Society for Range Management

Big landscapes meet big data: Informing grazing management in a variable and changing world

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On the Ground

- Rangeland-based livestock raising is the only agricultural production system that maintains native plant communities, providing ecosystem services in the same space as food and fiber production.
- Annual aboveground net primary productivity (ANPP) underlies forage production and multiple ecosystem services. ANPP is highly variable in rangelands in the western United States, across the landscape, from year to year, and within a growing season. Variability is also increasing as the climate changes.
- Grazing management decisions that determine when, where, and how much of ANPP is consumed by livestock, including stocking rate decisions, can ultimately determine rangeland health and the future sustainability of livestock production and provision of ecosystem services.
- Yet managers' access to data on available forage and its variability is limited, and existing field methods to quantify forage production accurately require extensive sampling and are prone to errors or bias.
- A variety of remotely sensed data sources exist to help characterize forage availability and how it has varied spatially and temporally over the last 30 or more years, as well as other datasets that can estimate available forage and inaccessible terrain for livestock.
- We discuss the need for a state-of-the-art decision support tool that integrates available remote-sensing data on forage availability with land managers' knowledge of local needs and information for managers to access to the depth and breadth of information they need to sustainably manage grazing under variable and changing conditions.
- Such a decision support tool could help land managers better manage rangeland ecosystems with flexible stocking rates and adaptive grazing management opportunities that adjust to variations in ANPP, leading to increased regional and site-specific rangeland resilience.

Keywords: Rangelands, dynamic stocking rate, decision support tool, interannual variability, forage availability data

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Introduction

Rangelands across the western United States, characterized by precipitation variability in space and time, provide critical resources for grazing livestock, generate essential ecosystem services, and support rural livelihoods and economies.[1] Grazing livestock depend on forage production. The ecosystem goods (e.g., forage) and services (e.g., biological diversity, wildlife forage and habitat, soil protection, water holding capacity, and carbon sequestration[1]) provided by rangelands are shaped by the timing and amount of precipitation,[2,3] as well as the productive potential of soils. In addition, the ability of rangelands to provide ecosystem services and forage is affected by the health of the rangeland resource, which in many cases is affected by historical and current management practices.[1,4] Yet grazing managers' access to data on available forage and its variability is limited, undermining their ability to effectively consider variations in time and space to make grazing management decisions.

Here, we discuss the potential of using new digital datasets and tools to support dynamic grazing management on rangelands. We first provide some background on sustainable grazing management and the importance of dynamic plans. Next, we discuss how a key metric, stocking rate, is currently calculated and the limitations of the data commonly used to inform such dynamic plans. Yet relevant data sources exist, so we discuss the opportunities provided by these data, which include data on past forage availability, its variability, and trends, as well as potential data sources to support projections of future change. Finally, we provide a roadmap by which ongoing technological advances could provide ranchers and public land managers the ability to develop and implement the kind of flexible, dynamic grazing plans needed to support sustainable rangeland management.

Sustainable grazing management

Rangeland health, defined as the degree to which the integrity of the soil and the ecological processes of rangeland ecosystems are sustained,"[5] has guided rangeland science and management over recent decades.[6] This concept and its application has been supported by the development of state and transition models that reflect the multiple, stable (whether desirable or undesirable) ecological states possible in most places.[7] Although abiotic factors may trump grazing factors as long as grazing pressure is light to moderate, there is widespread agreement that rangeland management decisions are critical factors influencing rangeland health,[8–10] and heavy grazing pressure can quickly lead to stable but undesirable ecological states.[7,11]

Managing grazing for rangeland health is especially important because degradation may be irreversible.[12] Multiple factors influence how grazing might impact rangeland health, whether positive, negative, or neutral. These include rangeland management factors such as the grazing strategy or system used and the breed and species of livestock, as well as factors that characterize a given situation and which are beyond the control of rangeland managers (e.g., vegetation type, soils, topography, and precipitation).[13]

Every rangeland manager grazing livestock must answer specific questions. Many of these decisions are informed by the information available, and then can be adjusted regularly or in response to additional information or change:

1. How many animals can be supported on a specific area in most years?
2. What species and class of animals will be used (e.g., mothers with young, yearlings, first-pregnancy females, dry mothers)?
3. What time of year will grazing occur?
4. How long is the grazing period?
5. How long is the nongrazing period?
6. What will be the density of livestock in a given rangeland or pasture unit if subdivisions exist within a larger area?
7. On what basis are animals moved between rangeland or pasture units (dates, animal unit month [AUMs] consumed, residual dry matter, stubble height, percent removal of biomass of key species, some measure of riparian impact, etc.)?

Good decisions depend on knowing how much plant material is available in an area, how much is grazable, the period of active plant growth, and the relative timing of growth for various plant functional groups (perennial grasses, annual grasses, woody species, forbs, etc.). In environments where grazable forage is defined as much by the variability as by the scarcity of precipitation, such as in the semiarid rangelands of the western United States,[14] management decisions about livestock grazing must be informed by, and responsive to, changing conditions at the scale and the rate at which such changes happen.[15] To reduce the risks associated with disconnects between forage availability and demand during years with below average or above average precipitation (Table 1), planning should be dynamic.[16] However, dynamic stocking has been mostly reactive. With some exceptions, predictions of future variation from some definition of average" have lacked

Table 1. Anecdotal, though common, risks and foregone benefits associated with mismatched forage availability and consumption during below average and above average precipitation years.

Below average precipitation years	**Above average precipitation years**
Forage demand higher than availability	*Forage availability higher than demand*
o Cow body condition decreases, with potential losses in lactation, reproduction, fetal programming*, and economic value efficiency o Weaning weight decreases, leading to decreases in ranch revenue o Increases the risk of overgrazing o Increases the risk of early forced withdrawal from a grazing lease and needing to alter scheduled grazing plan or provide feed o Increases the risk of invasive plant occurrence, which can outcompete native species in drought conditions o Increases the probability of triggering insurance payments (e.g., from Pasture Range Forage crop insurance) to offset decreased economic returns o Increases the risk of forced liquidation of cows at regionally depressed market prices and weight due to drought, lower value, and genetic merit	o Increases the wildfire risk due to higher fuel loads o Lost economic opportunities due to inability to: • Increases the herd size to increase calves weaned and sold • Flex herd size or stocking rate with weaned calves and yearlings through retained ownership or cattle purchases o Fixed AUM grazing lease limits realization of economic opportunities and grazing management opportunities o Increases invasive plant germination and seed formation

* Fetal programming refers to nutritional and health status of the cow during gestation that effects the developing fetus and growth performance following birth.[64]

* Note: This is a summary of our understanding based on multiple informal conversations with livestock producers in the western U.S.

accuracy, timeliness, and any certainty about magnitude, all of which would be necessary for supporting dynamic decisions.

In addition, circumstances could prompt the need to rethink important grazing management decisions, such as changes in land ownership, permit and lease transfers, public or private land trades, decadal updates to federal allotment management plans, shifts in management objectives, and timing and patterns of grazing. Current and expected impacts of climate change on vegetation, including expected increases in variability in forage production,[17] also require re-evaluation of grazing management. When credible data inform this re-evaluation, the likelihood of achieving sustainable management objectives is greater.

Grazing capacity: current calculations, data sources, and limiations

Determining the allocation of land for an animal or a group of animals over time, the stocking rate, is an important decision with numerous implications for the livestock operation and for rangeland health. Excessive grazing pressure (i.e., excessive in duration, frequency, severity of defoliation, or repeated grazing during critical phenological times) is unsustainable. However, with proper grazing management (see Terminology) a range of stocking rates could be sustainable for a given area, even if static forage production is assumed. Variability is an integral characteristic in rangeland systems; therefore, flexible management of stocking rates and other grazing decisions are key to sustainably managing these resources.[18]

Sustainable grazing management, from an ecological perspective, does not depend entirely on stocking rate, but it does depend, at a minimum, on starting with enough land for each animal, and on controlling the effects of grazing on the plant community and soil. For many livestock operations, a common approach to stocking decisions includes calculating an initial stocking rate using a single assessment of forage resources, monitoring whether grazing is promoting or degrading rangeland health, and adjusting livestock numbers as needed. Grazing capacity is calculated based on three elements:

1. Forage production on a parcel of land (see Terminology);
2. What amount of the total available forage can be safely allocated to domestic livestock and harvested; and
3. How grazing animals use the terrain.

We will discuss each of these elements, including sources of data that currently help managers quantify each element. However, our main focus is on forage production data because accessing and using existing data is challenging for managers. Investing in accessibility to improved and dynamic data that capture the variation in forage production across the landscape and through time could make an enormous difference when informing sustainable grazing management decisions.

Rangeland forage production

Most publications and tools used to calculate grazing levels treat forage production as something already known or easily obtained.[19,20] Neither assumption is accurate for rangelands of any size, especially given that forage production varies from year to year and across the landscape in response to soils, topography, vegetation type and condition, weather, and other factors.[7,11]

Annual aboveground net primary production (ANPP) is mainly dependent on precipitation and soils.[21] Annual grazable forage yield or forage production is related to, but always less than, ANPP. Amount and timing of precipitation, and therefore ANPP and forage production, vary significantly from year to year nearly everywhere in the western United States. Variations in forage production become particularly challenging when stocking rates are estimated using a single snapshot of rangeland resources, and livestock herd sizes remain static, as generally occurs on most ranches.[22,23]

Multiple sources of uncertainty complicate determining forage production, and these uncertainties are multiplicative rather than additive. For example, available forage can be calculated as:

$$\mathrm{AF} = \mathrm{A} \times \mathrm{ANPP} \times \mathrm{HC} \times \mathrm{TU} \quad (1)$$

where AF is available forage, A is area of land, ANPP is annual aboveground net primary production, HC is harvest coefficient, or the portion of ANPP assigned to grazing livestock (see Terminology), and TU is terrain use, or the portion of the landscape accessible to livestock. Consider the following hypothetical comparison of calculations for a sample location, where both sets of values are within the range of variation for a semiarid rangeland in the United States:

$$\mathrm{AF} = (10{,}000\ \text{acres}) \times (400\ \text{lb/ac}) \times (30\%\ \mathrm{HC}) \times (50\%\ \mathrm{TU}) = 600{,}000\ \text{lb forage available for livestock use, or } 770\ \text{AUMs}$$

$$\mathrm{AF} = (10{,}000\ \text{acres}) \times (800\ \text{lb/ac}) \times (50\%\ \mathrm{HC}) \times (70\%\ \mathrm{TU}) = 2{,}800{,}000\ \text{lb forage available for livestock use, or } 3{,}590\ \text{AUMs}$$

ANPP for a given area can vary ten-fold between soil types (Fig. 1). Historically, range production estimates have tried to address this spatial heterogeneity, which is challenging. In addition, recent satellite-derived plant production data (verified with field data) have shown the temporal heterogeneity in range production is larger than previously documented.[17]

Adequately accounting for spatial and temporal heterogeneity when field sampling forage production would require a complex and extensive sampling design, which is rarely feasible for a land management agency or a rancher. Standing forage estimates made by direct measurements, such as clipping a plot of a defined area and using that value to extrapolate across the landscape, is problematic due to inadequate sample sizes, as well as inconsistent or incorrect sampling methods.[24]

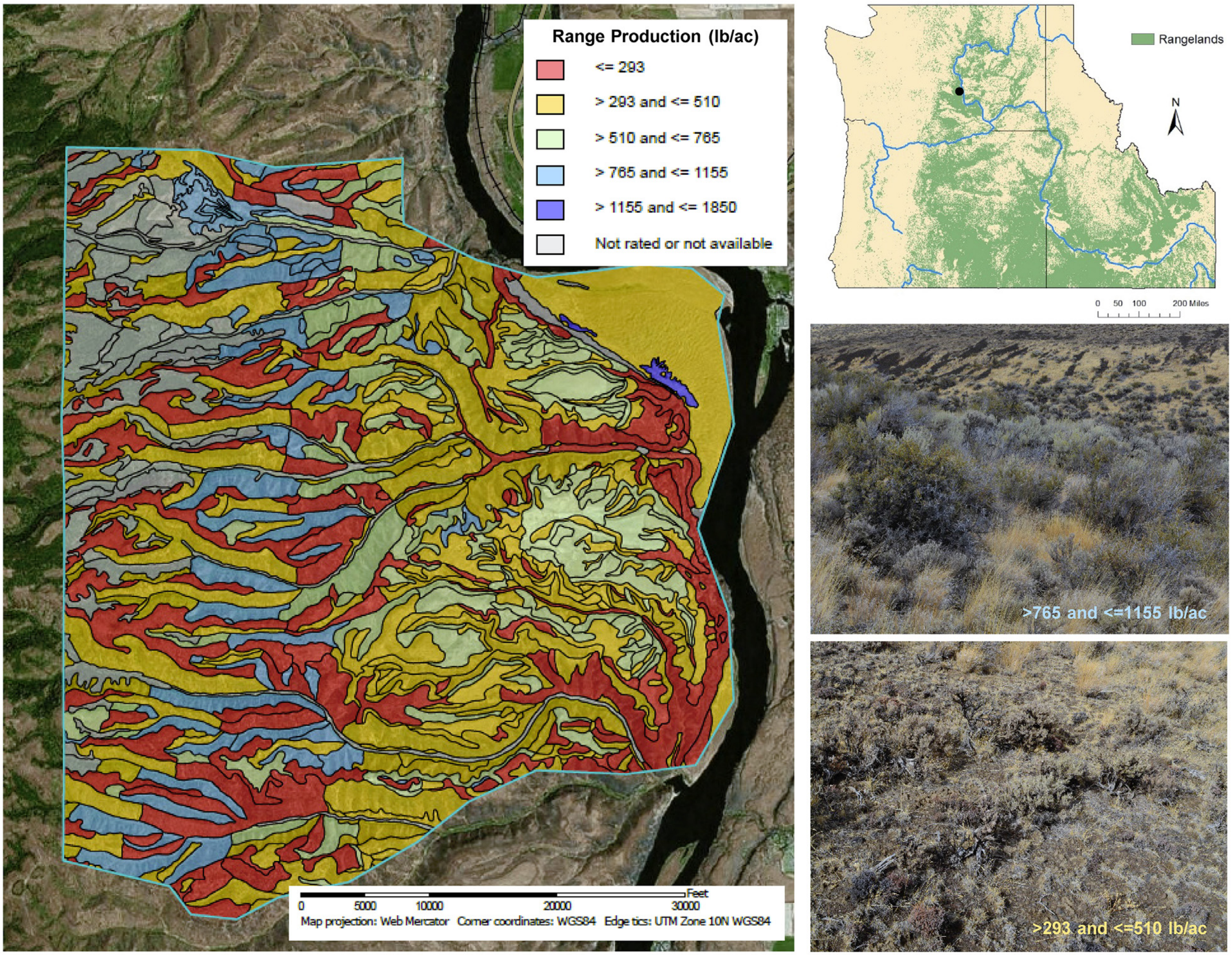

Figure 1. Range production for a "normal" year on an eastern Washington site. *Right panel:* map showing location of site within the Pacific Northwest (top); example of a productive site (range production in the 765–1,155 lb/acre category; middle); example of a low productivity site (range production in the 293–510 lb/acre category; bottom). Range production map obtained from Web Soil Survey.[25] Location map courtesy of S. A. Hall and K. Hamel-Rieken; rangelands mapped using data from Reeves and Mitchell 2011.[67]

Compounding these errors over large areas and across several factors produces inaccurate estimates.

Published forage production estimates in USDA soil survey reports (i.e., SSURGO) or Ecological Site Descriptions[25] are considered more reliable than individual clipping data, as estimates were produced through intensive field sampling.[26] Annual production estimates are described for years with above average, average, and below average precipitation (Table 2), capturing some temporal variability. These data are currently used for grazing plans on private and public lands. Two disadvantages of the SSURGO-based estimates of annual production are that 1) they do not seamlessly cover the contiguous United States (e.g., coverage is especially sporadic on U.S. Forest Service lands), and 2) they do not provide yearly estimates. Another consideration is that most of the data collected to represent annual production tends to be from areas with good to excellent rangeland condition. Hence, these estimates provide minimal guidance for representing forage production on degraded landscapes or in areas dominated by invasive species. Further, these are historical data and will not reflect impacts of recent land use decisions or those of a changing climate.

Available Forage and Harvest Coefficient

The stocking rate calculation (shown in Eq. (1)) includes the portion of ANPP that is considered acceptable or available for grazing. This reflects how much of the annual range production managers want to allocate to domestic livestock. To make this decision, range managers must consider that biomass needs to be left unconsumed to protect the soil and to maintain plant community function, and to provide forage for herbivores other than domestic livestock (i.e., insects, ungulates, rodents, etc.).

The portion of ANPP available for domestic livestock has been described using a variety of terms in the literature and in practice (see Terminology).[27–29] We use the term harvest coefficient" (HC) because this communicates the intent and actual use of this value, which is a calculation factor used to plan grazing by selecting the proportion of forage to make

Table 2. Summary of accessible datasets to quantify factors affecting calculations of stocking rates and other grazing management metrics.

Factor	Data source	Frequency of update	Spatial resolution (pixel size, in meters)	Spatial coverage	Key references
ANPP and/or ANPP-based estimates of annual forage production	SSURGO (range production)	Unspecified	N/A	Agricultural lands	NRCS SSURGO[25] https://websoilsurvey.nrcs.usda.gov/
	MODIS (Annual NPP)	Annual	1,000 or 30	Contiguous United States, Alaska, and Hawaii	Running et al. 2004[43]
	RPMS (range production)	Annual/weekly	250 or 30	Contiguous US rangelands	Reeves et al. 2020[45] https://www.fuelcast.net/
	Rangeland Analysis Platform (RAP) (NPP – planned)	Annual/weekly	30	Contiguous US	Robinson et al. 2018[47]
Vegetation composition	LANDFIRE (EVT)	Biannual	30	Contiguous US, Alaska, and Hawaii	Rollins 2009[51] https://www.landfire.gov/vegetation.php
Vegetation structure and cover	LANDFIRE (EVH and EVC)	Biannual	30	Contiguous US, Alaska, and Hawaii	Rollins 2009[51] https://www.landfire.gov/vegetation.php
	USGS (cover of functional groups)	Annual	30	Western states	Rigge et al. 2020[54] https://www.mrlc.gov/rangeland-viewer
	RAP (cover of functional groups)	Annual	30	Western states	Jones et al. 2018[39] https://rangelands.app/
Future conditions (simulated)	MC2 (ANPP; cover of functional groups; potential vegetation type)	Annual (future projections)	4,000	Contiguous US, Alaska, and Hawaii	Kim et al. 2018[65]
Streams and water bodies (from which distance from water can be calculated)	USGS (streams)	Unspecified	N/A (based on 1:100,000-scale data: USGS acknowledges many users require higher resolution)	Contiguous US, Alaska, and Hawaii	USGS 1999[66]
Slope, Aspect, Elevation	Digital Elevation Model (DEM) (slope and aspect are derived from DEM data)	Static (one time)	30 or 10	Contiguous US, Alaska, and Hawaii	Rollins 2009[51] https://www.landfire.gov/topographic.php

Note. Datasets included are focused on data that could be included in a decision support tool for sustainable grazing management.
ANPP indicates aboveground net primary productivity; EVC, Existing Vegetation Cover; EVH, Existing Vegetation Height; EVT, Existing Vegetation Type; MODIS, Moderate Resolution Imaging Spectroradiometer; NPP, net primary production; NRCS, Natural Resources Conservation Service; RPMS, Rangeland Productivity Monitoring System; USGS, United States Geological Survey.

available to livestock.[30] This calculation may differ from what is then used by livestock, especially if ANPP varies across the landscape.

Relatively few resources exist to help managers determine what HC to use. Holechek[31] is the main resource for determining an appropriate HC in the United States, though consistent values are available in Australian systems.[32] Holechek[31] does not use the term harvest coefficient," but he discusses the concept and provides suggested values (updated in 2011[30]) that represent a synthesis of grazing studies in various rangelands.[27,30,31] For semiarid plant communities dominated by perennials, a harvest coefficient of 25% to 35% is suggested, which is considered to represent a conservative to moderate stocking rate and sustainable grazing pressure. For annual grasslands and more mesic rangelands, such as mixed prairie, 40% to 50% is recommended. This HC range allows both forage species and livestock to maximize their productivity, allows for error in forage production estimates, greatly reduces problems from buying and selling livestock, reduces the risk of financial ruin during drought years, and promotes multiple use values."[27]

Terrain Use

Terrain use incorporates several factors for determining the amount of landscape livestock will actually graze. Portions of a management unit may be physically inaccessible to grazing livestock, and other portions may be accessible, but the livestock will not graze because of a lack of water within a reasonable distance (3.2 km [2 miles] is commonly used, though this distance can vary due to multiple factors, and is not easily measured[31,33]). Terrain use depends on multiple factors that interact to influence animal movement. Certain aspects of terrain use are unchangeable, and others can be altered through management:

- Slope.[34] Livestock typically use steep slopes less than gentle terrain. The use of various slopes can be specific to a group of animals for a specific reason,[31] and can be incorporated into custom calculations.[33]
- Distance from water.[35] Livestock avoid areas that are far in distance or high in elevation from water.[33]
- Geographical features influence animal movement (e.g., cliffs, canyons, etc.).
- Moisture in forage plants.
- Air temperature.
- Characteristics of the grazing animals, including species (e.g., goats behave differently from cows),[30] age class of animal (e.g., cows will behave differently than yearlings), and breed and genetics. For example, terrain use based on distance from water is strongly related to cattle breed.[36]
- Size of individual animal (e.g., large animals are less likely to use steep slopes or travel long distances).

Some factors that determine terrain use may interact with spatial variations in forage production. Therefore, including detailed, spatially explicit estimates of terrain use can help provide an accurate estimate of forage availability across the landscape. Millward et al.[33] provide guidance for incorporating measured livestock distribution data into terrain use models and stocking rate calculations.

Opportunities in the Digital Age

Two aspects of the digital age pose opportunities for addressing the limitations in our current approaches for calculating and using stocking rates across large rangeland landscapes: data availability and online access. Existing research and practice supports the use of freely available remote sensing data to estimate ANPP and forage production,[37–40] however, these data exist at varying spatial (i.e., 10 m to 8 km [32.8 feet to 5.0 miles]) and temporal (daily to 16-day repeat cycles) resolutions. There is a trade-off between resolutions, with higher spatial resolution data having greater temporal cycles. Finer resolution instruments may be available (e.g., LiDAR platforms and drones), but our focus is on easy-to-use, freely available datasets that are suitable for regional applications, and in particular, those from which operational products have been derived (see the Relevant Data and Remaining Gaps section, below).

Though challenges remain in rural areas, the internet has generally become a dependable resource for decision-makers, producers, public entities, and the public. There is an increasing number and diversity of online tools that share and synthesize complex data with which users can interact to tailor data to their needs. We are unaware (as of September 2020) of any such synthesizing tools designed specifically to support grazing management decisions, though the potential and the technological infrastructure to develop them is available. We believe it is possible to provide free, near real-time, on-demand calculations of stocking rate and other key grazing management metrics across landscapes, at a spatial resolution of a few 30-m by 30-m pixels, to any landowner or manager, and we are pursuing opportunities to do that.

The science and technological infrastructure already exists for short-term (i.e., within a grazing season) forecasting of ANPP and forage production (e.g., the Rangeland Productivity Monitoring System [RPMS], see Table 2) to project stocking rate and other grazing management calculations for the near term. Vegetation simulation models like MC2[41] enable longer term (i.e., decadal) projections of ANPP on rangelands in response to climate change scenarios.[17,42]

Relevant Data and Remaining Gaps

In traditional stocking rate calculations, annual forage production is considered a known quantity and guidance is provided to calculate the amount of the annual forage production available to livestock within a grazing unit. We believe a decision support tool that allows landowners and land managers to overlay, synthesize, and use available spatial and temporal datasets (described in more detail below) is a critical step to more informed calculations of stocking rates and grazing management decisions.

Annual forage production—We are aware of two data sources that directly, consistently, and seamlessly estimate annual primary production for rangelands in the contiguous United States (Table 2). First, the xannual net primary production (NPP) product from the Moderate Resolution Imaging Spectroradiometer[43] is an annual data product that represents total annual production, including above and below-ground biomass since 2000. This data product is useful in scientific endeavors at continental and global scales, but the units (g carbon/m^2) and coarse spatial resolution (1 km pixels) limit its utility for planning initial stocking rates or other grazing management metrics.

Second, the RPMS[44,45] is a dataset that represents annual production for aboveground vegetation at 250 m^2 (2691 ft^2) resolution since 1984. This dataset is calibrated across tens of millions of acres of rangelands and represents total annual production of all plant life forms, and thus forage elements are combined with nonforage elements, which reinforces the need to use multiple data sources for estimating available forage. These data are presently being used for numerous applications including determining regional trends and detecting anomalies,[45] evaluating forage losses from drought to prioritize rehabilitation efforts,[46] and quantifying carrying capacity for wild horse and burro populations in the desert Southwest (Judith Dyess, USDA Forest Service, personal communications).

Additional datasets that quantify annual production on rangelands exist, though they are not yet publicly available. For example, Robinson et al.[47] developed a spatially explicit dataset describing annual production for most western US rangelands. Thes dataset has a long time frame (1984–2017) and relatively fine spatial resolution (30 m [98.4 feet]). Further, this dataset has been partitioned between herbs and shrubs, which may help interpret the full forage amount in a given region. The intent is to integrate this dataset into the online Rangeland Analysis Platform (Brady Allred, University of Montana, personal communications).

Some datasets provide weekly estimates, which could be used to estimate the seasonal dynamics of forage production (Table 2). Understanding the temporal dynamics of forage and how variable production timing is from year to year is important for range management. However, this dataset does not quantify the timing of critical phenological stages of key species, as satellite data is as yet unable to resolve species-specific differences. Further research is needed to calibrate remote sensing data over >30 years with specific, field-based information on the phenology of key species to track critical phenological stages when grazing should be avoided.

Vegetation composition and structure—There are no consistently produced geospatial data products describing species assemblages across US rangelands, due to limitations of remote sensing. Although low altitude imagery acquired with drones has been used on an experimental basis for mapping individual species,[48] drones cannot yet produce species assemblage maps consistently across the region. However, there are data products that target invasive species that exhibit distinct phenological patterns, especially cheatgrass (*Bromus tectorum* L.) and other invasive annual grasses.[49,50]

Although not providing detailed species assemblages, LANDFIRE is a data source that offers seamless descriptions of vegetation types for rangelands using a consistent vegetation classification. LANDFIRE[51] (Table 2) includes an Existing Vegetation Type dataset that describes the extent of US Ecological Systems[52] circa 2014 at 30 m spatial resolution and that is updated approximately every 2.5 years. These data contain production values for different native vegetation types. LANDFIRE also provides data products characterizing Existing Vegetation Height, which could be used to estimate vegetation structure.

An alternative to vegetation type in the assessment of forage production is the relative vegetative cover of perennial and annual herbs, shrubs, and bare ground. The Rangeland Analysis Platform[47] currently produces cover estimates of different functional groups for most US rangelands. The online platform provides annual estimates from 1984 to 2019 at 30 m resolution, enabling trend analysis over this timeframe. The Existing Vegetation Cover data product from LANDFIRE[51] provides an alternate source of vegetation cover data, and the US Geological Survey is also mapping cover of perennial and annual herbs, shrubs, and bare ground[53,54] at 30 m spatial resolution across the sagebrush biome. Currently these data are available online only for 2016.[55]

Future conditions—Increasing concern about climate change impacts on rangelands has provided impetus for new data, models, and applications. The MC2 Dynamic Global Vegetation Model[41] provides annual estimates of ecosystem variables based on future climate (using two emissions scenarios with 20 global climate models) and fire expectations, including annual net primary production and potential vegetation type at 4 km spatial resolution. These data can be used to infer attributes of forage quantity, quality, and seasonality (i.e., cool season versus warm season), and are being used in regional scale evaluations of grazing capacity,[42] forage production,[56] and rangeland vulnerability.[57]

Roadmap for supporting dynamic grazing management

Understanding patterns in forage production and timing across landscapes and from year to year is a necessary component of grazing plans and carrying capacity estimates. As we have discussed here, datasets exist for western US rangelands that provide annual (and even seasonal) estimates of forage production at fine resolution (Table 2). However, a tool that can do the following is needed:

1. Collects estimates of aboveground forage production and allows users to visualize its spatial patterns and temporal trends,

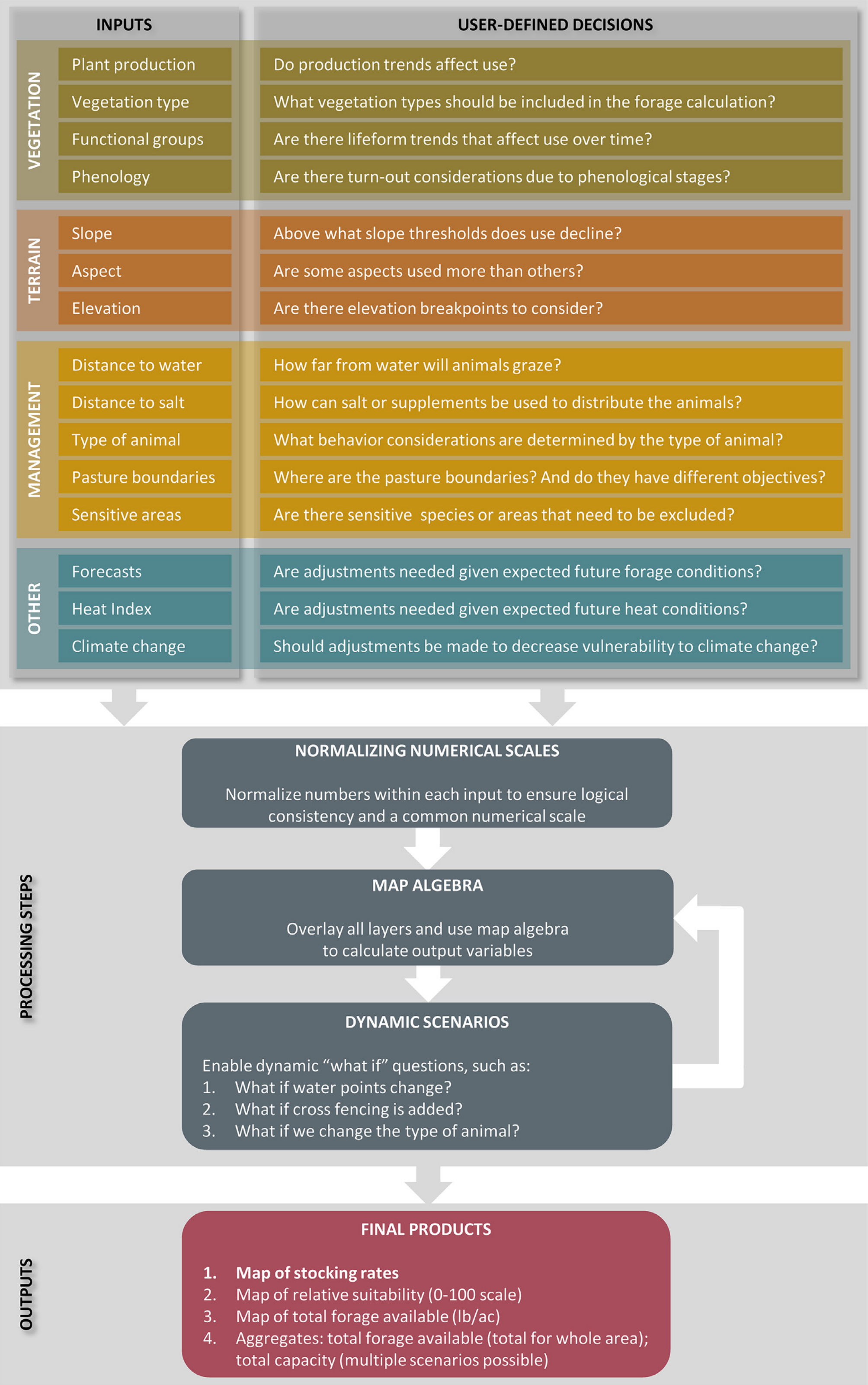

Figure 2. Flow chart characterizing our envisioned decision support tool to inform dynamic stocking rate decisions. Using existing remotely sensed vegetation data from 1984 to present (VEGETATION) allows the tool to include vegetation trends and interannual variability. The user could select these vegetation inputs, as well as terrain and management datasets, and other data that reflect additional considerations of the user (INPUTS). The user can also define parameters, thresholds, or other benchmarks and boundaries (USER-DEFINED DECISIONS). The tool, in a set of PROCESSING STEPS, would integrate the selected input datasets, adjusting the map algebra based on user-defined decisions to develop the final products (OUTPUTS). We envision this tool allowing users to run "what if" scenarios to explore the consequences of management changes or infrastructure investments, for example.

2. Allows users to spatially define the parameters for terrain use by livestock (e.g., slope, distance to water), harvest coefficient, and other non-stocking rate management factors, and
3. Combines these elements in the stocking rate equation, producing spatially explicit and aggregate values annually (e.g., 1984 to present).

Ultimately, we envision a tool that provides annual maps of stocking rates, how they vary between grazing management units, and how they have varied through time (Fig. 2). An advantage of using remotely sensed data as the foundation of such a tool is that reconstruction of the past 30 or more years is possible, which allows users to explore trends and patterns of variation from year to year. In addition, such a tool could use climate change projections to estimate future variation in forage production, the directional shift in average production in the future as the climate continues to change, and the impact that might have on future stocking rates.

Public and private decision support tools are becoming increasingly common strategies to provide timely information to agricultural sectors in complex situations.[58–61] Our envisioned tool could be developed by a private for-profit entity. However, the profitability required might mean the tool is only accessible to large operators able to pay for it. Developing this tool as a public and freely available service would therefore be beneficial, especially given the extent of public lands whose management could benefit from its use.

The decision support tool we envision could be beneficial from many perspectives. First, it could aid grazing management decisions and improve flexibility for producers and public land managers by utilizing the best available science and data, and by accounting for interannual variability. Second, the tool could improve accountability and transparency by providing public land managers with a platform to which all stakeholders could have free access, thereby increasing communication between managers and their constituents. In addition, with high turnover in the public land management workforce, institutional knowledge is not effectively passed on. Quantifying and mapping grazing capacity could help new managers more quickly become familiar with lands within their jurisdiction. Third, the tool could identify areas where forage supplies are mismatched with demand given the existing stressors rangelands experience today.

Lessons from past and current tool development efforts targeting resource management decision support are relevant for our proposed tool. First, users find decision support tools most relevant when combined into a decision support system that integrates multiple tools,[61] which can open up consistent communications for efficient transfer of model-based information that complements other relevant information (e.g., rangeland health information). Second, maintenance is essential to the long-term success of any decision support tool and should be considered at the outset. For public entities, funding agencies are generally eager to fund tool development, but less willing to fund the maintenance of a tool or system. This favors collaboration and centralized infrastructure to keep development and maintenance costs low over time.

Often existing successful decision support tools have relied on a combination of funding sources, including user fees, institutional support for public tools (e.g., from the hosting university or agency), and through ongoing expansion of existing decision support system by adding new tools.[58] We are not aware of systems that rely on selling advertising space, but this strategy may also hold promise. Private systems that rely mostly on user fees may have fewer concerns about maintenance but can limit the number and types of users who can access the information.

In conclusion, a dynamic stocking rate decision support tool is feasible given current data sources and technology and would be useful to grazing managers. This tool could improve resilience of landscapes by rapidly identifying conditions and areas within pastures or allotments where carrying capacity is declining, which may provide impetus for changes in management protocols for producers or public land managers. In essence, such a decision support tool could help ranchers and land managers better manage rangeland ecosystems with flexible stocking rates and adaptive grazing management opportunities that adjust to variations in ANPP, leading to increased regional and site-specific rangeland resilience.

Terminology

Our purpose in providing this glossary is to explicitly define how these terms are used in our paper. We make no attempt to comment on current scholarship regarding the appropriateness or shortcomings of the nomenclature or the concepts implicit in the terms.

Aboveground Net Primary Production (ANPP)
Portion of net increase in plant biomass within a specified area and time interval (i.e., primary production minus that used in metabolic processes) that is allocated to aboveground tissues (leaves, stems, flowers, seeds, etc.).[62] Technically the units of ANPP are unit of weight per unit of area per unit time (e.g., pounds per acre per year); however, this is sometimes simplified to unit of weight per unit of area (e.g., pounds per acre). ANPP represents, therefore, the total annual growth of all plants on a rangeland site, which is usually synonymous with range production[26] (defined below).

Carrying Capacity
The average number of livestock and/or wildlife that may be sustained on a management unit compatible with management objectives for the unit.[62] Carrying capacity is quantified as the long-term, sustained ratio of area to animals (e.g., acres per animal) that permits stable or improving rangeland

health. We consider carrying capacity a characteristic of the grazing management unit, and stocking rate (defined below) is the metric on which a grazing manager decides and implements.

Forage Production
The weight of forage that is produced within a designated period of time on a given area. The term may also be modified as to time of production, such as annual, current year's, or seasonal forage production.[62] The weight can be expressed differently. We consider forage production to be air-dried weight unless otherwise noted. Forage production is specific to that portion of range production (defined below) that is edible and palatable to grazing animals.

Grazing Capacity
The maximum stocking rate possible year after year without causing damage to vegetation of related resources.[62]

Grazing Management
The manipulation of animal grazing in pursuit of a defined objective.[62] We use the term to refer to all actions taken to control or influence animals' use of the landscape, including actions affecting the timing and pattern of resource use, as well as the front-end decision of amount of land to allocate to a specific number of animals (the stocking rate, defined below).

Harvest Coefficient (HC)
The percentage of total forage produced that is assigned to grazing animals for consumption.[27] This concept has also been called percent key species use,[31] proper use factor, degree of use, and harvest efficiency.[28] A broader definition has been associated with the term harvest coefficient.[29]

Range Production
The amount of vegetation that can be expected to grow annually in a well-managed area that is supporting the potential natural plant community. It includes all vegetation, whether or not it is palatable to grazing animals. It includes the current year's growth of leaves, twigs, and fruits of woody plants. It does not include the increase in stem diameter of trees and shrubs.[63]

Stocking Rate
The relationship between the number of animals and the grazing management unit utilized over a specified time period. This term may be expressed as animal units per unit of land area (animal units over a described time period and area of land).[62] Stocking rate may be more or less than the carrying capacity of the grazing management unit. We use stocking rate as the metric on which a grazing manager decides and implements, and carrying capacity is considered a characteristic of the grazing management unit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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