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The Land-Potential Knowledge System (LandPKS): mobile apps and collaboration for optimizing climate change investments

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Abstract. Massive investments in climate change mitigation and adaptation are projected during coming decades. Many of these investments will seek to modify how land is managed. The return on both types of investments can be increased through an understanding of land potential: the potential of the land to support primary production and ecosystem services, and its resilience. A Land-Potential Knowledge System (LandPKS) is being developed and implemented to provide individual users with point-based estimates of land potential based on the integration of simple, geo-tagged user inputs with cloud-based information and knowledge. This system will rely on mobile phones for knowledge and information exchange, and use cloud computing to integrate, interpret, and access relevant knowledge and information, including local knowledge about land with similar potential. The system will initially provide management options based on long-term land potential, which depends on climate, topography, and relatively static soil properties, such as soil texture, depth, and mineralogy. Future modules will provide more specific management information based on the status of relatively dynamic soil properties such as organic matter and nutrient content, and of weather. The paper includes a discussion of how this system can be used to help distinguish between meteorological and edaphic drought.

Key words: *agriculture; analytics; crowdsourcing; expert systems; extension; knowledge management; land evaluation; land-use planning; mobile apps; sustainability; sustainable land management.*

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Introduction

Massive investments in climate change mitigation and adaptation are projected during the coming decades.

Many will aim to modify how land is managed: mitigation to maintain or increase terrestrial carbon storage; adaptation to maintain one or more ecosystem services, including agricultural production and water availability, and to conserve biodiversity. Investments will also be required to build the adaptive capacity of socio-economic systems necessary to implement these management changes.

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Return on mitigation investments may be measured by the amount and duration of carbon sequestration. The return on adaptation investments is a function of the quantity and quality of ecosystem services conserved and, where these services cannot be conserved, the extent to which they can be replaced. The success of these mitigation and adaptation investments will depend on a variety of social, economic, and environmental factors (Webb et al. 2013, Herrick and Beh 2015).

Land potential is defined to include both potential productivity and potential resilience (Herrick et al. 2013). This definition integrates the potential to support virtually all terrestrial ecosystem services and biodiversity because they ultimately depend on some form of primary production. Both potential primary production and resilience ultimately depend on relatively static soil properties (texture, depth, and mineralogy), topography, and climate. Consequently, land potential provides an ideal spatial framework for targeting investments in climate change mitigation and adaptation.

Application of this framework to climate change is currently constrained by (1) a poor understanding of the difference between land potential (which cannot be easily modified by management) and soil fertility (which can), (2) limited access to land potential information at appropriate spatial and temporal scales, and (3) systems for testing and (4) sharing climate change mitigation and adaptation strategies among individual decision makers who are managing land with similar potential. Multi-billion dollar initiatives, such as the four per 1000 carbon sequestration proposal, are being promoted with little understanding of whether a positive return on investment is even possible across diverse types of land. At worst, uncritical, universal implementation of what can appear to be productive land management practices on some land types can increase both carbon emissions and land degradation when applied on lands with different potential.

Objectives and Overview

The objectives of this study were to address each of the four limitations described above. Section Land potential and ecosystem health reviews the land potential concept and its value for climate change mitigation and adaptation, concluding with an overview of existing systems for evaluating land potential. Section The Land-Potential Knowledge System (LandPKS; <http://landpotential.org>) introduces a System that is currently under development, and Sections Increasing access to land potential knowledge and information at appropriate spatial scales, Iterative testing of climate change mitigation and adaptation strategies and Sharing climate change mitigation and adaptation strategies discuss how this system will

increase global access to site-specific land potential information and sustainable land management practices, and the ability to easily test these strategies to ensure that they will work on specific types of land.

Land potential and ecosystem health

Agricultural production must be significantly increased to meet the needs of a growing global population while, at the same time, increasing terrestrial carbon storage and adapting to climate change (IAASTD 2009, UNEP 2014). Current efforts focus on intensifying production on currently used lands as well as expanding onto lands not currently used for agriculture. The long-term sustainability of both strategies, and their impacts on ecosystem health and biodiversity, require understanding the land's potential productivity, and its resilience—the ability to resist or recover from degradation (UNEP 2016). Potential productivity and resilience, and response to climate change, can vary widely within a field or watershed, depending on soils, topography, and climate (Webb et al. 2012). An understanding of land potential that accounts for both productivity and resilience is, therefore, needed by (1) governments for land-use planning and climate change adaptation, and for negotiating land contracts that will help ensure a nation's productive capacity will be maintained, (2) national extension and international development organizations to target and monitor their investments; and (3) individual farmers to empower them with information to value their land and to determine how best to manage their land today, while ensuring that future generations will also be able to feed themselves.

Many of today's efforts to intensify agricultural production and adapt to climate change focus on removing limitations to plant growth, for instance, through irrigation or fertilizer applications. While these investments may modify the short-term potential production of the land, the returns on these investments may be unsustainable and vary widely depending on soil and site properties controlling long-term potential. These differences are often most striking in drylands where differences in soil texture can determine crop success or failure during drought years, as well as the effectiveness of different types of fertilizers, erosion control structures, and other land management practices.

Failure to consider land potential has resulted in many disastrous development schemes, including attempts to cultivate the drier portions of the midwestern United States that resulted in the Dust Bowl (Worster 1982, Peters et al. 2004); the overstocking of rangeland in the southwestern United States (Wootton 1908, Herrick and Sarukhan 2007) that caused region-wide transitions of grasslands to shrublands with low forage value; and the huge East African groundnut scheme (Hogendorn and

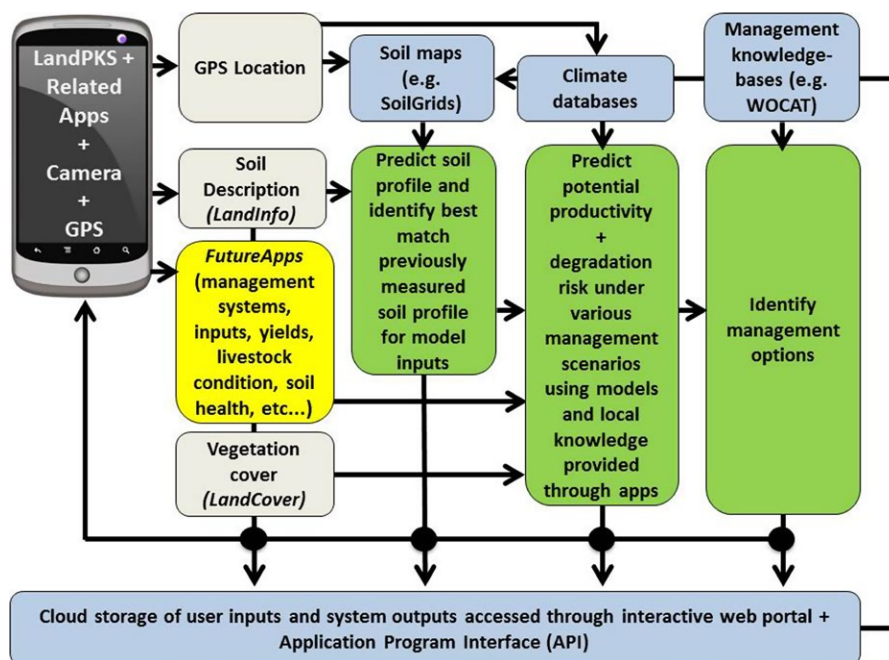


Fig. 1. Land-Potential Knowledge System (LandPKS) is being developed as a suite of mobile apps connected to an international network of knowledge and information sources.

Scott 1981). This massive agricultural development project was designed to convert rangelands to mechanized peanut production agriculture. It failed, in part, due to a lack of understanding of local soil limitations. In each case, environmental disaster could have been averted if land potential had been considered.

Benchmarking land potential is also vital for interpretation and evaluation of trends in land degradation or restoration. This is becoming increasingly important given the urgent need to target and monitor new political commitments, including Sustainable Development Goal 15.3 (land degradation neutrality—see also <http://unccd.int>), and forest and landscape restoration under the Bonn Challenge (<http://www.bonnchallenge.org>), and UNFCCC COP21 agreements.

Arguably the most comprehensive source of information on land potential is the FAO’s Global Agro-Ecological Zoning System (GAEZ; FAO 2013). It provides estimates of potential as well as current production, growing season periods, and estimated yields and yield gaps for major crops. It is a tremendous achievement and a dramatic improvement in the accessibility of land potential information for many parts of the world. However, the GAEZ is limited by: (a) coarse scale, which makes its application to specific locations problematic because land potential can vary over short distances, (b) unknown and highly variable accuracy of predictions, (c) the static nature of the model, which means there is no way to improve estimates based on new and locally available information and knowledge, and (d) lack of information on degradation risk and resilience.

The Land-Potential Knowledge System (LandPKS)

The LandPKS (<http://landpotential.org>) is being developed to provide individual users with point-based estimates of land potential based on the integration of simple, geo-tagged user inputs with data, information, and knowledge stored in the cloud (Fig. 1). LandPKS users provide site-specific land cover and soil profile information using primarily icon-based inputs. Short, animated, language-independent tutorials for determining soil properties are embedded in the mobile phone application. Users simply select the image that most resembles what they see.

These user inputs are then automatically uploaded from the mobile phone to the cloud the next time the phone has data access. The inputs are stored on remote servers and integrated with global climate and soils databases (e.g., SoilGrids), which then provide inputs for predictive models. In the future, these modeled predictions will be integrated with cloud-sourced local knowledge from land with similar potential. This will then be used to deliver point-specific estimates of long-term potential production and degradation risk under different management scenarios, and a subset of sustainable land management options that are likely to be feasible based on local diets, markets and access to different types of inputs. It will also help individuals to directly connect with others facing similar challenges locally, and in other parts of with world with similar land potential.

As of late 2015, three apps had already been released. The LandInfo app allows users to collect and store basic

land cover, topographic and soil profile information, and returns soil profile plant available water holding capacity and local climate information. LandCover is an app for vegetation and ground cover inventory and monitoring using the stick method (Riginos et al. 2011), and automatically calculates basic indicators, such as bare ground, litter or crop residue cover, and the cover of different types of vegetation such as grasses, shrubs, and trees. ISRIC's SoilInfo app provides direct access to SoilGrids—global spatial predictions of soil properties for six standard depths 0–5, 5–15, 15–30, 30–60, 60–100, and 100–200 cm and soil classes based on FAO and USDA soil taxonomy (Hengl et al. 2014). A web portal (landpotential.org) provides public access to all LandInfo and LandCover data. Our long-term goal is to facilitate the development of an open suite of connected apps, models, analysis systems, and data and knowledge portals.

The LandPKS complements the GAEZ by using mobile phone technologies and a web-based knowledge engine. It will allow policy makers and land managers to access and share current information and knowledge for their specific type of land. A further function of this system will be to directly connect farmers with other land managers, who have developed and tested innovative land management practices on the same type of land. In this way it will provide critical means for developing adaptive capacity in agricultural communities, which is dependent on networks and local education (Marshall et al. 2014). It will also increase the value, efficiency and efficacy of existing agricultural extension workers by providing them with the tools and information necessary to communicate more specific and timely recommendations to particular groups of farmers (e.g., providing information on drought management specifically to those farmers with soils that are the most sensitive to drought).

As the LandPKS evolves, we will work with partners to support its implementation globally. The authors consider LandPKS to be a global partnership that already involves ISRIC—World Soil Information (<http://www.isric.org/>), WOCAT (<https://www.wocat.net>), the World Agroforestry Center (<http://www.worldagroforestry.org/>), the USDA Natural Resource Conservation Service (<http://www.nrcs.usda.gov/>) and several others, rather than as a product belonging to any single institution. LandPKS is being designed to complement and increase the value of the work of a large number of other projects and initiatives, including the Africa Soil Information System (AFSIS; <http://africasoils.net/>), and Vital Signs. Like many other social innovations, the development and implementation process will rely strongly on partnerships as the benefits of participating in the system are expected to vastly exceed adoption costs for both individuals and organizations. As LandPKS promotes open data (<http://opendatacommons.org>) and tools based on open-source software, collaborative development strategy, we look forward to developing new partnerships as the system evolves. For example, knowledge-sharing

tools recently developed through South–South collaboration (Barrios et al. 2012) can be used to facilitate the systematic integration of local and scientific knowledge across different cultures settings and languages.

Increasing access to land potential knowledge and information at appropriate spatial scales

The LandPKS will increase access to knowledge and information specific and relevant to individual locations. It will do this by integrating users' descriptions of soils and land cover with global databases. For example, the LandInfo app uses a graphical interface with embedded training videos to help users estimate soil texture. Soil color, which is related to soil mineralogy and organic matter content, will be added in the future. This information, coupled with the location generated by the phone's GPS, is transmitted to a cloud-based database, immediately or as soon as the user moves into an area with Internet connectivity. Soil texture by depth will be used together with existing soil information to estimate soil properties at specific locations. This includes ISRIC's SoilGrids system—global gridded maps of primary and secondary soil properties and soil classes based on automated mapping and distributed data (Hengl et al. 2014, 2015). The relative importance of each of these two or three estimates will vary depending on their predicted reliability.

Iterative testing of climate change mitigation and adaptation strategies

One of the most significant challenges facing private and public investors in climate change mitigation and adaptation is uncertainty about the effectiveness and sustainability of any particular action. In the case of mitigation through carbon sequestration, this results in high discount rates, sharply reduces the amounts that investors are willing to commit and correspondingly increases their required return on investment. This can lead to unrealistic requirements that price many potentially profitable strategies out of the market. In many cases, the uncertainty is due to highly variable responses on different types of land or, where impact of the action has only been reported for one type of land, an inability to extrapolate to other types of land. The costs and time required for experimentally controlled and replicated research are barriers to reducing these uncertainties. Even where research results are reported, they are often based on "demonstration" areas that lack appropriate controls, making it difficult to determine whether "successes" were due to implementation of the action, or simply a function of short-term weather or other conditions independent of the action itself. In addition, formal trials conducted by institutions fail to generate accurate recommendations

at the fine resolution required by farm managers, and individual land users will still need to conduct their own tests.

Adaptation strategies face the same limitations, but the costs of consequent errors can be much more catastrophic. The failure of 100,000 farmers to sequester the predicted amount of carbon could have trivial mitigation impacts, while adoption of unsuccessful adaptation strategies can have regionally catastrophic social, economic and political impacts.

The LandPKS addresses these limitations in four ways. First, it allows for cost-effective, real-time, long-term (repeated observations) reporting of the results of field and iterative model tests of new strategies across a wide range of conditions. Second, it will help individuals with little or no soils background to select appropriate controls for these tests. Third, it empowers land managers to evaluate management options themselves, providing an additional information source to that coming from governments, scientific community and extension officers, thereby increasing the likelihood of adoption. Finally, future versions will allow comparisons to be made independently, *even where no formal control has been established*. This is possible because the databases generated by the LandPKS can be independently queried, for example, to identify areas with similar land potential where the proposed or promoted strategy has not yet been applied (a “control”). While there are clearly significant limitations to this approach associated with data quality, we believe that they can be at least partially overcome with data quantity: the number of replications can be increased at much lower cost than through traditional research approaches, and multiple sources of evidence can be accessed based on instantaneous access to all relevant knowledge and information, including modeled predictions, for a specific set of conditions. In summary, it will provide a range of options to facilitate both citizen science and its integration with more formal research initiatives.

Sharing climate change mitigation and adaptation strategies

One of the most promising future applications of a global LandPKS is the ability to rapidly share successful strategies with individuals *managing land with similar potential* to both sequester carbon (mitigation) and apply particular adaptation strategies. This capability will build on current knowledge systems, such as the World Overview of Conservation Approaches and Technologies (WOCAT; Fig. 1). Repositories for best-management practices like WOCAT are based on broad-scale classifications of the conditions under which these practices should be successful. As such, they are relatively static and require manual updating. The LandPKS will improve on these existing databases in two ways, both of which are critical for climate change adaptation as well as mitigation.

The first improvement of LandPKS relative to existing databases is that it will allow predictions to be made about the potential success of a strategy for a particular location based on site-specific conditions, using knowledge and information from sites with similar potential throughout the world. Similar algorithms are applied in JournalMap (www.journalmap.org; Karl et al. 2013) for scientific literature searches. This will allow the most relevant knowledge and information to be shared both locally and globally, in near-real time.

The second improvement is that it will allow the users to easily contribute their own knowledge and information to WOCAT and other knowledge bases, and allow this knowledge and information to be shared on a site-specific basis. The general principles associated with the implementation of many land management technologies are relatively simple, but success or failure is often determined by the enabling environment (Coe et al. 2014) and site-specific modifications are very often required. The adoption of minimum tillage technologies is a classic example. While national adoption of this technique was a significant factor in contributing to a 40% reduction in U.S. cropland soil erosion between 1982 and 2007, local implementation was fraught with challenges as yields sometimes declined during the first few years following cessation of tillage. The steep learning curve associated with adoption of this and other technologies that reduce, or even reverse soil carbon losses could be expedited by directly connecting farmers through cell-phone-based networks that may also facilitate the creation of local face-to-face networks (Urama and Acheampong 2013). The third improvement is the ability for individual LandPKS users, subject to privacy limitations, to identify and contact individuals who have successfully (or unsuccessfully) implemented strategies on lands with similar potential.

In addition to improving on predictions provided by current knowledge bases and connecting land managers facing similar challenges and conditions, LandPKS will increase the quality of the information included in knowledge bases as it will allow predictions to be tested, including predictions about the causes of drought (Box 1).

Individuals who have provided information about a particular location can be contacted and queried several years later about plant and soil responses to management (see *Iterative testing of climate change mitigation and adaptation strategies*). The responses to these queries, together with independent remote sensing information, can be used to test these predictions.

Summary and Conclusions

An understanding of land potential can be used to increase returns on investment in climate change mitigation and adaptation. Long-term land potential is one of the few variables that generally *cannot* be changed through investments in land management; therefore it

Box 1**Using LandPKS to distinguish between meteorological and edaphic drought**

An understanding of land potential, supported by the LandPKS, can help distinguish between different causes of drought stress in plants and support the application of appropriate and effect response strategies. There are three major causes of drought stress in plants: meteorological (weather), edaphic (soil), and biotic. Meteorological drought occurs when there is a significant decline in precipitation over a period of weeks to several decades. Edaphic (soil) drought occurs when soil degradation limits the amount of water that the soil can capture (infiltration) or hold (water holding capacity). Biotic drought occurs when water is available in the soil, but the plants cannot access it because they are too stressed due to insects, disease, or (for rangeland) overgrazing. The first two types of drought limit the amount of water that plants can take up through reduced soil water availability, while the third limits the ability of plants to take up available water through reduced root growth.

When drought conditions occur, it is critical to understand the underlying cause so as to develop and prioritize appropriate drought response strategies. Without this understanding, there is a risk that drought is attributed to meteorological conditions, when, in fact, water stress could be the result of land degradation. Such an error in attribution could lead to the abandonment of policies designed to reduce or reverse degradation without any reduction in the impacts of drought on food production or farmer livelihoods.

The linkage between land degradation and drought impacts make it even more important that the fundamental causes of drought conditions are fully understood. Land degradation and drought are related in three ways. (1) Degraded land experiences drought more often and more intensely due to edaphic (soil) drought. Even during years of normal precipitation, crops and rangeland on degraded land will show signs of drought stress due to reduced infiltration. (2) Land is more susceptible to degradation during drought for physical reasons: less plant production means that more of the soil is exposed to erosion. (3) Land is more susceptible to degradation during drought for socioeconomic reasons: during drought, people and their animals are more likely to take advantage of any growing plant, reducing its ability to grow roots to access water.

LandPKS technologies can help identify potential indicators of specific types of drought stress by documenting and analyzing specific soil properties (texture by depth), climate variables (average precipitation and its distribution), and ultimately deriving estimates of productivity, and land degradation risks for a deeper understanding of the land's potential. This improved understanding of long-term land-potential can help us better target future investments in appropriate mitigation and adaptation strategies, reducing the risk of poor and (sometimes) detrimental investment choices.

must be considered as a fundamental factor affecting their success. Finally, drought management strategies that recognize that some types of land are more resilient to drought than others can help save the land for the future and even promote recovery. LandPKS is one tool that can be used to increase our understanding of land potential, and to apply it to improve both climate change adaptation and mitigation activities. While we recognize that no single tool can function seamlessly to address all user needs across cultures and languages, we are committed to creating a suite of open land information applications that are as broadly relevant and usable as possible through active user involvement in the development process, and by using generic imagery instead of language wherever possible.

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