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Annual and 16-Day Rangeland Production Estimates for the Western United States☆

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A B S T R A C T

Rangeland production is a foundational ecosystem service and resource on which livestock, wildlife, and people depend. Capitalizing on recent advancements in the use of remote sensing data across rangelands, we provide estimates of herbaceous rangeland production from 1986 to 2019 at 16-d and annual time steps and 30-m resolution across the western United States. A factorial comparison of this dataset and three national scale datasets is presented, and we highlight a multiple-lines-of-evidence approach when using production estimates in decision making. Herbaceous aboveground biomass at this scale and resolution provides critical information applicable for management and decision making, particularly in the face of annual grass invasion and woody encroachment of rangeland systems. These readily available data remove analytical and technological barriers allowing immediate utilization for monitoring and management.

Introduction

Rangeland production—specifically herbaceous aboveground biomass–is a foundational ecosystem service upon which livestock, wildlife, and people depend. Estimates of production have long been available via field-based measurements, but such estimates are geographically and temporally limited. Although statistical sampling techniques employed by national monitoring programs (MacKinnon et al. 2011; Herrick et al. 2017) provide means to monitor production across rangelands, such techniques and programs do not capture temporal variability or spatial heterogeneity at scales relevant to management and decision making (e.g., within or across management units), with limited field-based plots often extrapolated to ecoregion scales (Karl et al. 2016). Satellite and airborne remote sensing methods (Smith et al. 2019) informed by field-based data can provide spatially contiguous and temporally continuous estimates of rangeland production. Methodologies often use empirical relationships between remote sensing indices (e.g., normalized difference vegetation index; NDVI) or terrestrial lidar retrievals and measured or estimated biomass from field plots to map production. This methodology is most often applied at local or regional spatial scales (Jansen et al. 2018) but has also been successfully implemented at broad national scales (Reeves et al. 2020).

Vegetation production may also be estimated using remotely sensed data in process-based models, such as a light-use efficiency model (Monteith 1972) that calculates gross or net primary production (GPP and NPP, respectively) based on remotely sensed estimates of absorbed photosynthetically active radiation, the biophysical properties of vegetation types, and water and temperature constraints. These GPP and NPP models are prolific (Running et al. 2004; Clark et al. 2011), but the common units of carbon (i.e., g C m^{-2} yr^{-1}) are not relevant to rangeland managers or practitioners. These models also require land cover data, which until recently were categorical at the pixel scale for US rangelands and produced

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at 5-yr time steps (Homer et al. 2015). Models could therefore not account for within-pixel heterogeneity of rangeland plant functional types (PFT) (e.g., annual grasses and forbs, perennial grasses and forbs, shrubs, or trees) or PFT variation in phenology and productivity (Browning et al. 2019). Accounting for this heterogeneity is especially critical considering the prominence of large-scale woody encroachment and annual grass invasion into rangeland systems (Jones et al. 2020). Continuous land cover datasets at annual time steps are now available (Rigge et al. 2020; Allred et al. 2021), allowing models to quantify changes in production in response to encroachment and invasion at temporal intervals relevant to management.

This technical note details the development of annual and 16-d rangeland herbaceous production estimates partitioned to perennial grasses/forbs and annual grasses/forbs across western US rangelands. The data are easily accessible, account for within-pixel vegetation PFT heterogeneity, and are provided at temporal and spatial resolutions (and units) relevant to management. We perform a factorial comparison of this new production dataset and three national-scale datasets. We highlight the value of using all data in a “multiple-lines-of-evidence” approach when implementing production estimates, where incorporating data derived from different methods into a decision-making process can spur greater data acceptance and application and advance conservation of this valuable rangeland resource.

Methods

Net primary production partitioning

Detailed descriptions of the method used to calculate NPP by PFT are provided in Robinson et al. (2019); we provide an overview here. We produced spatially contiguous 16-d Landsat NDVI composites (Robinson et al. 2017) using Landsat 5 TM, 7 ETM+, and 8 OLI surface reflectance (Vermote et al. 2016) from 1986 to 2019 across western US rangelands (Reeves and Mitchell 2011). Using the 16-d NDVI and a PFT cover dataset (Allred et al. 2021), we disaggregated pixel-level NDVI using linear mixing theory to its subpixel PFT components. In brief, the NDVI of a mixed pixel is disaggregated to the PFTs present in the pixel, weighted by their fractional cover and the ecoregion-scale phenology of each PFT; the mean of the PFT specific NDVI values equate to the mixed pixel NDVI. To capture and incorporate the geographically specific PFT NDVI phenological characteristics, we built an overdetermined set of linear equations (Robinson et al. 2019) to solve for each PFT NDVI value within US EPA Level IV regions (Omernik and Griffith 2014). The result is PFT NDVI estimations that capture NDVI amplitudes and regional PFT phenology. We reprojected and bilinearly resampled all Landsat imagery to a geographic coordinate system of approximately 30-m resolution before manipulation.

The PFT-specific NDVI values are then used in the MOD17 NPP model adapted for Landsat (Robinson et al. 2018). Using linear interpolation, we calculated daily NDVI values between each 16-d composite. We then calculated daily NPP for each PFT present in the pixel using daily PFT NDVI values, daily GRIDMET meteorology (Abatzoglou 2013), and specific PFT’s biophysical properties (Robinson et al. 2018). We multiplied NPP estimates by the PFT fractional cover estimates, resulting in total grams of carbon assimilated per PFT per pixel per d (g C m^{-2} d^{-1}). Daily values are summed to 16-d values (g C m^{-2} 16 d^{-1}) and to annual values (g C m^{-2} yr^{-1}).

NPP conversion to herbaceous aboveground biomass

The herbaceous NPP, partitioned to perennial grasses/forbs and annual grasses/forbs, is allocated to aboveground (ANPP) pools using these equations:

$$\mathrm{fANPP} = 0.129 \cdot \mathrm{MAT} + 0.171 \quad (1)$$

$$\mathrm{ANPP} = \mathrm{fANPP} \cdot \mathrm{NPP} \quad (2)$$

where *fANPP* is the fraction partitioned to ANPP and *MAT* is mean annual temperature (Hui and Jackson 2006). We convert ANPP (g C m^{-2} 16 d^{-1}) to biomass (kg ha^{-1} or lb $acre^{-1}$) using the pixel area and a 47.5% carbon content of vegetation estimate (Eggleston et al. 2006); the midpoint of a 45−50% carbon to dry matter estimation range (Schlesinger 2013).

Comparisons

We calculated Pearson correlation coefficients between the herbaceous aboveground biomass (HAGB) estimates and 16 591 Natural Resources Conservation Service (NRCS) National Resources Inventory (NRI) plot-level estimates of herbaceous biomass collected on rangelands from 2004 to 2018 (NRCS, USDA 2015). The HAGB estimate corresponding to each plot was sampled from the same year as the plot measurement.

We also compared HAGB estimates to US Forest Service Rangeland Production Monitoring Service (RPMS) data, provided annually from 1984 to 2018 at 250-m resolution (Reeves et al. 2020), and to the gridded Soil Survey Geographic (gSSURGO) database, which provides fixed estimates of unfavorable, normal, and favorable annual range potential production by soil survey units at 30-m resolution (Soil Survey Staff 2017). The RPMS and gSSURGO data estimate total rangeland productivity (not solely herbaceous) but are used here as the only available gridded productivity datasets that are specific to western US rangeland systems and cover a similar time period. To account for temporal variability, we compared the 50th percentile of the two temporally dynamic datasets using yr 2000−2018 and the gSSURGO “normal” data. We calculated Pearson correlation coefficients using a subsample (5 000 random rangeland locations) of each of the three datasets (RAP HAGB 50th percentile, RPMS 50th percentile, gSSURGO normal). For all comparisons we only included rangelands identified by Reeves and Mitchell (2011) inclusive of afforested, pasture, and barren categories. We also calculated the difference between the gridded HAGB, RPMS, and gSSURGO estimates and the plot level NRI herbaceous biomass estimates; scatterplots, correlations, and the geographic distribution of those differences are provided in supplemental information.

Results

Herbaceous aboveground biomass

Estimates of HAGB at 30-m resolution are provided annually (Fig. 1a−c) from 1986 to 2019 and as accumulating HAGB at 16-d intervals (see Fig. 1d). The HAGB is partitioned into perennial grasses/forbs and annual grasses/forbs and accounts for variation in pixel-scale fractional cover at annual time steps (Allred et al. 2021) and the phenology of each PFT. The data are accessible for viewing and analysis via a publicly available online application, the Rangeland Analysis Platform (https://rangelands.app/).

Data comparisons

The HAGB data available via the Rangeland Analysis Platform (hereafter RAP HAGB) are well correlated ($r = 0.63$) with 16 591 NRI plot-level herbaceous biomass estimates (Fig. 2). We sub-

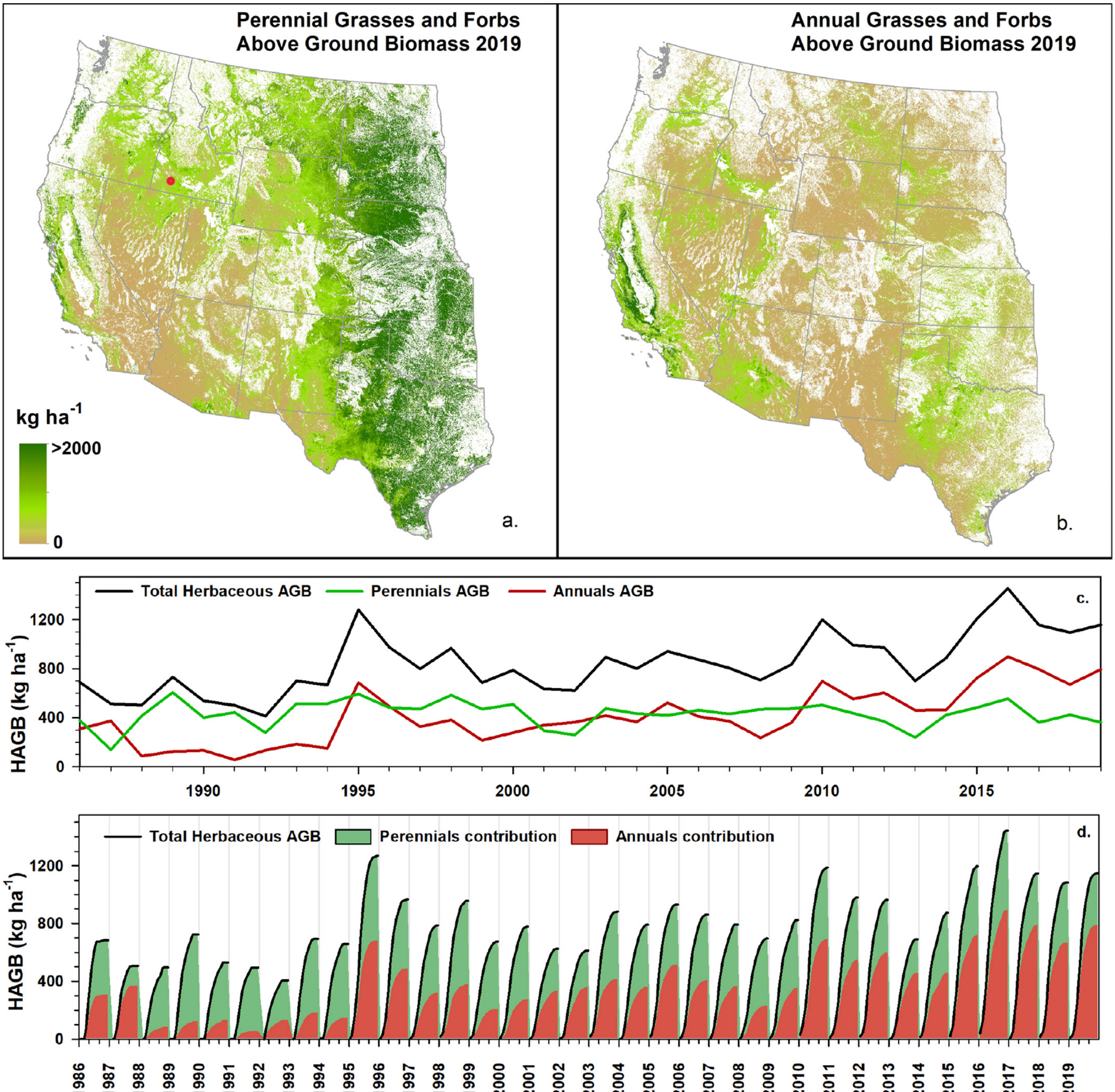

Fig. 1. Herbaceous aboveground biomass (HAGB) at 30-m resolution across western US rangelands available via the Rangeland Analysis Platform (https://rangelands.app/). Total annual 2019 HAGB partitioned to (**a**) perennial grasses and forbs and (**b**) annual grasses and forbs. **c,** Total yearly HAGB and portions attributable to perennials and annuals for a Bureau of Land Management grazing allotment in southwest Idaho (red point in **a**) from 1986 to 2019. **d,** For the same grazing allotment, 16-d accumulating total HAGB and partitioned contributions from perennial and annual grasses/forbs for 1986–2019.

tracted the RPMS 50th percentile and gSSURGO "normal" gridded data from the RAP HAGB 50th percentile (as well as the gSSURGO from RPMS), which provided the geospatial distribution of differences between the products. Mapped differences (Fig. 3a–c) and scatterplots of 5 000 randomly sampled rangeland locations (see Fig. 3d–f) display strong agreement as indicated by Pearson correlation coefficients. At lower biomass levels ($< \sim 1\ 500$ kg ha^{-1}) the RAP HAGB 50th percentile is well aligned with the RPMS HAGB 50th percentile (see Fig. 3d) and the gSSURGO normal (see Fig. 3e). The RAP HAGB displays generally lower estimates than the other two data sets at higher biomass levels while RPMS and gSSURGO are more evenly distributed along the 1:1 line (see Fig. 3f). These distributions are expected as RPMS and gSSURGO provide total production estimates while the RAP HAGB is herbaceous production only. Geographic distribution of the differences between the NRI herbaceous biomass estimates and the gridded HAGB, RPMS, and gSSURGO estimates (see supplemental article and **Fig. S1,** available online at doi:10.1016/j.rama.2021.04.003) demonstrate general agreement across the western United States with greater differences apparent in the southern Great Plains.

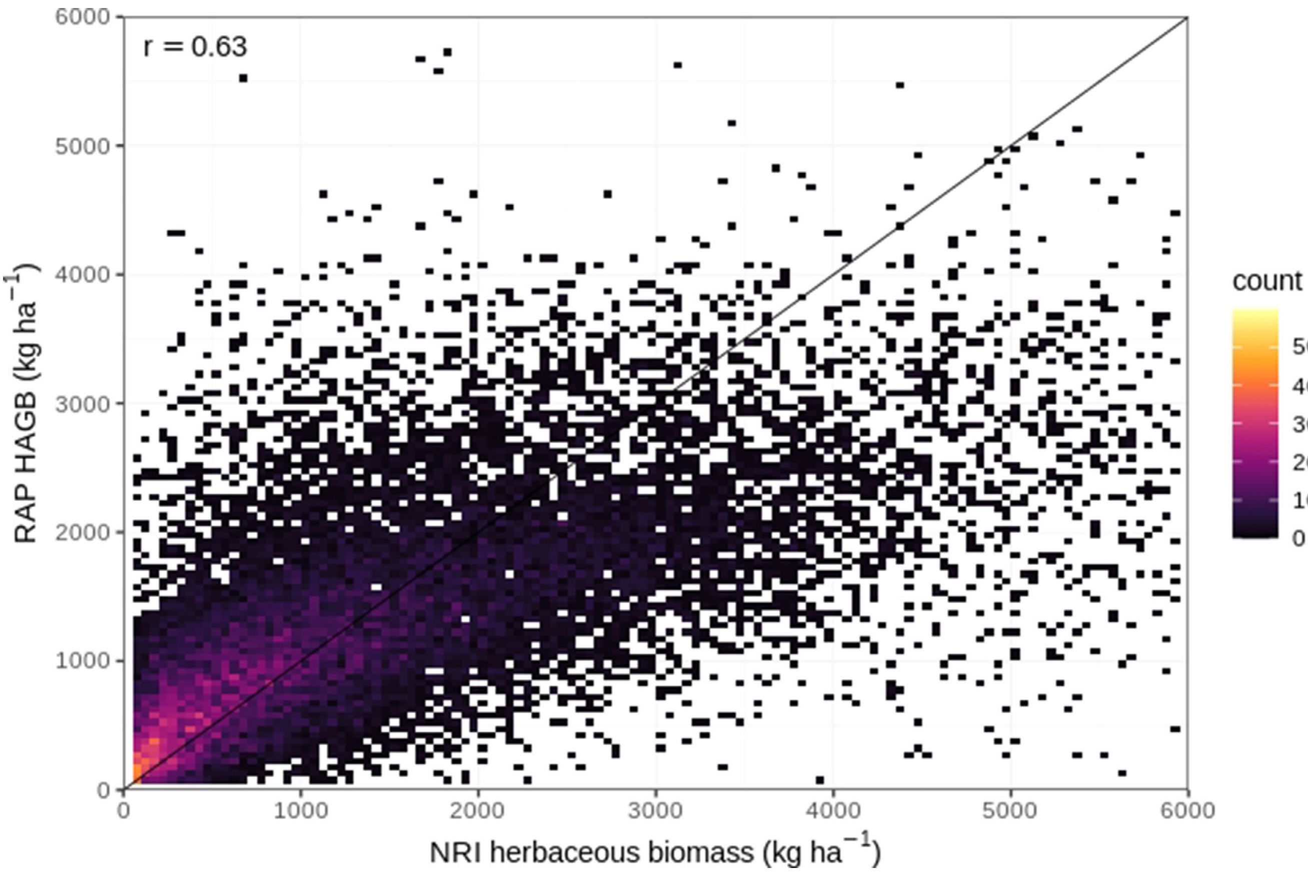

Fig. 2. Density scatterplot (bin width 50 kg ha^{-1}) of Rangeland Analysis Platform *(RAP)* herbaceous aboveground biomass *(HAGB)* and 16 591 National Resources Inventory *(NRI)* plot-level biomass estimates, 1:1 line (black), and Pearson correlation coefficient ($r = 0.63$). NRI biomass estimates > 6 000 kg ha^{-1} are not displayed.

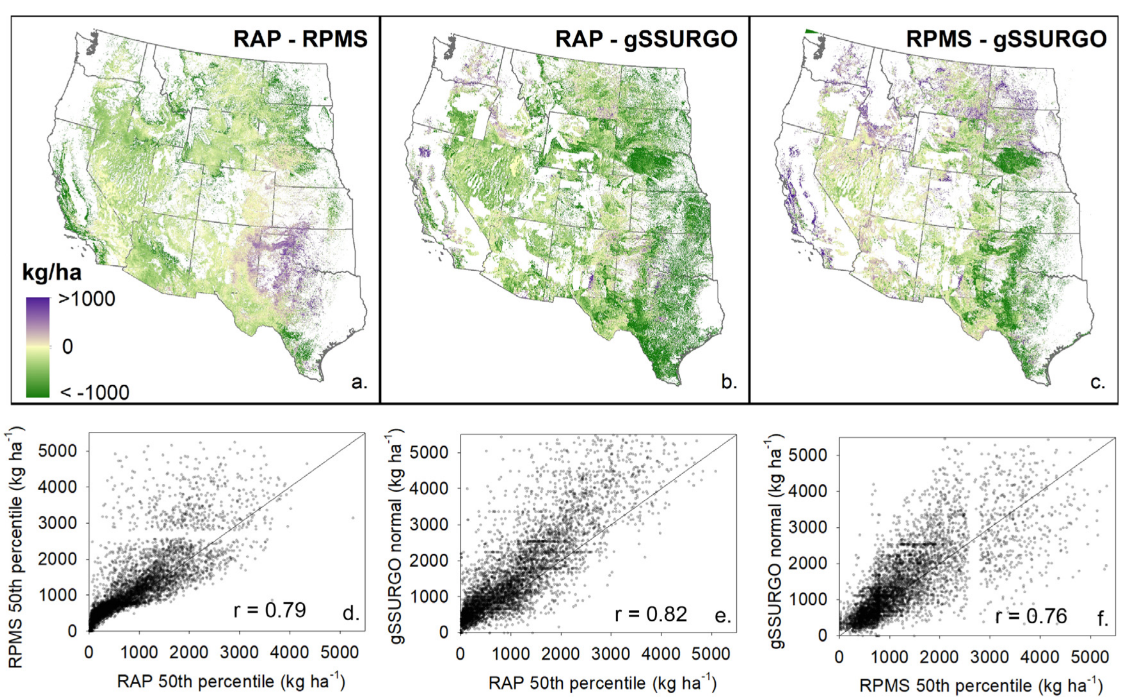

Fig. 3. Differences (**a–c**) between three gridded production datasets across western US rangelands using the 50th percentile of annual values (2000–2018) from Rangeland Analysis Platform *(RAP)* and Rangeland Production Monitoring Service *(RPMS)* data and "normal" values from gSSURGO. Scatterplots and Pearson correlation coefficients (**d–f**) of production values sampled from each data set for 5 000 randomly selected rangeland locations.

Discussion

Estimates of rangeland production—specifically herbaceous aboveground biomass or forage—are now available annually and at 16-d intervals from 1986 to 2019 at 30-m resolution across the western United States and represent five advancements specifically relevant to management. These data are 1) provided in units recognized by and applicable to management (i.e., kg ha^{-1} or lb acre^{-1}); 2) produced at temporal fidelities applicable to monitoring the effects of climate, disturbance, management, and other factors; 3) calculated at a spatial resolution (30 m) that allows for assessment of variability both within and across management units; 4) are easily accessible where monitoring, analysis, and interpretation can be achieved without the need for specialized technical knowledge or skills; and 5) account for annual pixel-scale changes in PFT composition (e.g., annual grasses or trees encroaching rangelands) and the relative contributions of annual forbs and grasses and perennial forbs and grasses to total herbaceous biomass. The availability of these data and other rangeland wide vegetation data (Pastick et al., 2020; Reeves et al. 2020; Rigge et al. 2020) has ushered in a new era where rangeland mapping from national to management scales is now a working reality (Jones et al. 2020).

These herbaceous biomass data provide land managers, practitioners, and decision makers novel, temporally continuous, and spatially contiguous data for enhanced rangeland management. These data can be paired with local knowledge and information to better inform management strategies at the scale of a grazing allotment or pasture. At larger scales, these biomass data shed light on persistent ecosystem threats like invasive annual grasses (Jones et al. 2020) that are contributing to the continual rise of annual grass/forb biomass on western rangelands (Fusco et al. 2019; see Fig. 1). Differences in forage quality and phenology between annuals and perennials also have important implications for rangeland functions including accelerated wildfire return intervals (Pilliod et al. 2017). These represent only a few of the many potential scenarios where such data can provide greater insight and better inform management of grazing, wildlife, fuel, and fire, as well as assessing outcomes of management practices.

This technical note does not present a traditional validation of these new RAP HAGB data due to the lack of plot-level HAGB data at the scope and scale of the data product. While NRI plot-level data do include *some* destructive sampling (i.e., clipping, drying, and weighing), the methods also incorporate subjective estimations and correction factors. Also, the model used to estimate RAP HAGB is process based and not empirical—it does not incorporate biomass field plots at any step. We therefore examine "multiple lines of evidence" and factorially compare the four available broad-scale data sets of rangeland production. This method demonstrates a best-practices approach when using these types of data in a decision-making framework; use all data sources, examine their similarities and discrepancies, and incorporate local knowledge to best inform a data-driven decision.

Implications

The temporally dynamic herbaceous aboveground biomass data represent a culmination of advancements in using remote sensing data to monitor rangelands more effectively and efficiently. The new geospatial datasets of rangeland production provide land managers and decision makers spatially contiguous and temporally relevant data to monitor rangeland forage, conduct meaningful comparisons of management outcomes using common data, and examine within-season variability of forage to better assess management actions. The readily available data (RAP, https://rangelands.app/; RPMS, https://www.fuelcast.net/) remove analytical and technological barriers, allowing for immediate utilization. Never before have so much data been directly available and applicable to rangeland management. We anticipate and look forward to new applications, analyses, discoveries, and innovations with these data that improve our understanding and management of rangelands.

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.

Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2021.04.003.

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