Viewpoint

Managing an arid ranch in the 21st century: New technologies for novel ecosystems

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On the Ground

- Rates of ecosystem change are accelerating in rangelands, but development of technologies to detect and react to change is accelerating at the same time.
- New management frameworks, including novel ecosystems and Resist-Accept-Direct (RAD) provide new ways of thinking about management strategies.
- We describe how we are integrating several digital tools and new management frameworks on the Jornada Experimental Range as an example to help land managers imagine how these tools might be applied in their contexts.

Keywords: digital tools, novel ecosystems, monitoring, precision ranching, remote sensing, virtual fencing.

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Introduction

Rangelands are becoming warmer and either more arid or wet, with persistent shifts in dominant plants, forage quality, and wildlife habitat quality.[1,2] They are being fragmented by cropland agriculture, residential development, and energy development in ways that affect remaining rangelands.[3,4] The inevitability and irreversibility of ecosystem change have upended land health concepts that guide management. Although conservation and restoration of historical ecosystem conditions continue to be a priority, land managers are considering the merits of managing for novel ecosystems (ecosystems with no historical analog) in parts of the landscape.[5] New decision-making frameworks, such as Resist-Accept-Direct (RAD), acknowledge that management decisions occur alongside uncontrollable forces, especially climate change, that push ecosystems away from what we considered to be the equilibria of the past.[6]

In contrast to a singular focus on historical conditions, the RAD framework offers land managers guidance for a broader array of management objectives (Fig. 1). Following the framework, a manager may opt to resist ecosystem change by maintaining or restoring a current or historical (i.e., reference) ecosystem under changing climate. Alternatively, a manager can accept change by judging the costs of intervening to resist change are too high relative to the likely future benefits or ongoing changes may ultimately be beneficial under a new climate. Finally, a manager may opt to direct change by encouraging change through active management toward ecosystems that are not historical but have desirable characteristics.

Increasing recognition of the forces driving ecosystem change and the development of new management frameworks such as RAD have been paralleled by the expansion of new technologies. Digital technologies allow managers to perceive and react to rangeland ecosystems in ways that were unimaginable a few decades ago. Tools include standardized field ecosystem monitoring databases[7]; web-accessible maps of vegetation dynamics,[8] production forecasts,[9] and climate risk[10]; sensor networks,[11] virtual fencing,[12] and associated dashboards; mobile applications to collect and access a variety of data[13]; and new models,[14] interpretive tools,[15] and tool libraries.[16] Together, these tools allow for site-specific and rapidly reactive—even proactive—management. They help managers avoid the pitfalls of "rules of thumb" and a reliance on generalizations about rangeland ecosystem behavior that grow weaker with each passing year.[17] Despite the promise of these tools, there are few examples of their integration and

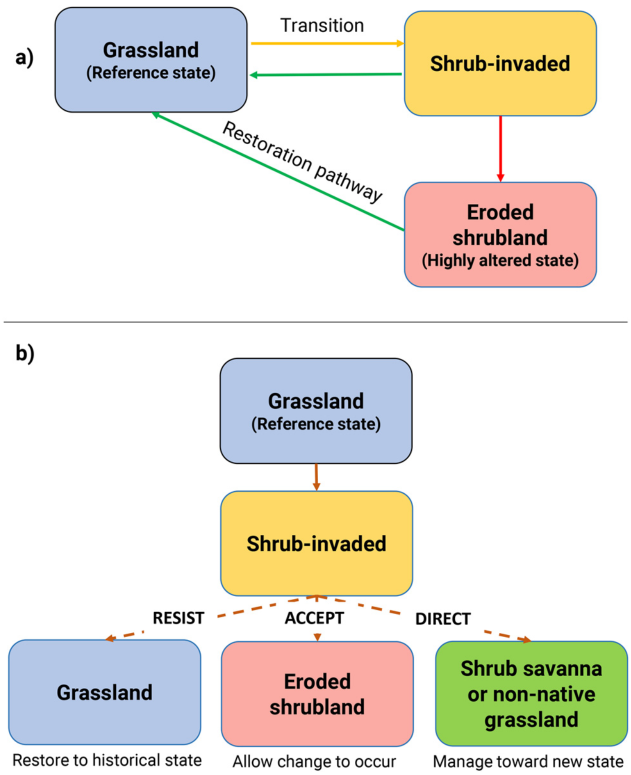

Figure 1. Example rangeland vegetation management models under a) a traditional state and transition framework with management objectives focused on restoration of the reference state (i.e., grassland) from alternative states; and b) a Resist-Accept-Direct framework in which different management objectives can be defined for an intermediate (i.e., shrub-invaded) state.

use at the scale of individual ranches or management areas for making decisions. Consequently, many managers are unaware of how digital tools might improve land management processes and outcomes.[18,19]

Research stations, such as the Jornada Experimental Range (the Jornada) contribute to numerous, long-term distributed experiments to improve our understanding of ecosystem behavior and to develop and test new management concepts and options. But we can also use research stations as "living labs" that produce knowledge by trying to solve complex problems in a real-world context.[20] For a rangeland research station, the living labs approach seeks to emulate the decision-making processes of private and public managers in lands they manage, but with the added benefit of rich long-term datasets, technical resources, and minimal risk for managers. In the living lab spirit, we describe our thinking about and use of a suite of digital tools alongside the RAD concept to manage ecosystem change on the Jornada.

Rangeland change and management on the Jornada

The Jornada is a working ranch and research area established in 1912, encompassing 781 km^2 (193,000 acres) of arid desert grassland and shrublands in south-central New Mexico. It is currently managed by the US Department of Agriculture (USDA), Agricultural Research Service. The Jornada has supported a variety of agricultural and ecological programs and technology development efforts over the past 110 years. It has hosted the National Science Foundation Long-Term Ecological Research program since 1982 and the USDA Long-Term Agroecosystem Research network since 2014, among others. The longevity and research history at the Jornada afford an unprecedented ability to understand past and current ecosystem change.

Historically, the Jornada was dominated by long-lived perennial grasses adapted to arid conditions, especially black grama (*Bouteloua eriopoda*). Average annual net primary production at the Jornada is low relative to many rangelands, at 136 g/m^2 (1200 lbs/acre) in the best condition upland grassland patches.[21] But production varies spatially and temporally from near zero to over 336 g/m^2 (3000 lbs/acre) in uplands, depending on soils and weather, and production can be even higher in playas receiving water from surrounding uplands. On top of this climate and soil-driven variation, historical variations in land management have produced a mosaic of contrasting ecological states, such as coppice dune shrublands that emerged from grasslands in the mid-20th century.[22] Mesquite (*Prosopis glandulosa*) shrubs continue to expand, displacing grasses. An invasive perennial grass, Lehmann lovegrass (*Eragrostis lehmanniana*) is also expanding from formerly isolated populations.[23] Wind and water erosion from bare ground areas is a primary resource concern. Our cow-calf research herd was reduced considerably during recent drought years. The herd is rotated opportunistically among large pastures (i.e., ~1,000-4,000 ha [2500-10,000 acres]) based on patchy rainfall and plant growth, known as the "best pasture" grazing strategy.[24]

Our data generally reflect the shared experiences and observations of land managers in the Southwest, including that the Jornada is becoming hotter, less predictable with respect to production, increasingly dominated by shrubs and invasive perennial grasses, dustier, and more difficult to manage.[25,26] Overall, our interrelated land management goals are to 1) maintain perennial grass cover where possible, 2) limit the spread of shrubs and the invasive Lehmann lovegrass into areas dominated by perennial grasses, 3) restore perennial grasses to areas dominated by bare soils, 4) minimize soil erosion and degradation of soil functions, and 5) sustain biodiversity.

How digital tools are used at the Jornada

Spatial planning

Following the RAD framework, we need to plan where in the landscape we will resist, accept, and direct change to best achieve our land management goals. To support these decisions, we recently completed a detailed map of ecological sites and ecological states (Fig. 2) in which soil map unit polygons were subdivided according to sites and then accord-

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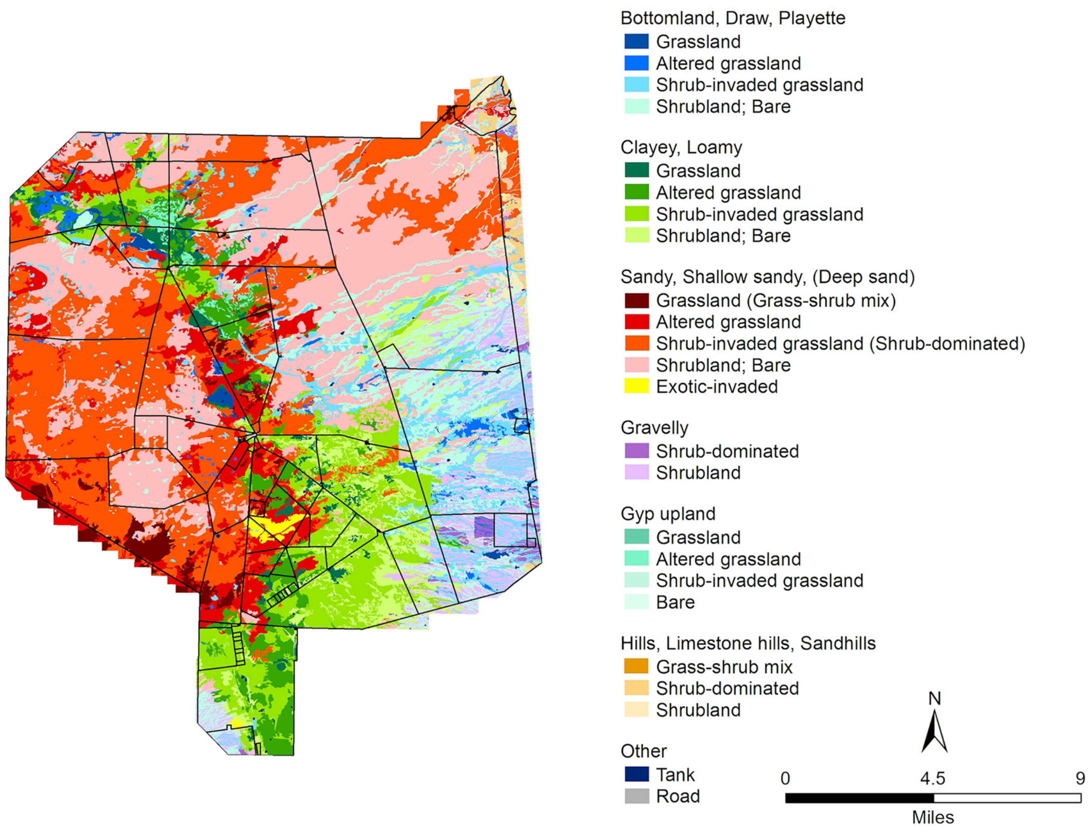

Figure 2. Map of ecological sites and states for the Jornada Experimental Range,[43] in south-central New Mexico, following a generalized ecological state classification.[27]

ing to general type states (e.g., reference grassland) based on aerial photography, existing georeferenced ground data, and rapid field survey.[27] This map provides a management baseline for developing location-specific objectives and management plans, including protection of remaining historical grasslands, monitoring the spread of invasives, managing grazing areas, prioritizing restoration opportunities via shrub removal treatments and other means, and evaluating the risk of undesirable transitions.

Monitoring tools

To track progress toward objectives, we are using standardized monitoring transect data,[28] recorded electronically,[29] to understand changes in species cover and composition, especially across the boundaries between grassland and shrubland states and in shrub removal treatments. Line-point intercept-based field monitoring and analysis tools[i] provide us with precise estimates of cover change at the species level and high-quality evidence of trends. These data are costly to gather and therefore limited to locations in the landscape where detailed information on vegetation change is of greatest interest. Fractional cover and production maps provide information across the Jornada and back in time, albeit at the plant functional group level (e.g., perennial grasses and forbs) and with limitations in accuracy inherent to satellite-based data.[8] With the benefit of field data, we have been able to quantify errors locally and we understand the nature of these errors. For example, we have found that satellite-based tools tend to underestimate vegetation production in more productive years. These kinds of comparisons will be used to improve the next generation of satellite-based production products.

Despite the uncertainties inherent to satellite-based data, we have used a time series of perennial herbaceous production estimates from digital maps to identify "hotspots" of rangeland degradation and apparent improvement (Fig. 3). This is accomplished by calculating a robust trend slope and significance statistic for each 30 m (98.4 foot) pixel across the Jornada for different time periods (to a maximum duration of 1986-2021). Significant positive or negative trends provide confidence that the trend has year-after-year consistency and is not caused by a few unusual years.[30] We can then use field observations on the current vegetation and surface soil processes occurring in hotspots to interpret the precise nature of vegetation change. For example, the degraded area in the southern portion of the Jornada (i.e., red area in Fig. 3) involves a loss of perennial grasses, shrub encroachment, and accelerated erosion. Based on a nearby long-term experiment, this hotspot was likely exacerbated by a 2019 extreme wind event acting on an area of low vegetation cover due to drought.[31] This knowledge has triggered planning to control the spread of this grassland-shrubland transition, fo-

[i] See a suite of monitoring design and analysis tools at the Landscape Toolbox (https://www.landscapetoolbox.org/).

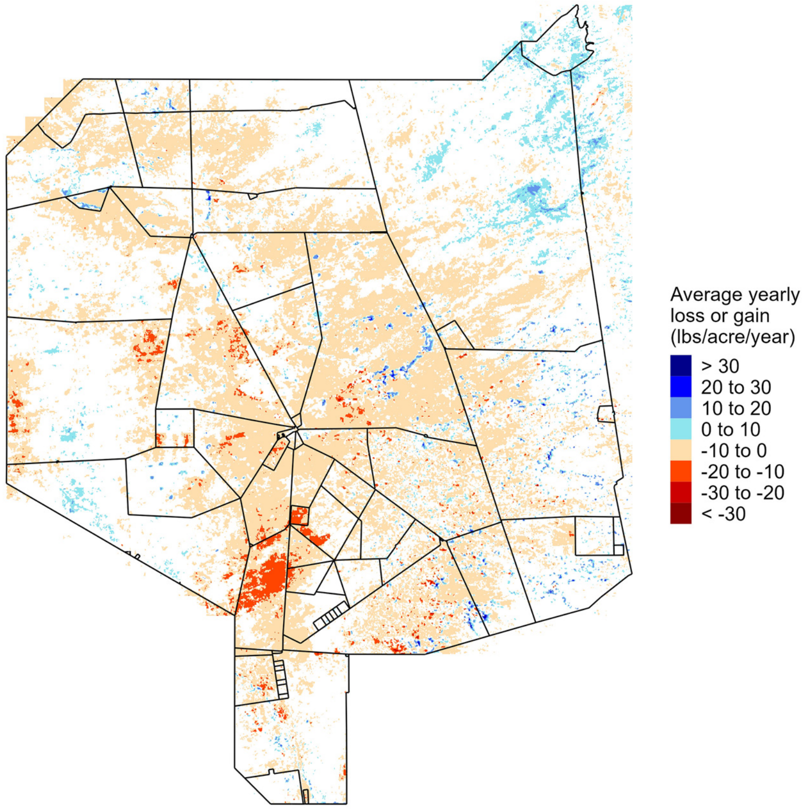

Figure 3. Trend analysis of herbaceous production from 1986 to 2021 by individual pixels on the Jornada Experimental Range, in south-central New Mexico, using Rangeland Analysis Platform (RAP) 2.0 data. Only pixels with significant Thiel-Sen slopes are shown. Blue colors indicate trends of increasing annual production and red colors indicate declining production.

Figure 4. A stand of Lehmann lovegrass (*Eragrostis lehmanniana*) established in an area formerly dominated by native black grama grass (*Bouteloua eriopoda*) that had declined in recent years. Evaluating the costs and benefits of different management options for this invasive species is central to novel ecosystems and RAD management decision frameworks.

cused on conserving adjacent intact perennial grass patches to the extent possible. We have also learned to temper our optimism about the blue patches of increasing production. Some are due to the invasive Lehmann lovegrass (Fig. 4), for better (see below) or for worse.

Management actions

The most important management tools at our disposal to resist or direct change are grazing management and shrub removal (i.e., brush management). We are investing in precision ranching technologies to better manage grazing pressure with respect to spatial and temporal variability in forage production. Virtual fencing collars,[12] for example, will be used to monitor livestock and manage grazing effects on vegetation based on our ecological state map (Fig. 2), long-term grass production trends (Fig. 3), and weekly to monthly changes of forage condition from satellite-based maps. Virtual fence boundaries can be dynamically altered to concentrate cattle on targeted grazing areas, remove cattle grazing from grass patches of declining productivity, or to make seasonal adjustments depending on the spatial distribution of rainfall and accounting for asynchronous grass green-up and brown-down typically observed in arid rangelands (Fig. 5).[11] Virtual fencing in conjunction with site-specific information on forage resources, sensitive soil and plant communities, and water resources allow grazing managers to adjust grazing dynamically, thereby managing grazing pressure to resist perennial grass loss without requiring increases in permanent fence infrastructure that further fragments rangeland. Virtual fencing could also be used to target grazing on Lehmann lovegrass stands and away from native grasses, although the ability to do so and the potential effects remain unclear.

Figure 5. A virtual fence boundary (white line) in pasture 12 of the Jornada Experimental Range, south-central New Mexico, (the center of Figs. 2 and 3) with patches of bottomland/draw ecological sites temporarily excluded from grazing.

Until recently, precision ranching options in extensive ranches like the Jornada have been limited by the lack of cost-efficient sensor communication technologies.[32] LoRa WAN (Long Range Wide Area Network) is a wireless communication technology that allows networking of multiple interconnected sensors to enable the efficient collection and exchange of large amounts of sensor data over the internet (i.e., "Internet of Things"). LoRa WAN overcomes the limitation of short-range protocols (Bluetooth, Wi-Fi) and the current high communication cost of long-range protocols (cellular, satellite).[33] In a LoRa WAN application, secure protocols for data exchange are implemented using license-free radio band communication (e.g., for the United States, 902-928 MHz). The procedure provides connectivity with low power needs and cost, making possible the transmission in real-time of high traffic over several kilometers (~5 to 15 km [3.1-9.3 miles]). With a focus on sensors for trough water levels, rainfall, and real-time cattle locations, a customizable dashboard application is under development at New Mexico State University to allow resulting data to be integrated with other datasets (e.g., vegetation maps).

Another well-known "resistance" strategy is brush management, which is being used to reduce shrub densities, reduce competition for soil water, catalyze grass recovery, and enhance the resilience of remaining perennial grasses. Alongside talented graduate students and agency partners, we are testing the efficacy of aerial applications of herbicides in different ecological sites and states. These long-term studies will identify the circumstances under which herbicide treatments enhance or sustain grass productivity over the coming decades. This work will also identify circumstances in which accepting shrub-dominated states may be the preferred option because grasses do not recover sufficiently to offset the increase in bare ground cover (see below).

Finally, we are considering ways to direct the recovery of vegetation cover on highly eroded soils in the areas between shrubs in coppice dune shrublands, using structures known as connectivity modifiers (i.e., ConMods). ConMods are x-shaped metal screens fastened to the ground that modify, or break up, the continuous bare ground and accumulate sediment, litter, and seeds.[34] The plants recruited may or may not be the same as those that dominated historical communities, but our objective in areas with highly degraded soils is to increase vegetation cover to improve soil fertility and minimize wind and water erosion. Our hope is that ConMods trigger positive feedbacks leading to expansion of vegetation cover across areas well beyond the ConMods themselves.

Modelling

The utility of monitoring data can be extended by joining them to measurements of ecological processes via models. For example, by integrating cover, canopy gap, and plant height data into a wind erosion model,[14] we can also consider the implications of shrub removal and grass recovery patterns for a process we have neglected in our decision-making to this point—the potential for management to increase or decrease wind erosion susceptibility. The defoliation and removal of shrubs might marginally increase grasses and livestock forage production, but at the expense of protection of the soil surface from wind erosion. Similarly, Lehmann lovegrass may provide protection from wind erosion in areas that would otherwise be sparsely vegetated, creating a tradeoff between limiting the spread of an invasive species and improving soil health and air quality. We also have yet to consider the implications of brush management treatments on other valued objectives such as carbon sequestration, wildlife habitat, and livestock production. Model-based indicators reflecting these processes are in development and we aim to develop guidelines and tools to evaluate the inevitable tradeoffs among ecosystem services.[35]

Tradeoffs under the RAD framework

Evaluation of tradeoffs presented by management actions (or inactions) lie at the heart of decision-making via the RAD framework.[6] To use the RAD language, we will resist the loss of native perennial grasses where we can via brush management, targeted grazing, or conservative grazing or grazing rest, acknowledging the possibility that these efforts may ultimately fail to sustain or recover grasslands in some cases. We may accept the spread of Lehmann lovegrass in areas where restoration of native perennial grasses is unlikely but lose opportunities to recover historical ecosystem conditions. Considering the large Lehmann lovegrass seed bank in the areas it dominates, acceptance is probably the only feasible option in those areas. And we seek to direct coppice dune shrublands to shrub savannas, accepting that his-

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torical black grama grass will not recover and that mesquite shrubs will continue to dominate, but any increase in herbaceous vegetation may have benefits for soil health and erosion control.

The future of management and technology at the Jornada

The Jornada and several other research teams continue to evaluate management concepts and improve digital tools as a primary means to navigate change in rangelands. It is our hope that the sum of site-specific, timely, and well-informed management decisions will enhance resilience of ecosystem services to climate and societal change in the years ahead. Overall, we find the integration of multiple digital tools, information sources, and lines of evidence helps us to reduce uncertainty and increase the quality of our decision-making.

We acknowledge that the tools discussed here are not currently available to many land managers due to financial and training limitations. Researchers and agencies are developing strategies to overcome these limitations. For example, when properly deployed, virtual fencing can be cost-effective compared with alternative physical fencing methods, providing justification for cost-share support and the support of federal agencies for infrastructure in public lands.[ii] Furthermore, we expect costs will continue to decrease, technologies will become more effective, and there will be increasing investment in training and support via programs, such as the USDA Climate Hubs. New technologies are also being developed—in fact, current virtual fencing technologies are based in part on research at the Jornada decades ago.[36]

Despite the technologies currently available, we have several blind spots in the information needed for decision-making that require additional research. For example, past successes in catalyzing grass recovery with woody plant removal may not be useful in predicting future outcomes. We have yet to incorporate future climate scenarios to determine if restored grass cover after brush management can be sustained (i.e., the "resist" strategy), or if we would have been better off maintaining a shrubland (i.e., the "accept" strategy) to maintain some ecosystem services, such as regulation of wind erosion and carbon sequestration.

We have a limited ability to relate vegetation management decisions to biodiversity (i.e., plant, animal, and microbial), and especially for animals, to understand how management decisions affect different elements of habitat quality. We need to evaluate how multiple management outcomes in different parts of the landscape scale up to affect the sustainability of animal populations.[37] For example, maintaining patches of shrubland adjacent to grasslands may support populations of bird species using both habitats for nesting and foraging, respectively. Similarly, we have limited understanding of the landscape-scale consequences of vegetation patch size and arrangement for livestock foraging, water capture, and erosion. The need for multiscale management has been recognized for a long time, but systematic processes to implement it do not yet exist and therefore we tend to default to local or patch-level management.[38,39]

Finally, in proactively managing and rapidly reacting to ecosystem change, we do not yet have tools to predict transition thresholds (tipping points) in a spatial context. Although there has been considerable theoretical progress on the use of early warning indicators[40] there are few practical tools available in rangelands that can estimate the likelihood of transition (both desired and undesired) in specific land areas. Recent work suggests spatial and temporal patterns in fractional cover or production from readily available satellite-based data could help anticipate thresholds.[41] It is, however, important to ask if, even with foreknowledge of impending transitions, we can manage them. Patchy transitions may be an inevitable consequence of long-term, landscape-scale processes such as species invasions or gradual increases in dryness (i.e., aridification), coupled with uncontrollable events like "flash drought".[42] For example, the hotspot of production loss (Fig. 3) associated with a sequence of extreme wind erosion events[31] was abrupt and unpredictable with available technologies. Despite the unpredictability of transition triggers, and the likelihood of failures to prevent many undesired transitions, we aim to develop processes to define rangeland resilience goals based on multiple indicators and identify strategies (both novel and tried and true) and map them to land areas to maximize the likelihood of achieving those goals. In the spirit of the living lab, we will focus on the Jornada but develop reproducible principles for adoption across global rangelands. Our strategies will involve a mix of resisting, accepting, and directing change. Digital tools will be essential for deciding what to do where, tracking outcomes, and adapting both our tactics and expectations. Come visit us in a few years and see how we are doing.

Acknowledgments

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