 20142014. Meeting the Need for Land Resources Information in the 21st Century—or Not: State-of-the Art Review, Environmental Governance Series No. 8, April 2014.

Gao, L., Zhang, W., Mei, Y., Sam, A., Song, Y., Jin, S., 2018. Do Farmers Adopt Fewer Conservation Practices on Rented Land? Evidence From Straw Retention in China. Center for Agricultural and Rural Development (CARD) at Iowa State University Working Paper 18-WP 584. https://www.card.iastate.edu/products/publications/pdf/18wp584.pdf.

Herrick, J.E., Brown, J.R., Bestelmeyer, B.T., Andrews, S.S., Baldi, G., Davies, J., Duniway, M., Havstad, K.M., Karl, J.W., Karlen, D.L., Peters, D.P.C., Quinton, J.N., Riginos, C., Shaver, P.L., Steinaker, D., Twomlow, S., 2012. Revolutionary land use change in the 21st century: is (rangeland) science relevant? Rangel. Ecol. Manage. 65, 590–598.

Herrick, J.E., Urama, K.C., Karl, J.W., Boos, J., Johnson, M.-V.V., Shepherd, K.D., Hemple, J., Bestelmeyer, B.T., Davies, J., Guerra, J.L., Kosnik, C., Kimiti, D.W., Ekai, A.L., Muller, K., Norfleet, L., Ozor, M., Reinsch, T., Sarukhan, J., West, L.T., 2013. The global Land-Potential Knowledge System (LandPKS): Supporting evidence-based, site-specific land use and management through cloud computing, mobile applications, and crowdsourcing. J. Soil Water Conserv. 68, 5A–12A.

Kimiti, D.W., 2017. The Global Land Potential Knowledge System: Use of Mobile Phone Applications in the Evaluation and Prediction of Restoration Outcomes. PhD Dissertation. New Mexico State University, Las Cruces NM USA.

Kimiti, D.W., Hodge, A.C., Herrick, J.E., Beh, A., Abbott, L.E., 2017. Rehabilitation of community owned, mixed use rangelands: lessons from the Ewaso ecosystem in Kenya. Plant Ecol. 28, 23–37.

Lal, R., 2019. Promoting "4 per thousand" and "adapting African agriculture" by south-south cooperation: conservation agriculture and sustainable intensification. Soil Tillage Res. 188, 27–34. https://doi.org/10.1016/j.still.2017.12.015.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well Being: Synthesis. Island Press, Washington DC, pp. 137.

O'Connell, D., Walker, B., Abel, N., Grigg, N., 2015. The Resilience, Adaptation and Transformation Assessment Framework: From Theory to Application. CSIRO, Dickson, ACT, Australia.

Okpara, U.T., Stringer, L.C., Akhtar-Schuster, M., Metternicht, G.I., Dallimer, M., Requier-

Desjardins, M., 2018. A social-ecological systems approach is necessary to achieve land degradation neutrality. Environ. Sci. Policy 89, 59–66.

Pacheco, F.A.L., Fernandes, L.S., Junior, R.V., Valera, C.A., Pissarra, T.C.T., 2018. Land degradation: multiple environmental consequences and routes to neutrality. Curr. Opin. Environ. Sci. Health 5, 79–86.

Quatrini, S., Crossman, N.D., 2018. Most finance to halt desertification also benefits multiple ecosystem services: a key to unlock investments in Land Degradation Neutrality? Ecosyst. Serv. 31, 265–277.

Rappaport, D.I., Tambosi, L.R., Metzger, J.P., 2015. A landscape triage approach: combining spatial and temporal dynamics to prioritize restoration and conservation. J. Appl. Ecol. 52 (3), 590–601.

Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5 (1), 014010.

Seybold, C.A., Herrick, J.E., Brejda, J.J., 1999. Soil resilience: a fundamental component of soil quality. Soil Sci. 164, 224–234.

Southgate, D., 1990. The causes of land degradation along" spontaneously" expanding agricultural frontiers in the Third World. Land Econ. 66 (1), 93–101.

Steinbeck, J., 1992. The Grapes of Wrath. Penguin Classics, New York, NY, pp. 459.

Stubbs, M., 2014. Conservation Provisions in the 2014 Farm Bill (PL 113-79). Congressional Research Service.

Tambosi, L.R., Martensen, A.C., Ribeiro, M.C., Metzger, J.P., 2014. A framework to optimize biodiversity restoration efforts based on habitat amount and landscape connectivity. Restor. Ecol. 22 (2), 169–177.

Tilahun, M., Singh, A., Kumar, P., Apindi, E., Schauer, M., Libera, J., Lund, H.G., 2018. The Economics of Land Degradation Neutrality in Asia: Empirical Analyses and Policy Implications for the Sustainable Development Goals. Available from. www.eld-initiative.org.

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. U.S.A. 108 (50), 20260–20264.

Turner, K.G., Anderson, S., Gonzales-Chang, M., Costanza, R., Courville, S., Dalgaard, T., Dominati, E., Kubiszewski, I., Ogilvy, S., Porfirio, L., Ratna, N., 2016. A review of methods, data, and models to assess changes in the value of ecosystem services from land degradation and restoration. Ecol. Modell. 319, 190–207.

UNEP, 2016. In: Herrick, J.E., Arnalds, O., Bestelmeyer, B.T., Brignezu, S., Han, G., Johnson, M.V., Lu, Y., Montanarella, L., Pengue, W., Toth, G. (Eds.), Unlocking the Sustainable Potential of Land Resources Evaluation Systems, Strategies and Tools. United Nations Environment Programs (UNEP), pp. 89.

USDA-NRCS, 2007. National Soil Survey Handbook. Title 430, Part 622. Accessed 1 September 2018 Available at:. http://soils.usda.gov/technical/handbook/.