Emerging technological and cultural shifts advancing drylands research and management

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Sustainable management of arid landscapes is complicated by extreme conditions that constrain biological responses to perturbation, great spatial complexity, and uncertain degrees of ecosystem resilience to climate change. Traditional approaches to the collection, management, and analysis of data from dryland monitoring efforts should consider these complications. Over the past century, research on drylands has gradually transitioned from short-term, plot-scale studies to long-term, regional- and biome-scale efforts. Two thresholds are imminent: a technological tipping point that will facilitate performing novel science using new techniques to collect, manage, and analyze data, and a cultural tipping point, where various research products are shared more freely and through different communication pathways. A new framework could be developed by promoting interdisciplinary collaboration and implementing standardized practices regarding data collection, curation, and sharing.

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Managing drylands for varied uses under escalating human demand is becoming increasingly complicated (MA 2005; Hochstrasser *et al.* 2012). Over the past century, drylands research has expanded both temporally and spatially in scope, allowing scientists and land managers to gain a better understanding of ecosystem dynamics at scales relevant to management (Bestelmeyer *et al.* 2011; Mueller *et al.* 2012). As a result, we now understand, for example, that the best practices for drylands management must include information about human factors such as legacy land uses affecting community structure and ecosystem services, as well as details regarding extreme climate conditions and resistance to management practices (Foster *et al.* 2003; Collins *et al.* 2014; Standish *et al.* 2014).

In a nutshell:

- Those conducting research and making decisions to support the sustainable management of dryland ecosystem services face many challenges
- The field is approaching technological and cultural "tipping points" that will expedite research and allow results to be shared openly and by different means
- Ecologists are poised to simultaneously develop both arenas – the technological and the cultural – and merge them in ways that allow for rapid, dynamic cycling of information between research and management communities
- Success will be achieved by collaborating more broadly across disciplines; adopting open practices regarding data collection, curation, and sharing; and mentoring and educating the next generation of research leaders and funders, to develop a mindset for discovery, innovation, and problem solving

The urgent need to stem further degradation and desertification in dryland ecosystems has been the underlying motivation for developing stronger linkages between research and management, but there remains a gap between the scales and directions of drylands research and the information needs of decision makers (Herrick and Sarukhan 2007; Sayre *et al.* 2012). Optimized management strategies require not only a mechanistic understanding of dryland ecosystem dynamics and their cross-scale biophysical interactions (Peters *et al.* 2007), but also research and application at appropriate spatial and temporal scales (Peters *et al.* 2004; Karl and Maurer 2010). Still, there must be tighter connections between research, management, and knowledge; Yahdjian *et al.* (2015), for instance, note that the need to meet changing demands for ecosystem services intensifies the need to integrate relevant local knowledge and real-time landscape monitoring.

Here we highlight several important technological and cultural advances that may transform drylands research and improve the links between research, management, and knowledge in dryland landscapes. We begin with a discussion about how new data collection, management, and analytical techniques that integrate large, disparate datasets will be pivotal in improving decision making for sustainable resource management. Second, we highlight several cultural advances that promote interactive environments for sharing, exploring, and using data. We envi-

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sion that iterative interactions across a range of interest groups that thrive on open access to data, information, and workflows will create positive feedbacks that bolster continued innovation (Peters *et al.* 2014a). Such innovative environments are likely to catalyze and speed up the approaches to the most compelling and "big-picture" questions in dryland ecosystem dynamics and the efficacy with which research findings are incorporated into policy by decision makers (Peters *et al.* 2014b). For example, Panels 1–3 and WebFigure 1 showcase innovations that are already influencing drylands research and management. We conclude with recommendations for leveraging technological and cultural advances to generate creative solutions for contemporary land management problems.

■ Emerging technologies enhancing dryland research and management

Several technological advances are helping to improve and transform drylands research and management.

Inexpensive, open-source, and/or repurposed hardware and software

Given increasing budget constraints, the need for diversified data streams with high sampling frequencies in drylands requires creative thinking and innovative approaches. Some new technologies are too expensive or are not well-suited to extensive replication. There is, however, a rapidly expanding pool of relatively inexpensive technologies (eg < US$200 per instrument) that are catalyzing the shift from plot-scale to regional-scale measurements. These include the use of inexpensive digital cameras at a fixed location to capture changes in the land surface (hereafter "phenocams"), which have been used to derive estimates of canopy greenness, photosynthesis, and carbon flux (Richardson *et al.* 2013), and the repurposing of mobile devices to record environmental data (Aanensen *et al.* 2009). Although repurposing of commercial off-the-shelf (COTS) technologies requires varying degrees of customized code or analytical software development (Boehm and Abts 1999), benefits to researchers and managers can include reduced research and development overheads, the relatively low cost and general availability of mass-produced non-custom devices, and a greater likelihood of a large user community. A plethora of COTS software and freeware is increasingly being adopted and adapted by research and management communities, including web mapping applications and virtual globe applications for two- and three-dimensional mapping, which will help in data/information publication (Pregenzer *et al.* 2005; Johnson *et al.* 2011).

Nested infrastructures of sensors and platforms

Many dryland landscapes are spatially extensive and logistically challenging to monitor, but networks of sensors can be used to extend, enhance, or replace traditional field data collection methods (Collins *et al.* 2006). Sensor networks often include a variety of instruments that collect continuous time series of physical (eg air temperature, soil water content, atmospheric gas fluxes) and biological (eg sap flow, animal movement) data over broad and remote regions (Benson *et al.* 2010) and that can be used in multi- and interdisciplinary research. Many automated sensors are cost-effective, compact, accurate, and resilient (Green *et al.* 2005); can communicate wirelessly with other sensors, data loggers, and computers; can be powered off the grid (eg via solar power; Cardei and Wu 2006); and can be programmed to alert researchers to equipment or data recording errors, or to self-regulate (eg recalibrate) based on environmental conditions (Aquino-Santos *et al.* 2011). Sensor networks can also be customized to meet the scope and extent of different research projects, while nested sensor arrays can use the varying spatial extents and spatiotemporal resolutions to both extrapolate processes and patterns across scales and infer the uncertainty associated with such extrapolations (Panel 2).

Dryland landscapes are characterized by nonlinear interactions between patterns and processes occurring over relatively small (eg < 1 m^2) to large (eg hundreds to thousands of hectares) areas (Peters *et al.* 2004). The potential for fine-scale processes to influence long-term or broad-scale patterns requires examination of more

Panel 1. Fine-grain, large-extent analysis of soil erosion in a managed dryland landscape

Land-management agencies seek evidence to identify effective vegetation removal methods that best minimize soil erosion, promote native understory species growth, and prevent exotic grass establishment. To meet this need, fine-grain, large-extent multi-temporal image and surface elevation analyses were used to quantify soil erosion in a desert pinyon–juniper woodland (*Pinus* and *Juniperus* spp) tree removal experiment near Moab, Utah. Very high-resolution imagery from piloted aircraft or unmanned aerial systems (UAS; ground sampling distance or spatial resolution ≤ 10 cm) can be used to generate complete coverage of a study area via a geometric mosaic process that combines overlapping images (WebFigure 1, a and b). Additionally, these image mosaics can be used to develop a stratified sampling design within larger landscapes (Karl *et al.* 2012). Mosaics can also be used to monitor changes in the composition and patterns of vegetation in drylands (Rango *et al.* 2009) and to accurately estimate functional attributes, such as vegetation cover and density (Booth and Cox 2008), and the extent and distribution of bare ground patches (ie canopy gaps). Comparisons of images taken over the same region at different times can be used to quantify soil erosion from multi-temporal surface elevation models, facilitating analysis of entire treatment areas in a cost-effective manner (WebFigure 1c). Forty overlapping aerial photographs (4-cm pixel resolution) were used to create high-precision digital terrain models for a 31-ha study area. Vegetation was masked out of the image and pre-treatment 2009 surface elevation values were subtracted from post-treatment 2010 values on a per pixel basis to yield a spatially explicit estimate of soil-surface change.

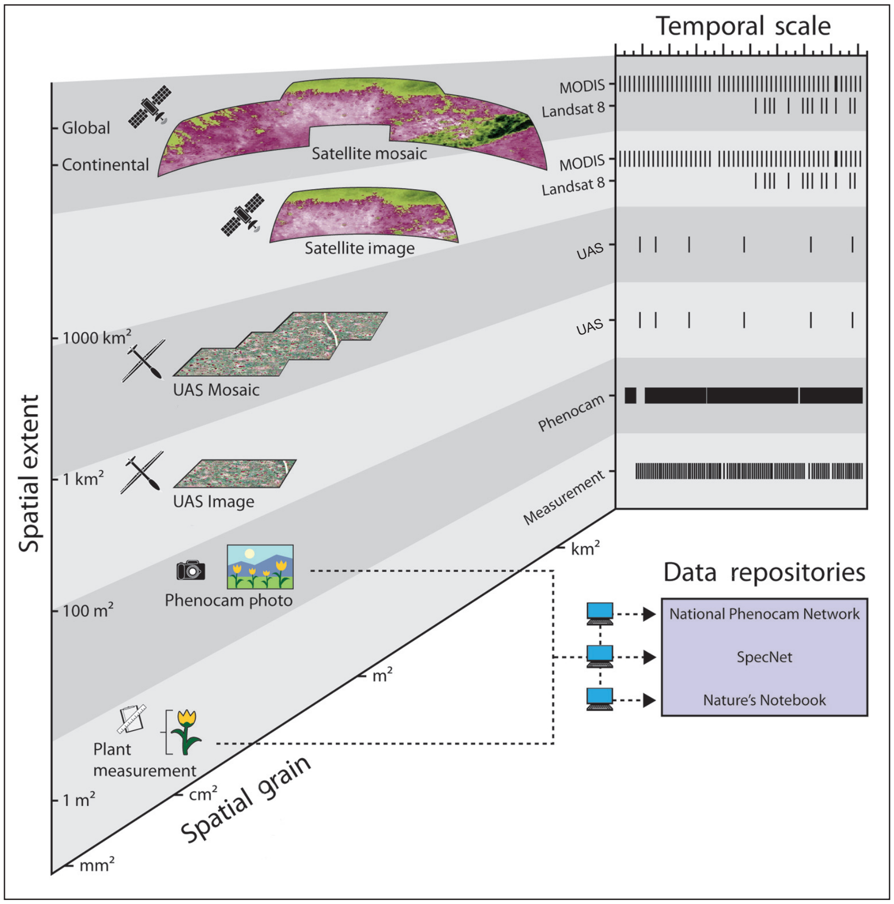

Figure 1. *Technological advances in sensors, data storage, and data analysis have improved our capacity to compile multi-temporal, high-resolution, remotely sensed datasets at the multiple spatial and temporal scales required to understand and manage dryland landscapes. The range of scales allows extrapolation between images of differing spatial extent and grain size, while the use of standardized indicators – with associated data deposited in federated repositories – facilitates collaborative work and cross-site comparisons.*

than one scale or level of observation (ie cross-scale) when working in dryland landscapes (Peters *et al.* 2007; Browning *et al.* 2012). New technologies – unmanned aerial systems (UAS), for example – now make it possible to collect image data at fine enough spatial resolutions and temporal extents so as to be aggregated and thus allow for cross-scale ecological processes in ecosystems, including drylands, to be captured. Technological advances that increase the availability of aerial and satellite imagery (as well as the software and hardware systems used to process these data) provide opportunities to incorporate data from multiple sensors into cross-scale study designs. These systems are particularly well-suited to filling gaps in the spatial and temporal realms associated with airborne remote sensing (eg aerial photography, satellite imagery; Figure 1). A UAS can operate at low altitudes with different types of payloads to accommodate a range of sensors, thereby greatly enhancing modeling activities in dryland landscapes (eg Anderson and Gaston 2013; Vivoni *et al.* 2014). For instance, Templeton *et al.* (2014) used 6-cm resolution digital photography from a fixed-wing UAS to generate digital terrain and canopy height models. The resulting high-resolution data products provided unprecedented opportunities to interpret terrain features spanning a range of spatial scales, such as detailed rill networks (small channels that form on hillslopes due to surface erosion), as well as vegetation and bare patch patterns (see Panels 1 and 2). In addition, analysis of the UAS-based terrain fields allowed Templeton *et al.* (2014) to discern the boundary of the study watershed much more precisely than was previously possible through ground-based surveys.

Expanded resources for data integration and management

A paucity of scalable, integrative analytical techniques – as opposed to a lack of data – is the primary factor constraining links between science and land management (Reichman *et al.* 2011). Improvements in data collection and computing capacity (Aanensen *et al.* 2009), computational algorithms (eg Cutler *et al.* 2007), and statistical tests (Pennington 2007) allow sensor network data to be coupled to ecosystem models to simulate complex dynamics such as those associated with extreme events. Frequent observations from a network of sensors collecting similar compatible data also permit quantification of the spatiotemporal heterogeneity of ecological phenomena (Panels 2 and 4; Richardson *et al.* 2013). Such advances in high-density data collection are especially beneficial in dryland landscapes, where infrequent and short pulse events – such as rain from convective monsoonal storms – have wide-ranging consequences for ecosystem function (Reynolds *et al.* 2004). Panel 2 highlights the integration of ground- and airborne-collected data to study ecohydrological processes at the USDA-ARS Jornada Experimental Range in Las Cruces, New Mexico. At that site, fine resolution, multiscale data from sensor networks and aerial platforms are integrated across scientific disciplines (eg hydrology, ecology, atmospheric science) to quantify landscape dynamics at the watershed scale.

For these technological developments to transform land-management decision making, information and knowledge of dryland dynamics must be discoverable (ie easily found through searches) and available for use in novel applications (Peters 2010; Karl *et al.* 2013a). The traditional data-management approach – that is, with the individual researcher as the ultimate curator of their data – complicates efforts to expand our analytical capabilities to address pressing broad-scale (ie continental or global) questions (Peters *et al.* 2014b). Ecological research needs to explicitly broaden this model to one that is open, transparent, and interactive.

Complex workflow and algorithm development for data integration

As research has become more sophisticated and reliant on complex simulations and analyses, the potential for computational errors that affect results has increased (Merali 2010). Furthermore, as the repeatability of scientific results in general has been called into question (www.newyorker.com/magazine/2010/12/13/the-truth-wears-off), the importance of documenting the research and analysis process more thoroughly through scientific workflow tools and scripting via programming languages (eg recording data processing steps, decisions, algorithms, and analysis parameters via executable code or workflow software) has increased (Reichman *et al.* 2011). These and other related efforts are affecting the culture of scientific research and broadening the traditional view of a scholarly journal article as the primary output of research to also include data, workflows (including algorithms and code), and metadata as public research outputs.

Workflows document the scientific method in a form that is more thorough, accessible, and reproducible than the methods section of a journal article. New tools such as the Kepler scientific workflow management system (https://kepler-project.org) are being developed to make documentation easier than scripting and less prone to error (Barseghian *et al.* 2010). Like data, many workflows have a temporal component (that is, they are relevant for a specific time period – ie version – and experimental context). We believe that the use of tools to document research methods should be encouraged and that the unrestricted publication of and access to workflows and data will facilitate the exchange and evaluation of ideas. Systems for archiving, discovering, and accessing data – as well as algorithms, code, and other workflows – need to be further developed, with an emphasis on integrating the different types of research products.

Panel 2. Integration of ground- and airborne-collected data yields ecohydrology insights

Landscape-scale process studies in ecohydrology are aided by the integration of environmental sensor networks and unmanned aerial systems (UAS) image data products (Figure 2a). Accurate surface topography and vegetation data from a UAS were used by Vivoni *et al.* (2014) to construct a hydrological model that reproduced observed soil moisture measurements from the environmental sensor network in the Tromble Weir watershed within the USDA-ARS Jornada Experimental Range. There are three major environmental sensor networks at the site: (1) a tower network consisting of an eddy covariance tower (Figure 2b) and soil sensor profiles (yellow crosses in [a]); (2) a watershed network consisting of rain gauges and flumes (Figure 2c), soil sensor profiles (white crosses), and a COSMOS (COsmic-ray Soil Moisture Observing System) sensor (Figure 2d); and (3) a phenocam (Figure 2e) and sampling locations to monitor plant phenology (white dots). The sampling areas of the watershed (black outlines upstream of flumes), COSMOS (red outline), and eddy covariance tower (blue outline) are shown. Sampling intervals vary from 1 minute (rain gauges and flumes) to 30-minute averages (soil sensors, eddy covariance tower, COSMOS) to weekly intervals (plant sampling). The possibility of conducting numerous UAS flights with multispectral sensors offers opportunities for testing spatially explicit, predictive models with fine-scale and large-extent observations.

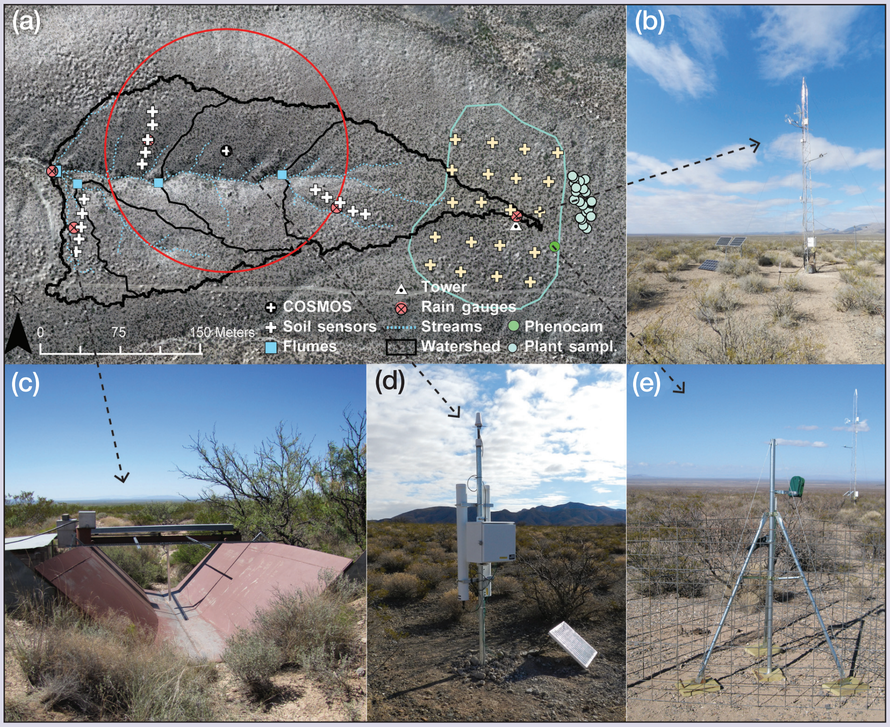

Figure 2. *(a) Sampling footprint of a UAS 6-cm resolution color ortho-image mosaic draped on a 1-m digital terrain model for which multi-temporal images are available. Nested instrument networks within the study area include: (b) an eddy covariance tower; (c) a rain gauge/flume; (d) a COSMOS sensor to characterize soil moisture dynamics; and (e) a phenocam to capture vegetation dynamics (ie "greening").*

Emerging cultural components

Although necessary, technological advances alone are not enough; modifying research practices is an essential counterpart. An incentive system that motivates researchers to document and publish data, workflows, and derived data products would be one way forward (Peters *et al.* 2014a). Data integration can be greatly enhanced through the adoption of standardized functional indicators and transparency in the use and availability of data that facilitates cross-site comparisons and reuse of data. Such an approach, involving open, collaborative, and interactive science, would be particularly beneficial in dryland ecosystems that are part of large federal land holdings – spatially heterogeneous landscapes that are both remote and expansive – and that are facing pressures associated with supporting growing human populations (Panel 3). Coordinated, multi-site, and multidisciplinary efforts will be required to address the greatest threats to these water-limited ecosystems worldwide (Peters *et al.* 2014b).

Deriving and applying standardized functional indicators across broad landscapes

The dynamic nature of dryland landscapes, along with the close links between functional indicators (eg perennial grass cover, frequency of bare soil gaps) and climate variability, complicates efforts to monitor trends in landscape condition and gauge the relative impact of management practices or disturbance. Coupled with stagnant or declining budgets for monitoring of drylands, this means that single-objective measurements and monitoring are often not feasible and, we argue, no longer an efficient practice for deriving knowledge relevant to the management of dryland landscapes. One solution to this dilemma is to adopt consistent sets of indicators based on functional ecosystem attributes and standardized methods for measuring these indicators (Herrick *et al.* 2010; Mackinnon *et al.* 2011). This approach facilitates data sharing across relevant agencies, simplifies synthesis of ecosystem dynamics across landscapes, and allows the reuse of data to address questions pertinent to drylands research and management.

Panel 3. Monitoring multiple scales of greater sage-grouse habitat across jurisdictional boundaries

In 2010, the greater sage-grouse (*Centrocercus urophasianus*; Figure 3b) was determined to warrant protection under the US Endangered Species Act, and action to determine its final listing status is expected in 2015 (USFWS 2013). Successful conservation of sage-grouse will hinge on the ability to ameliorate threats to the species' habitat across a broad geographic range (Figure 3, a and c). As part of the conservation strategy for the species, monitoring of management and conservation actions on sage-grouse populations and habitat has been identified as a priority (USFWS 2013). Because sage-grouse exhibit distinct habitat associations at multiple scales (Stiver *et al.* in press), local-level monitoring is insufficient to track the status of the species. Coordinated efforts for sage-grouse conservation (NRCS, BLM, USFS, and USFWS 2011) have highlighted the need for consistent methods and approaches to monitor sage-grouse habitat among the different land-management agencies and groups within the geographic range for sage-grouse distribution (BLM and USFS 2014). The use of consistent indicators of sage-grouse habitat and standardized methods for measuring those indicators will provide opportunities to assess and monitor the distinct scales of sage-grouse habitat across land-ownership types (Figure 3a) and the cumulative effects of efforts to manage that habitat. This form of cross-jurisdictional and cross-scale information has previously been unavailable. Management of greater sage-grouse habitat within its current range (heavy black line in Figure 3a) will require coordinated efforts among many public and private land stewards.

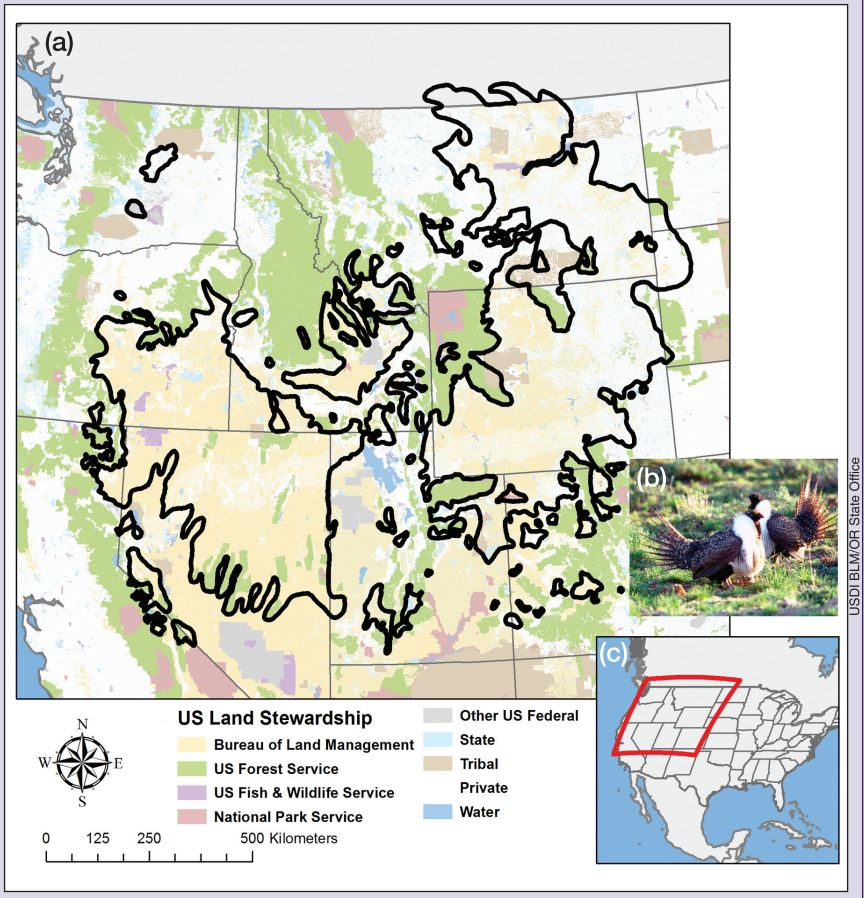

Figure 3. *(a) Geographic range of the greater sage-grouse (*Centrocercus urophasianus*) in the western US (black outline) in the context of land stewardship. Data from SAGEMAP (http://sagemap.wr.usgs.gov). (b) Greater sage-grouse. (c) Location index map depicting the spatial extent of conservation efforts in (a).*

One example of the derivation and application of functional indicators is recent research pertaining to the use of canopy gap size distributions to estimate and model wind erosion. The size and distribution of bare ground patches or "canopy gaps" in drylands is strongly related to the wind erosion potential of a given site (Okin 2008). Standardized protocols for measuring canopy gaps facilitated the development of models relating site-level gap distributions to wind erosion; these models have been used to generate broad-scale estimates of wind erosion across the western US (Herrick *et al.* 2010). Use of standardized protocols for ecosystem indicators is also integral to the continental-scale sampling design of the National Ecological Observation Network (Kao *et al.* 2012). Panel 3 highlights monitoring efforts coordinated between multiple organizations and based on a standardized set of functional indicators necessary for observing and managing the habitat of the greater sage-grouse (*Centrocercus urophasianus*), a species that has been proposed for listing under the US Endangered Species Act (ESA).

All data products are valid primary research outputs

There is an emerging capacity for scientists, organizations, and even private citizens to collect data for contribution to the scientific record. Such data can now be shared in a way that allows for effective and meaningful engagement among diverse stakeholders (Newman *et al.* 2012). In addition to increasing the possibility that measurements will be used for other purposes in the future and improving the mechanistic understanding of dryland landscapes, sharing data collected from these areas also provides usable knowledge for dryland management and conservation. Communication systems (eg web tools, networks, social media, funding programs) and research practices (eg standardized methods and technologies) have emerged that are improving the discoverability and accessibility of scientific research and data (Proctor *et al.* 2010). This has led to a shift in cultural attitudes beyond acceptance of peer-reviewed publications as the primary research product to one in which datasets, metadata, and complex visualizations are also highly valued research products. For example, many journals (eg http://esapubs.org/esapubs/DataReg.htm) now either require or encourage researchers to submit data underlying a publication to an online repository like Dryad (http://datadryad.org) or Pangea (http://pangea.de). Adoption of these practices as the standard in academic settings would promote the practices among members of the next generation of scientists and further encourage development of data discovery and problem-solving skills.

Supporting data integration services between multiple management agencies and user groups

Many dryland researchers, managers, and citizen scientists collect relatively low-volume but high-resolution datasets for the purpose of advancing understanding of local- to landscape-scale processes. Integrative analyses of these datasets have the potential to transform knowledge of dryland landscapes. However, there are few efficient mechanisms for data discovery that link data interpretations with raw data and associated workflows, including algorithms, to facilitate new and different applications (Karl *et al.* 2013b). As the culture of sharing data among researchers evolves (Hampton *et al.* 2012), technologies to streamline the data life cycle (ie from data collection to visualization and sharing) are also advancing. Many of the aforementioned technologies can take advantage of small datasets from many research groups to an extent that has not been possible previously, provided that such technologies are implemented following community standards and meet requisite data-quality criteria (Michener and Jones 2012; Laney *et al.* 2013). Panel 4 illustrates an integrative cross-scale study of plant phenology linked with land surface phenological patterns discerned via satellite-based sensors. The study entails monitoring phenological changes in different plant species using standardized protocols developed by the USA National Phenology Network (USA-NPN; Denny *et al.* 2014) and estimating plant greenness from phenocam images (Richardson *et al.* 2007). Data collected by these methods are deposited within federated data repositories and are proving useful for modeling landscape productivity and informing models predicting plant responses to climate change.

■ Conclusions and recommendations

Drylands research and management may benefit greatly from emerging environmental monitoring technologies, which will provide crucial information at temporal and spatial extents required to inform decision making. Nevertheless, it is not always clear which technologies will be most effective for each situation based on accessibility, available financial and human resources, and existing knowledge. Ideally, multiple, related, and diverse datasets spanning long timescales and vast regions would be available for any part of the world and could be readily incorporated into models and synthesized; however, the infrastructure to support these capabilities has yet to be designed and implemented.

To facilitate the convergence of technological innovation and transformations occurring in how science is conducted and data are shared, we offer some thoughts and guiding principles to researchers and managers alike.

First, a diverse range of data generators – including research networks (small and large), agencies, independent researchers, citizen scientists, technology specialists, traditional landowners (eg pastoralists, native populations), and land managers – have relevant data, other products (eg custom software), and knowledge to contribute to the advancement of drylands research and management (eg Peters *et al.* 2006; Herrick *et al.* 2013). Most systems for identifying and sharing ecologically relevant knowledge remain in their infancy (eg Karl *et al.* 2013a). We recommend that researchers and managers implement multiple practices in their future work, to add their respective data to the collective pool and to harness the power of the "data deluge" (Hey *et al.* 2009; Peters *et al.* 2014a). These practices include utilizing existing databases and data centers for storage; documenting data through the use of standard community practices and formats that promote discoverability and reuse; and incorporating existing databases, software, and documentation standards into third-party, web-based tools. Such tools include web-mapping applications and standardized web services that provide stakeholders with free and easy access to increasingly large pools of well-curated data and information within a management-oriented, geospatially relevant, and time-enabled framework. The development of integrated diverse infrastructure will require collective buy-in from publishing houses, government entities, and the private sector.

Second, we recommend that communities in the academic, public, and private sectors work together to improve systems for data dissemination and synthesis to enhance public understanding of sustainability issues in dryland environments. Some of the prominent technological advances that have aided ecosystem research include research collaborative portals such as the Arctic Observing Viewer (AOV; www.arcticobservingviewer.org), which connect a multitude of stakeholders with a wide array of broadly distributed research programs; wikis that allow for community discussion and knowledge building related to available technologies, such as the Earth Science Information Partners (ESIP)

Panel 4. Integrating standardized indicators of plant phenology with remotely sensed imagery to estimate landscape productivity

The ability to track landscape greenness in drylands in a cost-effective manner is important for managing grazing herds, monitoring plant biodiversity, and – when linked with field observations – understanding climatological drivers. Identifying environmental cues that trigger phases of the plant growing cycle will enhance the ability to predict plant responses to changing climates and the effectiveness of vegetation management activities. For example, phenocam estimates of canopy development indicate that honey mesquite (*Prosopis glandulosa*, a ubiquitous C_3 leguminous shrub) transitions from dormancy to full canopy greenness in approximately 14 days (brown line on graph in Figure 4b). Rapid canopy development does not appear to be triggered by rainfall and prompts further study of the role of air temperature and day length on patterns in mesquite canopy development. Phenological patterns can inform management plans to curtail woody plant expansion (eg herbicide applications) and promote perennial grass recovery. Alternatively, these high-temporal-resolution data can be linked with field observations and multi-temporal remote imagery collected at a range of spatial resolutions (eg UAS, Landsat, Moderate Resolution Imaging Spectroradiometer [MODIS]) to characterize scaling relationships for greenness and productivity in order to facilitate data extrapolation in vast dryland ecosystems. Figure 4a depicts spatial and temporal resolutions of multiscale measures of plant phenology at the USDA-ARS Jornada Experimental Range in southern New Mexico. Images from digital cameras (ie phenocams; insets in Figure 4a) can be acquired more frequently than field data or satellite images. Daily phenocam photographs are batch-processed and analyzed to depict species-specific patterns in canopy greenness (Figure 4b). These daily greenness values are correlated with standardized field methods for phenology and canopy greenness developed by the USA-National Phenology Network (Denny *et al.* 2014) and reveal species-specific responses to episodic rainfall events. Species-specific patterns in greenness are translated to larger spatial extents via satellite imagery using UAS mosaics produced throughout the growing season.

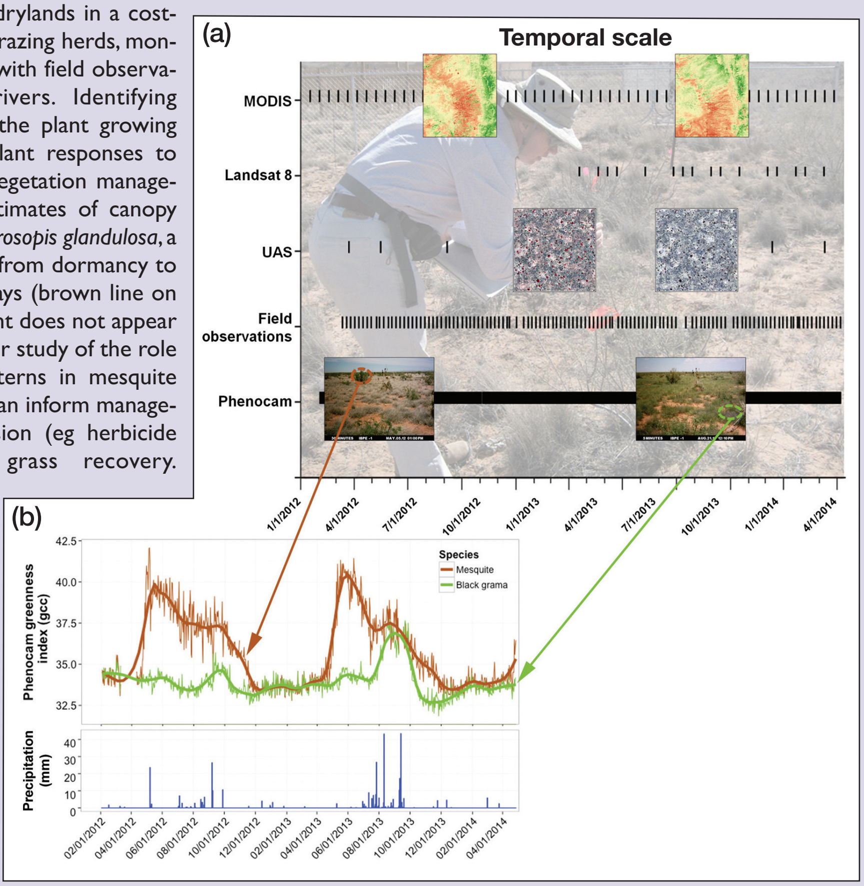

Figure 4. *(a) Frequency of data acquired for five hierarchical components informing a multiscale study designed to link patterns in plant phenology and land surface phenology in a Chihuahuan Desert ecosystem. (b) Species-specific patterns in greenness derived from daily phenocam images for two common species (green and brown lines) in arid and semi-arid grasslands in the context of daily rainfall (blue line).*

portal (http://esipfed.org/collaboration-areas); research networks for collecting, discovering, and sharing data, such as the USA-NPN (www.usanpn.org); web-based tools and portals that help researchers document and archive their datasets and models, such as Dryad; and web-based data dissemination portals, such as EcoTrends (www.ecotrends.info) and VegBank (www.vegbank.org). Yet relatively few research networks or portals are specifically focused on dryland landscapes, with the notable exception of the Landscape Toolbox (http://landscapetoolbox.org), which facilitates the accessibility of data for a diverse and distributed audience. For drylands in general, however, datasets are still widely dispersed and isolated; thus, work is needed to build linkages between researchers, land managers, citizen scientists, and networks to improve data discovery capabilities and enable collaborative synthesis research.

Finally, we propose that scientists employ practices that best promote cooperative and innovative environments for interactions between the many stakeholders associated with research and management in drylands – including, but not limited to, private land managers, native peoples, representatives from technology and industry, educators, and citizen scientists. Emerging cost-effective technologies and tools can provide crucial data for land-management decisions and thus promote the most efficient uses of limited resources for inventory and monitoring. In some cases, researchers and land managers must also consider compliance with state and federal regulations; for example, in the US, the use of UAS technology must be conducted within the regulations of the Federal Aviation Administration and the sharing of data on threatened and endangered species must be considered within the purview of the ESA. Data collection and sharing must therefore be performed while engaging with many relevant individuals and agencies in a way that will allow policy to evolve while simultaneously respecting external and important cultural, economic, and scientific considerations. The key to our success as a scientific community will be to collaborate more broadly across disciplines; adopt sensible and open practices regarding data collection, curation, and sharing; and train the next generation of research leaders and others (eg decision makers and funders) with a mindset for discovery, innovation, and problem solving.

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