A Decision Support System for Incorporating Land Potential Information in the Evaluation of Restoration Outcomes

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ABSTRACT

Regular monitoring and evaluation of rangeland restoration outcomes is necessary for accountability, adaptive management throughout the restoration process, and informing future project design. Monitoring and evaluating outcomes can help restoration practitioners and land managers identify restoration successes and failures. Often information about differences in potential vegetation productivity in restored areas is not collected, but it can help to understand and predict these different outcomes. Here, we provide a novel decision-tree based framework for designing monitoring programs for restoration projects. We emphasize the need to collect land potential information to help evaluate and contextualize restoration outcomes. We then highlight a new mobile phone application that can be used to collect basic land potential information with minimal time and training requirements.

Keywords: LandPKS, monitoring, restoration success, retrospective assessment

Restoration Recap

- Few easily accessible and widely applicable frameworks exist for monitoring and evaluation of restoration outcomes.
- Land potential information is instrumental for designing successful restoration treatments, however it can also be used to improve treatment monitoring design and evaluation efforts.
- We describe a decision tree framework for incorporating land potential information into restoration monitoring and evaluation programs.
- We highlight a mobile phone application that can be used to both help estimate land potential and collect monitoring data, potentially reducing the costs for both.
- The app provides restoration practitioners with a novel tool which allows non-soil scientists to complete soil and plant characterization and automatically determine other soil properties, manage documents, and to monitor both soil health and vegetation responses.

The continued degradation of rangelands worldwide has been widely documented (IPBES 2018). This loss of soil and vegetation resources, coupled with increased biological invasions, has tangible consequences for biodiversity conservation, sustainability of livelihoods, and food security. Consequently, efforts to reverse or mitigate degradation have been implemented at multiple scales, from national and regional to property level (Svejcar and Kildisheva 2017). These restoration projects are often carried out with unclear goals, limited indicators of success, and poor reporting, especially on rangelands outside the United States and Australia (Ruiz-Jaen and Aide 2005, Wortley et al. 2013).

Questions about where, what, and when to monitor with regards to restoration impacts have been extensively examined in the restoration literature. The most common recommendations involve monitoring of both ecosystem structure and function, with specific indicators selected according to restoration objectives (Hallett et al. 2013). Collecting these data continuously over time allows restoration practitioners to track changes in their ecosystems and assess whether restoration objectives have been met. This monitoring and evaluation cycle is often not carried

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out. Where it exists, it is only carried out for the first few project years, leading to possibilities of missing successful long-term restoration impacts, or overemphasizing the importance of short-lived restoration "successes" (Ruiz-Jaen and Aide 2005, Kinyua et al. 2010). Evaluating and reporting restoration outcomes facilitates immediate assessment of success of a restoration strategy, as well as the scaling up of successful new methods to similarly affected areas.

In addition to measuring restoration success as a pre- and post-restoration change, it is important to provide an ecological context for observed outcomes. Different factors could influence the success or failure of a given project, including selection of ineffective methods, insufficient precipitation, herbivory, or even poor choice of restoration location (Whisenant 1999, Hobbs and Kristjanson 2003, Harris et al. 2006). Understanding restoration outcomes is important both for adapting current restoration activities, as well as informing future efforts. This would help restoration practitioners avoid the pitfalls of the carbon-copy approach to development of restoration strategies and instead tailor restoration programs to specific ecological conditions present on the landscape (Hilderbrand et al. 2005).

One often underutilized strategy for improving restoration strategies is evaluating restoration outcomes using site-specific land potential (Herrick et al. 2013). Land potential can be generally described as the ability of land to produce specific kinds and amounts of vegetation, be resistant to degradation, and be resilient after degradation (UNEP 2016). The determination of land potential provides the land manager with the information necessary to 1) select areas on the landscape that would be most responsive to restoration efforts and resilient following restoration, 2) better evaluate restoration outcomes by identifying and matching treatment and reference or control sites, and 3) inform future ranking of restoration potential by matching restoration outcomes with land potential.

In many areas of the developing world, including Africa, lack of monitoring of restoration outcomes mostly stems from lack of financial resources (Ruiz-Jaen and Aide 2005, Wortley et al. 2013). Independent studies to generate the site-specific knowledge necessary to optimize restoration investments are generally not feasible on community owned land and on low-income, privately-owned rangelands. A simple restoration monitoring framework that uses widely available land potential information for design might therefore facilitate increased monitoring of restoration outcomes while still providing useful information for other restoration practitioners. This framework must also be flexible enough to allow managers to select feasible monitoring indicators given their time, financial, and human resources.

In this paper, we provide an overview of land potential and basic concepts needed for both restoration monitoring design and interpretation. We then present a decision-tree based framework for monitoring and evaluation of restoration projects that incorporates use of land potential information. Lastly, we highlight a land potential evaluation tool that uses a mobile phone application to provide valuable qualitative and quantitative information for restoration monitoring.

Land Potential

Land potential generally includes three elements: potential production of ecosystem services, degradation resistance and resilience, or the capacity to recover following degradation (Herrick et al. 2013). In some areas including the United States, Mongolia, and parts of Argentina, land potential is used to group soils into ecological sites. These are defined as a distinctive kind of land with specific soil and physical characteristics that differs from other kinds of land in its ability to produce distinctive kinds and amounts of vegetation, and in its ability to respond similarly to management actions and natural disturbances (USDA-NRCS 1997). This is important information because land potential will influence how different land areas will respond to different management decisions and restoration activities.

Major factors determining land potential

Land potential can often be placed into one of two categories, long-term and short-term land potential. Long-term land potential is primarily determined by three elements: the long-term climate, topography, and relatively static soil properties like soil mineralogy, soil texture throughout the soil profile, and soil depth (UNEP 2016). These factors generally work in concert with each other, and their overall dynamics determine plant water availability and subsequently primary production. The amount and types of vegetation that can be supported will in turn influence degradation resistance and resilience. For example, soils that are flat, deep, and loamy will generally support higher potential production, and will tend to have higher resilience and therefore be more likely to respond positively to restoration efforts than steep, shallow sandy soils (Herrick et al. 2013).

Short-term land potential can be lower than long-term potential if degradation of dynamic soil properties has occurred, or when there are negative deviations of weather from long-term climate, such as a multi-year drought (UNEP 2016). Dynamic soil properties include bulk density, soil organic matter, nutrient availability, and changes in soil salinity caused by human activity. In perennial rangeland and forest ecosystems, short-term potential also depends on existing vegetation cover and composition. These factors determine the ability of a piece of land to provide ecosystem services immediately but can generally be modified by management. When predicting the probability of success of a restoration strategy, short-term land potential is just as important as long-term land potential. For example, a flat loamy soil could be determined to have high probability for restoration success (long-term potential), but subsurface compaction might hamper infiltration and restrict plant water availability (short-term potential), undermining restoration efforts. The likelihood of an area to respond to restoration interventions is very important when planning restoration projects. However, it is just as important when designing restoration monitoring programs. Below, we describe two main ways land potential information can be useful for restoration monitoring and evaluation.

Selection of reference and control areas

Many suggested frameworks for assessing restoration outcomes recommend using reference conditions as targets (Aronson et al. 1995, SER 2004, Wortley et al. 2013). In rangelands of the United States, reference conditions are often characterized in ecological site descriptions and their associated state and transition models, as well as rangeland health indicator reference sheets (Pellant et al. 2005). This generally makes it easier to identify and characterize reference areas for restoration planning. The terms "reference area" and "control area" are often used interchangeably, but frequently describe different things. In the context of our framework, reference and control are used to describe two distinctly different concepts, both of which are valuable in determining restoration success.

A reference site can be defined as 1) a relatively intact ecosystem whose communities fall within the natural range of variability given natural disturbance processes, 2) the historical state of an ecosystem before human mediated disturbance, or as 3) the best attainable ecosystem conditions possible in a given area given prevailing management (Pellant et al. 2005, Stoddard et al. 2005). For all these definitions, there is a need to ensure that the land potential of the area targeted for restoration is similar to that of the reference sites. For example, in areas with highly complex and heterogenous soils, it would be easy to use a reference site located on a soil that has similar surface conditions to the restoration area while unintentionally ignoring subsurface differences in soil mineralogy and texture that render the two areas dissimilar in land potential.

A control area is an untreated area where restoration has not been carried out (SER 2004, Osenberg et al. 2006, Heleno et al. 2010). To function as a properly matched paired design, conditions at the implementation of restoration need to be the same. At the onset of restoration, matching the vegetation and dynamic soil properties that contribute to long-term potential is important for selecting proper controls. Additionally, it is necessary to include information on short-term land potential, taking care to ensure that the paired treatment and control areas are likely to respond similarly to the treatment. For example, two sites with similar soils could be dominated by an invasive shrub, and therefore display similar types and amounts of vegetation before restoration. However, one of the sites might have a steeper slope than the other. Subsequent clearing of the woody species on each of the sites might result in increased run-off on the steeper soil and slower recovery, while the flat area might benefit from slower run off, higher infiltration, and therefore possibly faster recovery. Making sure that treatment and control plots are properly matched is essential for proper evaluation of restoration success.

Interpreting restoration outcomes using land potential information

Adaptive management of the restored area needs to be an iterative process with feedback loops within the monitoring cycle (Folke et al. 2004, Herrick et al. 2006). Often these feedback loops are focused on the comparison between restoration outcomes and restoration objectives, as well as the relationship between this deviation and the restoration strategy. If the restoration strategy has achieved the desired objectives, then it can be deemed a success in this context (Zedler 2007). If the restoration strategy has not achieved the objectives, then it needs to be examined, modified, and potentially changed altogether (Herrick et al. 2006). Collection of land potential information during this process could help identify some of the reasons why restoration objectives may not have been achieved and allow the restoration practitioner to modify or discard the particular strategy being employed so that the desired outcomes can be achieved.

For example, an effort to reverse gully formation in the Westgate Conservancy in Kenya kept failing despite considerable efforts to construct gabions and brush barriers that had worked elsewhere (Kimiti, pers. obs.). A qualitative assessment suggested that although the "long-term" potential of the upslope contributing area was relatively high, degradation of the vegetation and soil surface properties (resulting in higher runoff volumes) meant that the "short-term" potential success of the of the barriers was quite low. Based on a simple assessment of the landscape from a land potential standpoint, we concluded that the placement of the restoration plots downslope from degraded areas meant that surface run-off velocities were destructively high by the time they reached the gully barrier. Restoration efforts therefore had to be directed towards increasing vegetation cover and water infiltration upslope and reducing overall surface run-off downslope.

In addition to informing the adaptive process of current restoration projects, incorporation of land potential information could help inform future restoration efforts. Monitoring and evaluating restoration outcomes in areas with differing land potential, but where similar restoration objectives and restoration strategies are being employed, can help restoration practitioners to identify locations

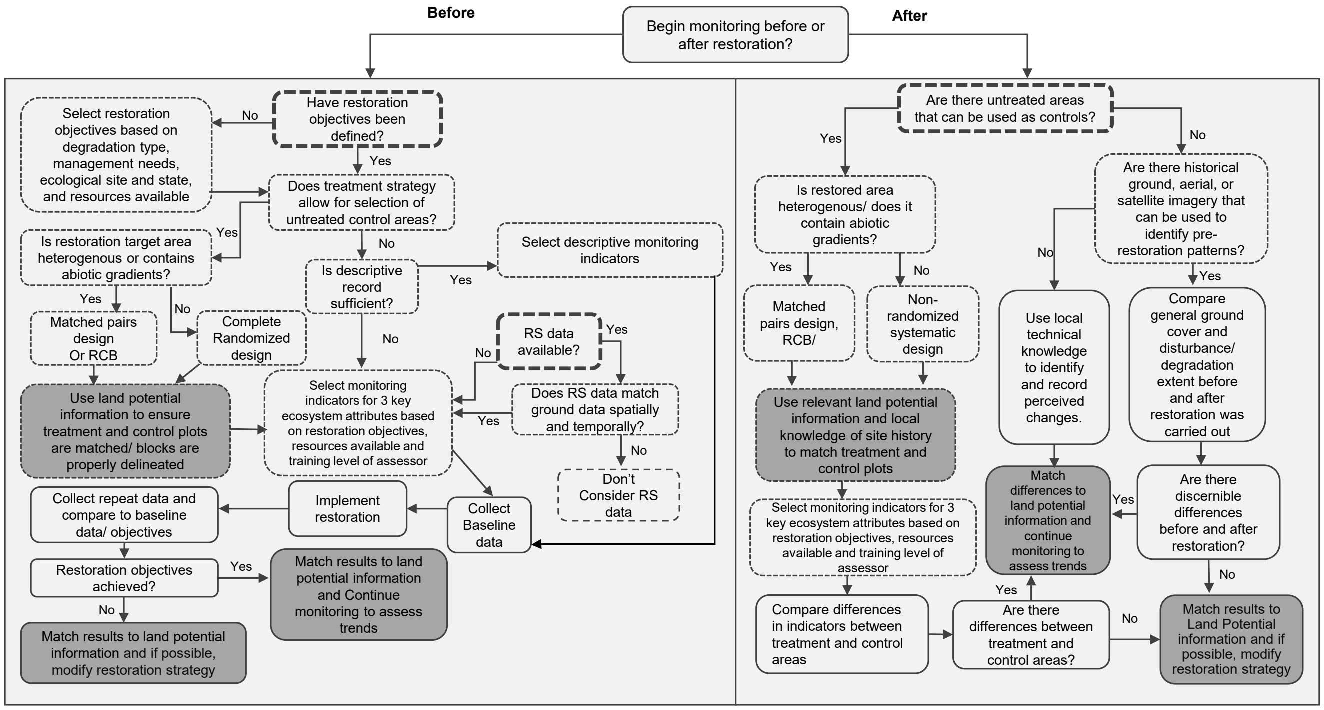

Figure 1. Decision tree framework for evaluating and monitoring restoration outcomes, identifying main decision points and highlighting steps where land potential information could be used to provide valuable context and help inform future restoration efforts. Dashed boxes indicate design phase while solid boxes indicate monitoring phase. Grey boxes indicate use of land potential information. RS: Remote Sensing. RCB: Randomized Complete Block.

on the landscape where these strategies are more likely to be successful. Similarly, by collecting information on the suitability of different restoration strategies in areas with similar land potential, information on best practices can be obtained and replicated in other locations with matching land potential and degradation characteristics. For example, the use of mobile cattle corrals, or "bomas" as tools to create vegetation hotspots is an increasingly popular restoration tool in many parts of Africa (Porensky and Veblen 2015, Sibanda et al. 2016). However, very little information exists about how effective these bomas are on different soil types, textures, slopes, and climates. Basic characterizations of land potential information at boma sites would allow an accumulation of knowledge about conditions most favorable or detrimental to boma success, allowing practitioners to rank and select potential boma sites on their landscapes based on their likelihood to create desirable vegetation.

There is therefore a need to provide restoration practitioners and resource managers with the tools necessary to better predict restoration outcomes and inform future restoration efforts by incorporating land potential evaluation into restoration monitoring. Below, we describe a generalized decision tree framework for monitoring restoration outcomes, highlighting the use of land potential information at key steps along the decision-making process.

A Decision Tree Framework for Monitoring Restoration Outcomes

Overview

Several prescriptive frameworks have been suggested to aid in the monitoring and evaluation of restoration success. Most of these frameworks include information about selection of restoration strategies and how to decide what, where, and when to monitor (Herrick et al. 2006, King and Hobbs 2006, Brewer and Menzel 2009, James et al. 2013). These frameworks range from relatively linear and simple to extremely complex. Few of these frameworks incorporate land potential evaluation, and the actual rate of adoption of most of them among practitioners is unclear (Wortley et al. 2013). Our framework focuses on the evaluation of restoration outcomes and does not deal with the selection of restoration strategies themselves. It is meant to provide a general guide for restoration practitioners, while highlighting the critical decision-making points where a more in-depth and critical analysis of land potential could result in a more effective monitoring and evaluation system.

The framework is presented as a decision tree, suggesting possible alternate actions that increase the adaptability of monitoring program design to real world constraints and opportunities (Figure 1). Our first and most important divergence point is whether the restoration monitoring is being conducted before or after restoration activities.

Initiating monitoring before restoration activities

In situations where a monitoring program is being designed for a restoration project that has not been implemented, the first consideration should be the definition of restoration objectives. Restoration objectives will provide the benchmark against which the restoration outcomes will be evaluated, and can vary between projects, even on land with similar potential, due to differences in "desired" outcomes (Hallett et al. 2013). Selection of restoration objectives is often informed by comparison to a reference condition, which is identified through local knowledge, historical photographs, pre-disturbance data, intact undisturbed areas, or even experimental enclosures (SER 2004).

When reference areas are used to define restoration objectives, care should be taken to make sure that what appear to be relatively intact areas are similar in land potential to the target treated areas. There is the possibility that potential reference areas are intact and undisturbed because they had differing resistance and resilience to disturbance than the degraded areas. For example, in the case of a wildfire, undisturbed areas that did not burn might have a differing composition of herbaceous understory due to differences in topography or soil conditions in those areas (Leonard et al. 2014).

The quality of monitoring and evaluation of the impact of a restoration project is greatly improved by using control areas. In contrast to reference areas, which provide ideal targets for restoration, control areas are untreated degraded areas intended to interpret restoration outcomes spatially and temporally. Where the treatment area is conducive to selection of control areas prior to treatment (e.g., when carrying out plot level reseeding trials) the ideal overall framework for the restoration should be a paired Before-After-Control-Impact (B.A.C.I.) design. This design has been used extensively to monitor landscapes for changes in select vegetation and soil variables after restoration activities (Smith 2014). Under B.A.C.I., multiple control plots are paired with multiple treatment plots, which allows plot-specific temporal changes unrelated to the restoration activity under measurement to be controlled (Smith 2014, Heleno et al. 2010).

The specific experimental design within the B.A.C.I. framework will be further determined by the nature of homogeneity of the landscape under restoration. In target areas that are generally homogenous in the major components of land potential, then the ideal experimental design is a complete randomized design, where treatment and control areas are selected randomly from within the disturbed landscape. However, if the target area is large or is characterized by high heterogeneity in soils, topography, or climate, then careful matching of treatment and control areas is necessary, and a matched pairs design is more ideal. Where there are multiple restoration treatments and the target area is heterogenous and the heterogeneity can be mapped, a randomized complete block design (RCB) would be preferred, ensuring that variability within blocks is lower than the variability between blocks.

Regardless of the experimental design selected, the main consideration should be the proper matching of treatment and control plots, ensuring that they are as similar as possible (Block et al. 2001). Depending on the natural variability of an area and the type of restoration, the components of land potential that will be most important might vary. For example, if the restoration project is aimed at reversing compaction in an area, soil texture and bulk density similarity between treatment and control areas will be a more important matching criteria than climate or nutrient availability (Horn et al. 1995). By collecting information on land potential and making sure it is similar between treatment and control areas at the time restoration is implemented, the restoration practitioner can be sure that the treatments selected would conceivably have had the same effect on both plots.

If the nature of the disturbance/treatment does not lend itself to selection of a control area (e.g., in the case of a vast wildfire where the entire affected must be treated), then the restoration practitioner can compare information on specific indicators of interest before and after restoration has been carried out, in a Before-After sampling design. Additionally, if only a descriptive record of changes due to restoration is desired, then fixed point ground based or aerial photography may be sufficient to provide the required information (Elzinga et al. 1998).

The deviation in the selected indicators is used to decide whether the restoration strategy implemented has been successful in achieving the restoration objectives. The measured success or failure within can then be used to determine whether the restoration strategy should be modified (Zedler 2007). However, care should also be taken to identify whether the original disturbance that necessitated restoration is still present or has been controlled. For example, if heavy off-road vehicles have created a compaction problem in an area, any efforts to remedy this compaction will be hindered by continued traffic, and restoration objectives are unlikely to be met unless the disturbance itself is addressed (Herrick et al. 2006).

One of the advantages of our suggested framework is the use of land potential information to explicitly interpret differences in restoration response between areas with varying land potential. This contextualization of results would further provide knowledge about the relative influence of different land potential components upon the likely success or failure of the project. Taken together with observations from similar projects on other landscapes, this information would contribute to the overall identification of best practices, thereby informing the decision-making process of future restoration projects.

Initiating monitoring after restoration activities

Retrospective assessments of restoration projects are often the only way to monitor large scale restoration projects that are implemented outside the purview of formal restoration experiments (Foster et al. 1990, Swetnam et al. 1999, Grady and Hart 2006). In the developing world especially, there are often not enough resources to allocate toward restoration monitoring. Even though over 70% of African rangelands have long been estimated to be moderately to severely degraded (Dregne and Chou 1992, UNCCD 1994), and despite the presence of several regional scale restoration initiatives including the West African Drylands Project and the African Resilient Landscapes Initiative, only 3–4% of studies in Restoration Ecology are from the continent (Ruiz-Jaen and Aide 2005, Wortley et al. 2013). This means that any current assessment of restoration projects on the continent would most likely have to be retrospective.

Although the general decision tree for monitoring before and after restoration is similar, there are a few key differences. Where selection of control plots is possible, retrospective selection requires careful matching of treatment and candidate control sites. Matching of long-term land potential through relatively static soil properties, topography, and climate could likely be accomplished without much difficulty. However, the status of short-term land potential is influenced by relatively dynamic soil properties and vegetation cover and composition, which requires some historical knowledge of the treatment and proposed control areas at the time treatments were initiated. In this case, best estimates of biophysical similarity at restoration should be obtained from multiple sources, and caveats placed onto any results obtained.

One important possible source of this supplementary information is the restoration practitioners themselves, as well as other land managers and land users with historical knowledge about the landscape in question (SER 2004). Historical imagery from ground, aerial or satellite images could also be instrumental in assessing biophysical similarity at the time of restoration (Swetnam et al. 1999). The concept of positive spatial autocorrelation, or that areas closer to each other are more likely to be similar, could be helpful in this situation, especially when the scale of environmental variability is known (Legendre 1993). By ensuring that treatment and control areas are within the limits of known spatial variability, the assumption that they would have been similar at the time of treatment is not unreasonable, especially if other markers of long-term potential are well matched. Local knowledge is generally most useful for historic vegetation, but anecdotal evidence suggests that pastoralists also retain a strong memory of differences in soil color (e.g., Herrick et al. 2010).

The actual experimental design of a retrospective assessment could still be viewed as a paired control-impact restoration design, since only current spatial differences (Control-Impact) are directly measured, while temporal differences (Before-After) can only be inferred using information from other historical sources. As with the decision tree when monitoring is carried out before restoration, environmental gradients and heterogenous landscapes can be corrected for by using matched pairs assessments or a block design. However, if the landscape is homogenous and there are available controls, then by necessity the sampling scheme would need to be a non-randomized quasi-experimental design.

Selection of monitoring indicators

Many frameworks have been developed that suggest the types of indicators that need to be collected, covering both ecosystem structure and function. One suggestion focuses especially on the need for a “preponderance of evidence” to decide which indicators to measure (Herrick et al. 2006). This framework identifies three key ecosystem attributes, namely hydrologic function, soil and site stability, and biotic integrity. Within these attributes, 17 different qualitative indicators are suggested, some contributing to multiple attributes (Pellant et al. 2005). The primary strengths of our proposed protocol emerge where land potential information is used to provide comparative baselines for these indicators. By matching treated and untreated areas, a catalogue of natural variability expected within areas of similar land potential in an ecosystem can be used to inform future restoration efforts.

The selection of indicators to be assessed will ultimately depend on the restoration objectives, type of disturbance, restoration method, as well as the skill level and resources of the restoration practitioner themselves (Lake 2001). For a project that is focused on reducing run-off and increasing infiltration, basic information on ground cover would be sufficient, with more emphasis placed on indicators measuring soil stability and hydrologic integrity. Furthermore, supplementary quantitative data on relative infiltration rates (e.g., by using infiltration rings) might be appropriate if resources allow. Similarly, for a project that is focused on restoring vegetation on a low cover or bare ground area, more emphasis would be placed on tracking changes in biotic integrity, and possibly collecting information on species composition and richness, as well as cover and density of any key species of interest. The attributes suggested here should serve as a general starting point for monitoring projects that do not have a specific set of indicators selected prior to restoration design.

Use of remotely sensed data

Remotely sensed (RS) data—especially aerial or satellite imagery—can be a very useful tool to supplement or, in certain cases, act as an alternative to data collected on the ground (Booth and Tueller 2003). Where the monitoring is initiated before restoration, then RS data could allow restoration practitioners undertaking landscape scale restoration activities to track changes over time by comparing various metrics, including basic cover and density measurements at one end of the complexity spectrum, to the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) on the other end (Graetz et al. 1988, Booth and Tueller 2003, Kawamura et al. 2005). For RS data to be a useful alternative to ground collected information, however, users must be certain that the patterns present in the satellite information are similar to patterns present on the ground. Ground truthing of selected sites could help confirm this information, at least spatially. Repeated measurements of the same sites over time would need to be conducted to compare temporal similarity. Satellite data can be obtained from multiple sources, with free Google Earth or USGS Earth Explorer imagery or for purchase high resolution Quickbird and DigitalGlobe data.

Where monitoring is carried out retrospectively, then RS data is even more valuable, as often it could provide the only comparison between treatment and control areas before and after restoration impacts were carried out (Washington-Allen et al. 2006). This information could allow a qualitative or semi-quantitative Before-After assessment of changes in the landscape and facilitate selection of suitably matched treatment and control plots which could be used to conduct quantitative Control-Impact retrospective assessments. The use of RS data is limited by availability, access, and the technical capacity of restoration practitioners to process and interpret the information collected. However, where there is an overlap of availability and analytical capacity, then RS data could help identify, match, and monitor restoration treatments.

Use of Mobile Phone Applications to Facilitate Land Potential Evaluation

The dawn of the information age and significant leaps in computing technologies have created an environment where our ability to collect, analyse, and store data has improved, and has become more affordable (Saylor 2012). Mobile application (app) technology has also increased, providing near instantaneous access to localized climate, soils, and topography data by facilitating access to larger regional or global databases.

The affordability, mobility, and adaptability of mobile phone devices and applications provides exciting opportunities for rapid assessment of natural resources and by extension restoration projects, especially where there are limited training and investment resources. Below, we highlight a mobile app that provides the basic information necessary to determine land potential and collect a set of vegetation indicators useful for providing basic information on the state of the biotic integrity, hydrologic integrity, and soil stability of an ecosystem.

LandPKS app

The Land-Potential Knowledge System (LandPKS) is a global mobile phone application supported by cloud computing that was created with the aim of providing simple tools for collecting, storing, and sharing scientific and local knowledge to inform and support decision making for sustainable land management (Herrick et al. 2017). The LandPKS app also allows access to global climate and soil datasets, as well as a cloud-based data storage and access portal. This app allows rapid collection of important rangeland indicators even by minimally trained assessors. LandPKS modules do not require access to the internet for data collection, but do require access to the device location function, as well as a data connection for backup of plot information and provision of climate data. The simplicity of this system and the large number of response variables it captures makes it an ideal rapid assessment environment that can be adapted for restoration evaluation. The system currently includes a flagship app, LandPKS, which has two main data input modules, LandInfo and LandCover.

The LandInfo module allows users to collect information on site characteristics related to long-term land potential, most importantly slope and slope shape, as well as soil texture and depth, all of which are critical for determining land potential and therefore instrumental in matching treatment and control plots. The current version of LandInfo includes sections for recording basic land cover types, slope classes, slope shape, presence of surface salts and vertical cracking, and soil texture by depth. A soil pit is dug in the center of typically a 50 m × 50 m plot. The dimensions can be modified based on sampling needs. Slope, slope shape, soil texture, and rock fragment volume are the most critical metrics for determining land potential when matching treatment and control plots (Herrick et al. 2017). By using the gyroscope contained within many smartphones, the app guides the user through the process of determining slope. Alternatively, the user can select the slope class from a range of pre-determined categories. Standard hand texturing methodology is used to select a soil texture class at various depths for each plot. There is a drop-down menu for more experienced users, as well as a text-based key and a series of embedded videos for novice users.

Once the user enters this information for cloud-based storage, LandPKS provides the user with site and profile-specific climate and plant available water holding capacity (PAWHC) and infiltration based on integrated pedotransfer functions. It also allows the user to explore possible positive hydrologic feedback loops by exploring the effects of increases in soil organic matter on both properties (Figure 2). It also predicts the soil type based on location and location plus user input data. New outputs are constantly being added, such as habitat suitability and erosion risk. The summary of user inputs and system outputs can then be used to compare the selected treatment plots to a

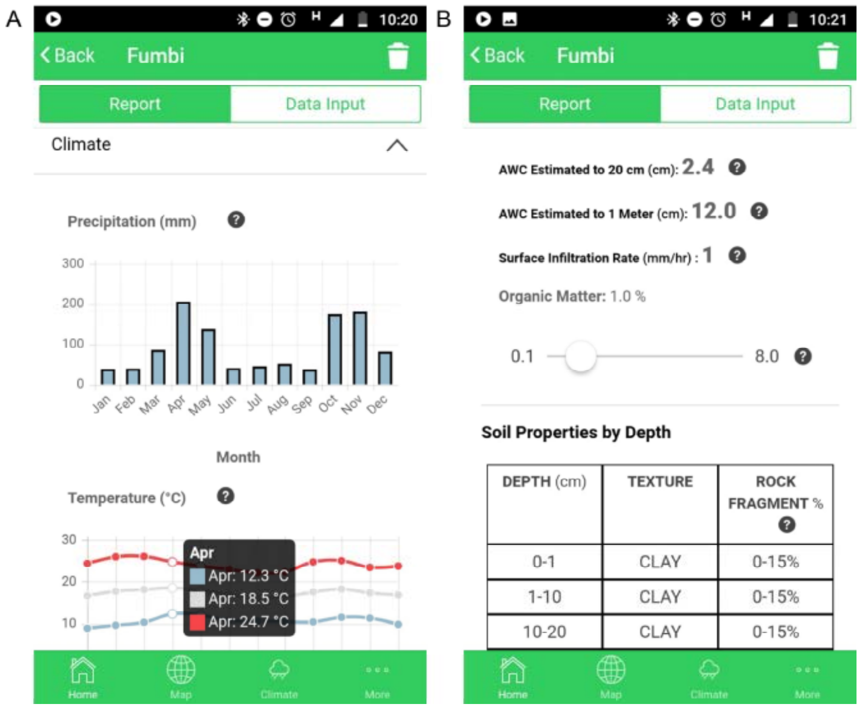

Figure 2. Screenshots from the LandInfo Module of LandPKS Version 3.2.0, showing A). plot climate summary, and B). AWC estimates.

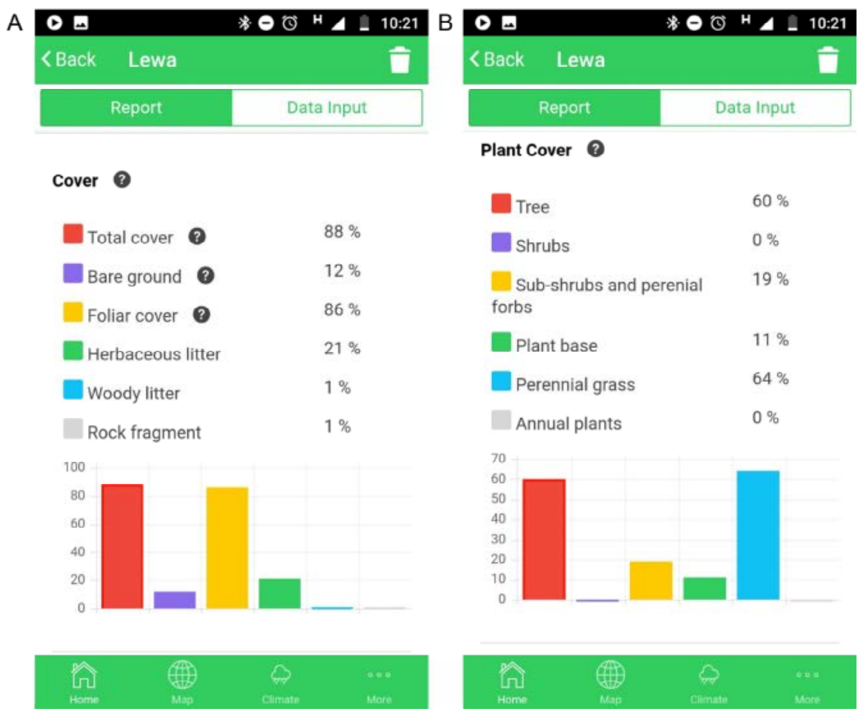

Figure 3. Screenshots from the LandCover Module of LandPKS Version 3.2.0, showing A). plot ground cover summaries and B). plant functional group cover summaries.

suite of candidate control plots, with the closest matching plots selected for pairing and baseline data collection.

The LandCover module is based on a modified line-point intercept methodology originally designed for use in eastern African rangelands. LandCover retains the simplicity of the methods contained in the "Monitoring Rangeland Health" manual but eliminates the need for paper datasheets (Riginos and Herrick 2010). A one-meter stick is used to make all the measurements along four, 25 m transects, one in each cardinal direction radiating from the plot center. The stick is placed five times along each transect at 5-m intervals, and intercept cover at each point recorded by selecting the appropriate icon on the app. This gives a total of 100 points at each transect, allowing a relatively straightforward calculation of percent foliar, litter, rock, and plant basal cover compared to the traditional stick method (Figure 3). In addition, estimates of plant density for up to two species of interest can be recorded, as can general observations about dominant woody and herbaceous species.

Table 1. LandInfo and LandCover attributes and their relationship to three main attributes of rangeland health for monitoring. Entire suite of suggested 17 indicators noted at the bottom and described in full by Pellant et al. 2005.

	Biotic Integrity	Soil and Site stability	Hydrologic integrity
LandPKS data	Ground cover (total, foliar, trees, shrubs, subshrubs and perennial forbs, perennial grasses, annual plants, litter, rock), plant height, canopy gap percentage, species count (density) for up to 2 species of interest	Bare ground cover, basal gap percentage	Litter cover, Bare ground cover, basal gap percentage
Supplementary data		Soil stability test, Erosion features Description	Soil stability test, Erosion features Description

1. Rills **2**. Water flow patterns. **3**.Pedestals and/or terracettes. **4**.Bare ground. **5**. Gullies **6**. Wind scoured, blowouts and/or deposition **7**. Litter movement. **8**. Soil surface resistance to erosion. **9**. Soil surface loss or degradation. **10**. Plant community composition and distribution relative to infiltration and runoff. **11**. Compaction layer. **12**. Functional/Structural groups. **13**. Plant mortality/decadence. **14**. Litter amount. **15**. Annual production. **16**. Invasive plants. **17**. Reproductive capability of perennial plants.

Finally, the app guides the user in estimating the number of times the stick falls entirely within large gaps between plant bases and (separately) between plant canopies. These indicators can be interpreted based on the users' contextual knowledge, and together with future app outputs, used to estimate restoration success relatively quickly. It also includes an option for taking and storing photographs linked to the geolocation through the LandInfo module. The LandPKS system allows collection of indicators that assess all three of the basic attributes suggested in the framework (hydrologic function, soil stability, and biotic function) and supplementary data can be added depending on the focus of the restoration project (Table 1).

The LandManagement module allows users to plan and record management actions in a calendar. The same calendar format is used for the SoilHealth module, which includes input fields for both observational indicators, such as for soil erosion and compaction, and measurements of soil organic carbon, pH, and electrical conductivity.

The use of the LandPKS app within our restoration monitoring framework is primarily intended as an easy entry point for rangeland restoration projects where limited resources are available for monitoring. However, its compatibility with data collected using existing methodologies widely used across the US makes it ideal for more rapid assessments within these more comprehensive frameworks, such as the Bureau of Land Management (BLM) Assessment, Inventory and Monitoring (AIM) program and the Natural Resources Conservation Service (NRCS) National Resources Inventory (NRI, Herrick et al. 2017). It is especially ideal for rangeland managers who require quickly measured indicators for decision-making within a constrained time scale.

Another advantage of the system is that data are permanently backed up in the cloud, in addition to being downloaded to individual computers. This ensures that the data are safe in the event of the loss of computers through theft, damage, or cyber-attacks. In addition to being available on the data portal, the user can access their data on any phone by downloading the app and linking to the Gmail account to which it was originally registered.

Opportunities and Limitations

Our suggested framework is only partially prescriptive and does not deal with selection of restoration strategies. Additionally, our framework is only meant to facilitate rapid assessment and incorporation of land potential evaluation, especially on landscapes where restoration practitioners are unlikely to have the time or resources to undertake more in-depth evaluations. Finally, landscape level processes are only partially addressed within the structure of the framework and are not explicitly measured in the overall decision tree aside from when interpreting restoration results. Future identification and refinement of suitable and realistic landscape level measurements, possibly through widely available remotely sensed information, will be needed to strengthen the scaling up of the framework.

As monitoring becomes an increasing part of the practice of restoration, lessons and ideas from different practitioners will help further inform some of the decision points in this framework. Additionally, increased practitioner engagement will help to further identify helpful tools and data analysis methods that increase the probability of the collection of monitoring information and subsequent sharing of ideas and best practices. Too often highly complex and extremely rigid restoration implementation and monitoring frameworks fail to transition from theory to practice, and increased engagement with the targeted end users will undoubtedly facilitate adoption and help build the study and practice of restoration ecology.

References

Aronson, J., S. Dhillion and E. Floc'h. 1995. On the need to select an ecosystem of reference, however imperfect: A reply to Pickett and Parker. *Restoration Ecology* 3:1–3.

Block, W.M., A.B. Franklin, J.P. Ward Jr., J.L. Ganey and G.C. White. 2001. Design and implementation of monitoring studies to evaluate the success of ecological restoration on wildlife. *Restoration Ecology* 9:293–303.

Booth, D.T. and P.T. Tueller. 2003. Rangeland monitoring using remote sensing. *Arid Land Research and Management* 17: 455–467.

Brewer, J.S. and T. Menzel. 2009. A method for evaluating outcomes of restoration when no reference sites exist. *Restoration Ecology* 17:4–11.

Dregne, H.E. and N.T. Chou.1992. Global desertification dimensions and costs. *Degradation and Restoration of Arid Lands* 1:73–92.

Elzinga, C.L., D.W. Salzer and J.W. Willoughby. 1998. *Measuring & Monitoring Plant Populations*. US Department of the Interior, Bureau of Land Management.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson and C.S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology, Evolution, and Systematics* 35:557–581.

Foster, D.R., P. Schoonmaker and S.T.A. Pickett. 1990. Insights from paleoecology to community ecology. *Trends in Ecology and Evolution* 5:119–122.

Grady, K.C. and S.C. Hart. 2006. Influences of thinning, prescribed burning, and wildfire on soil processes and properties in southwestern ponderosa pine forests: A retrospective study. *Forest Ecology and Management* 234:123–135.

Graetz, R.D., R.P. Pech and A.W. Davis. 1988. The assessment and monitoring of sparsely vegetated rangelands using calibrated Landsat data. *International Journal of Remote Sensing* 9:1201–1222.

Hallett, L.M., S. Diver, M.V. Eitzel, J.J. Olson, B.S. Ramage, H. Sardinas, et al. 2013. Do we practice what we preach? Goal setting for ecological restoration. *Restoration Ecology* 21:312–319.

Harris, J.A., R.J. Hobbs, E. Higgs and J. Aronson. 2006. Ecological restoration and global climate change. *Restoration Ecology* 14:170–176.

Heleno, R., I. Lacerda, J.A. Ramos and J. Memmott. 2010. Evaluation of restoration effectiveness: Community response to the removal of alien plants. *Ecological Applications* 20:1191–1203.

Herrick, J.E., G.E. Schuman and A. Rango. 2006. Monitoring ecological processes for restoration projects. *Journal for Nature Conservation* 14:161–171.

Herrick, J.E., J.W. Karl, S.E. McCord, M. Buenemann, C. Riginos, E. Courtright, et al. 2017. Two new mobile apps for rangeland inventory and monitoring by landowners and land managers. *Rangelands* 39:46–55.

Herrick, J.E., K.C. Urama, J.W. Karl, J. Boos, M.V.V. Johnson, K.D. Shepherd, et al. 2013. The global Land-Potential Knowledge System (LandPKS): Supporting evidence-based, site-specific land use and management through cloud computing, mobile applications, and crowdsourcing. *Journal of Soil and Water Conservation* 68:5A–12A.

Herrick, J.E., V.C. Lessard, K.E. Spaeth, P.L. Shaver, R.S. Dayton, D.A. Pyke, et al. 2010. National ecosystem assessments supported by scientific and local knowledge. *Frontiers in Ecology and the Environment* 8:403–408.

Hilderbrand, R.H., A.C. Watts and A.M. Randle. 2005. The myths of restoration ecology. *Ecology and Society* 10:19.

Hobbs, R.J. and L.J. Kristjanson. 2003. Triage: How do we prioritize health care for landscapes? *Ecological Management and Restoration* 4:S39–S45.

Horn, R., H. Domżżał, A. Słowińska-Jurkiewicz and C. Van Ouwerkerk. 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. *Soil and Tillage Research* 35:23–36.

IPBES. 2018. Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

James, J.J., R.L. Sheley, T. Erickson, K.S. Rollins, M.H. Taylor and K.W. Dixon. 2013. A systems approach to restoring degraded drylands. *Journal of Applied Ecology* 50:730–739.

Kawamura, K., T. Akiyama, H.O. Yokota, M. Tsutsumi, T. Yasuda, O. Watanabe and S. Wang. 2005. Comparing MODIS vegetation indices with AVHRR NDVI for monitoring the forage quantity and quality in Inner Mongolia grassland, China. *Grassland Science* 51:33–40.

King, E.G. and R.J. Hobbs. 2006. Identifying linkages among conceptual models of ecosystem degradation and restoration: Towards an integrative framework. *Restoration Ecology* 14:369–378.

Kinyua, D., L.E. McGeoch, N. Georgiadis and T.P. Young. 2010. Short-term and long-term effects of soil ripping, seeding, and fertilization on the restoration of a tropical rangeland. *Restoration Ecology* 18:226–233.

Lake, P.S. 2001. On the maturing of restoration: Linking ecological research and restoration. *Ecological Management and Restoration* 2:110–115.

Legendre, P., 1993. Spatial autocorrelation: Trouble or new paradigm? *Ecology.* 74:1659–1673.

Leonard, S.W., A.F. Bennett and M.F. Clarke. 2014. Determinants of the occurrence of unburnt forest patches: Potential biotic refuges within a large, intense wildfire in south-eastern Australia. *Forest Ecology and Management* 314:85–93.

Osenberg, C.W., B.M. Bolker, J.S.S. White, C.M. St. Mary and J.S. Shima. 2006. Statistical issues and study design in ecological restorations: Lessons learned from marine reserves in *Foundations of Restoration Ecology* vol. 280. Washington, DC: Island Press.

Pellant, M., P. Shaver, D.A. Pyke and J.E. Herrick. 2005. Interpreting indicators of rangeland health, version 4. Technical Reference 1734–6. US Department of the Interior, Bureau of Land Management, National Science and Technology Center, Denver, CO. BLM/WO/ST–00/001+ 1734/REV05.

Porensky, L.M. and K.E. Veblen. 2015. Generation of ecosystem hotspots using short-term cattle corrals in an African savanna. *Rangeland Ecology and Management* 68:131–141.

Riginos, C. and J.E. Herrick. 2010. Monitoring Rangeland Health: A Guide for Pastoralist Communities and Other Land Managers in Eastern Africa. ELMT–USAID/East Africa.

Ruiz-Jaen, M.C. and T.M. Aide. 2005. Restoration success: How is it being measured? *Restoration ecology* 13:569–577.

Saylor, M.J. 2013. *The mobile wave: How mobile intelligence will change everything*. Vanguard Press.

SER. 2004. Society for ecological restoration international's primer of ecological restoration (available from www.ser.org/resources/resources-detail-view/ser-internationalprimer-on-ecological-restoration)

Sibanda, P., A. Sebata, E. Mufandaedza and M. Mawanza. 2016. Effect of short–duration overnight cattle kraaling on grass production in a southern African savanna. African *Journal of Range and Forage Science* 33:217–223.

Smith, E.P., 2014. BACI design. Wiley StatsRef: Statistics Reference Online.

Stoddard, J.L., D.P. Larsen, C.P. Hawkins, R.K. Johnson and R.H. Norris. 2006. Setting expectations for the ecological condition of streams: The concept of reference condition. *Ecological Applications* 16:1267–1276.

Svejcar, L.N. and O.A. Kildisheva. 2017. The age of restoration: Challenges presented by dryland systems *Plant Ecology* 218:1–6.

Swetnam, T.W., C.D. Allen and J.L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* 9:1189–1206.

UNCCD. 1994. United Nations Convention to Combat Desertification, Intergovernmental Negotiating Committee for a Convention to Combat Desertification, Elaboration of an International Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa. U.N. Doc. A/AC.241/27, 33 I.L.M. 1328. United Nations, New York.

UNEP. 2016. Unlocking the sustainable potential of land resources: Evaluation systems, strategies and tools. A Report of the Working Group on Land and Soils, International Resource Panel of the United Nations Environment Programme.

USDA–NRCS. 1997. National range and pasture handbook. Washington, DC: USDA–NRCS.

Washington–Allen, R.A., N.E. West, R.D. Ramsey and R.A. Efroymson. 2006. A protocol for retrospective remote sensing–based ecological monitoring of rangelands. *Rangeland Ecology & Management 59*:19–29.

Whisenant, S. 1999. *Repairing damaged wildlands: a process–orientated, landscape–scale approach*. Cambridge, UK: Cambridge University Press.

Wortley, L., J.M. Hero and M. Howes. 2013. Evaluating ecological restoration success: A review of the literature. *Restoration Ecology* 21:537–543.

Zedler, J.B. 2007. Success: an unclear, subjective descriptor of restoration outcomes. *Ecological Restoration* 25:162–168.

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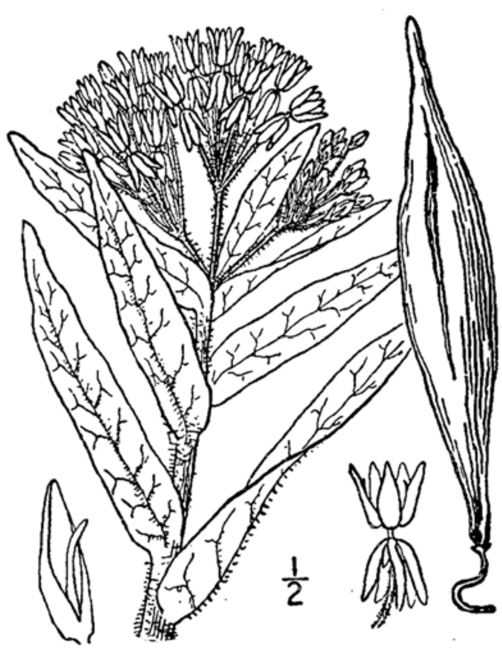

***Asclepias tuberosa*. USDA-NRCS PLANTS Database. Britton, N.L. and A. Brown. 1913. *An Illustrated Flora of the Northern United States, Canada and the British Possessions*. New York, NY: Charles Scribner's Sons.**