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Ecological Science Infrastructure for Sustainability Transformations in Rangelands

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Ecological Science Infrastructure for Sustainability Transformations in Rangelands

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Abstract

Sustainability transformations—deliberate and radical shifts in values, governance, and management regimes to achieve sustainability—are needed in rangelands as in other components of the Earth system. We review four concepts comprising an ecological science infrastructure to support such transformations. The foundation is standard measurement of rangeland conditions in the field, especially vegetation and soil properties that underpin the environmental aspects of sustainability. Big data resources, especially gridded spatial datasets produced by models and remote sensing, can be combined with field data and computational approaches to upscale information about rangeland conditions and produce additional indicators of ecosystem functions and services. State and transition models (STMs) linked to land types provide a means to interpret indicators and link interpretations to sustainable land management practices to manage change. Technologies for climate adaptation in rangelands also need to be linked to STM databases. Web and mobile technologies can put multifaceted science knowledge into the hands of pastoralists worldwide to support transformational changes in how rangelands are managed.

Introduction

Rangelands and pastoral peoples will face mounting challenges in the years ahead. Climatic change will cause increasing aridity, increasing frequency of extreme events, and decreasing productivity in many rangelands (Bradford et al. 2020; Godde et al. 2020; Zhang et al. 2020). The effects of climate change will interact with accelerating conversion of rangelands to more intensive uses, increasing the demand for resources in the remaining rangelands and reducing important ecosystem services in converted rangelands (Barral et al. 2020; Mirzabaev et al. 2019). A long standing disregard for the value of rangelands facilitates land use conversion and limits investments in management solutions (Hoover et al. 2020; Reynolds et al. 2007). Consequently, resource use-climate change interactions are poised to precipitate abrupt and undesirable transitions with long-lasting impacts on pastoral societies as well as the Earth system (Bestelmeyer et al. 2018; Menges et al. 2019; Mirzabaev et al. 2019).

The general threats to rangelands are reasonably well understood (Hoover et al. 2020). Pragmatic responses to those threats, however, are not. First, while it is clear that global change is altering social-ecological systems to varying degrees, the specific alterations that determine the severity of loss of ecosystem services, and options for adaptation or restoration, are poorly defined. The lack of specificity is especially problematic for rangelands, where human use of rangelands, that can have relatively minor impacts on biodiversity and ecosystem functions, are classified similarly to far more intensive uses such as deforestation or urbanization (Sayre et al. 2017; Williams et al. 2020). The "desertification narrative", for example, is commonly misused such that naturally arid systems are condemned as degraded and the people living in those systems are seen as agents of degradation (Davis 2016; Prince and Podwojewski 2020). Second, the urgency associated with global change has led to calls for transformation of resource use and agricultural systems (Pereira et al. 2020). Strategies to trigger transformation, however, are frustratingly non-specific and lack local contextualization (Stafford Smith 2016) or emphasize overgeneralized and over-hyped "one-size-fits-all" solutions that are poorly matched to most local situations (Huntsinger 2016).

Specific guidelines for achieving sustainability transformations at the local level, particularly in the face of ongoing global change, is the greatest challenge facing natural resource professions. There are many facets to transformation in rangelands that must be considered, including resource use strategies, enterprise structure, power relations, governance, markets, and policies (Meyfroidt et al. 2019; Osinski 2021; Spiegal et al. 2020). In this short paper, we consider how ecological science information and technologies can be created, organized, and used to support transformations in rangelands. We base these ideas on our ongoing efforts to develop knowledge systems to support rangeland management in the U.S., Mongolia, and Argentina.

Standard monitoring methods and data

The foundation of science-based decision making is observation. This might seem trite, but inconsistent rangeland monitoring methodologies, compounded by a lack of investment in data management, continues to limit a clear understanding of rangeland conditions and, ultimately, what is considered "sustainable", "degraded", or "restored." In the United States, standardized assessment and monitoring methods for rangelands were collaboratively developed with land management agencies and have been trained to thousands of rangeland managers worldwide (Herrick et al. 2017b). A common database structure and well-developed data management protocols ensures that vegetation and soil indicators reflect real differences in ecological conditions across space, over time, and among different observers (Courtright and Van Zee 2011; McCord et al. 2021). For example, there are now 65,000 monitoring plots globally (mostly in the U.S. and Mongolia) that use the same methods and are comparable, with time series of up to 20 years. Widely adopted standardization also offers opportunities for integration with tools for defining management benchmarks and computational tools that add information value to monitoring observations (see below). There are multiple, valid standardized monitoring systems (Oliva et al. 2020), but it is important to recognize that comparisons and benchmarks are method-dependent. Finally, we acknowledge the varying capabilities for implementing rangeland monitoring across world. For this reason, the Land Potential Knowledge System (LandPKS) mobile apps were developed using a simplified methodology that sacrifices some degree of precision and resolution of vegetation information, but is accessible to pastoralists in a wide range of socio-economic contexts (Herrick et al. 2017a).

Big data, data integration, and upscaling

"Big data" resources provide new opportunities for accessing information on ecological conditions from local to global extents. Big data products leverage spatial data layers, remote sensing, and standardized monitoring data to create gridded estimates of biophysical variables at fine scales (e.g. $900m^2$-$4km^2$) and at a continental extent. In the case of dynamic variables, including climate and vegetation, estimates have been produced over long time periods (1984-) at annual resolution (Bestelmeyer et al. 2020). These products provide a broadened perspective on sustainability and allow upscaling of observations from points to landscapes and regions. For example, standardized monitoring data have been used to train machine learning algorithms that estimate vegetation cover and production from remotely-sensed and modeled covariates (Allred et al. 2020; Jones et al. 2018). Using the computational power of Google Earth Engine, Landsat imagery dating to 1984 constitutes the basis for yearly and spatially continuous estimates of vegetation cover and production by plant functional group at a 30-m resolution, which users can query and visualize with a custom web application (https://rangelands.app/). Such tools can not only provide information on locations in the vast spaces between monitoring points, but they can provide information on landscape patterns needed to understand the impacts of livestock movements, spatial variations in weather, and other spatial processes (Bestelmeyer et al. 2011).

Continuous soil and vegetation predictions, in turn, can be combined with models to predict and scale up other processes of management interest, such as soil erosion. For example, bare soil cover, canopy gap distribution, and vegetation height estimates modeled in fractional cover products can be used as inputs in a sediment transport model to produce spatially-explicit dust flux estimates (Webb et al. 2020). It is important to recognize that the models underpinning such "value-added" indicators are ultimately based on (often distributed) long-term experiments carried out at research stations throughout rangelands of the world.

The integration of gridded climate data with remotely-sensed estimates of production are especially useful indicators of ecosystem function and services in rangelands, particularly Precipitation Use Efficiency (the ratio between aboveground net primary production and precipitation) and the Precipitation Marginal Response (the slope of the linear relationship between annual aboveground net primary production and precipitation) (Verón et al. 2018). These useful indicators can be made available to land managers globally using existing open access data.

Ultimately, consideration of multiple indicators is needed to base decisions on the multiple ecosystem services provided by rangelands and the synergies and tradeoffs associated with particular management decisions (Power 2010). For example, the removal of shrubs might marginally increase grasses and livestock forage production, but at the expense of carbon sequestration, wildlife habitat value, or protection of the soil surface from wind erosion (Archer et al. 2011). Thus, what is considered sustainable should be based on multiple types of ecosystem process and ecosystem service indicators (Manning et al. 2018), yet we often judge the merits of management decisions using narrower perspectives. Big data-based indicators reflecting various ecosystems services need to be made more widely available to land managers and pastoralists around the world to enable better decisions, which is now eminently possible via cloud computing and web and mobile services (Herrick et al. 2013; Jones et al. 2018).

Indicator interpretation via state and transition models

While state and transition models (STMs) were initially conceived to link rangeland management to the emerging concepts of ecosystem non-equilibrium and catastrophic transitions (Walker and Westoby 2011), they have become widely used as pragmatic tools for understanding and forecasting change in many types of ecosystems (Hobbs and Suding 2009). STMs represent the multiple potential states of a particular land type, where states are defined by vegetation, soil, or other dynamic characteristics and distinctions among states reflect differences in the ecosystem services provided as well as the risks and opportunities for change in ecosystem services provision (e.g., ecological thresholds) (Bestelmeyer et al. 2017). STMs also provide an opportunity for collaboration between scientists and pastoralists and for addressing power imbalances by the inclusion of diverse stakeholders in STM development (Kachergis et al. 2013).

Three advances in STMs will increase their utility for supporting sustainability transformations. First is the development of a global web-based platform to guide STM development, which is being led by the USDA-ARS Jornada Experimental Range in partnership with the USDA Natural Resources Conservation Service and New Mexico State University. The Ecosystem Dynamics Interpretive Tool (EDIT) is a database for housing state-and-transition models linked to land classifications and spatial data to make STM information available via the web and mobile devices (https://edit.jornada.nmsu.edu/). Application programming interfaces (APIs) allow STM data to be linked to a variety of other web and mobile applications, such as LandPKS. Once STMs are developed in EDIT, a pastoralist with a mobile phone will be able to relate a location to the appropriate STM and access tools for indicator interpretation and management options. Second, STMs are being linked to quantitative benchmarks that allow standardized monitoring data to be interpreted according to STMs. For example, STMs developed for Mongolia include quantitative criteria for states based on vegetation cover indicators, such that computational "keys" can classify a monitoring record to an ecological state in a rigorous and repeatable fashion (Densambuu et al. 2018). Such rigor is essential for a community-wide understanding of progress toward or away from sustainability goals. In addition, benchmarks can be included for "value-added" and other indicators discussed earlier, such as wind erosion potential. For example, STMs could communicate how subtle changes in vegetation structure within a particular soil type create non-linear increases in wind erosion susceptibility beyond benchmark value (Webb et al. 2020). Third is the linkage of STMs to sustainable land management (SLM) practices and other tools (Briske et al. 2017; Giger et al. 2018). STMs can provide a logic that winnows practices that are mismatched to the reference conditions and ecological drivers and feedbacks bearing on a particular state transition. For example, one would not consider a woody plant removal practice as progress toward sustainability for an STM in which woody plants characterize the reference state (Romme et al. 2009). The construction of a comprehensive database of evidence-supported SLM practices for rangelands that can be linked to STMs will be a priority of ours for the coming years.

Climate adaptation to steer transformation

The "elephant in the room" facing local sustainability transformation is how to cope with social-ecological drivers emerging from broader scales that cannot be affected by management decisions. State transitions associated with regional changes in climate and hydrology (i.e. novel ecosystems) do not have restoration options, only adaptation options. In this sense, adaptation is a means to direct inevitable transformation along the most desirable course available, even if we'd prefer to avoid transformation altogether (Bestelmeyer and Briske 2012). A variety of rangeland adaptation and mitigation strategies have been developed including traditional options at the enterprise, human and social levels (Joyce et al. 2013). In addition, novel technological solutions are emerging. Especially promising in rapidly responding to changing climatic conditions is the application of technological monitoring solutions and precision technologies, such as phenocams (Browning et al. 2019) and sensors for dust monitoring, cattle tracking, trough water level surveillance and fine-scale precipitation variability monitoring (Spiegal et al. 2020). Agrivoltaics, or producing solar energy in combination with agricultural enterprise and dual land uses, such as wind energy or bioenergy (i.e. algae), are creative options for novel, non-traditional revenue streams and reducing reliance on traditional energy sources.

A recent inventory by co-author E. Elias found more than 520 livestock and rangeland decision tools globally. A simple process to allow managers to find the most useful of these tools to address their local management challenge is critical to support climate-informed decision-making. Web-based and mobile tools, such as EDIT and LandPKS described earlier, could help serve this role. "Big data" type tools, such as Grass-Cast that provides an annual projection of above ground net primary productivity at a local scale, could be used for coping with climate uncertainty in rangelands throughout the world (Hartman et al. 2020).

Conclusions

Development of an ecological science infrastructure to support sustainability transformations in rangelands should be a priority for international rangeland science community, and similar calls have been made in the past (Verstraete et al. 2011). The proposed infrastructure is complex, but we now have the accumulated science, technologies, and ideas to make it a reality. The vision for the infrastructure we described is also incomplete, as societal indicators and benchmarks should also be included as well as mechanisms for using this infrastructure in collaborative decision-making (Reid et al. 2021). We also need to mobilize government, academic, and industry resources to support these uses. Nonetheless, our proposal can support a new narrative for the role of ecological science in rangeland (and dryland) sustainability. Not a story of degradation and helplessness that leads to paralysis and not Pollyannish silver-bullet solutions that distract and detract from real progress. In the words of (Stafford Smith 2016), "we need a narrative that presages solutions and empowerment". Thoughtful organization of technological resources can be a part of this new narrative.

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References

Allred, B.W., Bestelmeyer, B.T., Boyd, C.S., Brown, C., Davies, K.W., Ellsworth, L.M., Erickson, T.A., Fuhlendorf, S.D., Griffiths, T.V., Jansen, V., Jones, M.O., Karl, J., Maestas, J.D., Maynard, J.J., McCord, S.E., Naugle, D.E., Starns, H.D., Twidwell, D. and Uden, D.R. 2020. Improving Landsat predictions of rangeland fractional cover with multitask learning and uncertainty. *bioRxiv*: 2020.06.10.142489.

Archer, S.A., Davies, K.W., Fulbright, T.E., McDaniel, K.C., Wilcox, B.P. and Predick, K.I. 2011. Brush management as a rangeland conservation tool: a critical evaluation. In: D.D. Briske (Ed.), *Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps*. Allen Press, Lawrence, KS, pp. 105-170.

Barral, M.P., Villarino, S., Levers, C., Baumann, M., Kuemmerle, T. and Mastrangelo, M. 2020. Widespread and major losses in multiple ecosystem services as a result of agricultural expansion in the Argentine Chaco. *Journal of Applied Ecology*, 57(12): 2485-2498.

Bestelmeyer, B.T., Ash, A., Brown, J.R., Densambuu, B., Fernández-Giménez, M., Johanson, J., Levi, M., Lopez, D., Peinetti, R., Rumpff, L. and Shaver, P. 2017. State and transition models: Theory, applications, and challenges. In: D.D. Briske (Ed.), *Rangeland Systems: Processes, Management and Challenges*. Springer International Publishing, Cham, pp. 303-345.

Bestelmeyer, B.T. and Briske, D.D. 2012. Grand challenges for resilience-based management of rangelands. *Rangeland Ecology & Management*, 65(6): 654-663.

Bestelmeyer, B.T., Marcillo, G., McCord, S.E., Mirsky, S., Moglen, G., Neven, L.G., Peters, D., Sohoulande, C. and Wakie, T. 2020. Scaling up agricultural research with artificial intelligence. *IT Professional*, 22(3): 33-38.

Bestelmeyer, B.T., Peters, D.P.C., Archer, S.R., Browning, D.M., Okin, G.S., Schooley, R.L. and Webb, N.P. 2018. The grassland-shrubland regime shift in the southwestern United States: misconceptions and their implications for management. *BioScience*, 68: 678-690.

Bestelmeyer, B.T., Wu, X.B., Brown, J.R., Fuhlendorf, S.D. and Fults, G. 2011. Landscape approaches to rangeland conservation practices. In: D.D. Briske (Ed.), *Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps*. Allen Press, Lawrence, KS, USA, pp. 337-370

Bradford, J.B., Schlaepfer, D.R., Lauenroth, W.K. and Palmquist, K.A. 2020. Robust ecological drought projections for drylands in the 21st century. *Global Change Biology*, 26(7): 3906-3919.

Briske, D.D., Bestelmeyer, B.T., Brown, J.R., Brunson, M.W., Thurow, T.L. and Tanaka, J.A. 2017. Assessment of USDA-NRCS rangeland conservation programs: recommendation for an evidence-based conservation platform. *Ecological Applications*, 27(1): 94-104.

Browning, D.M., Snyder, K.A. and Herrick, J.E. 2019. Plant phenology: Taking the pulse of rangelands. *Rangelands*, 41(3): 129-134.

Courtright, E.M. and Van Zee, J.W. 2011. The Database for Inventory, Monitoring, and Assessment (DIMA). *Rangelands*, 33(4): 21-26.

Davis, D.K., 2016. The arid lands: history, power, knowledge. MIT Press, Cambridge, MA, 296 pp.

Densambuu, B., Indree, T., Battur, A. and Sainnemekh, S., 2018. State and transition models of Mongolian rangelands. Agency for Land Management, Geodesy, and Cartography, Ulaanbaatar, Mongolia.

Giger, M., Liniger, H., Sauter, C. and Schwilch, G. 2018. Economic benefits and costs of Sustainable Land Management technologies: An analysis of WOCAT's global data. *Land Degradation & Development*, 29(4): 962-974.

Godde, C.M., Boone, R.B., Ash, A.J., Waha, K., Sloat, L.L., Thornton, P.K. and Herrero, M. 2020. Global rangeland production systems and livelihoods at threat under climate change and variability. *Environmental Research Letters*, 15(4): 044021.

Hartman, M.D., Parton, W.J., Derner, J.D., Schulte, D.K., Smith, W.K., Peck, D.E., Day, K.A., Del Grosso, S.J., Lutz, S., Fuchs, B.A., Chen, M. and Gao, W. 2020. Seasonal grassland productivity forecast for the U.S. Great Plains using Grass-Cast. *Ecosphere*, 11(11): e03280.

Herrick, J.E., Karl, J.W., McCord, S.E., Buenemann, M., Riginos, C., Courtright, E., Zee, J.V., Ganguli, A.C., Angerer, J., Brown, J.R., Kimiti, D.W., Saltzman, R., Beh, A. and Bestelmeyer, B. 2017a. Two new mobile apps for rangeland inventory and monitoring by landowners and land managers. *Rangelands*, 39(2): 46-55.

Herrick, J.E., Urama, K.C., Karl, J.W., Boos, J., Johnson, M.V.V., Shepherd, K.D., Hempel, J., Bestelmeyer, B.T., Davies, J., Guerra, J.L., Kosnik, C., Kimiti, D.W., Ekai, A.L., Muller, K., Norfleet, L., Ozor, N., Reinsch, T., Sarukhan, J. and West, L.T. 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(1): 5A-12A.

Herrick, J.E., Zee, J.W.V., McCord, S.E., Courtright, E.M., Karl, J.W. and Burkett, L.M., 2017b. Monitoring manual for grassland, shrubland and savanna ecosystems. 2nd Ed. Volume I: Core Methods. USDA-ARS Jornada Experimental Range, Las Cruces, NM, USA.

Hobbs, R.J. and Suding, K.N., 2009. New models for ecosystem dynamics and restoration. Island Press.

Hoover, D.L., Bestelmeyer, B., Grimm, N.B., Huxman, T.E., Reed, S.C., Sala, O., Seastedt, T.R., Wilmer, H. and Ferrenberg, S. 2020. Traversing the Wasteland: A Framework for Assessing Ecological Threats to Drylands. *BioScience*, 70(1): 35-47.

Huntsinger, L. 2016. The tragedy of the common narrative: Re-telling degradation in the American West. In: R. Behnke and M. Mortimore (Eds.), *The End of Desertification? : Disputing Environmental Change in the Drylands*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 293-323.

Jones, M.O., Allred, B.W., Naugle, D.E., Maestas, J.D., Donnelly, P., Metz, L.J., Karl, J., Smith, R., Bestelmeyer, B., Boyd, C., Kerby, J.D. and McIver, J.D. 2018. Innovation in rangeland monitoring: annual, 30 m, plant functional type percent cover maps for U.S. rangelands, 1984–2017. *Ecosphere*, 9(9): e02430.

Joyce, L.A., Briske, D.D., Brown, J.R., Polley, H.W., McCarl, B.A. and Bailey, D.W. 2013. Climate change and North American rangelands: Assessment of mitigation and adaptation strategies. *Rangeland Ecology and Management*, 66(5): 512-528.

Kachergis, E.J., Knapp, C.N., Fernandez-Gimenez, M.E., Ritten, J.P., Pritchett, J.G., Parsons, J., Hibbs, W. and Roath, R. 2013. Tools for resilience management: Multidisciplinary development of state-and-transition models for northwest Colorado. *Ecology and Society*, 18(4).

Manning, P., van der Plas, F., Soliveres, S., Allan, E., Maestre, F.T., Mace, G., Whittingham, M.J. and Fischer, M. 2018. Redefining ecosystem multifunctionality. *Nature Ecology & Evolution*, 2(3): 427-436.

McCord, S.E., Webb, N.P., Zee, J.W.V., Burnett, S.H., Christensen, E.M., Courtright, E.M., Laney, C.M., Lunch, C., Maxwell, C., Karl, J.W., Slaughter, A., Stauffer, N. and Tweedie, C. 2021. Provoking a cultural shift in data quality. *Bioscience*, in press.

Menges, J., Hovius, N., Andermann, C., Dietze, M., Swoboda, C., Cook, K.L., Adhikari, B.R., Vieth-Hillebrand, A., Bonnet, S., Reimann, T., Koutsodendris, A. and Sachse, D. 2019. Late Holocene Landscape Collapse of a Trans-Himalayan Dryland: Human Impact and Aridification. *Geophysical Research Letters*, 46(23): 13814-13824.

Meyfroidt, P., Abeygunawardane, D., Ramankutty, N., Thomson, A. and Zeleke, G. 2019. Interactions between land systems and food systems. *Current Opinion in Environmental Sustainability*, 38: 60-67.

Mirzabaev, A., Wu, J., Evans, J., García-Oliva, F., Hussein, I.A.G., Iqbal, M.H., Kimutai, J., Knowles, T., Meza, F., Nedjraoui, D., Tena, F., Türkeş, M., Vázquez, R.J. and Weltz, M. 2019. Desertification. In: P.R. Shukla, J. Skea, E.C. Buendia, V. Masson-Delmotte, H.O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R.v. Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J.P. Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley (Eds.), *Climate change and land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change, Geneva, Switzerland, pp. 249-343.

Oliva, G., dos Santos, E., Sofía, O., Umaña, F., Massara, V., García Martínez, G., Caruso, C., Cariac, G., Echevarría, D., Fantozzi, A., Butti, L., Bran, D., Gaitán, J., Ferrante, D., Paredes, P., Domínguez, E. and Maestre, F.T. 2020. The MARAS dataset, vegetation and soil characteristics of dryland rangelands across Patagonia. *Scientific Data*, 7(1): 327.

Osinski, A. 2021. Towards a critical sustainability science? Participation of disadvantaged actors and power relations in transdisciplinary research. *Sustainability*, 13(3): 1266.

Pereira, L.M., Drimie, S., Maciejewski, K., Tonissen, P.B. and Biggs, R. 2020. Food System Transformation: Integrating a Political–Economy and Social–Ecological Approach to Regime Shifts. *International Journal of Environmental Research and Public Health*, 17(4): 1313.

Power, A.G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554): 2959-2971.

Prince, S.D. and Podwojewski, P. 2020. Desertification: Inappropriate images lead to inappropriate actions. *Land Degradation & Development*, 31(6): 677-682.

Reid, R.S., Fernández-Giménez, M.E., Wilmer, H., Pickering, T., Kassam, K.-A.S., Yasin, A., Porensky, L.M., Derner, J.D., Nkedianye, D., Jamsranjav, C., Jamiyansharav, K., Ulambayar, T., Oteros-Rozas, E., Ravera, F., Bulbulshoev, U., Kaziev, D.S. and Knapp, C.N. 2021. Using research to support transformative impacts on complex, "wicked problems" with pastoral peoples in rangelands. *Frontiers in Sustainable Food Systems*, 4:600689. doi: 10.3389/fsufs.2020.600689(273).

Reynolds, J.F., Stafford Smith, D.M., Lambin, E.F., Turner, B.L., Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M. and Walker, B. 2007. Global desertification: Building a science for dryland development. *Science*, 316(5826): 847-851.

Romme, W.H., Allen, C.D., Balley, J.D., Baker, W.L., Bestelmeyer, B.T., Brown, P.M., Eisenhart, K.S., Floyd, M.L., Huffman, D.W., Jacobs, B.F., Miller, R.F., Muldavin, E.H., Swetnam, T.W., Tausch, R.J. and Weisberg, P.J. 2009. Historical and Modern Disturbance Regimes, Stand Structures, and Landscape Dynamics in Pinon-Juniper Vegetation of the Western United States. *Rangeland Ecology & Management*, 62(3): 203-222.

Sayre, N.F., Davis, D.K., Bestelmeyer, B. and Williamson, J.C. 2017. Rangelands: Where anthromes meet their limits. *Land*, 6(2): 31.

Spiegal, S., Cibils, A.F., Bestelmeyer, B.T., Steiner, J.L., Estell, R.E., Archer, D.W., Auvermann, B.W., Bestelmeyer, S.V., Boucheron, L.E., Cao, H., Cox, A.R., Devlin, D., Duff, G.C., Ehlers, K.K., Elias, E.H., Gifford, C.A., Gonzalez, A.L., Holland, J.P., Jennings, J.S., Marshall, A.M., McCracken, D.I., McIntosh, M.M., Miller, R., Musumba, M., Paulin, R., Place, S.E., Redd, M., Rotz, C.A., Tolle, C. and Waterhouse, A. 2020. Beef production in the Southwestern United States: Strategies toward sustainability. *Frontiers in Sustainable Food Systems*, 4:114. doi: 10.3389/fsufs.2020.00114.

Stafford Smith, M. 2016. Desertification: Reflections on the Mirage. In: R. Behnke and M. Mortimore (Eds.), *The End of Desertification?: Disputing Environmental Change in the Drylands*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 539-560.

Verón, S.R., Blanco, L.J., Texeira, M.A., Irisarri, J.G.N. and Paruelo, J.M. 2018. Desertification and ecosystem services supply: The case of the Arid Chaco of South America. *Journal of Arid Environments*, 159: 66-74.

Verstraete, M.M., Hutchinson, C.F., Grainger, A., Smith, M.S., Scholes, R.J., Reynolds, J.F., Barbosa, P., Leon, A. and Mbow, C. 2011. Towards a global drylands observing system: observational requirements and institutional solutions. *Land Degradation & Development*, 22(2): 198-213.

Walker, B. and Westoby, M. 2011. States and transitions: The trajectory of an idea, 1970-2010. *Israel Journal of Ecology & Evolution*, 57(1-2): 17-22.

Webb, N.P., Kachergis, E., Miller, S.W., McCord, S.E., Bestelmeyer, B.T., Brown, J.R., Chappell, A., Edwards, B.L., Herrick, J.E., Karl, J.W., Leys, J.F., Metz, L.J., Smarik, S., Tatarko, J., Van Zee, J.W. and Zwicke, G. 2020. Indicators and benchmarks for wind erosion monitoring, assessment and management. *Ecological Indicators*, 110: 105881.

Williams, B.A., Venter, O., Allan, J.R., Atkinson, S.C., Rehbein, J.A., Ward, M., Di Marco, M., Grantham, H.S., Ervin, J., Goetz, S.J., Hansen, A.J., Jantz, P., Pillay, R., Rodríguez-Buriticá, S., Supples, C., Virnig, A.L.S. and Watson, J.E.M. 2020. Change in Terrestrial Human Footprint Drives Continued Loss of Intact Ecosystems. *One Earth*, 3(3): 371-382.

Zhang, P., Jeong, J.-H., Yoon, J.-H., Kim, H., Wang, S.-Y.S., Linderholm, H.W., Fang, K., Wu, X. and Chen, D. 2020. Abrupt shift to hotter and drier climate over inner East Asia beyond the tipping point. *Science*, 370(6520): 1095-1099.