UNEP

International Resource Panel

UNLOCKING THE SUSTAINABLE POTENTIAL OF LAND RESOURCES

EVALUATION SYSTEMS, STRATEGIES AND TOOLS

UNITED NATIONS ENVIRONMENT PROGRAMME

Acknowledgments

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About the International Resource Panel

This report was prepared by the Working Group on Land and Soils of the International Resource Panel (IRP). The IRP was established to provide independent, coherent and authoritative scientific assessments on the use of natural resources and its environmental impacts over the full life cycle and contribute to a better understanding of how to decouple economic growth from environmental degradation. Benefiting from the broad support of governments and scientific communities, the Panel is constituted of eminent scientists and experts from all parts of the world, bringing their multidisciplinary expertise to address resource management issues. The information contained in the International Resource Panel's reports is intended to be evidence based and policy relevant, informing policy framing and development and supporting evaluation and monitoring of policy effectiveness. The Secretariat is hosted by the United Nations Environment Programme (UNEP). Since the International Resource Panel's launch in 2007, fifteen assessments have been published. Earlier reports covered biofuels; sustainable land management; priority economic sectors and materials for sustainable resource management; benefits, risks and trade-offs of Low-Carbon Technologies for electricity production; metals stocks in society, their environmental risks and challenges, their rates of recycling and recycling opportunities; water accounting and decoupling; city-level decoupling; REDD+ to support Green Economy; and the untapped potential for decoupling resource use and related environmental impacts from economic growth. The assessments of the IRP to date demonstrate the numerous opportunities for governments and businesses to work together to create and implement policies to encourage sustainable resource management, including through better planning, more investment, technological innovation and strategic incentives. Following its establishment, the Panel first devoted much of its research to issues related to the use, stocks and scarcities of individual resources, as well as to the development and application of the perspective of 'decoupling' economic growth from natural resource use and environmental degradation. Building upon this knowledge base, the Panel has now begun to examine systematic approaches to resource use. These include the direct and indirect (or embedded) impacts of trade on natural resource use and flows; the city as a societal 'node' in which much of the current unsustainable usage of natural resources is socially and institutionally embedded; and the resource use and requirements of global food systems. Upcoming work by the IRP will focus on integrated scenarios of future resource demand, material flow database and analysis, resource implications of future urbanization, global resource efficiency prospects and economic implications, and remanufacturing.

UNLOCKING THE SUSTAINABLE POTENTIAL OF LAND RESOURCES

Evaluation Systems, Strategies and Tools

Preface

Dr. Janez Potočnik Alicia Bárcena
Co-Chairs, International Resource Panel

The International Resource Panel's first report on Land and Soil predicted that during the 45 years starting in 2005 there will be a net expansion of cropland of between 120 and 500 Mha. Compensating for land degradation and replacement of cropland with urban, industrial (including energy) and transportation infrastructure will result in a gross expansion of cropland of between 320 and 850 Mha under 'business as usual' conditions. This projected new cropland area is equal to over 50% of the current cropland area.

In addition to changing diets and reducing food waste and the demand for non-food uses of biomass, the Panel identified better matching of land use with land potential as a key factor in reducing the amount of land required to meet human needs. An improved understanding of land potential, in addition to more cost-effective and holistic tools for generating and sharing this understanding, is necessary to guide land use and management and, where necessary, to halt unsustainable land uses. More effectively matching land use with land potential is one of the few strategies available to decouple human development and economic growth from land degradation.

The first report on Land & Soil, "Assessing Global Land Use: Balancing Consumption with Sustainable Supply" concluded that two complementary strategies must be pursued: (1) apply sustainable land management strategies to all land, and (2) control the demand for the number of (cropland) hectares. The report identified several options for minimizing cropland expansion, including improved land use planning and land management "in order to minimize expansion of built-up land on fertile soils, and to invest in the restoration of degraded land". The current report focuses on land potential evaluation systems as a critical foundation for land use planning and management.

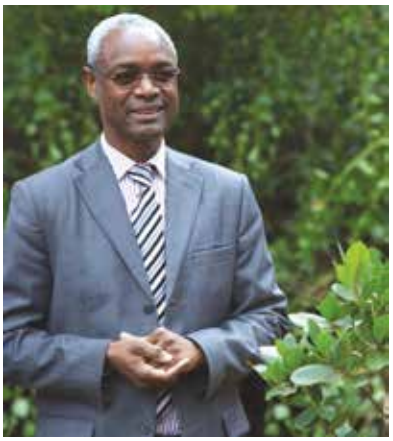
More specifically, land potential evaluation systems are needed to sustain and increase the provision of ecosystem services in the context of climate change, persistent land degradation and increasing global population and per-capita consumption levels by (a) guiding land tenure and land redistribution, and (b) promoting innovation to sustainably increase productivity and resource efficiency, including through sustainable intensification. Moreover, they can increase knowledge of locally-utilized food varieties already adapted to specific land environments.

The application of land evaluation to land use planning and management is limited by four factors. The first is a lack of understanding of how to select and apply appropriate, currently available tools. The second is that existing land potential evaluation tools fail to account for resilience. The third is that they emphasize limits to production based on current technologies while ignoring and, in some cases, even constraining the development of innovative management systems that could increase land potential through an increase in resource productivity. Finally, and most importantly, socioeconomic and cultural constraints to land use and management must be addressed after or at the same time as the biophysical land evaluation. These constraints include, but are not limited to, land tenure, transportation and storage infrastructure, markets, and dietary preferences.

Together with the new IRP report "Food Systems and Natural Resources", this report supports the implementation of the UN Secretary-General's 'Zero Hunger Challenge' by addressing the first three factors. More specifically, this report provides background information, tools, and policy options necessary to implement the concept of "land degradation neutrality" included in the Rio+20 outcome document "The Future We Want" and in the agreed 2030 Agenda for Sustainable Development.

We thank Jeffrey Herrick and the rest of the working group for putting together this innovative assessment. We are confident that the principles set out in this report paired with the technology developed therewith will contribute to the development of the next generation of land potential evaluation systems, one which allows the inherent long-term land potential to be sustainably realized.

Foreword



Land resources are one of nature's most precious gifts. They feed us and help our societies and economies to thrive. Some 2.5 billion agricultural smallholders worldwide manage around 500 million small farms, providing more than 80 per cent of food consumed in Asia and Sub-Saharan Africa.

These resources are being degraded at an alarming pace. An estimated 33 per cent of soil is moderately to highly-degraded due to erosion, nutrient depletion, acidification, salinization, compaction and chemical pollution. Each year we lose 24 billion tonnes of fertile soil and 15 billion trees, costing the economy around $40 billion.

We are rapidly expanding global cropland at the expense of our savannahs, grasslands and forests, and, as the world's population increases, the demand for food, fibre and fuel will only increase the pressure on our land resource base. As previously noted by the International Resource Panel (IRP), if current conditions continue, between 320 and 849 million hectares of natural land may be converted to cropland by 2050. This unsustainable expansion of cropland coupled with the effects of climate change would impede the achievement of the Sustainable Development Goals, in particular SDG 15, which calls for a land degradation-neutral world by 2030.

Policymakers are confronted with a fundamental challenge. How can we sustainably produce food, fuel and fibre to meet future demand without further depleting our finite land resources?

The IRP seeks answers to this critical question. In this scientific assessment, Unlocking the Sustainable Potential of Land Resources: Evaluation Systems, Strategies and Tools, the Panel proposes matching land use with its potential, and in some cases even exceeding this potential, as one of the options. Based on a comprehensive analysis of existing land potential knowledge systems like the USDA Land Capability Classification system and the FAO Agroecological Zoning System, the IRP suggests a new framework to evaluate land potential. This framework looks at variability in the factors that control land potential, addresses degradation resistance and resilience (the second of which is not considered at all in current systems), and acknowledges that the natural potential of the land to support multiple ecosystem services can be exceeded. The latter can be achieved through increased inputs and the implementation of innovative systems and technologies that increase resource use efficiency.

Important reductions in degradation have been achieved in the past through targeted policy interventions. For example, in the United States, owners of private land classified as "highly erodible land" were required to apply conservation practices as a pre-requisite to qualifying for some government programs. This requirement contributed to a dramatic 40 per cent reduction in soil erosion on US croplands between 1982 and 2007. Other policy tools proposed by the Panel include crop insurance subsidies limited to lands where the insured production system is sustainable, and tax breaks in exchange for long-term or permanent land conservation.

I am grateful to the International Resource Panel, for producing, under the leadership of Co-Chairs Alicia Bárcena and Janez Potočnik, a new kind of scientific assessment, one that provides practical policy guidance and technological solutions for the application of this guidance. I congratulate and thank the authors for this important effort in the road towards a land degradation-neutral world.

Ibrahim Thiaw
UNEP Deputy Executive Director

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Acronyms and abbreviations

AEC	Agro-Ecological Cell
AEZ	Agro-Ecological Zoning (FAO)
ALES	Automated Land Evaluation System
CQI	Climate Quality Index
DOS	Disk Operating System
ESA	Environmentally Sensitive Areas
ESI	Environmental Sensitivity Index
ESI/DIS4ME	Environmental Sensitivity Index/Desertification Indicator System for Mediterranean Europe
FAO	Food and Agricultural Organization of the United Nations
FAO-LADA	Food and Agricultural Organization of the United Nations - Land Degradation Assessment
GAEZ	Global Agro-Ecological Zoning
GIS	Geographic Information Systems
INTA	National Institute of Agricultural Technology (Argentina)
IRP	International Resource Panel
LandPKS	Land-Potential Knowledge System
LCC	Land Capability Classification system (USDA)
LQI	Land Quality Index
LUT	Land Utilization Type
MEA	Millennium Ecosystem Assessment
NASIS	National Soil Information System
RCMRD	Regional Center for Mapping of Resources for Development
REDD+	Reducing Emissions from Deforestation in Developing Countries
RUSLE	Revised Universal Soil Loss Equation
SKBP	Scientific Knowledge Brokering Portal
SOS	Safe Operating Space
SQI	Soil Quality Index
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
US	United States of America
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture - Agricultural Research Service
USDA-NRCS	United States Department of Agriculture - Natural Resources Conservation Service
USLE	Universal Soil Loss Equation
WOCAT	World Overview of Conservation Approaches and Technologies

List of Units

cm	Centimeters
ha	Hectare
kcal	Kilocalories
kg	Kilograms
kha	Thousand hectares
kW	Kilowatt
l	Litre
m^2	Square meters
m^3	Cubic meter
Mha	Million hectares
Mt	Million tones
W	Watt

Glossary

The following terms are provided with definitions that are specific to this report without external hyperlinks.

Accuracy. A description of systematic errors, a measure of statistical bias.

Cadastral. A comprehensive register of the real estate or real property's metes-and-bounds of a country.

Conservation easements. A voluntary legal agreement between a landowner and a land trust or government agency that permanently limits uses of the land in order to protect its conservation values.

Conservation plans. A written record of your management decisions and the conservation practices and systems you plan to use, develop, and maintain on your farm or ranch

Crop per drop. An initiative to utilize water more efficiently and in lesser quantities to produce crops.

Degradation. A negative change in the capacity of the system to provide ecosystem services.

Discount rates. Theoretical or observed rates at which people discount future payoffs.

Disturbance. Broadly includes anything that causes a change to the state of a system, including management.

Erodibility index. Determined by dividing the potential erodibility for the soil map unit by the loss tolerance (T).

Growing period. The period (in days) during a year when precipitation exceeds half the potential evapotranspiration.

Land degradation neutrality. A state whereby the amount of healthy and productive land resources, necessary to support ecosystem services, remains stable or increases within specified temporal and spatial scales.

Land use planning. The systematic assessment of physical, social and economic factors in such a way as to encourage and assist land users in selecting options that increase their productivity, are sustainable and meet the needs of society.

Land utilization type (LUT). A kind of land use defined in more detail, according to a set of technical descriptors in a given physical, economic and social setting.

Net primary productivity. The rate at which all the plants in an ecosystem produce net useful chemical energy; it is equal to the difference between the rate at which the plants in an ecosystem produce useful chemical energy (GPP) and the rate at which they use some of that energy during respiration. Some net primary production goes toward growth and reproduction of primary producers, while some is consumed by herbivores.

Opportunity costs. The loss of other alternatives when one alternative is chosen.

Precautionary principle. States that if an action or policy has a suspected risk of causing harm to the public, or to the environment, in the absence of scientific consensus (that the action or policy is not harmful), the burden of proof that it is not harmful falls on those taking an action that may or may not be a risk.

Precision. A description of random errors, a measure of statistical variability.

Resilience. The capacity to recover from disturbance.

Resistance. The capacity of a system to maintain function through a disturbance.

Restoration. The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed.

Yield gaps. The comparison between simulated potential yields and production with observed yield and production of crops currently grown, provides yield and production gap information for the analysis of major causes of rural poverty.

Abstract

Better matching of land use with its sustainable potential is a “no-regrets” strategy for sustainably increasing agricultural production on existing land, targeting restoration efforts to where they are likely to be most successful, and guiding biodiversity conservation initiatives. Land potential is defined as the inherent, long-term potential of the land to sustainably generate ecosystem services.

This report provides an introduction to land potential evaluation systems, strategies and tools necessary to implement this strategy. It provides information that both private landowners and policymakers can use to increase long-term productivity and profitability, while at the same time addressing global objectives defined through land-related Sustainable Development Goals, and particularly 15.3 (land degradation neutrality). The focus of the report is on the inherent long-term (decades) potential of the land to sustainably generate ecosystem services, based on soils, topography and climate. In general, land that can sustainably support higher levels of vegetation production, including crop, forage and tree, has higher potential.

Short-term land potential (1-5 years) depends on a combination of long-term potential, weather, and the current condition of the land (e.g. fertility, compaction, current vegetation cover). Matching land use with its potential determines whether the inherent long-term potential is sustainably realized. Sustainability depends on (1) potential degradation resistance, and (2) potential resilience, which is the capacity to recover from degradation. Land with similar potential should therefore respond similarly to management. Policymakers have a tremendous number of opportunities to leverage land evaluations to both increase returns on investments, while minimizing risks of catastrophic failures, such as Britain’s post-world war II peanut scheme in Tanzania, and the United States Dust Bowl, which resulted from an ill-informed agricultural expansion in the early part of the 20th century.

Policy options for applying land evaluation include, but are not limited to:

1. setting realistic, practical targets for land degradation neutrality,
2. general land use planning to decide which lands should be reserved for agricultural production and biodiversity conservation,
3. agricultural land use planning to sustainably increase food security and the profitability of the farming sector,
4. land reform and redistribution to ensure that (a) objectives for equitability are met and (b) tract sizes meet requirements for minimum economic production units, and (c) providing new landowners with appropriate information on the best available management practices specific to their land,
5. designing incentive and other programs to minimize degradation risk, and
6. optimizing climate change adaptation and mitigation initiatives by effectively targeting resources to where the greatest returns on investments are likely to occur. The report provides an overview of existing land evaluation systems, options for making them more useful by integrating resilience, and for applying land evaluation to policy.

Executive Summary

This report provides an introduction to land evaluation systems, strategies and tools necessary for "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The text focuses strongly on how to better match land use with its sustainable potential, in order to reduce the amount of land required to meet human needs, minimize land degradation, and cost-effectively restore already degraded lands. The report provides information that private landowners can use to increase long-term productivity and profitability, while at the same time addressing global objectives defined through land-related Sustainable Development Goals, and particularly 15.3 (land degradation neutrality).

1. What is land potential?

The focus of this report is on the inherent *long-term* (decades) potential of the land to *sustainably* generate ecosystem services, based on soils, topography and climate. In general, land that can sustainably support higher levels of vegetation production, including crop, forage and tree, has higher potential. *Short-term* land potential (1-5 years) depends on a combination of long-term potential, weather, and the current condition of the land (e.g. fertility, compaction, current vegetation cover).

Matching land use with its potential determines whether the inherent long-term potential is sustainably realized. Sustainability depends on (1) potential degradation resistance, and (2) potential resilience, which is the capacity to recover from degradation. Land with similar potential should therefore respond similarly to management.

2. What are the benefits of land potential evaluation?

Land potential evaluations help people make better decisions. Policymakers, development organizations, and land managers, including farmers and conservationists, can apply land evaluation to:

- Increase productivity while adapting to climate change
  - Identify the most productive lands for a particular crop
  - Identify the most productive crop and management system for a particular piece of land
  - Determine what, and what level, of inputs are required to overcome limitations such as fertility, salinity, and drainage.
  - Target climate change adaptation investments to the soil x climate combinations with the greatest predicted return on investment
- Minimize social, economic, and environmental risks of land use change
  - Identify lands with high degradation risk
  - Identify management practices that can cost-effectively reduce degradation risk
  - Identify lands with high productivity and plan urban settlements out of these areas to minimize environmental impacts of next urbanization wave
- Increase restoration and biodiversity conservation success
  - Determine where restoration is most likely to be successful
  - Predict where endangered species are most likely to occur, for plants, soil biota and the animals that depend on them
  - Understand the restoration limitations for a particular piece of land

- Promote innovation and knowledge sharing
    - Allow innovators with different perspectives to quickly connect, find collaborators working on similar types of land and exchange best practices
    - Provide the ability to rapidly evaluate potential innovations under similar conditions
    - Increase the rate of upscaling of innovations by targeting areas where the innovations are most likely to be successful

3. Systems, strategies and tools

The report reviews widely applied currently available systems, (Section I), defines principles for improvement (Section II), and then provides practical information about the wide range of tools that can be used for land evaluation.

Currently available systems that have been globally applied during the past several decades include the FAO's Agroecological Zoning (AEZ) approach and the USDA's Land Capability Classification system. The AEZ is a much more comprehensive system that focuses on the potential production of a broad variety of crops in virtually every part of the world. It is often used for regional agricultural land use planning. It provides little to no information on degradation resistance and resilience. The USDA's 8-class Land Capability Classification system considers degradation risk and is much simpler to apply. However, it was not designed to provide crop-specific information.

Principles for improvement include integrating an understanding of how disturbance, degradation and recovery processes determine resilience, and the importance of spatial scale for management. Future systems must also consider ecosystem services in addition to agricultural production.

There are a large number of tools for land evaluation that can be applied independently, or together with the two major land evaluation systems. First generation tools still useful today include paper maps and aerial photographs, and field observations and measurements focusing on a single attribute, such as erosion risk due to slope. Second and third generation tools include dedicated computer programs that often address multiple land attributes and land use objectives, including increasingly sophisticated Geographic Information System (GIS) packages. The fourth generation of tools that is increasingly available is dominated by systems that integrate data- and knowledge-bases in the cloud with local knowledge and information through mobile applications. These tools will increasingly be supplemented by small, inexpensive sensors to help provide much more localized evaluations that is currently possible with generalized soil maps.

4. Policy options

Policymakers have a tremendous number of opportunities to leverage land evaluations to both increase returns on investments, while minimizing risks of catastrophic failures, such as Britain's post-world war II groundnut scheme in Tanzania, and the United States Dust Bowl, which resulted from an ill-informed agricultural expansion in the early part of the 20th century. Policy options for applying land evaluation include, but are not limited to:

- Setting realistic targets for safe operating space and land degradation neutrality.
- General land use planning to decide *which* lands should be reserved for agricultural production and biodiversity conservation.
- Agricultural land use planning to sustainably increase food security and the profitability of the farming sector.

- Land reform and redistribution to ensure that (a) objectives for equitability are met, (b) tract size meets requirements for minimum economic production unit, and (c) new landowners are provided with appropriate information on the best available management practices specific to their land.
- Taxation.
- Designing incentive and other programs to minimize degradation risk.
- Climate change adaptation and mitigation optimization by effectively targeting resources to where the greatest returns on investments are likely to occur.

5. Conclusions

Land potential evaluations must be completed and applied *before* changes in land use or management are implemented. No farmer or nation can afford to invest in land management systems that ignore existing knowledge and information. Despite this, land conversions to a single crop and management system continue to occur across areas in which soil, topography, and sometimes climate conditions are so variable that failure across at least part of the project is virtually inevitable. In most cases, we can predict which types of production systems are likely to be sustainable on which types of land and what the impacts on other ecosystem services, including those provided by biodiversity, are likely to be.

Land evaluations can also support development of innovative systems to *increase* land potential by accelerating the sharing of existing innovations and how they worked, or did not work, on land with different potential. Agriculture continues to be the primary use of land from which native vegetation has been removed. A better matching of production systems with land potential on existing agricultural lands and increased innovation supported by carefully developed policies and strong institutions will not by themselves allow us to live within our means—but they can make it easier.

Objectives, scope and audience

The ***objectives*** of this report are to:

1. Provide an introduction to the key concepts and definitions necessary to apply an understanding of land potential to land use policy and management.
2. Review existing and emerging land potential evaluation systems. The report will focus on land potential evaluation systems that address the potential to support agricultural production while also providing an overview of those that address other ecosystem services (Section I).
3. Define principles and strategies for improving the next generation of these systems (Section II).
4. Identify policy options for applyxing land potential evaluation to land use planning and management (Section III).

The *scope* is limited to reviewing and improving tools for defining land potential as the foundation for a diverse variety of land use decisions at multiple scales. These decisions may be made by individual, communal and corporate landowners, as well as through multi-stakeholder land use planning processes. Governments and development organizations may use the tools to target resources to influence or facilitate implementation of these land use decisions. These decisions may be designed to support one or more of a broad variety of ecosystem services, including, but not limited to: agricultural production, human habitation, natural resource extraction, biodiversity conservation, water quality and quantity, and carbon sequestration.

Our focus on land potential rather than land use planning is designed to ensure that this assessment report will be equally useful to all individuals and organizations involved in land use decisions, whether these decisions are made through a multi-stakeholder land use planning process, or by a corporate or individual landowner, investor, or national government operating outside of a formal land use planning process.

The report focuses on land potential as defined by biophysical factors that have similar impacts on the types and amounts of ecosystem services that are sustainably *possible.* Local land use decision-makers must then decide what is *realistic* and *desirable* based on governance, land tenure, access to capital, markets and other socioeconomic factors. The report does not address these factors because they vary *locally*, while the basic principles affecting biophysical potential are relevant *globally*.

This assessment report includes identification of policies for applying an understanding of land potential to facilitate management and land use planning. For reasons of length and focus, this report will not attempt to explicitly review or prescribe land management or land use planning strategies. For the same reason, we have not engaged in a scenario analysis that quantitatively predicts the benefits of land potential evaluation.

The target *audience* for this report includes civil society organizations, university students, teachers, extension workers, and natural resource scientists working on land use-related issues, in addition to land managers and policymakers.

Credit: Ecuadorpostales, Shutterstock.com

Introduction

What is land potential?

Land potential is defined as the inherent, long-term potential of the land to *sustainably* generate ecosystem services. Management determines whether the inherent potential is sustainably realized. Sustainability depends on (1) potential degradation resistance, and (2) potential resilience, which is the capacity to recover from degradation. Land with similar potential should therefore respond similarly to management.

Historically, land potential has been evaluated based almost exclusively on inherent potential production and/or resistance to degradation (Klingebiel and Montgomery 1961, Helms 1997, Dent and Young 1981, FAO 1976). Specific tools and indicator systems exist to predict the degradation risk (resistance) given a particular suite of drivers (ESI/DIS4ME, USLE, RUSLE, and FAO - LADA). Most of these methods for degradation risk assessment are either geographically specialized (e.g. Environmental Sensitivity Index or ESI) or are limited to a particular discipline (e.g. soil science, Revised Universal Soil Loss Equation or RUSLE) and do not integrate potential production and socio-economic variables. They also do not effectively address resilience.

This report is based on a functional definition of land potential relative to sustainable net primary production (i.e. how much vegetation can be produced in a year with a management system that does not degrade the land), while recognizing that land use decisions must also consider the value of land for other uses, including urban and the extraction of sub-surface resources. These considerations are briefly addressed in the sections on "Land potential evaluation for valuation and taxation" and "Sub-surface resources: a footnote". Our definition of land potential, however, is not as limited as it might appear. In addition to agricultural production, all of the following ecosystem services depend almost entirely on the *types* and *amounts* of vegetation that can be potentially produced: the provision of safe and reliable water supplies, air quality (especially in drylands), timber, biofuel and peat production, and carbon sequestration.

Social, economic and environmental benefits of land potential evaluation

Our next meal, homes, clothing and energy all depend in whole or in part on the land. Land-derived resources support the majority of our food and energy demands. Nearly all of the materials used to make our clothes and to build and fill our homes and workplaces with objects are grown on land or extracted from beneath its surface. Consumption of land-based products and services is increasing, while the amount of undegraded land available to generate these goods and services is declining due to a number of factors including expansion of urban and industrial uses (Preface; Figure 1).

Figure 1. Expansion of Addis Ababa onto fertile agricultural land

Source: G. Zeleke.
Note: The expansion of Addis Ababa onto some of the most fertile agricultural lands illustrates a challenge experienced by virtually every country, as cities were often established in areas with high potential for agricultural production.

We have three options. All of them require an understanding of land potential. (1) We can better match land use and management with land potential to *reduce the rate of land degradation*. (2) We can increase the production of currently managed lands by setting attainable targets based on an understanding of the potential of each hectare of land. (3) We can increase the potential production of currently managed lands through the development of innovative management systems and improved crop varieties. Each of these new technologies must be carefully evaluated and adapted for each type of land in order to (a) maximize their impact, and (b) avoid unintended consequences, including both degradation of the land itself, and off-site impacts. For example, a technology that increases corn production but also increases soil erosion on some types of land must be promoted only for those lands where it is sustainable.

Virtually all land has the potential to support multiple ecosystem services. In some cases, provision of these services is non-exclusive (e.g. the provision of clean water and wood products is complementary in sustainably managed forests), while in others it is exclusive only for the period of use (Table 1). Pavement (sealing) and many types of land degradation, including but not limited to soil erosion, result in high opportunity costs unless very high discount rates are assumed for the value of future ecosystem services from the land. Evaluation of land potential is necessary to target efforts to maintain and restore natural ecosystems. Evaluation may also enable land managers to increase the factor productivity of land while reducing land degradation and increasing resilience.

This document briefly reviews existing tools for land potential evaluation, how they have been applied and how their application can have significant, positive impacts on national food security (Section I). It highlights opportunities for improvement of these tools to make them more useful and relevant to changing societal challenges (Section II), and introduces specific policy options for applying land potential evaluations at hectare to national scales (Section III).

Land potential evaluation for decoupling increased agricultural production from land degradation

Knowledge and understanding of land potential can be used in at least five ways to decouple increased agricultural production from additional land use change (including surface sealing associated with urbanization and infrastructure development) and land degradation. For additional discussion of policy opportunities for decoupling, please see Section III.

Table 1. Impacts of different land uses on land potential over the short-, medium- and long-term *

	Short-term (during period of use)	Medium-term (next human generation)	Long-term (future generations)
Biodiversity + watershed conservation	Moderate	None	None
Crop production (nutrient replacement; limited soil loss)**	High	Low	Low
Crop production (no nutrient replacement; limited soil loss)**	High	Moderate	Low
Crop production (no nutrient replacement; high soil loss)**	High	High	Moderate
Mining (with regulation - soil stored and replaced)	High	Moderate	Moderate
Housing, industrial, commercial and infrastructure	High	High	High

Notes:
*Actual extent and duration of impacts will vary, depending on the precise nature of the land use, local and regional variability in soils, topography and climate.
**Crop production scenarios assumes re-colonization by plant, animal, microbial communities by the next (human) generation

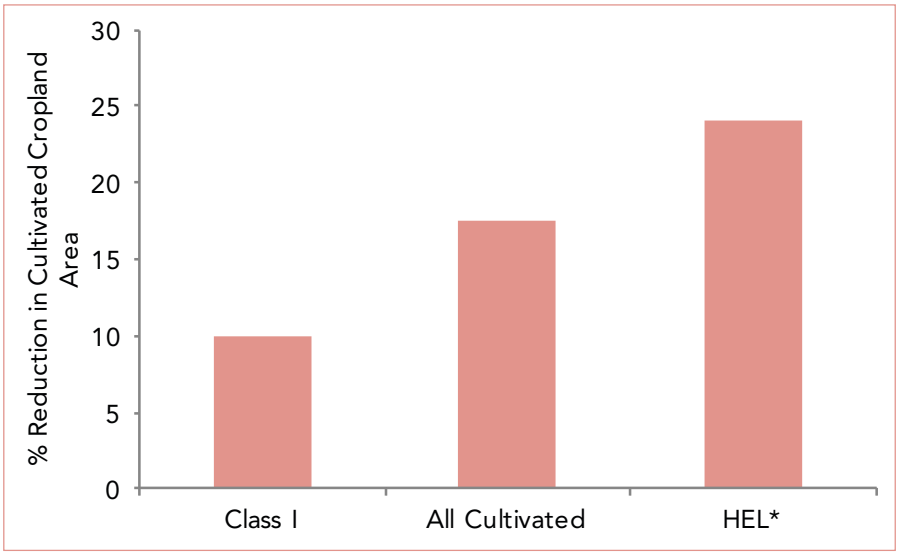
1. **Identify existing agricultural lands where current production systems are unsustainable.** A series of relatively high rainfall years in a semi-arid or dry sub-humid region can make some agricultural production systems appear to be sustainable in areas where, when long-term weather patterns are considered, they are not. Catastrophic examples of the impacts of ignoring land potential and the sustainability of production systems include the degradation of southwestern United States rangelands in the late 19th and early 20th centuries. Unsustainable land use and the resultant "Dust Bowl" stripped billions of tons of fertile grassland soil from cultivated fields in the United States Great Plains during the 1930's (Figure 2). This application requires careful risk analysis, including long-term climate data for predicting probabilities of extreme events.
2. **Identify existing agricultural land where "yield gaps" exist.** A yield gap results when yields are below the sustainable potential based on current technologies and management systems. Current national and global estimates of yield gaps are often inaccurate because they are typically calculated by comparing observed yields to the region's highest yield. The highest yielding fields may be managed in unsustainable ways that enable high yields for a limited period of time. Additionally, these high yields are generally located on soils with the highest production potential in the region and are not generalizable to the region's yield potential as a whole. These types of estimations are not only misleading as regional generalizations, but are also imprecise at the farmer field scale because of local variability in land potential. Note that the application of yield gaps should be used with caution to avoid unintended consequences, (e.g. CIAT 2014). See also the discussion of current land use and land cover above.
3. **Carefully match land use and management with land potential,** ensuring the maximum sustainable benefit is achieved from each hectare of land, and target soil conservation to those lands with the greatest degradation risk. The concept of sustainable land use efficiency is similar to that of water use efficiency through greater "crop per drop". It has been most effectively applied through policies designed to limit soil erosion on cultivated lands. For example, targeted incentives and other measures promoted through the EU's Common Agricultural Policy contributed to a 20% reduction in soil erosion on arable lands, and a 9.5% reduction overall (Panagos et al. 2015; Figure 4). This included the adoption of innovative farming systems tailored to farmers' unique needs and objectives.

In the United States, Farm Bill policies focusing on reducing cultivation of highly erodible lands based on the Land Capability Classification System contributed to a much higher reduction in the area of these lands that were cultivated between 1982 and 2012 (Figure 3).

Figure 2. The United States of America's "Dust Bowl"

Source: USDA.
Note: Crop failure and soil erosion on land that lacked the potential for sustainable crop production resulted in significant environmental disaster, economic upheavel, and social dislocations in the central United States during the 1930's "Dust Bowl".

Figure 3. Reduction in cultivated cropland between 1982 and 2012 for each of three types of land guided by application of the Land Capability Classification system



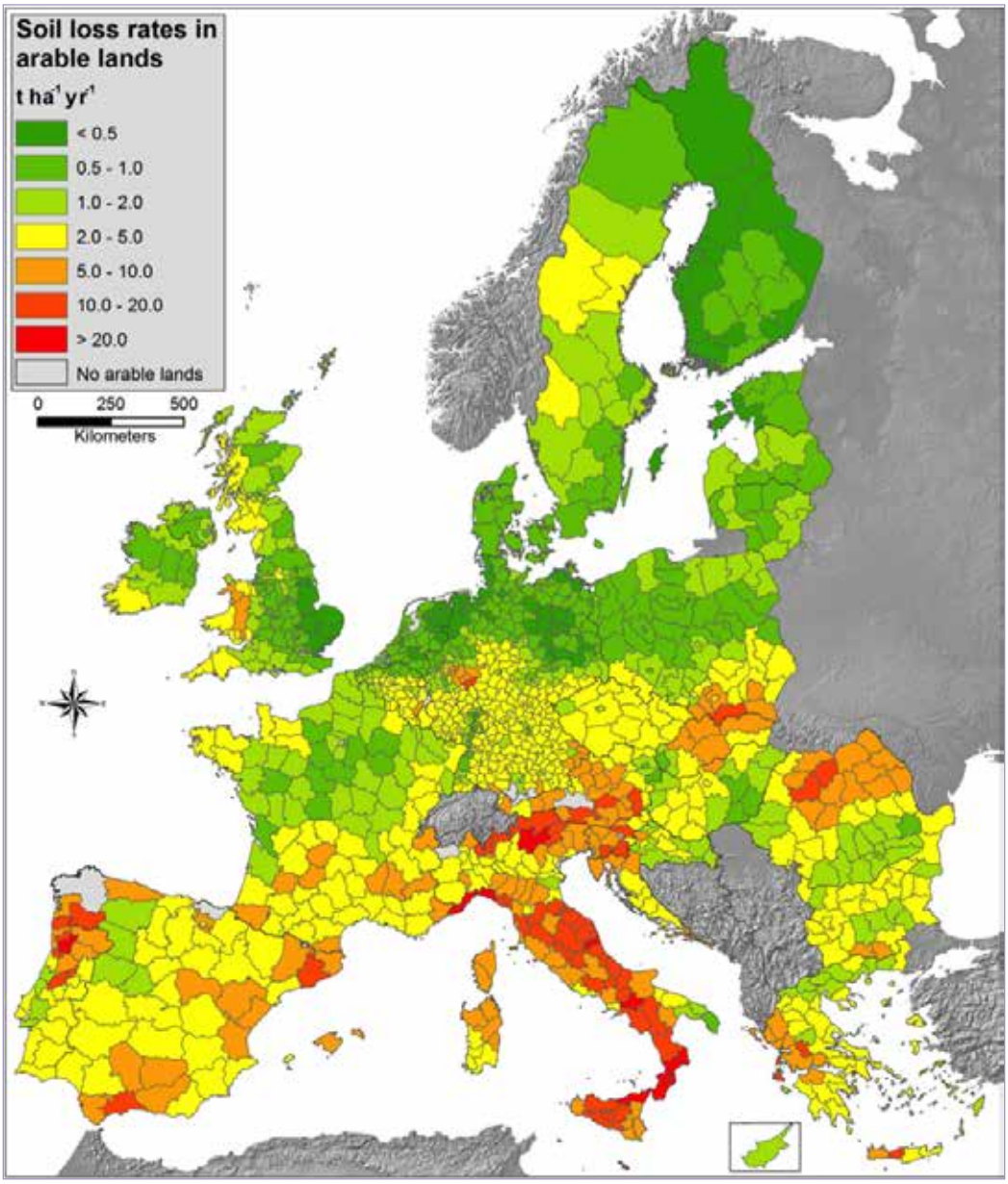
Source: USDA.
Notes: Figure shows that reductions were highest for land at highest risk of degradation.
Class I land has no limitations to crop production (including low erosion risk). HEL (Highly Erodible Lands) were defined for this figure to

include classes IIIe, IVe, VI, VII, and VIII.

4. **Promote innovation** for new management systems and technologies designed to exceed current production potential (See Section II "Innovation").
5. **Promote innovation by facilitating more rapid knowledge and information sharing** among individuals managing similar types of land. One of the key factors limiting the rate of innovation is the rate of relevant knowledge and information sharing among innovators. By linking new management systems to land potential, individuals can rapidly identify innovations developed under similar conditions. These innovations should have a higher probability of success on their own land than new management systems developed under much different conditions.

Each of these benefits may be individually and often synergistically achieved through the development of new tools for generating and sharing knowledge and information about land potential (Section II) and through targeted policy interventions, education, and both public and private investments (Section III).

Figure 4. Modeled average annual soil loss in arable lands in EU countries



Source: Panagos et al. 2015.

Land potential evaluation for targeting efforts to maintain and restore natural and semi-natural ecosystems

Knowledge and understanding of land potential can also be used to increase the short- and long-term returns of conservation and restoration initiatives, including those designed to support biodiversity conservation, restoration and forest management (e.g. REDD+ ;UNEP 2014). Applications include:

1. Prediction of current and future threats of land conversion based on the potential value of the same land for other uses.
2. Prediction of the resilience of natural and semi-natural ecosystems to future stressors. This is a critical, but often ignored, element of biodiversity conservation plans, with the exception of recent increased awareness of climate change. However, even these analyses often ignore how soil variability mediates climate impacts, including drought.
3. Targeting of restoration investments in areas with both high potential to support ecosystem services and a high probability of restoration success, while avoiding those areas with a low probability of success.
4. Identification of areas with the highest probability for supporting rare and endangered species (e.g. Baker et al. 2016).

Land evaluation as a tool for supporting ecosystem services at landscape to regional scales

One of the most promising opportunities is to use the next generation of land potential evaluation tools to support and promote the development of agricultural production systems that match land potential at landscape to regional scales. In addition to increasing production while maintaining, or increasing, soil quality at the field scale, land potential-based management at landscape to regional scales can, for example, result in increased air and water quality, healthier fisheries and estuarine systems, and prolonged production of hydroelectric power through reduced sedimentation of reservoirs.

Land evaluation for forestry

Short-term forestry decisions are based on the age, condition and species present. As forest production increasingly shifts to plantations, however, soil information can be used to help predict potential productivity and fertilizer requirements. Land evaluations can also be used to predict the risk that catastrophic drought may either kill the trees directly, or significantly increase susceptibility to insects and disease. While irrigation is not generally practical, species selection may vary across soil types, following an analysis similar to that in Table 2 below.

Specific applications of land potential evaluation

Land potential evaluation is most commonly used by (1) governments for land use planning and taxation at local to national scales, (2) agribusiness for selecting and guiding large-scale land investments, (3) individual farmers, ranchers, and private consultants for on-farm planning at a number of different scales (Figure 9). In this report, we will show how each of these groups can use an improved understanding of land potential to sustainably increase agricultural production while maintaining or increasing other ecosystem services. We will argue that existing land potential knowledge and information could be more effectively applied by a number of other groups, including local and international development organizations, to increase returns on investment.

Key concepts and definitions

What determines long-term land potential and how is it related to short-term potential, and relatively static and dynamic soil properties?

Lands with similar *long-term* potential have similar (1) inherent (relatively *static*) soil properties including soil texture, depth and mineralogy, (2) topography, and (3) climate. These are the fundamental intrinsic properties of the land that control primary production. Together, these properties and the primary production they support determine potential degradation resistance and resilience. For example, land with deeper soils and higher precipitation will usually support more vegetation production, which offers both greater resistance to erosion through protection of the soil surface and greater resilience through quick regeneration of soil organic matter and soil structure. Soils with higher water holding capacity (clays and loams) require irrigation less frequently than those with low capacity (e.g. Table 2). Table 2 also shows that individual crops vary in response to soil properties.

Figure 5. Land potential knowledge applications and scales at which the knowledge is commonly applied

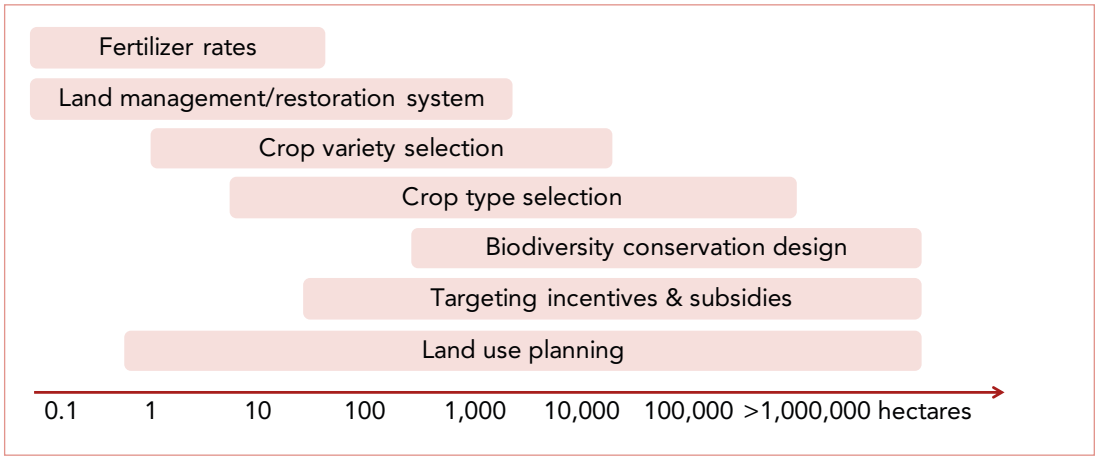


Table 2. Average percent of years when various crops can be grown without irrigation for different soils in Norfolk, England

Soil Type	Spring barley	Sugar beets	Potatoes
		%	
Peat	80	60	15
40 cm peat on compact till	55	35	15
Fine sandy loam	40	20	10
40 cm fine sandy loam over sand	30	10	5
Fine loamy over clay	20	15	5
Sand	5	5	0

Source: Calculated from data in Dent and Scammell, 1981.
Note: This illustrates that some soils have lower potential than others (e.g. Sand), and that potential varies by crop, with spring barley being most tolerant to droughty soils. For example, spring barley can be grown on a fine sandy loam soil without irrigation 4 of 10 years (40%), but only 1 out of 20 years (5%) on sandy soils.

The *short-term potential* for an area of land to provide specific ecosystem services at a particular point in time depend on: (1) relatively *static* soil and climate properties that also determine land potential, (2) *dynamic* soil properties, and (3) the condition and productivity of the vegetation itself. Vegetation productivity depends on soil and climate, but is also independently affected by management (Figure 1). Relatively *dynamic* soil properties change rapidly with time and can usually be managed through the use of external inputs, plant cover and species composition (e.g. cover crops), and disturbance (e.g. tillage). Dynamic properties include water table depth (Figure 7), soil organic matter, nutrient availability, structure, and often salinity. Salinity can also be a relatively static property if the material from which the soil is derived is saline.

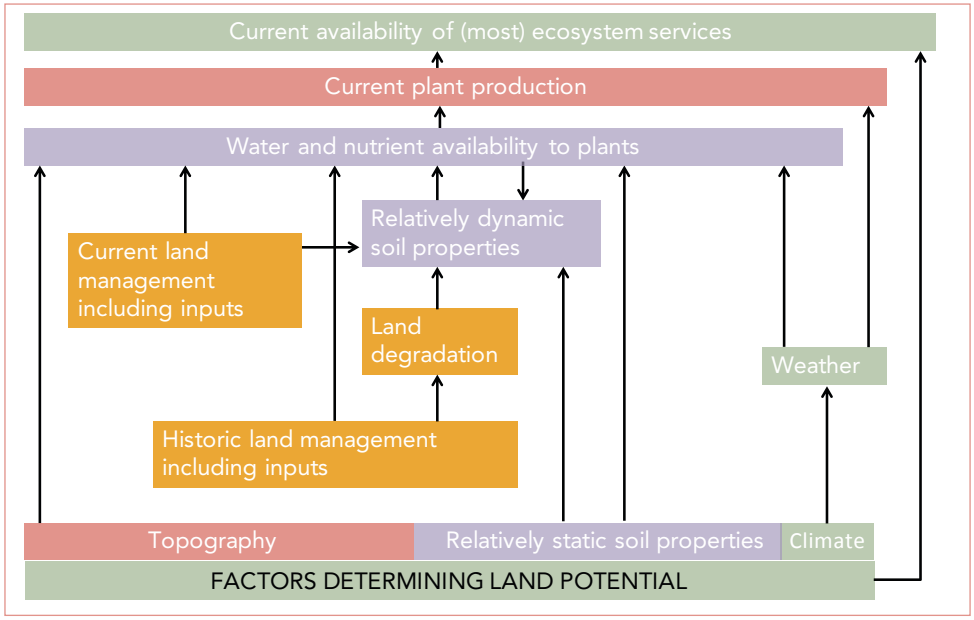
Can land potential be permanently or temporarily increased?

Sometimes. The inherent potential of a particular piece of land can be *relatively permanently* increased or decreased through a change in the following three groups of factors. (1) *Relatively static soil properties* change with erosion, deposition, mechanical inversion of the soil profile, (2) *Topography* can be changed through the modification of the land surface, provided that the modification is geomorphically stable without maintenance. Terraces that are not maintained, however, can ultimately increase soil erosion (Figure 8). (3) *Climate change* permanently modifies land potential, but irrigation does not. Like fertilization and terracing, irrigation represents an attempt by humans to temporarily exceed land potential.

Land potential can be *temporarily* increased through the provision of inputs that reduce limits to plant growth, such as fertilizers and irrigation. Where the problem is too much water, excess amounts can be removed by installing and maintaining sub-surface tile drains, or even through active pumping, as occurs in many low-lying areas of northern Europe.

Instead of increasing plant limiting resource availability through water and nutrient inputs, which is a temporary solution, land potential can also be *permanently* exceeded by increasing resource use efficiency. This can be achieved by breeding plants that are better able to extract, conserve and utilize these resources, and through the development and adoption of innovative management systems that do the same. Please see "Raising the bar" below.

Figure 6. Relationship between factors determining long-term land potential and the land's short-term potential to generate ecosystem services.



Note: Inputs include nutrients, water, organic matter and energy

Figure 7. Effect of soil type on relative declines in potential grass production with lowering of the water table for four soils in the Netherlands

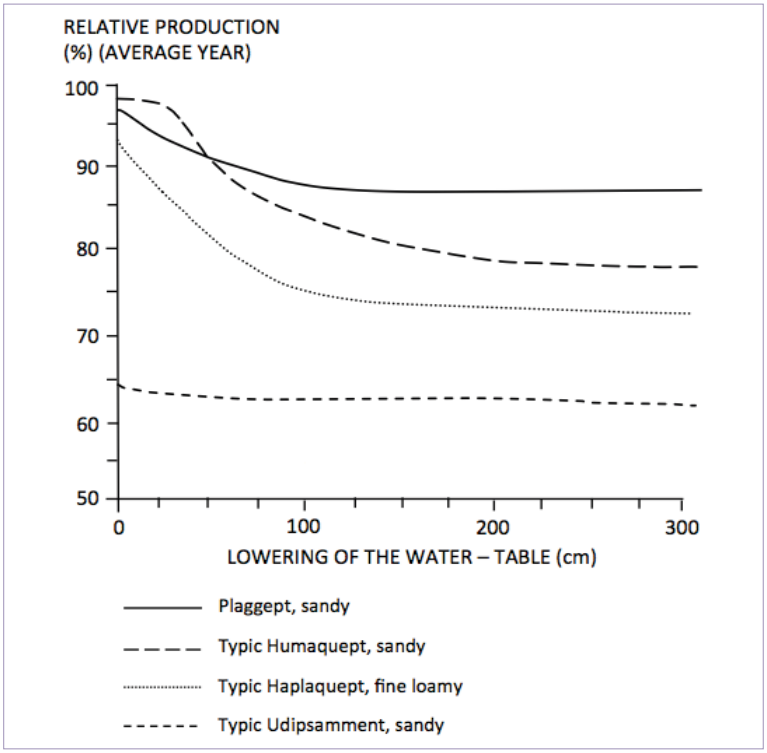


Figure 8. Terraced hillsides in Northern Germany (a) and Ethiopia (b)

Source: J. Herrick and G. Zeleke.

Note: Lack of terrace maintenance, likely associated with changes in the ratio of the value of agricultural production and the cost of labor necessary for maintenance, resulted in destabilization of terraced hillsides in northern Germany (a), while they are being maintained in this photo from Ethiopia (b). This demonstrates that terraces allow land potential to be exceeded only while they are maintained. When abandoned, they can leave the land susceptible to even greater rates of erosion than before it was converted to agriculture until the original slope is re-formed and stabilized by native vegetation.

Does soil biodiversity contribute to land potential?

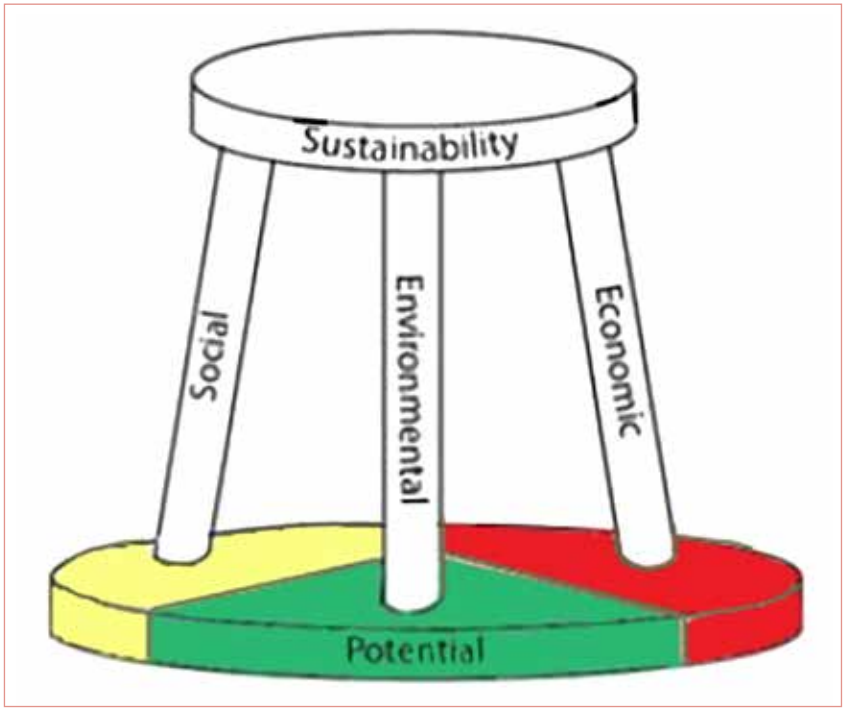
Soil biodiversity is a dynamic property of the soil, like soil organic matter and soil fertility, which *depends* on long-term land potential. The vast majority of soil biota ultimately depends on photosynthetically fixed carbon (i.e. plants). Where there are no plants or other organic matter, there are virtually no soil biota. Additionally, the potential biomass and diversity of the soil biota community depends on the physical factors that determine overall land potential, including climate and soil texture, mineralogy and depth. Feedbacks between plant and soil biota communities and soil disturbance (e.g. by management) determine the soil biodiversity at any particular point in time.

Potential soil biodiversity is much higher, for example, in the Amazon than in Antarctica. Like vegetation, managing for soil biodiversity is necessary to realize the full potential to support many ecosystem services (Wall et al. 2012). In summary, soil biota *depend* on long-term land potential, and *contribute to* short-term potential through, for example, soil biota contribute to soil nutrient cycling, which is necessary to maintain soil fertility. For more information on the role of soil biodiversity in supporting ecosystem services, please see Wall et al. 2012 and the new Global Soil Biodiversity Atlas.

What is the role of current land use and land cover in determining land potential?

There is a strong tendency to confound current land use and land cover with inherent land potential. This confusion exists in many of the existing land potential evaluation systems. For this reason, it is critical to first define land potential for a particular piece of land, then identify potential land uses, and *only then* select from among the sustainable land uses that is based on potential. Evaluation of land potential is therefore an *element* of land use planning processes, which are frequently designed to address specific land use objectives based on social and economic factors (Jones et al. 2005; Figure 9). See also the discussion of yield gaps below.

Figure 9. Three legged sustainability stool showing land potential as the foundation of the environmental leg for terrestrial ecosystems



What is the relationship between land potential and land evaluation?

In 1985, the Food and Agriculture Organization of the United Nations (FAO) defined land evaluation as "the process of assessment of land performance when [the land is] used for specific purposes" (FAO 1984). Land evaluation was later defined as "all methods to explain or predict the use potential of land" (van Diepen et al. 1991), while Rossiter (1996) defined land evaluation as the "process of predicting the use potential of land on the basis of its attributes".

Land evaluation aims to answer the following questions (FAO 1976):

1. How is land presently managed, and what will happen if present practices remain unchanged?
2. What possible improvements of management practices are feasible within the present use?
3. What other uses of land are physically possible, economically and socially relevant, and which of these offers sustained production and benefits?

This report focuses on the potential net primary production of the land as the *foundation* for use-specific land evaluations. Evaluations must consider social and economic factors that may increase the potential for a particular piece of land through external inputs and technology, or may limit potential uses based on, for example, the impacts of a particular land use on the use of adjacent land (Rossiter 1996, FAO 2007).

What is the relationship between land potential and "safe operating space"?

The concept of a safe operating space (SOS) has been proposed for a number of earth system processes, including land use change (Rockström et al. 2009, UNEP 2014). An understanding of land potential is necessary to maintain land use within the SOS. From local to global levels, an understanding of land potential can be used to reduce the amount of land required to meet human needs by taking advantage of unexploited opportunities to sustainably increase generation of ecosystem services per unit area.

Additional definitions

Hyperlinks are provided for other key terms used in this report where commonly accepted definitions exist. Where necessary, we have also included in-text definitions the first time a term is used. The primary sources for these definitions are: http://www.unep.org/resourcepanel/Portals/24102/PDFs/IRP_Draft_Glossary.pdf and Oxford Dictionaries.

Existing literature

There is a large body of literature that includes textbooks describing, promoting, and assessing individual land evaluation systems (e.g. Dent and Young 1981, EUROCONSULT 1989, McKenzie et al. 2008). The FAO completed a review of the Agro-ecological zoning system that included recommendations for the system's enhancement (FAO 2007). This included a strong emphasis on participatory land use planning processes. This literature, and the earlier development of the Land Capability Classification and Agro-Ecological Zoning Systems (see Section I), supported the generation of a large number of local to national studies between 1960 and 1990 that were generally published in the grey literature. Some have been scanned, but many of the earlier ones are slowly disappearing into refuse and recycling heaps. Land resource surveys in current and former British overseas territories were cataloged in a fascinating book by Young (2007). The summary in Appendix 2, together with the WOSSAC.com and ISRIC.org websites can be used as a starting point for locating archived copies of these maps and publications. The survey dates reflects the global decline of work on land evaluation (Dent and Dalal-Clayton 2014; Young 2007).

A recent review of the current status of land resource information (Dent and Dalal-

Clayton 2014), concludes that (a) the amount of information necessary to complete land evaluations that is currently being collected is woefully inadequate (page 9), and (b) the technical capacity necessary to generate and interpret this information has declined significantly (page 45). Both of these conclusions are supported by the decline of soil survey and land evaluation in countries such as the United Kingdom, Australia and Namibia. The Namibian Ministry of Agriculture, for example, employed just one soil scientist in 2015.

Our report is influenced by a theoretical framework for land evaluation (Rossiter 1996), and by published responses to it (Bouma 1996, Burrough 1996, de Gruijter 1996, van Ranst 1996, Johnson 1996, McBratney 1996). In particular, we took note of the observation that, "the theoretical approach, does not provide "…answers to often-asked questions, such as how to determine weighting factors or how to rate land-use requirements" (van Ranst 1996). Recognizing this limitation, we have focused this report on providing practical policy and management options that can be applied immediately, while acknowledging that many of the ideas proposed by Rossiter remain relevant and merit further research.

Recent conversations with national policymakers involved in land use planning in several countries indicate that a review is necessary to provide policymakers with the capacity to select appropriate land evaluation tools for informing decisions based on land potential. These tools need to be able to (1) advise on solutions to emerging land use conflicts, (2) take advantage of newly available technologies and sources of information, (3) evolve with the development of innovative technologies and climate change, and (4) explicitly consider land *resilience* in addition to land potential production and degradation resistance.

All of the literature cited in this report is available on the report's website at http://landpotential.org/additional-resources.html. This website is being continuously updated with links to additional relevant reports and websites. The entire contents of the literature database can be downloaded to both commercial and free (e.g. Mendeley) bibliographic software programs.

Public website and embedded hyperlinks

Website

This report is supported by a publicly-available website (http://landpotential.org), which provides additional information, including links to the tools described in this report. It also allows users to connect directly from the electronic version of this report to cited articles and publications (subject to access limitations). The authors, in cooperation with the U.S. Department of Agriculture's Agricultural Research Service (USDA-ARS) Jornada Research Unit, will continue to update this website as resources allow.

Hyperlinks

In addition to the hyperlinks to cited publications, the electronic version of the article will include numerous links to directly connect readers with additional online resources, including definitions, and relevant webpages.

Credit: DnDavis, Shutterstock.com

SECTION I

Existing land potential evaluation systems: review and applications

1.1 Introduction

This section provides an overview of two of the more widely applied land potential evaluation systems (1.2 and 1.3). This is followed by a brief overview of applications of land evaluations. A set of case studies illustrating the global diversity of applications is provided in the Appendix. The summary and conclusions consider the utility of existing systems and identify challenges to their application. This section is limited, in part, by the dwindling number of individuals engaged in land potential evaluation, and qualified to provide case studies. A somewhat more extensive and even more critical review of the current status of land evaluation globally is provided in the International Institute for Environment and Development report (Dent and Dalal-Clayton 2014).

1.2 USDA Land Capability Classification (LCC) System and Highly Erodible Lands (HEL)

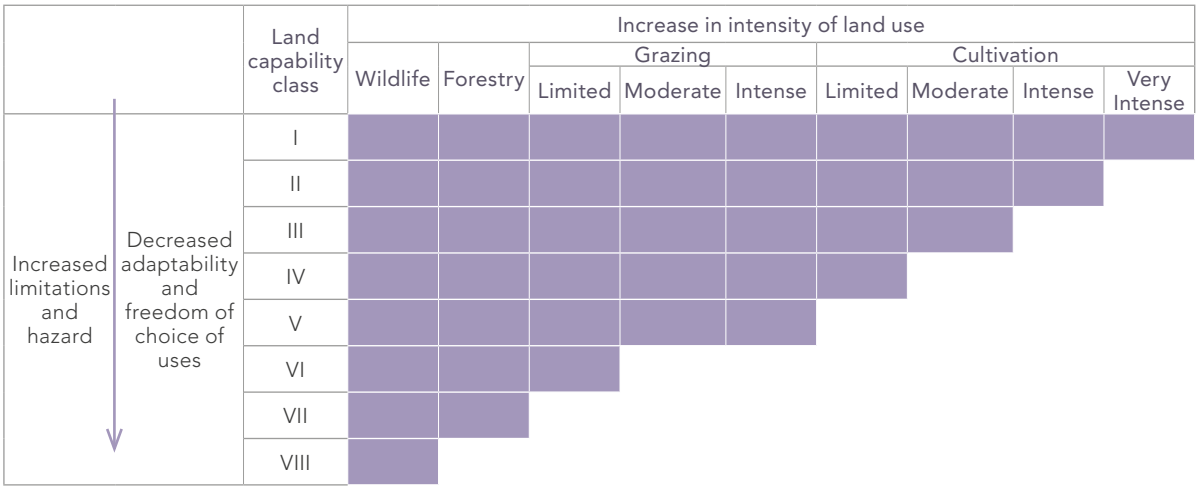
The Land Capability Classification (LCC; Figure 10) system, developed in the United States in the 1930s, was one of the first widely applied land potential evaluation systems designed specifically to inform appropriate land use in efforts to prevent land degradation. The LCC provided a framework for classifying land by grouping soils on the basis of their capacity for producing commonly cultivated crops and pastures relative to the capacity of other soils in the same region (Klingebiel and Montgomery 1961, NRCS 1973). The LCC system parses land into eight classes based on broad interpretations of soil and topographic factors that affect agricultural yields and soil erosion. Criteria include location in the landscape, soil texture and depth, slope, and other soil properties that impact plant growth and erosion risk. Classes I to IV are considered suitable for agronomic production and cultivation, with varying levels of conservation treatments required to ensure sustainable yield and minimize environmental impacts based on the above criteria. Classes V to VII have limitations associated with them that make the land more suitable for pasture, range, or other management uses. Limitations of Class VIII land are so severe that it generally cannot be sustainably and productively managed for any type of resource extraction.

There are eight classes:

- Class I soils have only slight limitations that restrict their agronomic use.
- Class II soils have moderate limitations, which reduce the producer's crop selection and/or require moderate conservation practices.
- Class III soils have severe limitations that reduce the crop options and/or require special conservation practices.
- Class IV soils have very severe limitations that restrict the crop options and/or require robust conservation management plans.
- Class V soils are not prone to erosion, but agronomic production is restricted by other limitations that are impractical to remedy; these soils are typically used as pasture, rangeland, forestland, or wildlife habitat.
- Class VI soils have severe limitations that make them unsuitable for cultivation; these soils are more suitably managed as pasture, rangeland, forestland, or wildlife habitat.
- Class VII soils have very severe limitations that make them unsuitable for cultivation; these soils are typically managed as rangeland, forestland, or wildlife habitat.
- Class VIII soils are unsuitable for cultivated cropland production or grazing management, but may be used for recreation, wildlife habitat, water supplies, and/or aesthetic purposes.

All soils, except Class I, exhibit one or more limitations that must be managed for agronomic production to be sustainable. These limitations are defined by four "capability subclasses" which are defined based on the factor causing the limitation. They include erosion susceptibility, excess water, climatic limitations, and other soil limitations. Soil limitations can include stoniness, low-moisture holding capacity, low levels of fertility that are difficult to correct, high salinity, rooting restrictions, or tendency for shrinking and cracking when drying.

Figure 10. USDA Land Capability Classification system matrix showing that the range of sustainable land use options declines for land with high (Class I) to low (Class VIII) potential



Land in each subclass may be further divided into "capability units" on the basis of common response to management. The soils in each capability unit are similar enough that their production and conservation plans will be the same: they will be suited to grow similar crops, require similar conservation management, respond similarly to the same management, and provide similar production.

Soil class determinations in the LCC system can change over time due to management-induced changes. For example, accelerated erosion and salt accumulation can reduce soil potential, while new crop varieties or new farming technologies, such as no till, may support sustainable production on land where it was not previously possible.

In his review of the LCC, Helms (Helms 1997) emphasizes that the system was designed to support farm-scale soil and water conservation. The qualitative LCC system is based on local observations, local farmer and rancher knowledge, and science, enabling provision of sound management guidance at the land-manager scale. However, the qualitative and subjective nature of the assessment, while making the system adaptable to local conditions, also contributes to a limitation— inconsistency at larger spatial scales. The LCC was not designed to be used as a decision support tool across large areas, but rather to contextualize land use decision-making in a specific geographical area. In other words, a specific soil series may be classified as a class II soil in one location, while in a distant location the same soil might be classified as a class III soil. Where required, the extent of inconsistency can easily be evaluated, at least for soil erosion, by applying soil erosion models to a range of soil types in each of several states with similar soils, climate, and topography.

In 1985 the application of LCC as a soil conservation policy tool was largely replaced in the United States by use of "Highly Erodible Lands" designations: land with an erodibility index of 8 or more. In order to receive government support for crop production on these lands, producers must develop a conservation plan, and maintain a conservation system of practices that keep erosion rates low (USDA-FSA 2012).

However, the LCC assessments continue to be made available for most land in the United States through the Web Soil Survey (USDA-NRCS 2013). It is used in the development of some farm-level conservation plans, which are required for some government support programs, including the Conservation Reserve Program, which pays farmers not to farm highly erodible lands, wetlands, and land with high

value for wildlife habitat. It is also used in some areas for land valuation for taxation, and has also been applied by other countries, including New Zealand, which developed 1:63,360 scale maps for the entire nation (New Zealand Ministry of Works and Development 1979).

1.3 FAO Agro-Ecological Zoning (AEZ and GAEZ) System

Overview

The FAO has developed both a framework for land evaluation (FAO 1976, FAO 1996, Verheye 2007) and a system for predicting the potential production of a wide variety of crops for specific different types of land.

The original FAO evaluation framework was first presented at a meeting in Wageningen, the Netherlands, in 1972. The framework was further discussed and refined, and eventually published in 1976 as "A framework for Land evaluation" in an FAO soils bulletin (FAO 1976, Verheye 2007). This framework differed from earlier systems by starting with the requirements for a particular land utilization type (LUT), which was then matched to the land under evaluation. A land utilization type is a "kind of land use defined in more detail [than a major land use], according to a set of technical descriptors…in a given physical, economic and social setting" (FAO 1976). The term LUT is often equated with the "farming system".

The framework describes land evaluation as being concerned with the assessment of land performance when used for specified purposes, and stresses that alternative land use types have not only to be limited by climate, soils and vegetation, but also physical, social and economic context of the area being considered (FAO 1976).

The 2007 revision emphasizes the need for a bottom up approach to evaluation, involving stakeholders at all stages of the process and including the addition of an environmental impact and risk assessment section to the valuation process. It expands on many of the criteria from the first framework, reflecting contemporary problems like carbon sequestration and the value of biodiversity. The revised framework also reflects the importance of monitoring the agro-environment and accounting for problems, both environmental and socio-economic, arising from the competition among land uses. It is still, however, based on the understanding that land use options are ultimately constrained by the biophysical potential of the land. This biophysical potential is operationally defined through the Agro-ecological Zoning system.

Agro-ecological Zoning (AEZ)

The 1976 framework established the conceptual and methodological basis for land evaluation (Figure 11). In 1978, the FAO Agro-ecological zones project was initiated (FAO 1976). This was an early application of land evaluation to large areas based on biophysical potential. It involved land characterization using quantified information on climate, soils, and other physical factors. The end product was aimed at predicting the potential production for various crops according to their specific combination of management and environmental needs.

An Agro-ecological Zone is a land resource mapping unit, defined in terms of climate, landform, soils, and/or land cover, and therefore with a specific range of potentials and constraints for land use.

The essential elements for classification are:

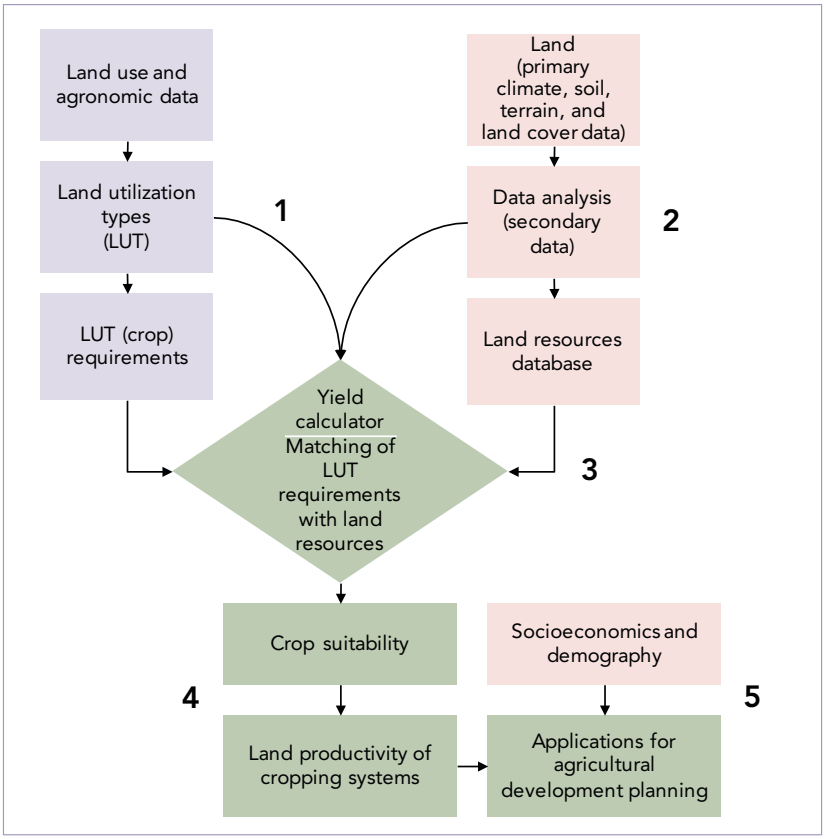
- Land resource inventory
- Inventory of land utilization types and crop requirements
- Land suitability evaluation, including:
    - Potential maximum yield calculation
    - Matching of constraints and requirements

The Agro-ecological Cell (AEC) is the basic processing unit for physical analysis in an AEZ study. An AEC is defined by a unique combination of landform, soil, and climatic characteristics. In

theory, the methodology and input variables into the AEZ are scale independent. The objectives of the study and the map scale define the level of detail to which factors, such as soils, climate, and land utilization types, are defined.

The concept of the growing period is essential to AEZ, and provides a way of including seasonality in land resource appraisal. In many tropical areas, conditions are too dry during part of the year for crop growth without irrigation, while in temperate climatic regimes cold temperatures limit crop production in winter. The growing period defines the period of the year when both moisture and temperature conditions are suitable for crop production.

Figure 11. Conceptual framework for the Agro-ecological zones methodology.



Source: FAO

For estimation of potential productivity, AEZ uses the concept of a maximum attainable total biomass and yield. For a specified Land Utilization Type (LUT), the potential maximum yield is determined by: (1) the radiation and temperature characteristics of a particular location, (2) the photosynthetic efficiency of the crop, and (3) the fraction of net biomass that the crop can convert to economically useful yield. This potential maximum yield is used as an input to the process of matching of agro-climatic and edaphic requirements with the qualities and characteristics of the land units defined in the inventory.

The FAO has done an impressive job of developing thousands of LUT's and effectively documenting the range of variability in current agricultural production systems. The result, however, also illustrates the practical limitations of any classification system that mixes land use with land potential. First, the number of possible combinations is virtually infinite. A commonly cited example from Kenya illustrates that despite the complexity of the system, the recommendations remain quite general. Even at this finest level of definition, statements such as the following are necessarily common: "…The major constraint

is the unreliable rainfall in both short and long rainy seasons. Shallow stony soils may occur, which render ox-farming both technically and economically impossible, as well as slopes…" (FAO 2014). Second, like the LCC, the FAO AEZ system has the potential to stifle innovation by forcing innovative land management systems into pre-existing boxes, rather than dynamically evaluating each new system (see Section II). The AEZ has been adapted for application for a number of countries, including Canada, where it was used to develop the "Land Potential Data Base" (Kirkwood et al. 2013).

Global Agro-ecological Zoning (GAEZ)

Advances in information technology since 2000 have made classification of *Global* Agro-ecological zones possible. The GAEZ is a powerful, web-based tool that allows anyone to determine the potential production of hundreds of crops virtually anywhere in the world based on global soil and climate databases (Fisher et al. 2002). Accessing the "Agro-ecological suitability and productivity" sub-section of the "Suitability and Potential Yield" section of the GAEZ Data Portal allows the user to select from three different levels of inputs. Please note that simple registration with FAO is required, with subsequent guest login (located in the upper right corner of portal as of 7 October 2014). This system enables general predictions of potential production of different crops. Unlike the LCC, which focused on sustainable long-term production and minimal soil deterioration, the GAEZ focus is on agricultural productivity rather than sustainability.

1.4 Land potential evaluation for valuation and taxation: the European experience

Europe provides numerous examples of how land evaluation has been used to guide resettlement, reclamation, and especially taxation. It has been an integral part of many cadastral surveys. Recorded use of surveys dates back to the Roman Empire and there are numerous examples of how land potential was implicitly or explicitly integrated into land valuations. "The Cadastral Map in the Service of the State: A History of Property Mapping" (Kain and Baigent 1992) provides a thorough review of land mapping, and includes a large number of specific examples. A 1:15000 map of a lowland area in Italy commissioned in 1570, identified land susceptible to flooding (ibid, p. 332).

There are a number of historical examples of potential-based land evaluations being used to support cadastral registries. Russia has been using a land rating system based on potential yields and underlying soil information since 1859 (Goryelik 1967). The Austro-Hungarian monarchy introduced land cadaster and 1:2.880 scale map sheets, including yield capacity-based land values dating back to 1875 (http://www.cadastraltemplate.org/). As a first step towards a multi-purpose cadaster, detailed soil assessment data have been recorded in German cadasters since 1934 (Mohr and Ratzke 2009).

To the extent that different types of land were valued differently based on their characteristics, the current use and condition or *status* of the land, rather than its potential, historically received sometimes more attention. This was particularly the case for forested land where tree cover could be viewed as an asset, because of the value for timber (e.g. France, ibid, p. 210 ff), or as a liability, where removal of woody vegetation was a cost of conversion to agriculture.

Today, the contribution of biophysical land potential to land valuation in wealthy, densely populated countries is often minimal relative to other considerations, such as location of the land in relation to markets, infrastructure, and other amenities. This is due to the premium placed on land for residential and commercial purposes. It also reflects the extent to which some factors limiting land potential, such as low rainfall, soils with low nutrient retention capacity, steep slopes, and poor drainage, can be overcome with management inputs, such as

irrigation, slow-release and split applications of fertilizers, terracing, and drainage systems (Figure 12). The use of technology to overcome land potential limitations can, however, result in catastrophic degradation in the future if inputs are not maintained (e.g. Figure 2).

1.5 Sub-surface resources: a footnote

Defining potential of land for "above ground land uses" by implication can help inform decisions regarding the use of the land for other competing uses, such as mining of sub-surface resources. The land-potential evaluation systems described here do not address potential for sub-surface resource development. However, they *can* be used together with additional information to support benefit-cost analyses of different sub-surface resource exploitation strategies. For example, directional drilling is much more expensive, but allows for a much smaller footprint on the land surface per unit resource extracted because a larger volume of oil and gas is accessed with multiple wells from a single platform than is possible from a single, vertical well. An evaluation of surface land potential can be used to help decide whether to make a larger investment in minimizing surface impacts.

Figure 12. Land near Berlin, Germany with low potential for agricultural production due to poor drainage

Source: J. Herrick.

Figure 13. Sub-surface resources should be considered when applying land evaluation to land use planning

Crédit: HildeAnna, Shutterstock.com.

1.6 Summary and conclusions: existing land evaluation systems

Land potential evaluations based on both the LCC and AEZ systems have been widely applied at farm to national levels throughout the world. More complex, and in some cases comprehensive, evaluations have been generated using systems such as ALES (Section 3.1) and by applying the basic concepts of land evaluation as described in textbooks (e.g. Dent and Young 1981, McKenzie et al. 2008). A subset of these evaluations has been used to guide land use planning. An even smaller subset of these plans appears to have been used to guide management (Bacic et al. 2003).

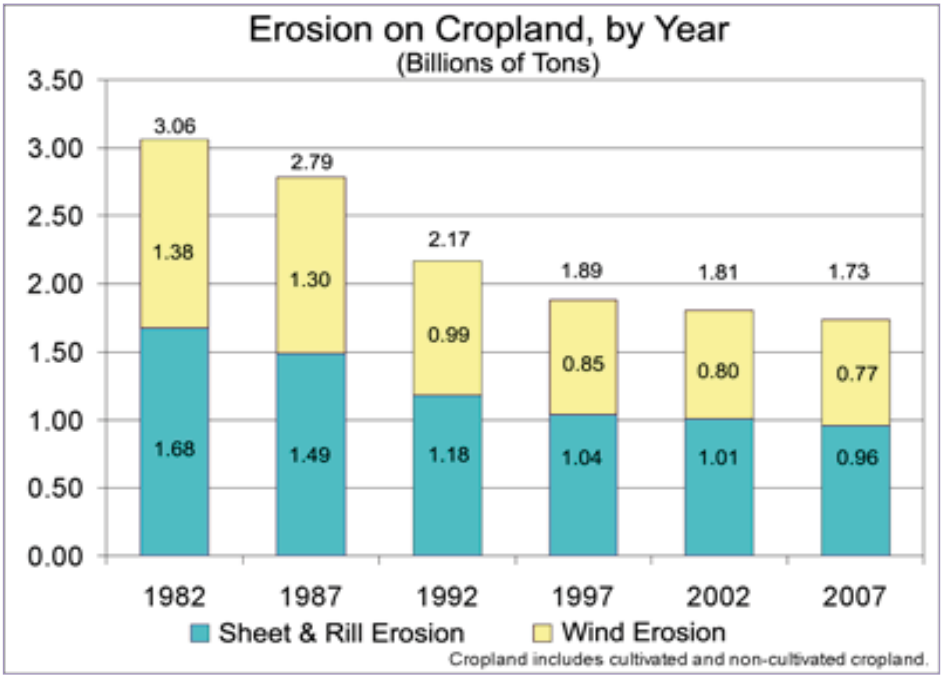
The widespread application of the simpler LCC system long after the introduction of the AEZ and other more sophisticated approaches is perplexing. There are two possible explanations why it, together with the US Bureau of Reclamation's classification system for irrigated land (FAO 1985), remain the most widely used systems land evaluation systems (Dent and Dalal-Clayton 2014). One is that the LCC addresses both sustainability (erosion) and productivity limitations, while AEZ focuses on potential productivity. The second is that it is simpler to apply and understand. In Zambia, for example "soil maps and land evaluation following the latest FAO guidelines were eschewed by planners who continued to use the familiar Land Capability Classification" (Woode 1981 cited in Dent and Dalal-Clayton 2014).

In one of the few published studies attempting to explain the lack of application of land use decision support tools, agricultural extension specialists were surveyed to determine the "success of a large land evaluation exercise undertaken as part of micro-catchment project in the Santa Catarina State, southern Brazil" (Bacic et al. 2003). The primary limitations cited included the lack of: (1) risk assessments of environmental degradation, weather, yields, profits, and markets, (2) financial analysis, (3) social analysis of decision-makers' attitudes and preferences, and (4) lack of a specific definition of land use types. Our own informal conversations with policymakers in several countries reinforces the importance of the fourth limitation, while at the same time reflecting concerns that the more detailed system (AEZ) is too complicated to both implement and interpret. This is despite the fact that the GAEZ has made generalized AEZ predictions easily available to anyone with basic internet navigation skills.

Nevertheless, where land evaluations have been applied to policy and management, they have often had a tremendous impact. Australia, for example, has effectively applied its soil surveys and land evaluation systems through a wide variety of legislation (Capelin 2008). Some of the largest impacts have been achieved with the simplest systems. For example, the USDA has a relatively simple definition of "highly erodible lands" to require the application of conservation practices to millions of hectares of private lands in the United States as a pre-requisite to qualifying for some government programs. This requirement, together with the application of minimum tillage technologies to limit erosion, is often cited to explain the dramatic 40% reduction in soil erosion on US croplands between 1982 and 2007 (Figure 14).

Similarly, the reduction of freshwater wetland loss in the continental United States excluding the state of Alaska from approximately 100,000 ha/year between the mid-1970s to the mid-1980s (calculated from Dahl and Johnson 1991) to less than 2,000 ha/year between 2004 and 2009 (Dahl 2011) was achieved in part by the willingness of policymakers to acknowledge that wetlands provide sufficient ecosystem services to justify preservation and federal support, of scientists to accept a relatively simple definition of wetlands, and of landowners to adopt wetland construction, remediation, and/or conservation on their privately held agricultural lands. The decision to accept a simple definition was at odds with the recommendation of many land evaluation experts who wanted to increase complexity of the definition.

Figure 14. Changes in soil erosion from US croplands between 1982 and 2007



Source: Based on USDA-NRCS National Resource Inventory data.

Based on these observations together with the rates of land degradation described in the first IRP report on land (UNEP 2014), we conclude that there are significant benefits to applying existing (including simple) tools now while also continuing to develop more sophisticated evaluation systems. Even the simplest tools, such as a land use classification systems based on soil erosion risk, can result in massive reductions in land degradation. As the Brazilian study (Bacic et al. 2003) demonstrates, however, application of the biophysical land potential evaluation is necessary, but not sufficient step to applying the results: they must applied with an understanding of socioeconomic and cultural factors that ultimately drive land use decisions.

Credit: ndphoto, Shutterstock.com

SECTION II

Principles for improving existing land potential evaluation systems and developing the next generation

2.1 Overview

Land potential evaluation requires an understanding of numerous biophysical processes interacting at multiple spatial and temporal scales. Ideally, it also requires foresight to predict the climate, human needs, land management systems, and technologies over the next 10, 50, 100 years and beyond. While this is clearly impossible, we *can* increase our ability to accurately predict the response of the land to different *types* of disturbance, because the response of the land depends on a fundamental set of biophysical processes.

This section begins with a brief overview of the biophysical processes that link disturbance, degradation, and recovery. The discussion of recovery is expanded to include resilience in the following chapter. Suggestions are provided on how to incorporate an understanding of spatial scale into land potential evaluations. These suggestions are followed by an introduction to ecosystem services, land potential evaluation tools, and how land potential can be used to promote innovation. The section concludes by integrating the information provided into a simple, practical strategy for estimating land potential today, while continuing to improve estimates for the future.

2.2 Disturbance, degradation and recovery

Disturbance broadly includes anything that causes a change to the state of a system, including management. *Degradation* occurs when the disturbance causes a negative change in the capacity of the system to provide ecosystem services. Whether or not a disturbance causes degradation depends on the properties of both the disturbance and the system being disturbed.

There are 5 types of properties that define a disturbance: type, timing, frequency, intensity and duration. The impact of disturbance on the land is governed by a relatively limited set of well-understood biological and physical forces and processes. The impact of new disturbances on soils can often be predicted simply by analogy with past disturbances through their cumulative effects on these processes. For example, soils that are sensitive to compaction from livestock trampling when wet are also likely to be easily compacted by vehicle traffic. Similarly, an understanding of how a particular soil and climate combination respond to a management system in one part of the world can be applied to predict the response of similar soil and climate combinations to similar management systems in another part of the world. This is the principle that allows tools such as at the Automated Land Evaluation System (ALES) and the global Land-Potential Knowledge System (Section 3.1) to be applied globally.

The same principle applies to recovery. Soils that have a high capacity to recover fertility through weathering under a particular climate will have that capacity, regardless of the cause of the fertility loss. This of course assumes the soil biota that contribute to soil weathering are still present, or can re-colonize the site. Finally, this ability to extrapolate based on physical principles also extends to landscape processes, such as gully formation. In summary, while it is impossible to predict land response to disturbance with certainty, an understanding of soil and landscape processes can be used to improve predictions of land potential.

The relative importance of different types of land degradation therefore varies widely depending on the disturbance regime and recovery capacity (see Resilience). In much of the world, soil erosion is the primary form of relatively irreversible land degradation. In parts of China and other areas with a history of intensive and relatively unregulated industrial activity,

however, soil contamination is believed to be as great or greater of a challenge due to both point-source and diffuse deposition. Pesticides and other agricultural inputs can also cause soil contamination. The Chinese government recently reported that 16.1% of its soil and 19.4% of its farmland has been contaminated by one or more pollutants (Strub 2014).

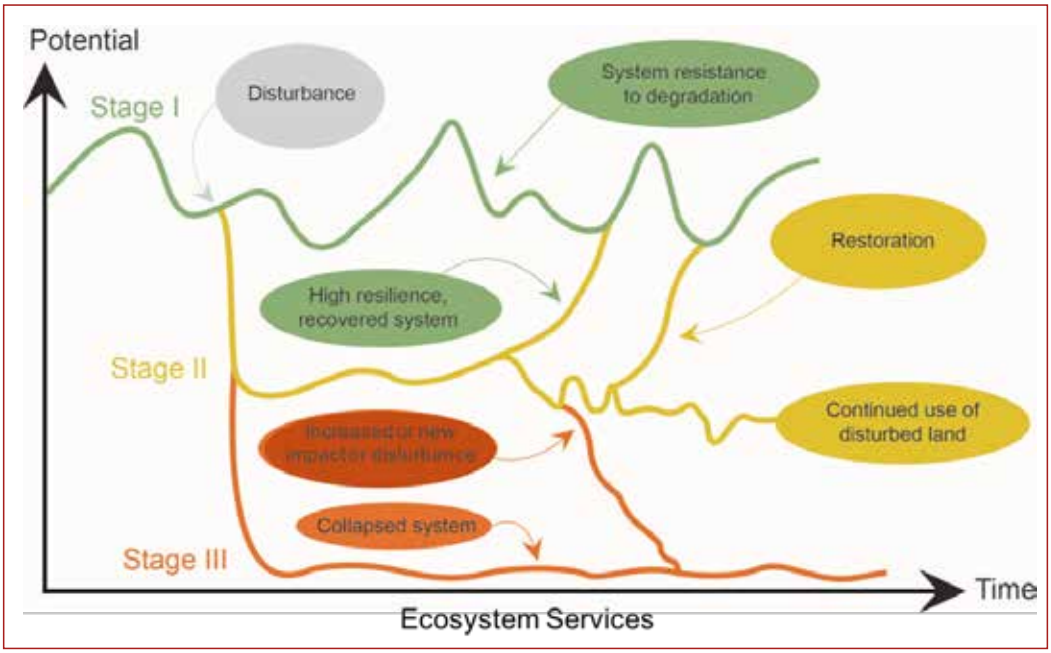
2.3 Resilience

Introduction

Land can maintain its potential to provide ecosystem services by either resisting or rapidly while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al. 2004); Figure 15). From a practical perspective, however, the concepts of resistance and resilience are more effectively applied independently following the definitions used by engineers (Seybold et al. 1999, Pimm 1984, Lal 1997), with resistance defined as the capacity of a system to maintain function through a disturbance and resilience defined as the capacity to recover from disturbance. Resilience can be quantified either in terms of the rate or extent of recovery within a specified time period at one or more spatial scales.

The factors and processes that confer resistance are often quite different from those that support resilience. For example, while the most important factors contributing to long-term erosion resistance are slope and ground cover, long-term resilience primarily depends more on soil depth, which ensures that material remains to re-generate topsoil lost to erosion, while high plant productivity provides the organic matter inputs necessary to support the regeneration of soil structure and nutrient cycling processes. Degradation resistance is already integrated into some widely applied land potential evaluation systems, including the LCC (Chapter 1.2) and ALES (Section 3.1), so the focus of this section is on recovery capacity (resilience).

Figure 15. Conceptual illustration of the impacts of resistance and resilience on temporal changes in ecosystem services



Factors determining potential resilience

The potential resilience of land and soil depends on the same factors that determine potential productivity: topography, relatively static soil properties, and climate. All three of these factors affect resilience primarily through their effects on water and nutrient availability to plants, which provide the organic matter inputs necessary to support nutrient cycling and soil structure development. As for productivity, the *actual* resilience of an area at a particular point in time depends on vegetation and the status of relatively dynamic soil properties (below). Finally, both potential and actual resilience can vary depending on the type, timing, frequency, and intensity of the disturbance (White and Jentsch 2004).

Climate

Climate is clearly the primary factor controlling potential productivity at the global scale. For this reason it is also the primary factor controlling recovery potential.

Topography and geology

Topography affects resilience primarily through the effect of slope, slope shape and landscape position on water runoff rate. Runoff rates are generally higher on steeper, convex slopes, which reduce water infiltration relative to gentler, concave slopes in lower landscape positions, which tend to have higher water infiltration rates. Lower water infiltration rates mean less water available to plants and therefore slower soil organic matter production. Slope and aspect also affect resilience by controlling water loss due to evapotranspiration, particularly at higher latitudes. In colder climates aspect may also impact snow accumulation, depending on the dominant wind direction. Therefore, all of these factors affect plant water availability. Over longer periods, higher soil moisture content also generally results in higher rates of soil weathering, which tends to increase soil nutrient availability, enabling more biomass production, which enhances site productivity with positive feedback loops. Furthermore, topography and geology affect factors such as soil depth, with soft sedimentary rocks more likely to result in resilient ecosystems than shallow soils over hard bedrock. Finally, geology is the ultimate control on soil mineralogy. While mineralogy is also affected by the duration and types of weathering of the parent material, the physical material from which the soil is composed of limits the types and relative amounts of minerals that can occur in a soil. These minerals, and particularly the clay minerals, have an overriding effect on both water holding capacity and the ability of the soil to retain and make available plant nutrients, in addition to serving as the ultimate source of virtually all of these nutrients.

Relatively static soil properties

Relatively static soil properties contribute to long-term soil resilience. These include soil texture and depth (Table 3). Soils rich in clay can store large amounts of nutrients, while those high in silt are better for storing plant-available water, but soils high in sand generally have higher potential water infiltration rates. Therefore, soils with high clay content tend to be more productive and resilient than shallow sandy soils on shallow slopes, in which, if waterlogging is not an issue, nutrients tend to be more limiting than water.

Soil depth affects resilience both directly and indirectly. Very deep (>2m) homogenous soils have higher potential resilience to soil erosion than shallow soils. However, deep soils that are not homogenous vary in their potential resilience. For example, water infiltration rate of a soil with 20cm of sand over a clay layer drops precipitously as the soil surface is removed. Soils with coarser surfaces are quite common throughout the world because clay is translocated to deeper depths as soils form over time.

Table 3. Typical impacts of some relatively static soil properties on resilience in semi-arid to sub-humid regions.

Texture	
High clay content	Ability to store nutrients increases resilience*
High silt content	Ability to store water increases resilience
High sand content	A higher potential water infiltration rate increases resilience, but lower water storage decreases.
Depth	
Deep vertically homogeneous soils	Higher potential resilience
Deep non-homogenous soils	Vary in potential resilience
Shallow soils	Low potential resilience

*Can also reduce resilience where clays reduce availability of nutrient inputs (e.g. from organic matter decomposition and mineralization).

Relatively dynamic properties

Relatively dynamic soil properties, such as soil organic matter, also contribute to resilience. Because they are dynamic, however, they are often impaired as part of the degradation process. Consequently, while they may contribute to degradation resistance, their contribution to resilience depends on their resistance to the particular disturbance. Relatively static properties are therefore better predictors of long-term resilience.

In forest and rangeland systems, vegetation also contributes to resilience (Bestelmeyer and Briske 2012). Plant communities of all types can be, and usually are, dynamic at management timescales. The contribution of different types of vegetation to resilience depends on their persistence through time and response to different types of disturbance, as well as their impacts on key ecosystem processes, such as slowing runoff on sloping soils, or cycling nutrients in low-fertility systems.

Variability and interactions

The impact of topography, soils, and climate on resilience vary widely. An Arctic system may be adapted to drought and have adequate to large nutrient reserves in belowground biomass, but the system may be quite susceptible to wind erosion and trampling. A dryland system with low annual rainfall may be susceptible to overgrazing or cropping, as the organic matter reserves are easily depleted; these same systems may be well adapted to moderate grazing pressures, droughts and other disturbances.

For example nitrogen recovery through natural processes can take tens or even hundreds of years under cold and/or dry conditions where inputs and nutrient cycling (biological activity) are slow. Similarly, natural nitrogen recovery may be slow where the natural substrate is poor (sand, rocks, etc.). Nitrogen cycling rates can clearly be accelerated and directed by human inputs of various kinds (Aradottir and Hagen 2013). Finally, current species composition, a dynamic property of the system, has a major effect on the rate of vegetation changes associated with restoration of natural systems (Whisenant 1999). This in turn, has significant impacts on dynamic soil properties, including soil structure and organic matter content and composition.

Specified vs. general resilience

A distinction between *specified* and *general* resilience (Walker et al. 2009) can help more clearly define the resilience of the system to specific threats, vs. the overall resilience of the system relative to a broad range of disturbances. While all of the factors discussed above are important for a broad range of disturbances, some are more important than others for resilience to more types of disturbance. For example, deep soils with uniform texture throughout the profile often have higher *general* resilience because the soil profile can be reconstructed following soil surface loss or degradation simply through the accumulation of soil organic matter. However, a soil with a higher clay content may have a higher *specified* resilience to contamination by particular types of chemicals because of the larger number of available exchange surfaces.

For a comprehensive guide to integrating resilience into development projects that takes into account both specified and general resilience, please see O'Connell et al. 2016.

Limitations of existing land potential evaluation systems or frameworks in addressing resilience

Some widely applied land potential evaluation systems address degradation resistance (e.g. the LCC). None, however, reflect resilience: the ability of the land to recover, or the potential rate of recovery.

Integrating resilience into land potential evaluation systems

Consideration of all of the factors that affect resilience related to all possible types of degradation is clearly impossible. However, resilience to the dominant forms of land degradation can be predicted through application of a relatively small number of indicators (Table 4). These predictions are necessarily general, and there are many exceptions.

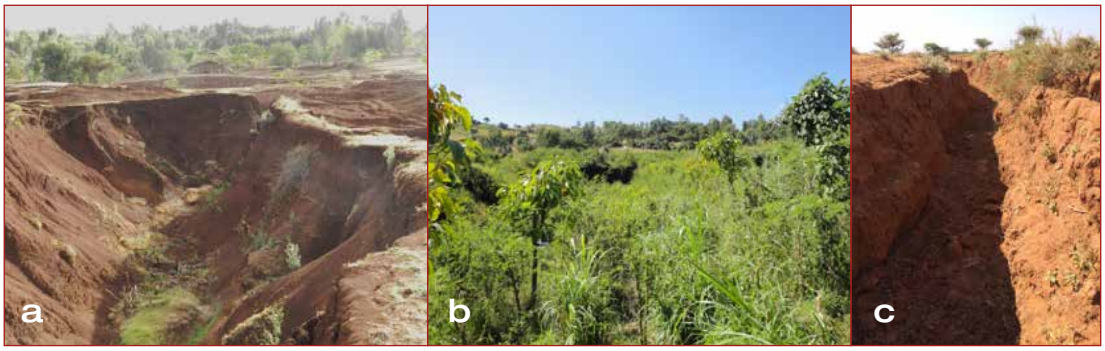
In general, deeper soils, with high soil water holding and nutrient retention capacity, tend to recover from disturbances faster and more completely than shallower soils. The relationships also vary with climate. Topographic positions with high solar insolation will tend to have higher resilience in systems where production is limited by low temperatures, while those with lower insolation will tend to be more productive, and therefore more resilient, where water is limiting.

Table 4. Indicators that can be used to predict resilience to the dominant forms of land degradation.

	Degradation Type			
	Erosion (wind, water, tillage)	Salinization due to elevated saline groundwater	Salinization due to saline irrigation water	Compaction
Resilience Indicators	• Precipitation*	• Drainage	• Precipitation	• Precipitation+
	• Soil depth and texture by depth		• Freshwater flooding	• Clay mineralogy
	• Soil water holding capacity			• Climate with freeze-thaw cycles

+higher plant root production and organic matter inputs to support biological activity
*higher plant production following degradation increases recovery, but precipitation can also cause degradation, especially when plant cover is low.

Figure 16. Examples of results from restoration treatments in Ethiopia and Kenya



Source: G. Zeleke (a, b) and J. Herrick (c).
Note: A combination of differences in soil, climate and management can all help explain the very different responses of a gully in Ethiopia (a) and (b) which resulted in a dramatic response after just 1 year, and a drier region of Kenya (c) which had not recovered after more than three years of restoration treatments.

2.4 Spatial scale

Scale matters. This phrase has been uttered many times, but its implications for land management continue to be poorly recognized (Cumming et al. 2013). Scale matters because it determines the patterns and processes we perceive and act upon through management and policy (Wiens 1989). If we restrict the scales at which we perceive, measure, and communicate about land, we limit our understanding of the processes affecting land conditions and the management options to be considered. The goal of this section is to illustrate the kinds of decisions that are influenced by scale and how to account for scale in managing for land potential and resilience (Figure 15).

A brief introduction to scale

Spatial scale refers to the "spatial dimension of a measured attribute or process, characterized by its grain (smallest resolved unit) and extent (the area across which measurements are taken) (Turner et al. 2001). Spatial scale affects the spatial patterns that we recognize and, therefore, the ecological processes that we consider. For example, if we view a plot of land at the scale of a typical human observer, say a single small field, we may perceive it as homogeneous and its vegetation characteristics as being determined by how it is used (e.g. grazing or cropland use) and its soils (e.g., soil water availability). By viewing the same area at other scales, we can perceive the effects of other important processes. Finer scaled patterns in the field, such as patches of bare ground interspersed with patches of vegetation, can reveal the effects of erosion processes that may expand to the field scale, or the effects of fine-scaled soil variations such as areas of poorly-drained soil. Viewing the field as part of a broader landscape mosaic can reveal the contributions of its soils and vegetation to the viability of a farming enterprise, habitat for a population of grassland birds, and the stream flow and nutrient movement within a watershed. Conversely, we can detect how the characteristics of adjacent fields affect our focal field. Three fundamental scaling principles that managers and policymakers should bear in mind as they consider land potential are outlined below.

Spatial patterns and interactions: the whole is greater than the sum of its parts

The significance of a land area may not be adequately assessed by considering only its internal or local characteristics (Rossiter 1996). The arrangement of distinct land areas within a landscape mosaic may produce emergent properties as a consequence of spatial interactions among adjacent land areas. Spatial interactions include processes such as the transport of water, sediment, seeds, or animals among land areas. Thus, in order to "scale up" our understanding of land potential to an entire landscape or watershed, it may not be enough to know only the total area of different classes of land. We also have to know how those classes are spatially arranged, if spatial interactions are important and if the arrangements of land classes vary among landscapes, which is usually the case. The combination of class, area, and arrangement comprise a whole that is greater than, or at least different than, the sum or average of its parts.

For example, in Mongolian grazing systems where certain pastures are grazed in summer and others in winter, the spatial proximity of those pastures can have important consequences for cooperative herd management. Seasonal pastures that are too close to one another may facilitate out-of-season grazing, compromising the ability of winter pastures to provide needed forage in periods of high herder vulnerability and causing societal dysfunction (Fernandez-Gimenez 2002). Furthermore, traditional norms, such as the reciprocal sharing of forage resources among herder groups occupying different landscapes, can moderate the effects of localized, temporary forage limitations (Fernandez-Gimenez et al. 2012). In a similar way, key resource areas are spatially localized but play a critical role as dry season forage reserves

in African rangelands (Ngugi and Conant 2008). These small, productive areas play an outsized role in the social-ecological systems in which they occur. Thus, planning for resilience may require an understanding of the spatial patterns of resource availability at broad spatial scales, rather than just average conditions. The health of certain parts of a landscape may be far more important than the health of other parts.

Averaging land and soil characteristics without consideration of spatial variability may lead to unrealistic assumptions about land potential. As demonstrated in the previous paragraph, spatial interactions across the landscape determine the sustainability of managed animal populations. These spatial patterns are also important for wild animal populations, particularly in the context of habitat loss and fragmentation (Fahrig 2003). Similarly, shrub encroachment into landscapes fragmented by residential development may be related to the disruption of natural fire cycles that are suppressed in the fragmented landscape (Morton et al. 2010). In northeastern Australia, the spatial arrangement of vegetated and bare patches had a significant influence on erosion and sediment loss on two experimental watersheds with similar vegetation cover (Ludwig et al. 2007). The catchment with vegetation cover arranged into only a few large patches had 43 times greater sediment loss than the watershed with comparable cover spread out more evenly in many smaller patches. This is because the watershed featuring large vegetation patches also had highly connected bare ground areas allowing resources to move through the site. With similar amounts of total cover, vegetation patches can be arranged such that they either slow runoff and retain sediment or allow it to leave the site. In a similar way, the increasing connectivity of multiple eroding farm fields contributed to the American Dust Bowl and influenced atmospheric processes (Peters et al. 2014).

Spatial context: location matters

A complementary principle to the role of spatial pattern in "scaling up" to broad-scale processes is that spatial context provided by the landscape can influence the properties, and therefore potential, of localized areas. The importance of spatial context is evident at the Jornada Experimental Range in New Mexico, USA. Due to historical episodes of overgrazing through the 1950s, eroding shrublands became sufficiently extensive that many remaining grassland areas were converted to coppice-dune shrublands even when domestic grazers (and native grazers) were excluded via fencing (Peters et al. 2006). Overgrazing no longer directly caused grassland-to-shrubland transitions after the 1950s. Instead, they were controlled by broad-scale erosion and sediment movement which led to local soil instability with abrasion, burial, and mortality of grasses, occurring even in grazing exclosures (Okin et al. 2009). A similar mechanism occurred during the Dust Bowl of the United States in the 1930s (Phillips 1999). In such cases, the local management of vegetation or soils may not be adequate to predict the trajectory of vegetation change. Understanding and managing patterns in the broader landscape would be required. Management of land potential has to be considered at a sufficiently broad scale to ensure that all of the factors that affect land potential are considered. It also has to be *applied* at a sufficiently broad scale to ensure that destabilization of upslope or upwind areas do not compromise what would otherwise be sustainable management of the target area. .

Maps may lie (or, rather, the user may lie if the map is misinterpreted)

Thus far the focus has been on expanding our perception of spatial extent, but it is equally important to understand the spatial grain of the information that is available. In what geographers have termed the "modifiable areal unit problem", the classifications and data provided in maps are often modifiable relative to natural units or point data (e.g., soil bodies, plant communities) occurring in an area (Jelinski and Wu 1996). That is, maps may represent landscape features at a more coarse (aggregating together adjacent features) or more fine resolution (more closely approximating natural features). One consequence of this problem is that soil

maps may be created at varying resolutions and according to different aggregation rules. Thus, the results of analyses conducted using geographic information systems software may depend strongly on the rules by which the map was produced and how the mapped units are interpreted. Furthermore, coarsely-scaled maps may obscure important features (such as key resource areas described above) that are ecologically important yet spatially minor components of a map unit. Finally, it is important to recognize that point samples gathered in map units without sufficient replication or internal stratification to different patch, soil, or community types can lead to misinterpretations about resource conditions when extrapolated to a map unit or averaged across map units (Bestelmeyer et al. 2011). For example, a sampling strategy in Western Australia based on placing transects in only the most common upland landforms effectively missed important erosion processes taking place in adjacent swales. The erosion occurring in swales eventually spreads to affect the uplands, but this process would be detected too late to prevent landscape degradation if monitoring is focused only on uplands (Pringle et al. 2006). Sampling that ignores spatial heterogeneity, spatially-explicit hypotheses for landscape change, and replication is a common source of failure in assessment and monitoring. The lesson here is that managers need a conceptual model of physical or ecological processes in order to interpret mapping data and manage land effectively.

Integrating an understanding of spatial scale into land potential evaluation systems

When considering land classifications and making management decisions, it is important to ask the following questions related to the three scaling principles described above: 1) What is the role of a land unit vs. the aggregation of units for landscape-level outcomes? 2) How can spatial interactions from the surrounding landscape affect my management objectives for a particular land unit? 3) How does the mapped information I have represent, or misrepresent, the spatial features of primary interest? There is more to scaling than represented in this short contribution (Liu and Taylor 2002, Bestelmeyer et al. 2011), but attention to the basic scaling principles outlined here can improve land management and the development of land potential evaluation tools.

2.5 Ecosystem Services

Introduction

An ecosystem is a "dynamic complex of plant, animal, and microorganism communities and the non-living environment interacting as a functional unit" (MEA 2005). Ecosystem services are benefits obtained from ecosystems that are essential for human existence. The Millennium Ecosystem Assessment (MEA) grouped ecosystem services into four broad categories:

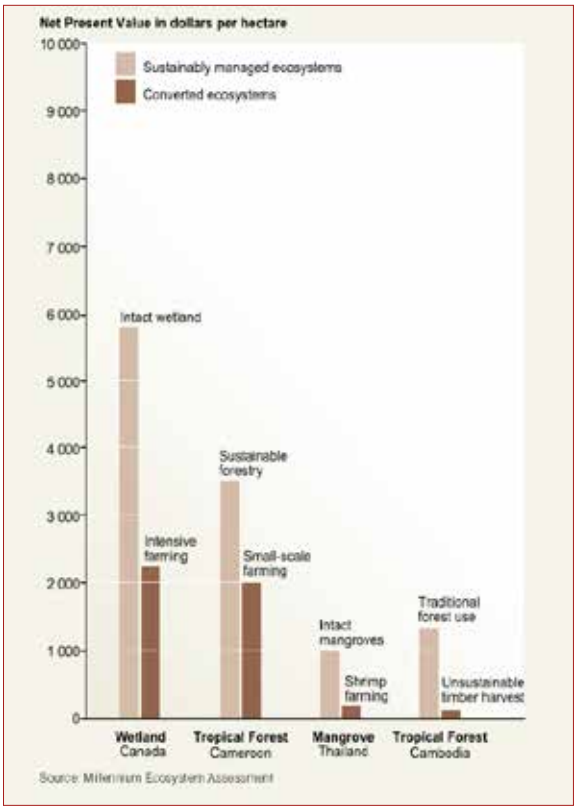
1. Provisioning (food, fiber, wood, gene, etc.)
2. Regulatory (flood control, climate change, health, hydrology, etc.)
3. Cultural services (culture, religion, aesthetic values, etc.)
4. Supporting services which are vital for the functioning of all other ecosystem services such as primary production (photosynthesis), soil formation, nutrient cycling and water cycling.

Limitations of existing land potential evaluations systems for addressing key ecosystem services

Nearly all existing major land potential evaluation systems, including the USDA's LCC (Section 1.1) and the FAO's AEZ (Section 1.2) were designed, or have been primarily applied, to prioritize food production over other ecosystem services. The case studies in Section I reflect this bias. For instance, both the FAO and USDA systems classify wetlands as temporarily or permanently not suitable for crop production while ignoring the value of wetlands in providing other ecosystem services (Figure 17). This agricultural production bias is mirrored in the economic valuation of most non-urban lands, except

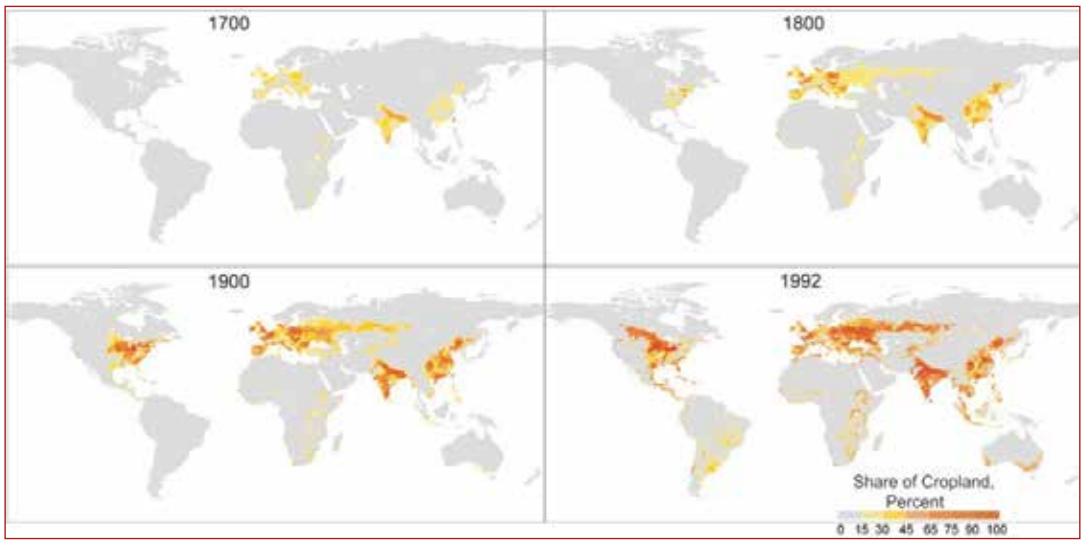
where land-dependent cultural values, such as recreation, can be commoditized. Global trends reflect humans' continuously growing demand for land conversion to agriculture (UNEP 2014; Figure 18).

Figure 17. Examples of contrast in estimated economic value of ecosystems in sustainably managed (estimated values) and converted (measured values) states



Source: MEA 2005.

Figure 18. Evolution of cultivated systems from pre-industrial to contemporary times



Source: MEA 2005 after Ramankutty et al. 2002.

Integrating ecosystem services into land potential evaluation systems

We propose a three-step approach to facilitate the consideration of multiple ecosystem services in next generation land potential evaluation systems. This approach recognizes that, while it is clearly impossible to consider all ecosystem services provided by a particular piece of land, virtually all ecosystem services ultimately depend on vegetation cover and production. In general, soil and climate combinations that have higher potential productivity also have a higher potential to support most other ecosystem services.

Step 1. Determine potential net primary productivity for the native ecosystem associated with a soil and climate combination. A range of values should reflect temporal variability in response to both weather variability (e.g. drought cycles) and the successional stage or plant community phase of the undegraded state (Caudle et al. 2013). Remote sensing analysis can increasingly be used to provide this type of information (Bai et al. 2008; Bai et al. 2015) *provided that it is carefully ground-truthed and interpreted with soil information from the field.* (Brammer and Nachtergaele 2015).

Step 2. To the extent possible, determine the maximum level of each ecosystem service that can be supported on a per-hectare basis without reducing the future potential of the land to support other ecosystem services. Identify tradeoffs and synergies when managing for multiple ecosystem services within the land's potential. Note that this approach is consistent with the definition of sustainability included in the Brundtland report (UNEP 1987).

Step 3. Determine the optimum level of each service that can be supported for the set of ecosystem services of interest, taking into account tradeoffs and synergies, within the land's potential. Quantitative and participatory strategies for Step 3 should be considered here, but are beyond the scope of this report: their application depends on the objective of the land evaluation, and the specific socioeconomic conditions of the area being evaluated.

Credit: Yongyut Kumsri, Shutterstock.com

SECTION III

Tools, resources and a strategy for unleashing the sustainable potential of land resources

The amount of information, and the number and power of the tools available to apply this information to land evaluation is increasing dramatically every year. This section provides a brief overview of the history and current status of these tools, along with some links to specific tools that were available at the time this document was published.

3.1 Tools for land evaluation – historical, current and future

First generation – paper maps, photos, and field observations for a single attribute

The first generation of tools generally addressed a single attribute of land potential, such as potential productivity, or soil erosion resistance. These systems, and the tools that supported them, are still used, and are useful, today, particularly for farm-scale planning. Printed aerial photographs with available soil mapping units printed on them can be a very powerful tool for completing land potential evaluations at the farm or small watershed scale. A trained technician with a solid understanding of soil-landscape relationships and the effects of local soil variability on productivity and erosion risk can work with land managers to create additional very useful maps tailored to individual requirements.

Second generation – dedicated computer programs often addressing multiple attributes

The next generation of tools were designed to be adapted to address one or more specific objectives, including limiting land degradation while optimizing production. The Automated Land Evaluation System (ALES; Rossiter 1990, Rossiter 1996, Rossiter 2012) is a DOS-based computer program that allows land evaluators to build their own knowledge-based systems with which to compute the physical and economic suitability of individual land mapping units in accordance with the FAO's framework (Rossiter and van Wambeke 1991). ALES is a framework within which it is possible to build one's own model of the local specific conditions. It also allows the economic potential per unit area of a particular land use to be estimated based on predicted annual gross margins.

The relevance of the program varies with the evaluation models that are incorporated in it. According to Rossiter (1990), ALES was developed with the objective of allowing agricultural scientists to present natural resource data to land use planners in a usable form, and to facilitate the analysis of soil and other biophysical data, which are often publicly available but underutilized in most countries. Unfortunately, as of the writing of this report, it appeared that while ALES is still available, neither it nor the GIS system with which it was connected (ILWIS) was being actively updated. ALES and other dedicated land evaluation systems, including MicroLEIS, together with their user documentation, continue to serve as useful frameworks for applying third-generation land evaluation systems using increasingly powerful Geographic Information Systems (GIS).

Third generation - Geographic Information Systems (GIS) and digital mapping-based analyses

Virtually any Geographic Information System (GIS) can be used to organize and analyze the information required to complete a land evaluation. Application of GIS to land potential evaluation requires a team of individuals with expertise in both GIS and land evaluation, including soil science.

A wide variety of both open-source and commercial systems are available. Wikipedia lists dozens of GIS products and provides limited information on the attributes of each. As of the writing of this report, the list was being updated on a regular basis. Many of these systems provide descriptions of recent applications of their software, including those for land evaluation. These can serve as a useful starting point. However, caution is required as many applications are flawed. One of the most

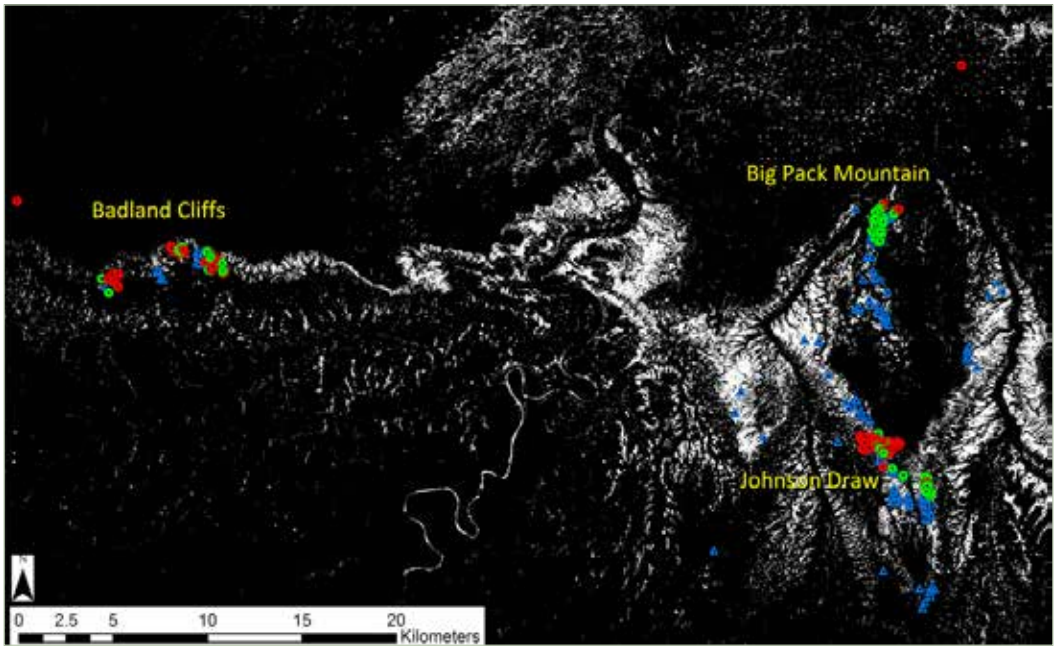
common errors is making the assumption that an attribute assigned to a map unit or polygon, such as soil texture, applies to the entire polygon. There is nearly always variability within map units. This variability is lost in GIS map units because they are forced to use the average or dominant value for a particular attribute (Figure 23; Brammer and Nachtergaele 2015). This is a very significant limitation of the use of GIS. It can cause catastrophic errors, particularly where two soils with very different properties occur in the same map unit. For example, the two soils in Figure 22 co-occur in northeastern Namibia at a scale that is too fine to be mapped separately, but only one has the potential for crop production.

Combining traditional soil maps with remote sensing and digital soil mapping tools can be extremely effective for addressing very specific questions, such as identifying the potential habitat of rare species (Baker et al. 2016; Figure 19).

Next generation - integrative tools and knowledge systems delivered via mobile phones

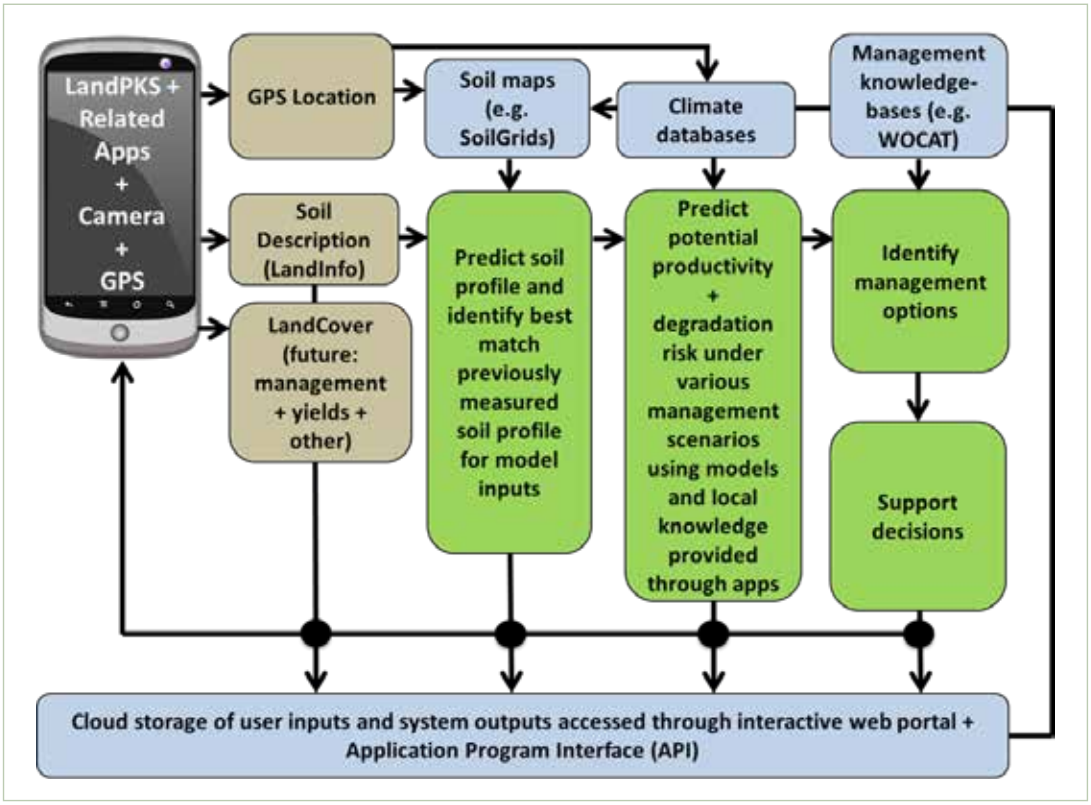
The Land-Potential Knowledge System (LandPKS) is one of the first tools being developed to provide real-time estimates of site-specific potential productivity, degradation resistance, and resilience via mobile technology. It integrates user inputs (soil and topography) with cloud-based geospatial layers and analytics to generate land potential estimates for specific locations. Future versions will integrate local and scientific knowledge to provide more detailed management options, including links to sustainable land management knowledge bases (such as WOCAT) and portals (such as the UNCCD's SKBP) (Figure 20). It can also be used as a crowd-sourcing tool to support remote sensing calibration and improve GAEZ estimates and GIS-based land evaluations (Figure 21).

Figure 19. Map predicting where shrubby reed mustard, a rare plant species, is most likely to occur in Northeast Utah, USA, based on land potential



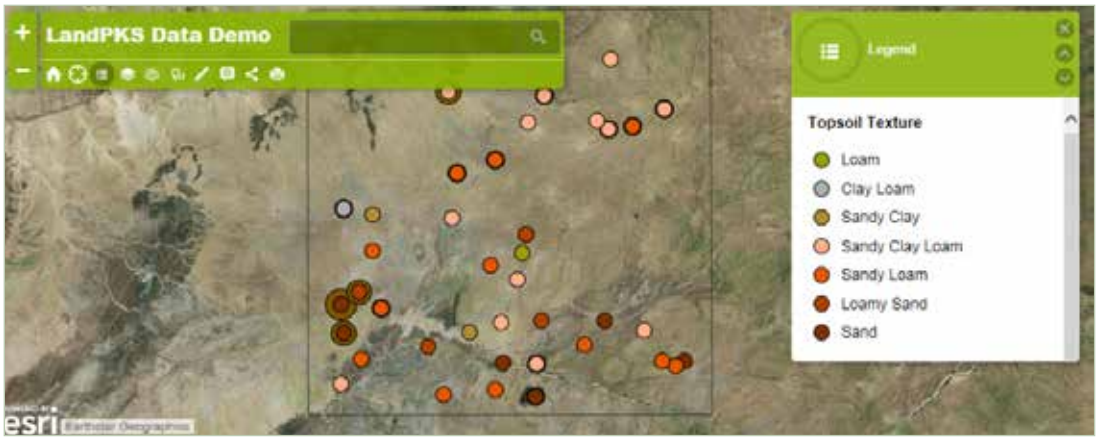
Source: Baker et al. 2016 for detail.
Note: The original model based on field soil properties had an error rate of 10%, and the rate increased to just 23% when extrapolated using a spectral-topographic model.

Figure 20. The Land-Potential Knowledge System



Source: Adapted from Herrick et al., 2016.
Note: Flowchart shows how the Land-Potential Knowledge System (LandPKS – landpotential.org) combines user input from mobile apps with cloud-based knowledge and information will provide site-specific knowledge and information that is relevant to the user's needs.

Figure 21. Illustration of how site-specific soil information can be used to interpret land potential from north-west central Namibia

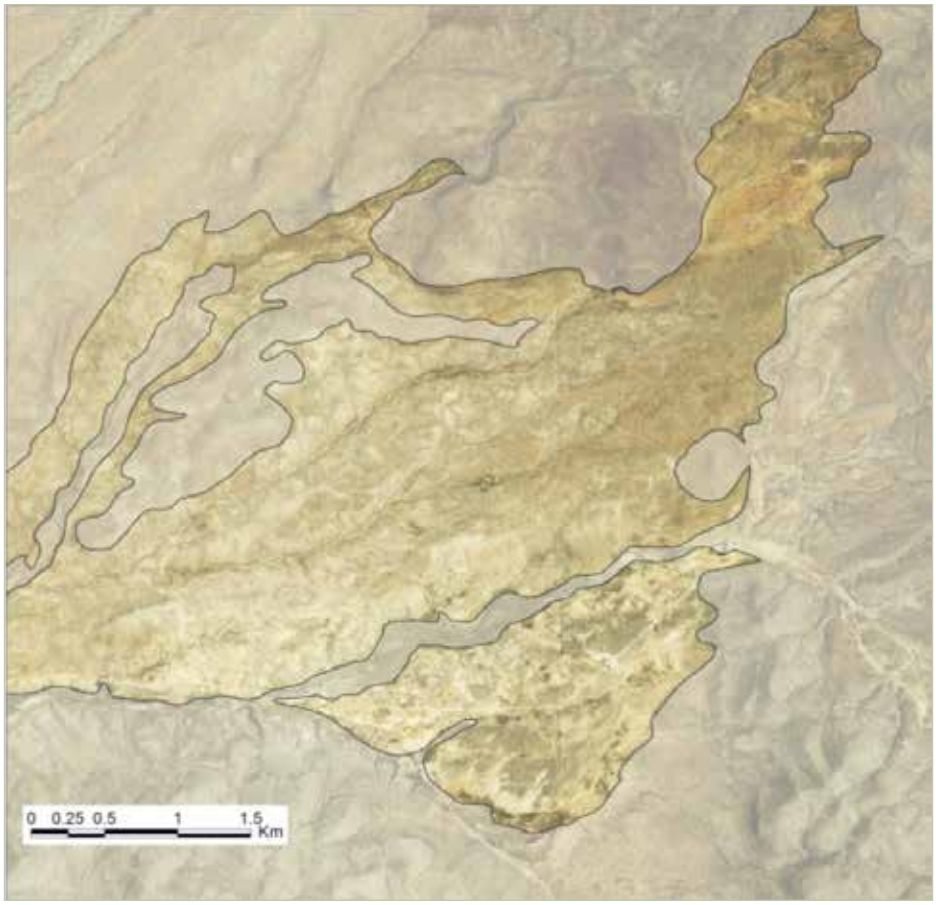


Source: http://landpotential.org (accessed 3 May 2016). Created by M. Buenneman.
Note: The sandier soils, which have less water-holding capacity necessary to support plant growth during droughts, show higher bare ground values. This type of information can be used together with more general GAEZ information to help determine what should be generally possible for soils in the region (GAEZ) and possible for a specific location (LandPKS – see Chapter 3.3).

Figure 22. Soils with contrasting potential in northeast Namibia

Source: Jeff Herrick.
Note: The loamy soil (lower left) will support both perennial grass and annual crop production, even during dry years, due to its high water holding capacity. Annual crop production is possible on the sandy soil (upper right) only during wet years.

Figure 23. Typical variability within a GIS soil polygon



Source: Matt Levi.
Note: The soil map unit in the center of the photograph incudes several soil types. Potential net primary production for these soils for native rangeland vegetation ranges from 336 to 560 kg/ha for a year with average rainfall. The area is in Southeast Arizona, USA in the Malpai Borderlands area. Map unit 91 (center) is Kahn-Zapolote complex receiving 12-16" ppt/year at elevation of 3700-4200'.

3.2 Selected sources (please see LandPotential.org for additional sources and current links)

For the latest available information and tools, we recommend visiting one or more of the growing number of web portals, including ISRIC.org, LandscapeToolbox.org, JournalMap.org, as well as LandPotential.org, the website where the online resources for this report are housed. Landon (2014) provides a concise, practical reference for much of the technical knowledge necessary to implement land evaluation and management.

- FAO.org The Food and Agriculture Organization of the United Nations provides a tremendous and constantly increasing amout of tools, data, information and knowledge relevant to sustainably increasing food production. Please see Section 1.3 above for just one of its many resources and the Global Soil Partnership to connect with the international community in promoting and supporting sustainable land management.
- ISRIC.org (ISRIC World Soil Information). This website currently serves as the primary global repository for soil information. As of 2014, it provided access to over 25,000 articles and 8,000 maps. It also provides a constantly improving global soil map at the 1km pixel scale that is based on cutting edge digital soil mapping technology. One of the strengths of these maps is that they provide not only the best available prediction of the dominant soil for every point on the globe, they also include the level of confidence. No soil map is perfect and ISRIC's are no exception. But they do provide an excellent starting point for field validation, and ISRIC is very interested in receiving user feedback to improve its predictions.
- LandPotential.org. In addition to hosting this report, this website is being continuously updated with land evaluation resources, and examples of how land evaluation has been successfully used around the world.
- LandscapeToolBox.org. This web portal provides access to a wide variety of tools, including automated sampling design, data analysis and reporting, and some very simple image analysis tools that anyone can learn in under an hour. It also includes a Wiki, which, among other things, helps decide what remote sensing imagery is most appropriate based on objectives.
- JournalMap.org. The ability to search for articles based on where the research was completed, rather than where the author's office has been, is nearly impossible in Google Scholar and other bibliographic search engines. JournalMap allows users to search for articles based on location, as well as the biophysical characteristics of a location.
- UNEP.org. UNEP is continuing to increase access to tools, data and knowledge resources, including through UNEPLive.
- National departments and ministries of agriculture and the environment, and related NGO's. In addition to knowledge and information, and tools tailored to national conditions, these organizations provide access to people. While impossible to list them all here, relevant sources can increasingly be found through the UNCCD's Knowledge Portal and Capacity Building Marketplace.
- Another useful website is the LandscapeToolbox. In addition to land inventory and monitoring methods and GIS-based sampling design tools, it provides a summary of the attributes of different types of remote sensing imagery.
- The GAEZ described in Chapter 1.3 allows users to access previously-run evaluations using a geospatial interface. The evaluations are based on the FAO's Agro-ecological Zoning system. This system is valuable for comparing the agricultural productivity potential for a region, but was never designed to provide point-scale estimates, consider sustainability issues (e.g. erosion risk) in detail, or consider the many other factors involved in land use decisions. Other tools are available that address many of these limitations. Each of these tools, however, requires additional input from the user and generally requires greater technical knowledge than the GAEZ.
- WOSSAC.com. The World Soil Archive and Catalogue provides access to soil survey reports, maps, imagery and photographs from 344 territories worldwide.

3.3 A simple, practical strategy for evaluating land potential TODAY while continuing to improve estimates for TOMORROW

Even the simplest land potential evaluation tools presented in Section I can be used to prevent the types of catastrophic degradation associated with previous societal collapses (Liu and Diamond 2005). The principles and strategies described in Section II can be used to increase the quantity and quality of information provided. This chapter provides a series of steps for estimating land potential at the field scale. The same principles and many of the same tools can be applied at regional to national scales. The steps are listed in order of simplest to most complex, with each step increasing the accuracy or relevance of the estimate.

The list is intended to highlight the types of information that can be generated today, while pointing out how these estimates can be improved and made more useful. It is not a replacement for books and manuals that provide specific instructions. Please see "Existing Literature" and "Tools" for more explicit instructions using currently available tools, and check the "LandPotential.org" and UNEP's websites for new systems.

The following steps are intended to be applied iteratively. They describe the basic process at the field, farm, or watershed scale. The strategy and principles are the same across larger scales, but much more powerful tools and larger databases are required to complete the process.

1. Clearly identify the objective of the land potential evaluation, who will use it, how they will use it to make decisions, and what level of accuracy and precision are required.
2. Complete an Internet search and query local experts to determine if an evaluation has already been completed, or if an organization is already working on one. The authors of this review were astounded by the number of land evaluations that have been completed in the past century that are virtually unknown to current policymakers. While most could be updated, the information is often better applied "as is" than ignored.
3. Review potential production predictions for the region on the Global Agro-ecological Zoning (GAEZ) website. This provides general estimates of potential production for a wide variety of crops for the dominant soils in each area. FAO and other organizations, such as the Regional Center for Mapping of Resources for Development (RCMRD), can be contracted to generate more precise estimates by integrating the latest available GIS layers into the estimates.
4. Generate potential land degradation resistance (including erosion resistance, at a minimum) predictions for different types of land and management systems within the area. Unlike potential production, there are no global estimates for land degradation.
    - **Option 1:** previous estimates (see Step 2).
    - **Option 2:** sample locations using the Land-Potential Knowledge System (LandPKS) where it has been implemented (see "Land-Potential Knowledge System").
5. Generate the information for Steps 3 and 4 using local data using a framework such as ALES ("Second generation – dedicated computer programs") in conjunction with new tools ("Third generation – Geographic Information Systems (GIS)" and "Fourth generation – mobile apps and cloud computing).
6. Modify the results based on the resilience (Section 2.3). For example, catastrophic degradation risk due to soil erosion is far greater on shallow than deep soils assuming similar soil erosion rates.
7. Expand the analysis to consider where the land is located relative to other land, how the surrounding land is being used (spatial context), and how the scale of the land use may affect land potential (Section 2.4). This is particularly important when a single management system is planned for application across areas of land with

much different potential. Taken together, considering spatial context and scale can help avoid degradation of a large area due to the mismanagement of a small, vulnerable area embedded within the larger area, such as land that is susceptible to gully initiation.

8. Integrate multiple ecosystem services into the analysis (Section 2.5). This is by far the most complex part of the process. At a minimum, a qualitative evaluation should be completed on the impacts of the preferred land use on major ecosystem services, including biodiversity conservation, and air and water quality. Please see the references in Section 2.4 for additional guidance.
9. Promote and accelerate innovation by clearly identifying the limiting biophysical processes that must be overcome to increase land potential, by developing systems to rapidly communicate innovations and the soil and climate conditions under which they are successful (#10), and create policies that ensure that new and existing land evaluation systems (such as the LCC and AEZ) are applied in a way that they in no way limit land managers' ability to innovate (see "Raising the bar").
10. Develop and provide access to tools, such as the LandPKS, that allow individuals to rapidly access and share knowledge and information about how to sustainably manage specific types of land.

Credit: Peter Kunasz, Shutterstock.com

SECTION IV

Policy options for applying land potential evaluation to land use planning and management

The scale at which each of these opportunities is relevant is listed at the end of each section.

4.1 Policy opportunities: specific issues

Land potential can be applied to partially decouple economic growth from (1) land degradation, (2) conversion of natural ecosystems to agriculture, and (3) conversion of natural and agricultural systems to biologically non-productive uses including urban, infrastructure, and many forms of energy production. It can be used to decouple economic growth from *land degradation* by limiting land management systems to those that are sustainable for each type of land. Conversion of natural systems to agriculture can be reduced using a knowledge of land potential to maintain and increase production on existing agricultural lands in three ways: (1) limitation of productivity declines caused by degradation, and (2) close yield gaps by better matching of production systems with land potential, and (3) targeting inputs to where they will result in the greatest return on investment and least harm to other ecosystem services.

Land potential can be used to inform policy interventions in all three ways. The benefit of applying an understanding of land potential on the impact of these polices depends on the amount of variability in, and level of understanding of, land potential. The decoupling benefits of an understanding of land potential are likely to be greatest when it is applied across large areas, where there is high variability in land potential, and where land potential is well understood. *How* an understanding of land potential is applied to inform policies depends on a number of factors including the scale of the intervention, technical capacity, and governance.

We have included general guidelines for applying an understanding of land potential for each type of policy tool. A constantly growing list of examples is available at http://landpotential.org. The scale at which each of these opportunities is relevant is listed at the end of each section.

International targets: safe operating space and land degradation neutrality

Land potential can be used to define safe operating space for human-dominated land uses. Defining safe operating space requires an understanding of the extent to which different land use by soil combinations results in permanent vs. non-permanent losses of ecosystem services associated with natural ecosystems. As discussed above, the land potential-informed policies below can be used to meet human needs without crossing planetary boundaries.

Land potential evaluation applied at local levels can help to achieve land degradation neutrality at national levels, effectively contributing to the achievement of a land degradation neutral world. This is key to staying within the safe operating space for land use.

Relevant scale: regional to international.

Land use planning - general (including agricultural, urban, mining, energy production)

Land use planning based on this report's broader definition of land potential, including productivity, degradation resistance, and resilience allows for the consideration of both short- and long-term tradeoffs. Other suggestions include:

- Provide stakeholders with information on land potential before soliciting input on desired land use. This helps limit the discussion to sustainable options.
- Provide information on potential production to inform trade-offs based on short-term opportunity costs.
- Provide information on resistance and resilience, and restoration potential: for each land use by land type combination, determine the extent and persistence of loss in potential (Table 1). Persistence depends on both the type of land use and the land itself. The extent of

loss is related to the inherent capacity of land to provide a variety of ecosystem services, which are disproportionately affected by different management systems. Replacement of a humid temperate grassland with a parking lot will result in a persistent, total loss of potential for crop production or ecosystem restoration on a shallow soil, but only a temporary, partial loss on a deep soil with uniform soil texture throughout the profile. This is because the soil profile remains intact; as soon as the asphalt is removed or maintenance is halted, recovery begins.

Relevant scale: individual land management unit to national.

Land use planning – agricultural

Agricultural land use planning has been extensively discussed throughout this report because it has been the primary historical application of land potential evaluation, and is extensively discussed in other documents. The key conclusion of this report for policy is that agricultural land use planning, like more general land use planning, should consider crop and animal production as just one of many ecosystem services that agricultural lands provide. Agricultural land use planning should evaluate degradation risk and potential resilience associated with proposed management to determine the likely persistence of degradation associated with a particular production system applied to a particular type of land.

Relevant scale: individual land management unit to national.

Land reform and redistribution: equity, sufficiency and sustainability

Land potential knowledge can be used to ensure that land reform is equitable by adjusting the land area allocated to each beneficiary based on potential productivity differences. It can be used in the same way to support equitable compensation schemes for privately owned land. Ensuring that *sufficient* land is provided based on sustainable potential production levels is also critical to the success of land and redistribution policies. The 1930s Dust Bowl and other less extensive social dislocations in the US in the early 20th century were due to overestimates of land production potential based on yields in other areas and a misunderstanding of the types of production systems that could be sustained on previously uncultivated soils.

Relevant scale: local to national.

Land investments and land grabs: pricing fairness and sustainability

Knowledge of potential productivity is necessary for the market to price agricultural land and for individual landowners to negotiate a fair price for their land. Where leases are involved, potential degradation, and resistance and resilience, are critical to establishing constraints on what the land can and cannot be used for, to ensure that it is maintained. While an understanding of land potential cannot be used to prevent land grabs, it can increase transparency and fairness, as emphasized in the recently published "Voluntary Guidelines on the Responsible Governance of Tenure", which stated that "States should ensure that appropriate systems are used for the fair and timely valuation of tenure rights for specific purposes, such as operation of markets, security for loans, transactions in tenure rights as a result of investments, expropriation and taxation" (FAO 2012, p. 30).

Relevant scale: individual land management unit to national.

Taxation

As the arguably oldest policy application of land potential, traditional taxation requires little explanation. A comprehensive understanding of resilience and potential to support ecosystems that are currently either not valued or are undervalued can, however, be used to design a taxation system to support broader sustainability goals, as described in the following section.

Relevant scale: local to national.

Land use and land management incentives

Both taxation and other financial incentives can be used to encourage landowners to match land use with land potential. These incentives can be applied broadly to promote sustainable land management, or to promote specific

practices that, in addition to being sustainable, may increase the provision of other ecosystem services (e.g. integrated cropping systems and other agro-ecological approaches).

- Crop insurance subsidies can be limited to lands where the insured production system is sustainable.
- Tax breaks in exchange for long-term or permanent land conservation (e.g. conservation easements) can be targeted and priced based on both conservation and alternative land use values.
- Drought de-stocking subsidies, including subsidized livestock purchases, can target grazing lands with high potential production and low resilience.
- Agro-ecological and Organic Practices Promotion. Production systems based on an understanding of agroecology, including many organic production systems, often result in more diverse biologically diverse agroecosystems with higher soil carbon and improved watershed function than landscapes dominated by monocultures.
- Please see Section 5.3 in ASSESSING GLOBAL LAND USE: Balancing Consumption with Sustainable Supply (UNEP 2014) for additional examples.

Relevant scale: local to national.

Degradation and other land use disincentives

Both legal and market-based disincentives to land degradation must be carefully designed to avoid unnecessarily limiting production on lands that are already human-appropriated. Legal disincentives are often based on some interpretation of the precautionary principle. This often causes conflicts with landowners who believe that they can sustainably apply a prohibited management practice. Fine-scale spatial differentiation based on land potential can increase effectiveness by increasing compliance. For example, implementation of a wetland conservation policy, using soil map to prohibit development in all map units that include potential wetlands (based on soil features) will unnecessarily exclude non-wetland areas from development. Alternatively, a policy that only prohibits development on map units where wetlands are the dominant component will result in unnecessary loss of wetlands in units where they are subdominant.

Relevant scale: local to national.

Capacity building and awareness-raising

Applying an understanding of land potential, and the limitations to land potential at multiple scales can increase the effectiveness of policies designed to promote capacity building and awareness-raising. At the national scale, information on potential production and resilience, together with predictions of changes in drivers of land use change and land management can be used to target both the location and type of capacity building required. At the local level, generic extension materials, where available, can be replaced with materials specifically designed to address resource limitations for specific local soils and land uses.

Providing land potential evaluation training and tools to farmers can empower them to experiment with new production systems and technologies. An often-cited barrier to the adoption of new technologies is perceived risk due to uncertainty about whether the technology will work on the farmer's own land. Many farmers will wait to watch for successful adoption by a neighbor. In addition to slowing adoption, it only works if the neighbor is farming similar soils. Land potential evaluation can help reassure farmers that the technology has been tested under conditions that are *similar to their own*. It can also help them identify other farmers facing similar challenges.

Relevant scale: local to national.

4.2. Additional opportunities: biodiversity conservation, restoration planning, and climate change mitigation and adaptation

Biodiversity conservation, restoration planning, and climate change mitigation and adaptation are relatively new applications of land potential evaluation that have received relatively little attention. Instead, all three tend to rely on current land cover or land use as the primary basis for decision-making. Integrating knowledge of land potential can help identify hidden opportunities, while avoiding costly errors associated with unbridled optimism for what is desired, but not possible.

Biodiversity conservation and restoration planning

The types of habitat that can be supported determine alpha diversity, which is the number of species that can be supported on a particular piece of land. The number of species that can be supported at the landscape scale, is higher where (1) there are different types of land with the potential to support different soil, plant, and animal communities, (2) there is land that can sustainably support multiple communities, that are, for example, in different successional states. The same information can be used for restoration planning and for determining the feasibility of creating wildlife habitat corridors.

Relevant scale: individual land management unit to international.

Climate change mitigation

Land-based climate change mitigation relies on assumptions about the rate at which a given amount of carbon can be stored in a particular soil, and the rate of carbon accumulation under different management systems. Mitigation therefore also requires knowledge of both current soil carbon content and the potential storage. Current estimates tend to generalize and fail to consider variability in both the soil carbon storage potential and resilience of a soil. Improved land potential information generated to support land use planning can also be used to target climate change mitigation investments, and to reduce uncertainty. This should reduce the discount rate applied by investors in carbon trading schemes. Reducing the discount rates by reducing future uncertainty increases the amount that investors are willing to pay for carbon credits: they are more confident that the carbon will (still) be in the soil at the end of the contract (Herrick et al. 2016).

Relevant scale: individual land management unit to international.

Climate change adaptation

Land potential evaluations for specific soil and climate combinations can be easily adjusted to identify sustainable production systems under predicted climate change scenarios. In light of funding projections for climate change adaptation, this is an area where land potential evaluations could have an extraordinary impact.

Relevant scale: individual land management unit to international.

4.3 Promoting innovation through policy

The most common way that an understanding of land potential can be used to sustainably increase production, without expanding onto non-agricultural lands, is better matching of land use with land potential. But what if an understanding of land potential could be used to make the production of ecosystem services increase *beyond* the current potential?

Land management innovations that increase productivity have typically been driven by a desire to overcome a particular limitation on a particular type of land: new irrigation systems where water is limited, development of salt-tolerant cultivars for saline soils, and terraces to control runoff and erosion on hillslopes.

One of the risks of applying traditional land evaluation systems is that they are based on current assumptions of sustainability based on *today's* technologies and land management systems. Because these land management systems are finite, they tend to address only the dominant technologies for the most widespread soil-climate combinations. Existing systems tend to focus on *technologies* and exclude *integrated management systems*, such as multi-species agricultural production systems, simply because they are so complex and diverse. In part because of this complexity, integrated management systems often require higher levels of adaptation to different soil and climate conditions in order to be successful. This is because each of the components of the management system (e.g. different species) responds uniquely to soil and climate. While one component may be adapted to a wide range of conditions, another may not, or may interact differently with other components (e.g. plant species with soil microbial community) under different conditions. In this section we discuss how applying an understanding of land potential, and a more flexible approach to land potential evaluation, can be used to increase the development of innovation and dissemination of both technologies and management systems.

Increasing innovation rates

One of the simplest ways to accelerate innovation is to create knowledge sharing systems that allow innovators to easily and rapidly share their successes and failures. Rather than wasting time unknowingly replicating an existing system, innovators with access to knowledge can build on previous successes and avoid the failures. This accelerated communication is now occurring thanks to the Internet: news articles, blog posts, and videos quickly go viral. The problem is that this information is rarely contextualized by the conditions of where the innovation did or did not work. For example, conservation tillage systems can be used to sustainably produce annual crops on low slopes, but are ineffective on steep slopes unless they are combined with other types of soil conservation measures. Even the steepness of the slope where they are sustainable depends on erodibility and infiltration capacity of the soil. This emphasizes the importance of promoting understanding of land potential in capacity building and awareness raising programs (see Policy Opportunities).

Increasing adoption rates

Providing information about the factors that define land potential (soil, climate, and topography) for the locations where the innovative technologies and systems are tested is one of the simplest ways to accelerate the rate of innovation while reducing the costs. It is also one of the best ways to increase adoption of effective new systems. Innovators frequently complain that farmers are conservative. Research has shown that farmers are more likely to adopt systems they can easily test at relatively low cost (Pannell et al. 2006). This is due in part to the fact that innovations are often promoted as universally applicable, when in fact they only work under certain conditions. This creates skepticism and doubt among farmers. Providing contextual information about the conditions under which the innovation has, and has not, been successful should increase rates of successful adoption. This, in turn, should increase willingness to invest in new technologies in the future.

Due to cost limitations, innovations can only be tested under a few soil-climate combinations. Linking tests of an innovation to the factors that determine land potential also opens the door for early adopters to contribute to testing and further innovation. Even if the early adopters are limited to those with similar land potential, they will necessarily include untested conditions. The development of global crowdsourcing systems, which includes the ability to document or access existing soil, climate, and topography information for a given field location, now allows the results of these early adopters' tests of an innovation to be shared (e.g. the Land-Potential Knowledge System described in Section 3.1).

Raising the bar

Traditional land potential evaluation systems explicitly set an upper limit to what is possible. As discussed in the introduction, this potential can be exceeded by changing the relatively static

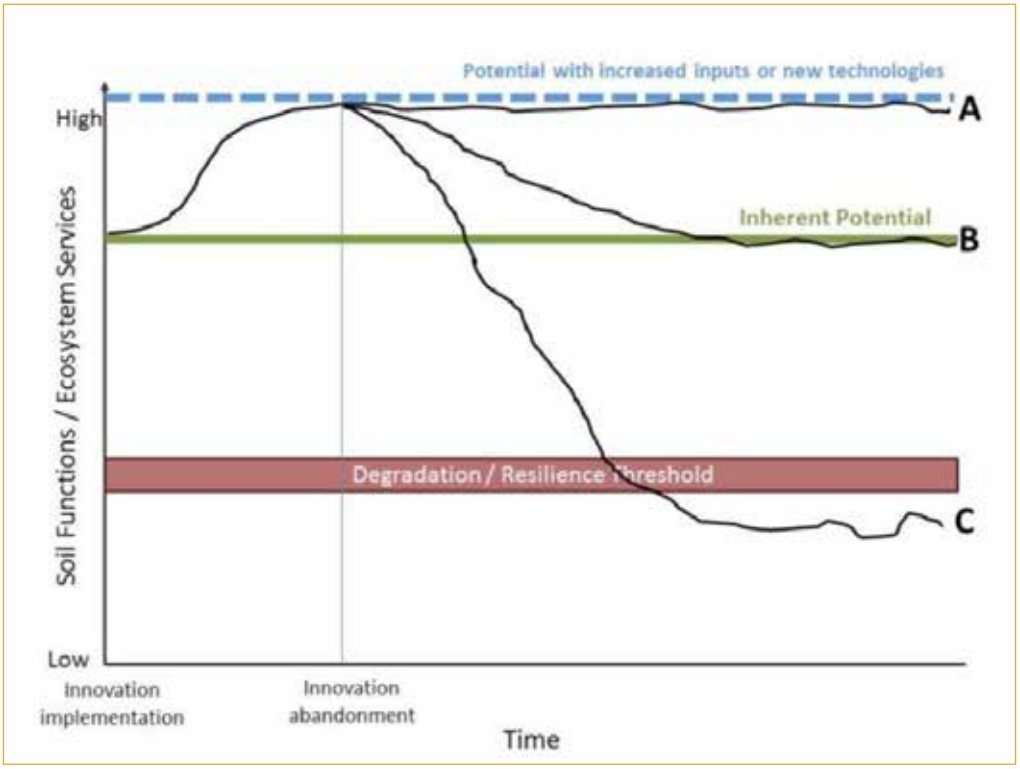
properties that define the inherent potential. It can be temporarily modified with water and fertilizer inputs, or drainage systems.

Perhaps most exciting from a sustainability perspective, is that land potential can be increased using through the implementation of innovative practices that effectively change the way that the plants growing on a piece of land use existing water and nutrient resources. In other words, increasing resource use efficiency. Joel Salatin (Salatin 2007) is just one of many farmers who have been frustrated with the limitations imposed by assumptions of land potential based on current production systems, particularly where these limits are implemented through subsidy programs and environmental regulations. While the specific claims included in his book "Everything I Want to do is Illegal" are often debated, his basic point that simple classification systems tend to exclude and even penalize innovators, is accepted by all of the land managers and policymakers with whom we reviewed this issue.

In response to this concern, we propose a conceptual framework, illustrated by Figure 24 that (1) addresses variability in the factors that control land potential (see "Key Concepts and Definitions"), (2) addresses both degradation resistance and resilience by integrating thresholds, and (3) acknowledges that the natural potential of the land to support multiple ecosystem services can, in fact, be exceeded. Exceeding the current potential can be achieved through permanently or temporarily modifying the inherent potential, through increased inputs, and through the implementation of innovative systems and technologies that increase resource use efficiency.

This new framework must, however, be applied extremely carefully by considering (1) the impacts on a broad range of ecosystem services (Chapter 2.5), and (2) in the case of temporary changes, what happens when the inputs are withdrawn or the management system is abandoned.

Figure 24. Possible outcomes following abandonment of an innovation or inputs that had increased the provision of one or more ecosystem services.



Note: Please see text for further explanation.

There are three general possible outcomes. The first (Figures 24, line A) is that the new level is sustained. An example would be removal of rocks from the soil. This has been done by farmers throughout the world to make soil easier to till. It has persistent positive impacts on potential production by increasing the plant-available water and the nutrient-holding capacity of the topsoil. There are, of course, other situations where increasing soil rock content, especially at the surface, can improve plant growth conditions (Lightfoot and Eddy 1994; Figure 25). The second possible outcome (Figure 24, line B) is that the land returns to something closer to its inherent potential. This is a typical outcome where, for example, phosphorous is applied to soils with a high phosphorous fixation capacity. Over time, the excess phosphorous is retained by the soil in a form that is inaccessible to plants. An example of the third possible outcome, degradation (Figure 24, line C), was presented in the discussion of terraces (Figure 5).

Figure 25. Exceeding land potential limitations due to climate: quinoa

Source: J. Herrick, Nov 2006 near the Salar de Uyuni, Bolivia
Note: Quinoa plants in the Bolivian altiplano are sometimes planted next to rocks, which retain heat during the night, to protect them from freezing in the high Bolivian plateau. This allows the farmer to exceed land potential limitations due to climate.

4.4 UN Sustainable Development Goals

Land potential evaluation is key to the successful achievement of several of the UN Sustainable Development Goals (SDG's). It can help address nearly all of those that depend on food security, and air and water quality.

- 12.1 Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries.

- 12.2 By 2030, achieve the sustainable management and efficient use of natural resources.
- 12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.
- 12.a Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production
- 15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world. Land potential evaluation is essential to 15.3. The determination of degradation risk, and what lands can be restored, and to what level of function, depends on land potential. Well-meaning efforts to plant trees where they will not grow, or produce crops where the soil is highly susceptible to erosion, can only result in failure, or worse. The US Dust Bowl and other environmental and social catastrophes remain tragic reminders of the perils of arrogant ignorance.

4.5 Conclusions

In 1909 during a period of rapid agricultural land expansion, US President Theodore Roosevelt said, "It is an irrefutable proof that the conservation of our natural resources is the fundamental question before this nation, and that our first and greatest task is to set our house in order and begin to live within our means" (Roosevelt 1909). "Our means" referred to the potential of the land to sustainably support agricultural production and resource extraction. This may seem ironic given the subsequent devastation of the Dust Bowl, which was caused by the land settlement policies of the Roosevelt and subsequent administrations. The seeming contradiction provides a strong warning that a general awareness and commitment to conservation is useless without a specific understanding of the potential of every area of land, and the willingness and ability to act on this understanding.

Living within our means requires both an understanding of what those means are (land potential) and a willingness to limit consumption to avoid exceeding them. Yet most of the farmland that was abandoned during the Dust Bowl of the 1930s was first cultivated during the 25 years following Roosevelt's speech. This failure to apply an understanding of land potential was due to a combination of ignorance, overconfidence, and the desire of an expanding population for a better life. This report provides access to the knowledge, information, and tools necessary to avoid the types of catastrophic land degradation that occurred during the Dust Bowl, while increasing production on existing agricultural land.

The primary conclusion of the authors is that land potential evaluations must be completed and applied *before* changes in land use or management are implemented. We can no longer afford to perform large-scale experiments that ignore existing knowledge and information. In most cases, we can predict which types of production systems are likely to be sustainable on which types of land, and what the impacts on other ecosystem services, including those provided by biodiversity, are likely to be.

Completing these evaluations also facilitates development of innovative systems to *increase* land potential by accelerating the sharing of existing innovations and how they worked, or did not work, on land with different potential throughout the world. Agriculture continues to be the primary use of land from which native vegetation has been removed. A better matching of production systems with land potential on existing agricultural lands and increased innovation supported by carefully developed policies and strong institutions will not by themselves allow us to live within our means—but they can make it easier.

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Please see http://landpotential.org/IRP for searchable bibliography, including pdf links where available. The final printed version will include a printed bibliography.

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Appendix 1.
Country and regional case studies

The following case studies illustrate the range of variability in the global application of land potential evaluations and related land use and land cover classifications. Readers are encouraged to review Dent and Dalal-Clayton (2014) for additional critical reviews of individual countries, and the landpotential.org website, where new case studies and examples of current best practices will be continuously updated.

Case Study #1: China

Introduction

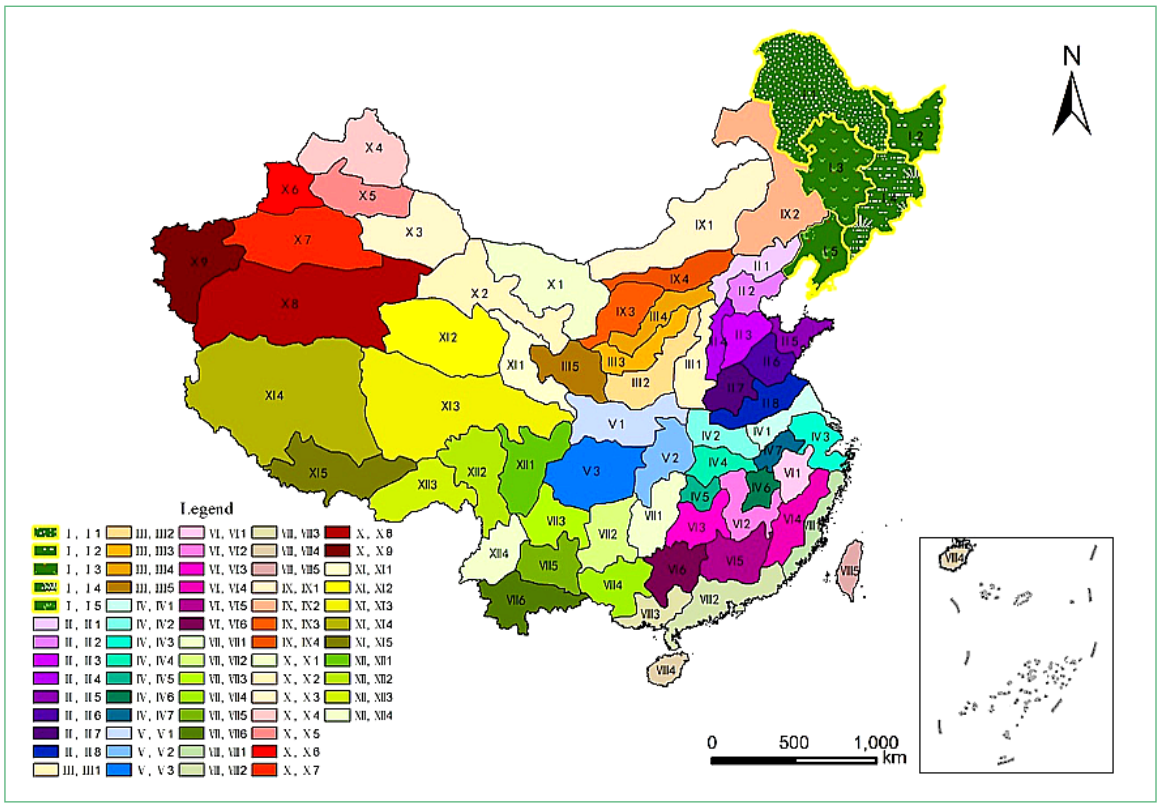
China is a vast territory with a wide variety of land uses reflecting both local and national needs. In addition to having highly variable soils and topography, China's climate ranges from the tropical and sub-tropical lowlands of the southeast, to the Himalayan Mountains and Tibetan Plateau in the southwest, arid deserts of the west, and the semi-arid Inner Mongolian plains in the central north. China is also an ancient country and humans have been intensively modifying much of its land for millennia. Consequently, land evaluation and classification in China have integrated biophysical land potential with current land use in addition to socioeconomic factors that affect land use. The general objective has been to guide development and to provide a scientific basis for effectively protecting cultivated land by using land in more efficient ways, and coordinating land use between industry and agriculture. China has developed diverse approaches to land evaluation depending on the objective. These include evaluations for agriculture and specific crops and also for the economic valuation of urban land uses, tourism, and land degradation (Ni 2003). At the national scale, spatial zoning has been developed for macro-scale land use management, ecosystem management, and environmental conservation (Fu et al. 2004).

National scale land use zoning

A land use zoning scheme was developed based on detailed land surveys in China. An index system was initially set up using historical zoning of land resource use in China and applied between the 1950s and 1980s. This was modified to create the new zoning system and grading method for land resource utilization (Feng 2001). The criteria included (a) biophysical potential (based on climate and topography), (b) degradation sensitivity, (c) the current status and spatial structure of land resource utilization, (d) location relative to infrastructure and markets, (e) social and economic conditions, and (f) prospects for development of various types. Cluster analyses were used to generate 12 land utilization regions (Table 5) and sixty-seven land utilization sub-regions (Figure 26).

The Southeast Coastal Areas and the Southwest Tibet-Hengduan Mountains (Figure 26) were highlighted as two land use regions, which have both high development potential and high sensitivity to environmental degradation due to low resistance and/or resilience to degradation. These criteria were emphasized in the division of these regions into sub-regions.

Figure 26. Map of land resources zoning in China



Source: Feng 2001

Table 5. The twelve land use regions of the land use zoning scheme in China

	Geographic Location	Type(s) of land	Uses of land
I	Northeast mountains/plains	Woodland/dry farmland	Farming and forestry region
II	Northern China plain	Irrigated/dry farmland and residential/industrial land	Farming and construction region
III	Loess Plateau	Dry farmland/grassland/ woodland	Farming, husbandry, and forest region
IV	Middle and lower reaches of the Yangtze River Plain	Paddy fields/waters/ residential/ industrial land	Farming, fishery, and construction region
V	Sichuan-Shannan basins	Woodland/dry farmland/paddy fields	Farming and forestry region
VI	Hilly and mountainous area south of the Yangtze River	Woodland/paddy fields	Farming and forestry region
VII	Yunnan-Guizhou Plateau	Woodland/shrubby/dry farmland	Farming and forestry region
VIII	Southeast coastal areas	Woodland/paddy fields/garden and residential/industrial land	Farming, forestry, fishing, and construction region
IX	Inner Mongolian Plataeu	Grassland/dry farmland	Husbandry region
X	Northwestern arid lands	Unused land/grassland//irrigated farmland	Husbandry and oasis farming region
XI	Qinghai-Tibet Plateau	Grassland/unused land	Husbandry region
XII	Southeast Tibet-Hengduan Mountains	Woodland/grassland	Forestry and husbandry region

Adapted from Feng (2001).

Recent zonal land use change

Based on the land use transition analysis using the land use data re-sampled to 250m resolution from the 30m land use dataset in China between 2000 and 2010 (Wu et al. 2014), land use change characteristics were briefly quantified using an index of land use change intensity (LUCI) (Liu et al. 2014) in the 12 land utilization regions (Figure 27 and Table 6).

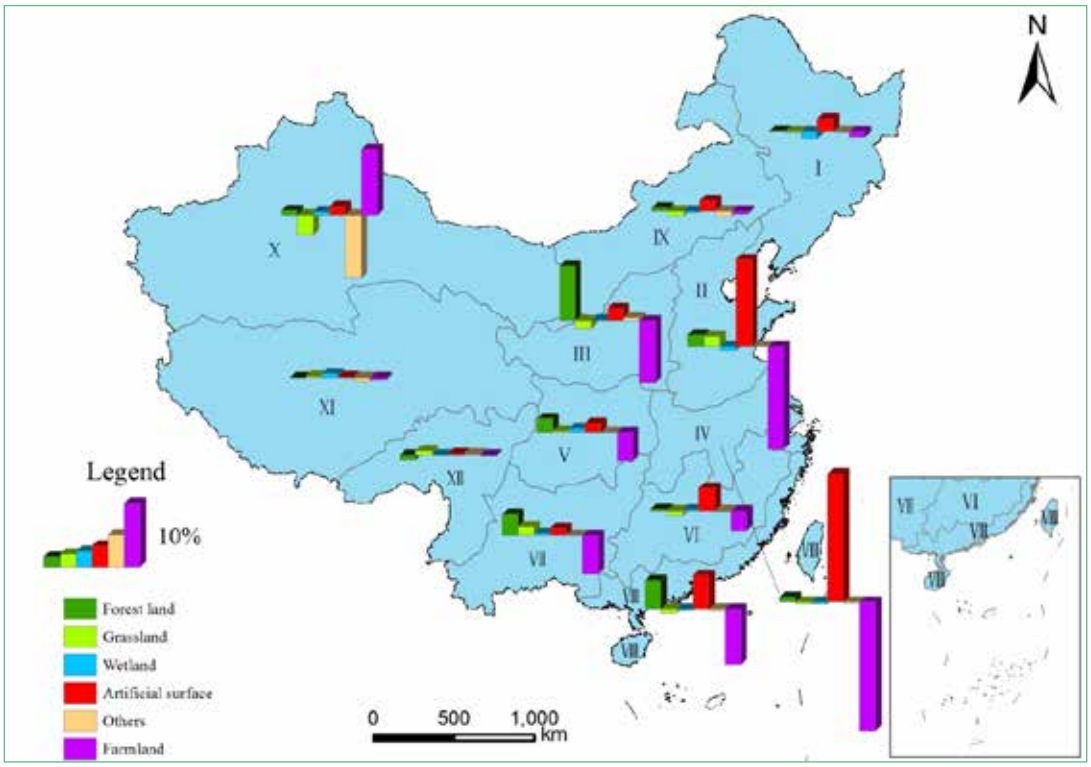
Results indicated that land use zones III and IV experienced the most intensive land use change with over 30% of the land use changed; Land use zone III was mainly changed by reforestation but land use zone IV was mainly changed by urbanization and industrialization; Land use zones X and XII experienced the least intensive land use change with a change rate lower than 2% (Table 6). It is also clear from Table 6 that farmland in seven land use zones suffered significant loss due to the ecological restoration of non-agricultural vegetative cover (three zones), and urbanization or industrialization (four zones), while, only land use zone X experienced significant farmland expansion.

Figure 27. Land Use Change Intensity index.

$$LUCI = (1/t) \times 100\% \times \sum_{ij}^{n} (\Delta LU_{ij}/LU_i)$$

Source: Feng 2001.
Note: LU_i is the area of land use i at the beginning of the period, ΔLU_{i-j} is the total area of land use i converted into land use j; t is the years for the land use conversion; and $LUCI$ is the land use change intensity in the t years.

Figure 28. The net land use change in the first 12 land zones (parts of the country) between 2000 and 2010 in China



Source: Liwei Zhang and Yihe Lu based on land use change between 2000 and 2010 in China with reference to the land use zoning scheme by Feng (2001).

Table 6. Zonal land use change characteristics between 2000 and 2010 in China

Zone	Land use change intensity %	Main characteristics of land use change
I	10.16	Farmlands to artificial surfaces; The bidirectional transitions among farmlands, forest lands, and wetlands. The final results are represented as the decrease of wetlands, farmlands, grasslands, and the increase of artificial surfaces and forest lands. Wetland is the land use type with the largest rate of loss, while artificial surface is the one with the largest increase rate.
II	24.04	Farmlands to artificial surfaces, grasslands, and forest lands. The final results are represented as the decrease of farmlands, wetlands, and the increase of artificial surfaces, grasslands, and forest lands. Wetland is the land use type with the largest rate of loss, while artificial surface is the one with the largest increase rate. Farmland is the land use type with the largest rate of loss, while artificial surface is the one with the largest increase rate.
III	30.12	Farmlands to grasslands, forest lands, and artificial surfaces; The bidirectional transitions between grasslands and forest lands. The final results are represented as the decrease of farmlands and grasslands, and the increase of forest lands, artificial surfaces, and wetlands, and the increase of artificial surfaces, grasslands, and forest lands. Farmland is the land use type with the largest rate of loss, while forest land is the one with the largest increase rate.
IV	30.13	Farmlands to artificial surfaces, and the transitions within farmlands. The final results are represented as the decrease of farmlands, wetlands, and grasslands, and the increase of artificial surfaces and forest land. Farmland is the land use type with the largest rate of loss, while artificial surface is the one with the largest increase rate.
V	5.36	Farmlands to forest lands, artificial surfaces, grasslands, and wetlands. The final results are represented mainly as the decrease of farmlands, and the increase of wetlands, forest lands, and artificial surfaces. Farmland is the land use type with the largest rate of loss, while wetland is the one with the largest increase rate.
VI	8.27	Farmlands to artificial surfaces, grasslands to forest lands, grasslands to farmlands, and the bidirectional transition between farmlands and forestlands. The final results are represented mainly as the decrease of grasslands and farmlands, and the increase of artificial surfaces, wetlands, and forest lands. Farmland is the land use type with the largest rate of loss, while artificial surface is the one with the largest increase rate.
VII	8.42	The bidirectional transition between farmlands and forest lands, and farmlands to artificial surfaces and grasslands. The final results are represented mainly as the decrease of farmlands, and the increase of forest lands, grasslands, wetlands, and artificial surfaces. Farmland is the land use type with the largest rate of loss, while artificial surface is the one with the largest increase rate. Farmland is the only one that experienced loss, while forest land is the one with the largest increase rate.
VIII	15.10	Farmlands to artificial surfaces; Bidirectional transitions between farmlands and forest lands or grasslands; Grasslands to forestlands. The final results are represented mainly as the decrease of farmlands, wetlands and grasslands, and the increase of artificial surfaces and forest lands. Farmland is the land use type with the largest rate of loss, while artificial surface is the one with the largest increase rate.
IX	5.78	Farmlands to artificial surfaces and grasslands; Grasslands to artificial surfaces, forestlands, and wetlands. The final results are represented mainly as the decrease of farmlands, grasslands and wetlands, and the increase of artificial surfaces and forestlands. Grassland is the land use type with the largest rate of loss, while artificial surface is the one with the largest increase rate.
X	25.65	Grasslands to farmlands, wetlands, artificial surfaces; Forestlands to farmlands. The final results are represented mainly as the decrease of grasslands and other land uses, and the increase of farmlands, artificial surfaces, wetlands, and forestlands. Other land uses experienced the largest rate of loss, while farmland is the one with the largest increase rate.
XI	1.76	Transitions between farmlands and grasslands; Grasslands to wetlands. The final results are represented mainly as the decrease of farmlands and other land uses, and the increase of wetlands, artificial surfaces, grasslands, and forestlands. Other land uses experienced the largest rate of loss, while wetland is the one with the largest increase rate.
XII	1.92	Transitions between forestlands and grasslands or farmlands; Deforestation; Farmlands to artificial surfaces and grasslands. The final results are represented mainly as the decrease of forestlands and farmlands, and the increase of grasslands, artificial surfaces, wetlands, and other land uses. Forestland experienced the largest rate of loss, while grassland is the one with the largest increase rate.

Challenges

It is usually claimed that land use zoning as a macroscopic approach can contribute to science-based land use development at national level and in key regions, which meet the specific objectives of effective farmland protection, high efficiency land utilization, while coordination of land use by different socioeconomic sectors (Feng 2001). From the land use change analysis in the 12 land use zones in the first decade of the 21st century, it is clear that the above objectives have been largely compromised owing to a very strong policy motivation of ecological restoration (e.g., the Grain to Green Program launched at the end of 1990s) and the urbanization and expansion of other built-up areas motivated by rapid economic growth. The decrease of farmland in most of the land use zones implied potential risks on food security in China. The expansion of farmland in the northwest dryland area of X may induce risks of land degradation. Therefore, the coordination of different land use demands raised from different socioeconomic sectors and regions remains to be a great challenge in implementation of the land use zoning as a macroscopic approach for sustainable land use planning and management.

In land use planning and management, trade-offs are unavoidable. Therefore, more considerations beyond land uses and their biophysical attributes need to be incorporated. In this sense, ecosystem services (i.e., supporting services, provisioning services, regulating services, and cultural services) relevant to land uses at different scales and geographical locations are helpful as functional criteria to improve land use zoning methodologically. This depends on the development of ecosystem service science in general and of the quantification methods of ecosystem services in particular.

Case Study #2: Hungary

Introduction

Hungary has one of the longest histories of land evaluation in Europe. The preparation of the first provisional land cadaster began in 1850. In 1875, a permanent cadaster was ordered by law, including an account of the profitability of lands based on soil productivity and market conditions. With the enhancement of soil information after the Second World War, new systems have been worked out to plan crop systems, nutrient management, etc. (Fekete 1965). A new quantitative soil capability rating system was adapted in the Land Evaluation Act in 1986, and soil capability indices were introduced in the official cadasters (Hungarian Official Journal 1986). The new indices were based on the information content of detailed soil maps, which were based on the factors controlling soil formation (Hungarian Ministry of Agriculture 1986). After the fall of the communist regime in 1990, the century-old cadaster system was reintroduced to support the re-privatisation of land based on its historic values. Preparatory work then began with the objective of developing a comprehensive land evaluation system, which could take advantage of new information technologies and serve multiple purposes, from productivity evaluation to optimization of land use according to climatic variability. This chapter introduces the so-called D-*e*-Meter system (Toth 2011), which was developed in the early 2000s as a joint effort between universities, research institutes, private companies, and the state soil survey organization.

Principles

Development of the land evaluations system D-*e*-Meter was based on the following principles:

1. The system must be applicable for all climatic and terrain conditions as well as soil types, and thus to all croplands, or possible arable lands in Hungary.
2. The land evaluation system should be crop specific and reflect general production potential.
3. The index should be based on a series of crop specific indices.

4. The land evaluation system should cope with the effects of climatic variability.
5. Land evaluation has to be performed on different fertilizer input levels.
6. Productivity indices must be quantitative and based on statistical analysis.
7. The system must be implemented on an internet-based GIS platform using digital maps (soil and cadastral) and its functionalities have to be accessible and controllable for various stakeholders with different level of access rights, including farmers, government bodies, etc.
8. Information on productivity must be available on a parcel level; therefore the system has to be available on a detailed scale (at least 1:10,000).

Applications

The elements of the system are (Vass et al. 2003):

1. Land registry and land use registry module
2. Soil map (GIS) module
3. Land productivity evaluation module
4. Production risk (inland water, drought) module
5. Input intensity (fertilization) module

Additionally, the D-*e*-Meter system was extended to productivity evaluation of other agricultural land use types (forest, grassland) and was supplemented with comprehensive economic evaluations (Sz cs et al. 2008).

Various modules of the system have been tested in pilot studies and used in both small and large farms. The country-wide introduction of the system is still on hold (as of December 2014). Apart from the legal framework for the full introduction to the cadastral system, the completion of detailed digital soil map coverage (currently at approximately 67%) of the country is also needed.

Case Study #3: India

India also has a long history of soil survey and land evaluation in the adaptation of existing systems, including the FAO GAEZ and USDA LCC described above. The country is also designing its own innovative approaches to meet local needs.

Soil surveys

The earliest Indian soil classification systems included four major soil groups: Indo-Gangetic Alluvium, Black Cotton Soil, Red Soil, and Laterite Soil (Voelcker 1893, Leather 1898). The functional significance of this categorization is widely understood, even by individuals with little or no soil training, thus illustrating the power of simple classification systems. Its global relevance is illustrated by the fact that the distinction between “black cotton” and “red” soils is also applied throughout much of Africa. In both India and Africa, the black cotton soils are usually flat and associated with relatively high fertility. However, black cotton soils are difficult to cultivate and can be impassable to vehicles when wet. The variability in potential of various types of black soils in South India is so well known that a local soil classification was developed by farmers based on the variable responses of different soils to management (Mosi Dhanapalan et al. 1991). Red soils in India generally have better physical properties for cultivation, but are more often nutrient limited.

Systematic soil survey investigations in India during the 20th century produced soil maps for specific areas and purposes (Viswanath and Ukil 1943, Raychaudhary and Govindarajan 1971, Bhattacharyya et al. 2009, Bhattacharyya et al. 2013). A soil map of India at the 1:1,000,000 scale is now available (NBSS&LUP 2002).

Land potential evaluation

An early rating exercise of Indian soils followed a modified Storie system and used 3 factors (Shome and Raychaudhuri 1960). It was applied to soils in 294 of India’s 640 districts. More recently, Velayutham (1999) used the FAO Agro-Ecological Zoning Approach to divide India into 60 Agro-Ecological sub-regions for developmental planning. In addition to the soil map of each state, detailed soil descriptions

and land use planning prospects are covered in independent soil reports (e.g. Jain 2000).

Mandal et al. (2001) developed a land quality index (LQI) for sorghum in the Indian semi-arid tropics (SAT). LQI is a function of a climate quality index (CQI) and soil quality index (SQI). The LQI was well correlated with actual sorghum yields obtained from benchmark soils. The LQI class map indicated that out of a total rain fed sorghum area of 11.7 million hectares, 43% was classified as high LQI, 38% as moderate, and 19% as low, indicating the need for better soil management measures in these areas.

A 9-fold classification of land cover of the country is currently being applied (Table 7). Out of the total geographical area, 120 million ha are estimated to be degraded and waste lands with different degrees of the severity of degradation (NAAS & ICAR 2010).

Table 7. Land cover in India (Indiastat 2000).

Land Cover Type	Area (millions ha)
Forests	70
Area under non-agricultural uses	25
Barren and unculturable land	17
Permanent pastures and grazing lands	10
Tree crops and groves	3
Culturable waste land	13
Long fallow lands	10
Current fallow lands	14
Net sown agricultural lands	143
Subtotal	305

Developing a national land potential evaluation system

Recent efforts have focused on developing detailed maps of soil and land resources at the village level using cadastral maps (1:10,000) in conjunction with Indian remote sensing data and products. When completed, all of the approximately 120 million farms can be superimposed on the soil maps of the village. This will allow technology transfer based on soil-specific recommendations for soil-water-fertility management strategies to be developed and applied at individual farm and watershed scales.

Experiences in the states of Tamil Nadu and Karnataka have supported development of a new approach for land resource inventory and land potential evaluation. The new approach works through the implementation of the Land Capability Classification system in GIS frameworks as demonstrated for the cluster of villages in Sivagangai Block of Tamil Nadu (Natarajan et al. 2006). This framework, which is open-ended and query based will become accessible at national informatics district centers, village knowledge centers, and village resource centers. It will facilitate a dynamic interaction between farmers, land managers, and knowledge and technology providers. By 2020, this initiative is expected to culminate in the development of a national soil information system (NASIS) and a land potential assessment system. The development will affect prospective land use planning and management on a macro-level, and pragmatic farm level planning and land management on a micro-level. This will enable India to take full advantage of the "Information Age" through e-Land use planning and sustainable management of natural resources (Velayutham 2012, Velayutham 2015).

Case Study #4: Uganda

The Uganda case illustrates a number of challenges faced by many countries in the development and application of land evaluation systems. Uganda is well endowed with land that possesses potential for high levels of agricultural production (Yost and Eswaran 1990). Ugandan farmers feed much of the population of the Great Lakes region of Africa, which is over 250 million. Uganda's natural resources also support tourism, mining, and oil production, creating employment and livelihood infrastructure for a fast growing population (Government of Uganda 2012). However, the country also faces many challenges, including a population growth of 3.5 %, a deforestation rate of 10% (Obua et al. 2010), and poor land use practices (UBOS 2010). The situation is exacerbated by a history of inappropriate land use planning and allocation. Land degradation, and conflicts over land use, are increasing, with associated declines in land productivity in many areas (MAAIF 2010, Berry et al. 2003, Adger 2000).

In response to these challenges, a National Land Policy was adopted in February 2013 (Uganda Ministry of Lands 2013). The policy includes (1) creation and maintenance of an inventory on land availability and suitability for specific uses, (2) development and application of land condition indicators, and (3) adaptation of regional and national instruments to comply with international principles and standards (Government of Uganda 2010). Implementation of the Land Policy is supported by a range of qualitative and quantitative land evaluation systems (Table 6) that have been adopted and used since before Ugandan independence in 1962. Through targeted academic studies, common international systems— including land suitability, land capability, and the Automated Land Evaluation Valuation System (ALES – see Section 3.1) — have been validated and customized to local Ugandan conditions (Isabirye 2005, Abongo 2008).

Table 8. Overview of land evaluation Systems in Uganda

No	Evaluation System	Scale	Evaluation criteria	Structure	Application	Reference
1	Productivity potential	1:1000,000	(i)Environmental (rainfall, vegetation, relief) (ii) Soil (Depth, texture, structure, drainage, nutrient status) (iii) Management (crops, tillage, liability to accelerated soil erosion	10 class (Adopted from USDA (1951)	Agricultural productivity potential assessment	Chenery 1960
2	Land systems	1: 250,000	Topography, soil, vegetation, Drainage	22 classes based on series and catena (Adopted from CSIRO)	Land resource inventory; Potential yield calculation	Ollier 1967
3	Agro ecological zonation	1:50,000	(i) Landscape, soils, land use, climate, cropping system	33 (detailed) zones aggregated into 14 zones	Land use Carrying capacities; Land use optimization modeling; Land management targeting	Wortmann and Eledu 1999
			(ii) Soil, topography, climate	9 Broad Zones1		Musiitwa and Komutunga 2001
4	Farming system	1:50,000	Soils, rainfall, cropping characteristics	7 systems	Agricultural land use and policy planning	Musiitwa and Komutunga 2001, MAAIF and MFPED 2000
5	Land Resources assessment for Bio-fuel Feedstock Suitability	1:50,000	Temperature (based on 1961 data); Rainfall and soil productivity (based on 1960 surveys)	4 classes: Highly suitable; Suitable; Marginally suitable and Not suitable	Land use assessment; Policy analysis towards Bio-fuel feedstock production	NEMA 2010

Successful application of these systems is, however, limited by a number of factors. The first is that they are largely based on old data sets that date back to the 1960s and many of these datasets are qualitative. The second limiting factor is that the systems are based on rigid scenarios and are skewed towards arable agriculture, ignoring the potential of the land to support other ecosystem services. Third, the concept of resilience is generally lacking. Finally, a lack of standardization of classification parameters undermines data sharing beyond projects and sites, and creates ambiguities that limit the smooth dissemination of information. Additional challenges include (1) weakness in policy implementation; (2) low technical capacities at several levels; and (3) coordination difficulties among stakeholders.

In conclusion, Uganda has a number of unique opportunities to develop and apply land potential evaluation systems to increase sustainable land management. However, it faces a number of challenges that are common to many countries. Possible solutions for some of the technical challenges are provided in some sections of this document, while others require more fundamental changes in land use policy.

Case Study #5: Argentina

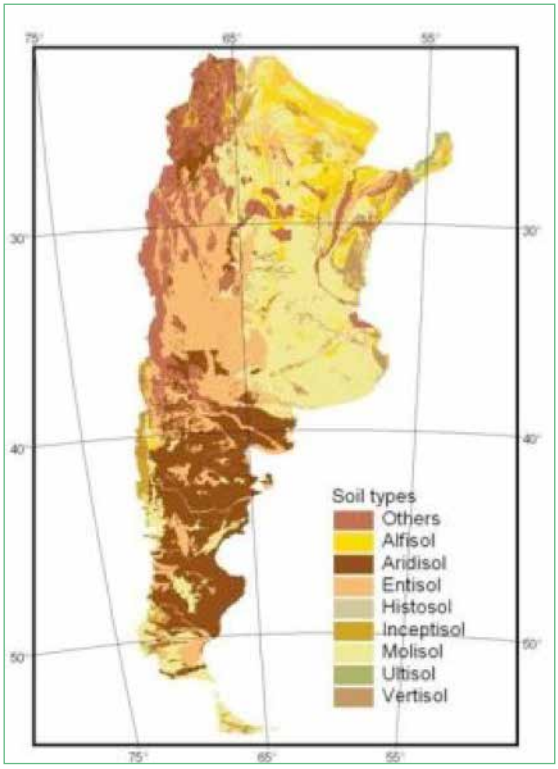
Like China, Argentina is an extremely diverse country. It extends through 32 degrees of latitude and over 6900m of altitude. Together, these factors generate large differences in temperature, precipitation, and evapotranspiration. Variability in land potential is further increased by diverse geology and soils (Figure 29). The most abundant soil order is the Mollisol, which supports *cash crop* agriculture and intensive cattle operations. Dryland agriculture is significant in most humid areas, where this group comprises the most fertile soils of the Pampas. Entisols and Aridisols are undeveloped soils with low water holding capacity, prevalent in arid and semiarid areas. The fourth most dominant soil, in terms of the occupied area, is the Alfisols, located mainly in the humid subtropical areas of northeastern Argentina. These four soil groups account for more than 80% of the country's lands, most of which are undergoing an intense process of conversion to agriculture.

Land in the Pampas region is currently undergoing rapid conversion from grassland to annual crop production (Demaria et al. 2008). These soils, like loess soils in China and the United States, have high potential production where rainfall is adequate (Moscatelli and Barsky 1991). However, many of these soils also have a high potential for degradation when cultivated due to their susceptibility to wind erosion (Mendez and Buschiazzo 2010, Michelena and Irurtia 1995). This illustrates the importance of considering potential production together with degradation resistance and resilience.

Land studies in Argentina started around 1850. Over time, these have been driven by a combination of concerns about land degradation (especially wind erosion), interest in increasing agricultural production, and the government's need to assess land values for taxation. Several Soil Map Projects were developed by the National Institute of Agricultural Technology (INTA), focusing on areas with high agricultural production potential. The Soil Atlas of Argentina was also developed under a United Nations project to cover the entire country at a scale of 1:2,500,000 (Godagnone et al. 2002).

More recently, the "Ecoregions" approach (Morello et al. 2012) has provided a more holistic assessment of land potential, including identification of constraints (Figure 13). This initiative is conceptually similar to the one described for China, in that it combines factors that define land potential, such as soil, climate, and topography, with those that reflect current land use, land cover, and even conservation status. While useful for describing the current status of the land, these types of evaluations must be disaggregated to effectively use them for land use planning because they confound land potential with current use and land cover.

Figure 29. Major soil types in Argentina according to Soil Taxonomy orders.



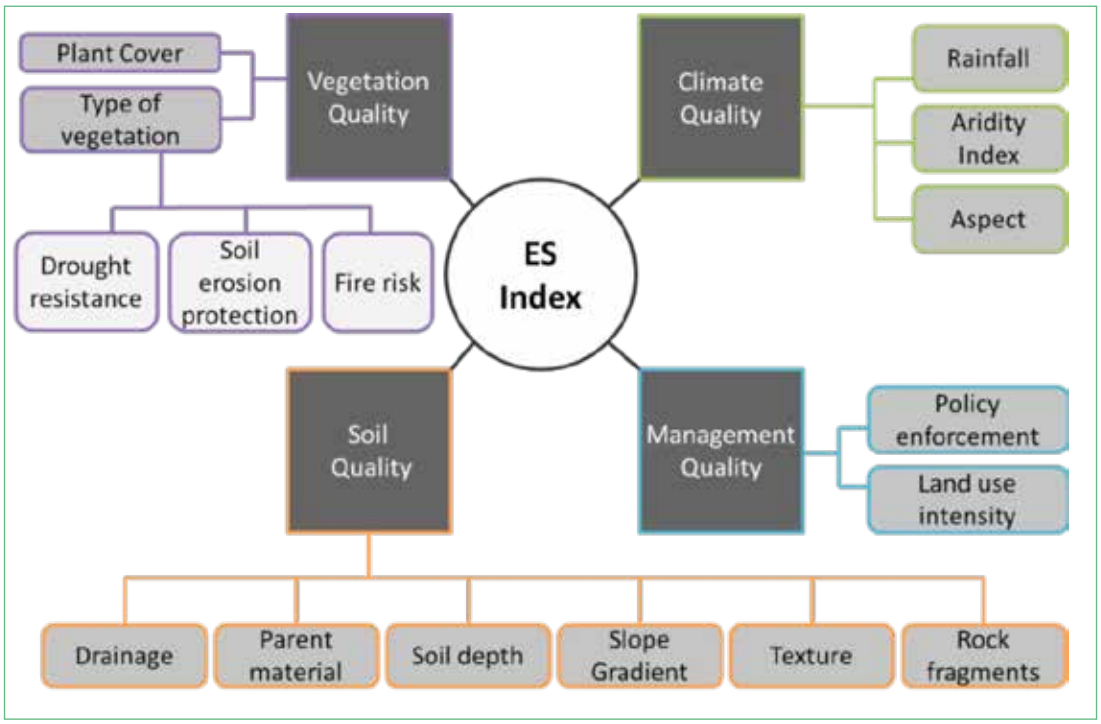
Source: Morello et al. 2012.
Note: "Others" include urban, continental water and rocky areas, based on the Soil Atlas of Argentina.

Case Study #6: Environmental Sensitivity Index: Expert System for Mediterranean Europe

The Environmental Sensitivity Index (ESI) (Figure 30) is an example of an online decision support tool developed for a specific region. It is an excellent example of both the strengths and limitations of many current attempts to provide public access to land potential knowledge and information, with a focus on degradation risks or resilience. In this sense, the ESI is conceptually more similar to the limitations-focused Land Capability Classification system, than to the production-focused Agro-ecological Zoning System. It illustrates the potential value of simple on-line tools, while exposing the limitations of simple scoring systems and the challenges of attempting to integrate parameters like "land use intensity" and "policy enforcement" as generic inputs.

The ESI was developed under the European Commission funded DESERTLINKS project - an international and interdisciplinary project with the objective to develop a desertification indicator system for Mediterranean Europe (Ferrara et al. 2012). The ESI system is a key indicator based system, which uses a suite of indicators to calculate an area's susceptibility to degradation. This enables land managers or policymakers to identify Environmentally Sensitive Areas (ESA) (Figure 29).

Figure 30. Indicators used to calculate the Environmental Sensitivity Index



Source: Modified from: Fererra et al. 2012.

Three key classes of data are essential in this system (1) physical, (2) vegetative, and (3) socio-economic variables. Four general data layers are used to provide these data:

Soils: This layer comprises information on parent material, soil depth, drainage, texture, and slope.

Climate: This layer includes information on aspect, rainfall, as well as the aridity index.

Vegetation: This layer includes data on fire risk, erosion protection, drought resistance and plant cover, the proportion of the soil surface covered by vegetation.

Management: This layer describes policy and land use enforcements.

The ESI system uses a series of drop down menus for user input of the indicators. The output gives the user information about the following:

- An evaluation of the quality of the land being examined for the four main components (Figure 30).
- The estimate of the Environmental Sensitivity to desertification of the area (ESI and ESA).
- An evaluation of the most critical factor(s) present in the area.
- An evaluation of the critical interactions among factors in the area.

The complexity of the data analysis involved depends on the complexity of the questions posed. The system is theoretically transferable to other spatial locations, but in order to apply the tool, the underlying datasets would need to be obtained for areas outside Mediterranean Europe.

Appendix 2.
Land resource surveys in current and former British overseas territories.

Country	Institutions	Coverage	Years (Publication)
Bangladesh	FAO/Government	Full	1965-1977
Belize	Government	Full	1959
Botswana	LRD	Part	1966-1972
Brunei	Consultants	Full	1969
Fiji	Government	Full	1965
Gambia	LRD	Full	1969-1977
Ghana	Government	Part	1961-1967
Guyana	FAO	Full	1965
Hong Kong	University	Full	1960
India	Government	Part	1947 ongoing
Jamaica	RRI	Full	1961-1971
Kenya	Government/Netherlands	Full	1980
Kenya, Uganda, Tanzania	Government	Full	1936
Lesotho	LRD	Full	1967-1968
Malawi	Government	Part	1938
Malawi	Government	Full	1965-1971
Malaysia: Malaya	Government	Full	1958-1970
Malaysia: Sabah	LRD	Full	1975-1976
Malaysia: Sarawak	Government	Full	1962-1966
Myanmar	FAO	Limited	1972
Nigeria (regions other than West)	LRD	Part	1966-1979
Nigeria (W. Region)	Government	Part	1962
Pakistan	Consultants/FAO	Full (excl. mts.)	1971
Papua New Guinea	CSIRO Australia	Full	1964-1070
Samoa	Government (NZ)	Full	1963
Seychelles	LRD	Full	1968
Sierra Leone	Government	Full	1926
Sierra Leone	Various	Part	1963-1974
Solomon Islands	LRD	Full	1974
Somalia	Consultants	Limited	1969-1979
Sri Lanka	Government	Part	1945
Sri Lanka	Government/Canada	Full	1962
Sudan	Government	Limited	1930's
Sudan	Consultants	Part	1950-1970
Sudan	Consultants	Part	1970-1979
Swaziland	Government	Full	1963-1970
Tanzania	Government	Part	1967
Tanzania: Zanzibar	Government	Full	1955
Uganda	Government	Full	1959-1962
West Indies	University	Part	1936/1947
West Indies (other than Jamaica)	RRI	Full	1958-1967
Zambia	Government	Full	1937-1943
Zambia	Government	Full	1970
Zimbabwe	Government	Full	1955-1960

The International Resource Panel showed in its first report on Land and Soil that without significant productivity increases, or decreases in the global per capita consumption of food and non-food biomass, the world's growing population will necessarily lead to an expansion of global cropland. The gross expansion of cropland under business as usual conditions will be 21 - 55% from 2005 to 2050. Matching land use with land potential is, therefore, a key factor in reducing the pressure on our land resources.

An improved understanding of land potential, in addition to more cost-effective and holistic tools for generating and sharing this understanding, is necessary to guide land use and management and, where necessary, to halt unsustainable land uses. More specifically, land potential evaluation systems are needed to sustain and increase the provision of ecosystem services in the context of climate change, persistent land degradation and increasing global population and per-capita consumption levels by (a) guiding land tenure and land redistribution, and (b) promoting innovation to sustainably increase productivity and resource efficiency, including through sustainable intensification. Matching more effectively land use with the land's potential is one of the few strategies available to decouple human development and economic growth from land degradation.

This new IRP report provides background information, tools, and policy options necessary to implement the concept of "land degradation neutrality" included in target 15.3 of the United Nations Sustainable Development Goals.

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