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Caleb P. Roberts

David E. Naugle

Brady W. Allred

Victoria M. Donovan

Dillon T. Fogarty

See next page for additional authors

Authors

Caleb P. Roberts, David E. Naugle, Brady W. Allred, Victoria M. Donovan, Dillon T. Fogarty, Matthew O. Jones, Jeremy D. Maestas, Andrew C. Olsen, and Dirac L. Twidwell Jr

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Research article

Next-generation technologies unlock new possibilities to track rangeland productivity and quantify multi-scale conservation outcomes

Caleb P. Roberts[a,*], David E. Naugle[b], Brady W. Allred[b], Victoria M. Donovan[c], Dillon T. Fogarty[c], Matthew O. Jones[b], Jeremy D. Maestas[d], Andrew C. Olsen[e], Dirac Twidwell[c]

[a] *U.S. Geological Survey, Arkansas Fish and Wildlife Cooperative Research Unit, University of Arkansas, SCEN 522, Fayetteville, AR, 72701, USA*
[b] *WA Franke College of Forestry and Conservation, University of Montana, USA*
[c] *Agronomy & Horticulture, University of Nebraska-Lincoln, NE, USA*
[d] *USDA Natural Resources Conservation Service, OR, USA*
[e] *Intermountain West Joint Venture, MT, USA*

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ABSTRACT

Historically, relying on plot-level inventories impeded our ability to quantify large-scale change in plant biomass, a key indicator of conservation practice outcomes in rangeland systems. Recent technological advances enable assessment at scales appropriate to inform management by providing spatially comprehensive estimates of productivity that are partitioned by plant functional group across all contiguous US rangelands. We partnered with the Sage Grouse and Lesser Prairie-Chicken Initiatives and the Nebraska Natural Legacy Project to demonstrate the ability of these new datasets to quantify multi-scale changes and heterogeneity in plant biomass following mechanical tree removal, prescribed fire, and prescribed grazing. In Oregon's sagebrush steppe, for example, juniper tree removal resulted in a 21% increase in one pasture's productivity and an 18% decline in another. In Nebraska's Loess Canyons, perennial grass productivity initially declined 80% at sites invaded by trees that were prescriptively burned, but then fully recovered post-fire, representing a 492% increase from nadir. In Kansas' Shortgrass Prairie, plant biomass increased 4-fold (966,809 kg/ha) in pastures that were prescriptively grazed, with gains highly dependent upon precipitation as evidenced by sensitivity of remotely sensed estimates (SD ± 951,308 kg/ha). Our results emphasize that next-generation remote sensing datasets empower land managers to move beyond simplistic control versus treatment study designs to explore nuances in plant biomass in unprecedented ways. The products of new remote sensing technologies also accelerate adaptive management and help communicate wildlife and livestock forage benefits from management to diverse stakeholders.

1. Introduction

In working rangelands, herbaceous plant above ground biomass (hereafter 'plant biomass') is a key ecosystem service that benefits people and wildlife (Kremen and Merenlender, 2018; Naugle et al., 2019). Plant biomass sustains rural economies as forage for domestic livestock, and conservation practices that increase plant biomass, such as prescribed fire, prescribed grazing, and mechanical tree removal, increase abundance and habitat quality of iconic threatened species like Sage-Grouse (*Centrocercus* sp.), Prairie-Chicken (*Tympanuchus* sp.), and American Burying Beetle (*Nicrophorus americanus*) (Walker Jr and Hoback, 2007; Hagen et al., 2013; Lautenbach et al., 2017; Severson et al., 2017; Ludwig et al., 2021; Olsen et al., 2021; Sullins et al., 2021). These wide-ranging benefits allow plant biomass to serve as a rallying point for creating a shared vision among conservationists, private landowners, and public land management agencies that has potential to restore entire biomes (Burger et al., 2019; Naugle et al., 2020; NRCS, 2021a, 2021b, 2021).

But to be a rallying point, plant biomass responses to conservation practices must be quantified accurately, transparently, and at relevant

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* Corresponding author. U.S. Geological Survey, Arkansas Fish and Wildlife Cooperative Research Unit, University of Arkansas, SCEN 522, Fayetteville, AR, 72701, USA.

E-mail address: cr065@uark.edu (C.P. Roberts).

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scales. Historically, this has been challenging due to two primary constraints. First, geospatial data have been unable to capture fine-scale heterogeneity in plant biomass (Fuhlendorf et al., 2017; Bielski et al., 2018). Second, geospatial data on plant biomass have lacked the precision and geospatial extent to track responses to on-the-ground treatments of the most commonly used conservation investments in grasslands (e.g., grazing, fire, and tree removal; Archer and Predick, 2014; Karl et al., 2017). Because of these constraints, consistently quantifying management outcomes in terms of plant biomass has been infeasible due to the cost of field-based sampling across millions of hectares (Natural Resources Council, 1994), meaning outcomes assessments relied on extrapolations from very limited field sampling (West, 2003). This constrained inference and forced assumptions of scale invariance in management outcomes (Levin, 1992; Archer et al., 2017; Briske et al., 2017).

Built from decades of basic research on quantifying vegetative above ground productivity (Knapp and Smith, 2001; Running et al., 2000), new technologies now allow conservation practice outcomes to be quantified via plant biomass at unprecedented scales (Zhou et al., 2017; Jones et al., 2020; Reeves, 2020; Allred et al., 2021). New datasets like the Rangeland Analysis Platform provide plant above ground biomass data partitioned by functional group (e.g., perennial forb and grass, annual forb and grass) at fine spatial resolutions that are updated annually and cover the entirety of the contiguous United States (Jones et al., 2018; Robinson et al., 2019; Jones et al., 2021). As a result, outcomes relevant to working lands conservation, such as plant biomass, now have the potential to be tracked at scales from 30 × 30 m pixels to biomes, across years and decades. However, it remains unclear if these technologies can capture heterogeneity in plant biomass responses to conservation practices at conservation-relevant scales.

Here, our objective is to test the ability of new technologies to capture heterogeneity in plant biomass and to quantify multi-scale plant biomass outcomes of prescribed grazing, mechanical tree removal, and prescribed fire in space and time. To accomplish this, we partnered with three working lands conservation initiatives—the Sage Grouse Initiative, the Lesser Prairie-Chicken Initiative, and the Nebraska Natural Legacy Project—to obtain confidential private lands conservation practice history data in three conservation priority landscapes. Each of these landscapes in the United States supports an iconic threatened rangeland species: lesser prairie-chickens in the Lesser Prairie-Chicken Initiative's Shortgrass Prairie Focal Area in Kansas, sage-grouse in Sage Grouse Initiative's Warner Mountains Priority Area in Oregon, and the imperiled American burying beetle in Nebraska Natural Legacy Project's Loess Canyons Experimental Fire Landscape in Nebraska (Fig. 1). Each of these landscapes also focuses on a particular conservation practice to restore plant biomass and their vulnerable species: prescribed grazing in the Shortgrass Prairie, mechanical tree removal in the Warner Mountains, and prescribed fire in the Loess Canyons (Fig. 1). With conservation practice history data, we assessed spatial and temporal trends in plant biomass before and after conservation practices were implemented. Because our objective here is to test new technology's ability to capture heterogeneity—not to assess efficacy of particular conservation practices—we purposefully searched for variation and divergent responses in plant biomass.

2. Methods

2.1. *Study site*

2.1.1. *Warner Mountains*

The 265,129-ha Warner Mountains Priority Area (hereafter 'Warner Mountains') is in Lake County, Oregon, USA (Fig. 1). The Warner Mountains contain some of the most productive sagebrush steppe habitat and highest densities of Greater Sage-grouse in Oregon. Elevation ranges from 1,200 to 2,200 m, with a mean of 1,700 m.

Mechanical tree removal is the primary conservation practice managers use to restore plant biomass and combat woody encroachment in the Warner Mountains (Fig. 1). Western juniper (*Juniperus occidentalis*)

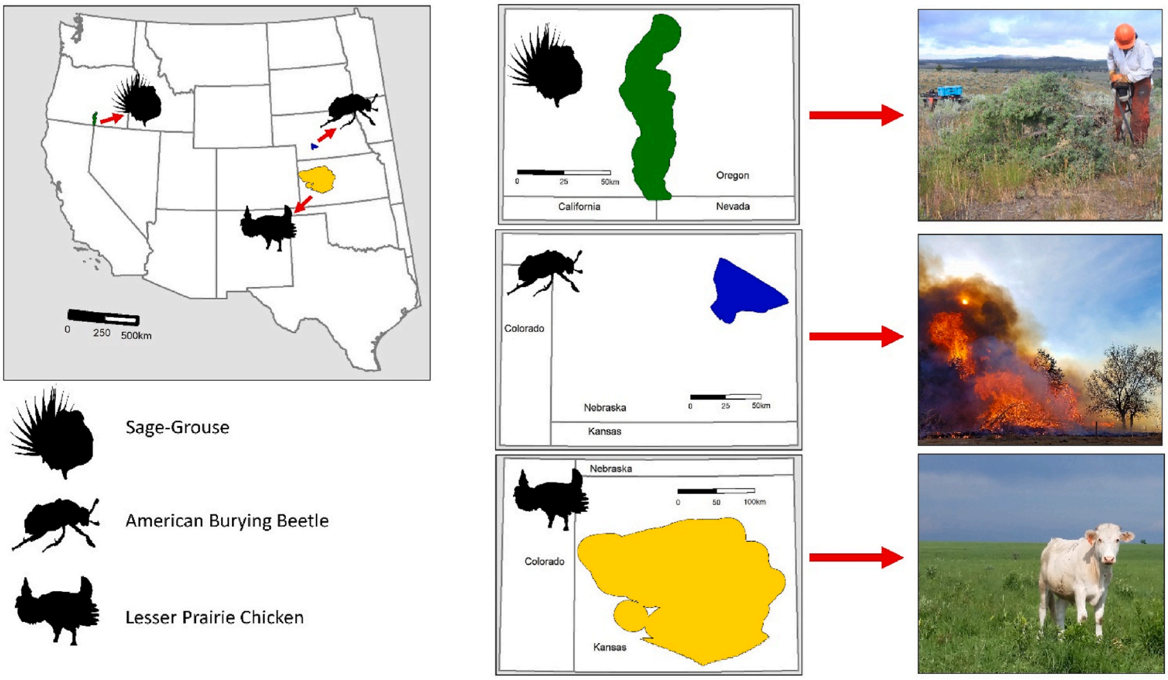

Fig. 1. Three conservation priority landscapes shown in a map of the United States with arrows pointing to the threatened species associated with each landscape. From top to bottom, the enlarged maps of the conservation priority landscapes depict the Warner Mountains Priority Area, Oregon, USA (green; Sage-Grouse), the Loess Canyons Biologically Unique Landscape, Nebraska, USA (blue; American Burying Beetle), and the Lesser Prairie Chicken Initiative Shortgrass Prairie Focal Area (gold; Lesser Prairie Chicken). To the right of the maps, arrows indicate which conservation practice dominates each landscape: from top to bottom, they are mechanical tree removal (photo credit: Jeremy Roberts), prescribed fire (photo credit: Christine Bielski), and prescribed grazing (photo credit: Christine Bielski).

expanding into these shrubland plant communities was removed by the Bureau of Land Management and U.S. Department of Agriculture-Natural Resources Conservation Service with the objective of maintaining and enhancing sagebrush steppe habitats for sagebrush dependent species such as the Greater Sage-grouse. Most of the tree removals targeted low density western juniper woodlands with largely intact sagebrush steppe plant communities in the understory (BLM 2011). Hand cutting was the primary removal technique used which minimized disturbance to understory vegetation and establishment of invasive annual grasses such as cheatgrass (*Bromus tectorum*) relative to use of heavy machinery and broadcast burning; (BLM 2011). Where trees were sparse, the limbs of felled trees were lopped and scattered to minimize slash height (BLM 2011). When fire was used to remove slash, an effort was made to limit the effect of fire to slash piles for individual trees and their stumps (i.e., pile burning). Burning took place during winter and early spring months when risk of fire spreading to non-target fuels was minimal. Junipers that established prior to European settlement were not removed (BLM 2011).

2.1.2. *Loess Canyons*

The Loess Canyons Experimental Fire Landscape (hereafter 'Loess Canyons'), located in southcentral Nebraska, USA and is approximately 136,767 ha. The Loess Canyons host a variety of at-risk species, including the threatened American burying beetle, and were historically dominated by mixed-grass prairie with native plant communities (Schneider et al., 2011; Fig. 1).

Managers primarily use large-scale prescribed fire to restore plant biomass and combat woody plant encroachment in the Loess Canyons (Twidwell, 2021). Woody plant encroachment by Eastern redcedar (*Juniperus virginiana*) is one of the greatest threats to livestock forage and endemic grassland species in the Loess Canyons and has been the focus of conservation efforts since the early 2000s (Fogarty et al., 2020, 2021). Managers typically burned sites between early February and late April, and managers target fuel and weather conditions to induce tree mortality (*sensu* Twidwell et al., 2013b, 2013a). Brush management activities supported prescribed burning by removing isolated eastern redcedar and stuffing them beneath more dense patches to provide additional fuel for burning (Bielski et al., 2021).

2.1.4. *Shortgrass prairie*

The Shortgrass Prairie Lesser Prairie-Chicken Focal Area (hereafter the 'Shortgrass Prairie') covers approximately 1,840,091 ha and was designated as a priority area for conservation by the Lesser Prairie-Chicken Initiative (NRCS, 2016; Fig. 1). The Shortgrass Prairie is in northwestern Kansas, nested within the broader mixed-grass and shortgrass prairie regions. Grassland communities consist of native prairie and former croplands enrolled in the Conservation Reserve Program. The Shortgrass Prairie contains some of the most productive habitat and highest densities of Lesser Prairie-Chicken in the Great Plains (Nasman et al., 2021).

Prescribed grazing is the primary conservation practice used to increase plant biomass in the Shortgrass Prairie. Prescribed grazing programs offer financial incentives to ensure that treated areas provided sufficient herbaceous structure to maintain nesting and brood-rearing habitat and/or to aid with infrastructure development required to initiate sustainable grazing on lands at high risk of re-cultivation (i.e., lands formerly enrolled in Conservation Reserve Program). For instance, a prescribed grazing plan may dictate that only 16.5% of available forage is harvested annually, to ensure that nesting and brood rearing habitats are maintained. Prescribed grazing was primarily targeted on lands near active lesser prairie-chicken lek sites.

2.2. *Data*

2.2.1. *Aboveground biomass data*

To calculate aboveground biomass partitioned by functional type, we used 1) data from the plant productivity dataset from the Rangeland Analysis Platform (RAP), which is an interactive internet application that tracks vegetation in US rangelands over time (Jones et al., 2018), and 2) an algorithm that estimates above ground herbaceous biomass partitioned by functional type. Details on how the RAP calculates plant productivity can be found in Robinson et al. (2019). For the above ground biomass algorithm, we applied the Landsat implementation of the MOD17 Net Primary Productivity algorithm and calibrated for aboveground herbaceous production (Robinson et al., 2019; Jones et al., 2021). Briefly, this algorithm converts net primary productivity to aboveground net primary productivity partitioned by functional type (perennial forb and grass, annual forb and grass) using mean annual temperature, land surface reflectance, land surface cover, meteorology data, and the equation found in Hui and Jackson (2005). The algorithm then converts aboveground net primary productivity to biomass using pixel area (~900m^2) and a vegetation carbon content estimate of 47.5% (Eggleston et al., 2006). This estimate represents the midpoint of a 45−50% carbon to dry matter estimation range (Schlesinger and Bernhardt, 2013). These biomass estimates align with other remote sensing and field-based plot estimates for herbaceous production (Jones et al., 2021). Productivity and biomass data are freely-available available via RAP version 3 (https://rangelands.app/).

2.2.2. *Prescribed grazing, mechanical tree removal, and prescribed fire data*

We obtained historical geospatial prescribed grazing, mechanical tree removal, and prescribed fire data from the Shortgrass Prairie, Warner Mountains, and Loess Canyons, respectively. For the Shortgrass Prairie, we obtained areas that received prescribed grazing treatments from The Nature Conservancy and private ranchers from 2010 – 2019. For the Warner Mountains, Sage Grouse Initiative and Working Lands for Wildlife provided areas that received mechanical tree removal treatments from 2007 – 2017. For the Loess Canyons, landowner-led Prescribed Burn Associations provided areas that received prescribed fire treatments from 2002 – 2019. Stocking rate data were not available for any landscape or treatment. Because most treatments occurred on private lands or privately leased lands, we could not map treatments in any way that would identify their locations.

2.2.3. *Quantifying heterogeneity in multi-scale grazing, tree removal, and fire outcomes*

We quantified spatiotemporal patterns in plant biomass and compared it to management history data at two scales. First, we quantified plant biomass at a "pasture-scale", the scale at which conservation practices are implemented (e.g., a fenced pasture for prescribed grazing, a perimeter surrounded by fire breaks for prescribed fire, a grazing allotment for mechanical tree removal). Second, we quantified plant biomass at a 30 × 30 m "pixel-scale", the finest scale possible with the Rangeland Analysis Platform.

2.2.4. *Pasture-scale conservation outcomes*

2.2.4.1. Pasture-scale outcomes in time. To capture pasture-scale temporal heterogeneity and outcomes, we searched for three focal 'pastures' (i.e., discrete spatial extents in which an individual conservation practice was implemented) in each landscape that exhibited divergent plant biomass annual trends (1986–2019) following prescribed grazing, mechanical tree removal, and prescribed fire. To do this, we first summed plant biomass of all pixels for all pastures in each landscape. We used generalized additive models (GAMs) to quantify temporal trends in plant biomass, setting perennial plant biomass as the response variable and time (years) as the smoothed (thin plate spline) predictor variable (Wood and Wood, 2015). To assess plant biomass before and after conservation practices were implemented, we noted the year mechanical tree removal and prescribed fire occurred and the year prescribed grazing began. Using the GAMs, we selected three focal pastures in each landscape that exhibited divergent trends after conservation practices were implemented.

2.2.4.2. Pasture-scale outcomes in space. With the rayshader package in R (Morgan-Wall, 2022), we applied three-dimensional imaging to qualitatively assess the level of heterogeneity in plant biomass pre- and post-conservation practice implementation that new technologies can capture. To do this, we selected one focal pasture, and, again using perennial plant biomass, we created three-dimensional images annually, starting three years before and ending three years after conservation practices were implemented.

2.2.5. Pixel-scale conservation outcomes

2.2.5.1. Pixel-scale outcomes in time. To capture pixel-scale heterogeneity and management outcomes in time, we selected three focal pixels in each landscape that represented a gradient of conservation practice presence (e.g., burned vs. unburned) or intensity (e.g., levels of grazing intensity). For each of these focal pixels, we quantified annual trends (1986–2019) in perennial, annual, and the sum of perennial and annual plant biomass. We chose focal pixels that were relatively close together to facilitate our spatial pixel-scale analysis (see below). In the Loess Canyons, we chose one pixel that captured a location that had not experienced prescribed fire and had been heavily invaded by trees, one pixel that captured a location that had not experienced prescribed fire and also had not been invaded by trees, and one pixel that captured a location that had been invaded by trees but experienced a prescribed fire. In the Warner Mountains, we chose two pixels that captured locations that experienced mechanical tree removal–one that had been heavily invaded by trees and one less invaded–and we chose a pixel that was heavily invaded by trees but did not experience tree removal. In the Shortgrass Prairie, all three focal pixels captured locations that experienced prescribed grazing, but we chose pixels at increasing distances from a livestock watering tank to capture potential differences in plant biomass resulting from grazing intensity and trampling.

We developed separate GAMs for perennial, annual, and the sum of perennial and annual plant productivities in each focal pixel. Specifically, we set perennial, annual, and the sum of perennial and annual plant biomass from 1986 - 2019 as response variables, and we set time (year) as the smoothed (thin plate spline) predictor variable.

2.2.5.2. Pixel-scale outcomes in space. To assess pixel-scale spatial heterogeneity in plant biomass, we extracted raster images of perennial plant biomass data from RAP that contained the three focal pixels from the temporal pixel-scale analysis above. We selected three images in each landscape: an image $\geq$ 19 years before conservation practices were implemented, an image from 7 - 10 years before practices were implemented, and an image from 1 – 3 years after practices were implemented. We visually assessed outcomes by comparing plant biomass rasters to historical aerial imagery from Google Earth (Google Earth, 2021).

3. Results and discussion

Using new technologies for estimating plant biomass, we can now show where, when, and at which scales working lands conservation initiatives are producing desired outcomes for wildlife and stakeholders. Because our objective is to test and showcase new technologies' capabilities—not to assess efficacy of particular conservation practices or focus on individual sites—we center our discussion on salient examples in each landscape. Whatever results we do not discuss are shown in the supplemental materials (Appendix S1).

3.1. Pasture-scale conservation outcomes

At the pasture-scale, we demonstrate how new technologies have overcome historical obstacles that forced the implicit assumption that conservation practices produce uniform effects (Hiers et al., 2020; Briske et al., 2017) and forced reliance on costly field data to provide only a small sample of conservation target responses to management (West, 2003). For instance, we can now use datasets like the RAP to produce high-resolution maps of plant biomass across all pastures and grazing allotments in the contiguous United States every year and then use these maps to assess management outcomes (Fig. 2 S1S1). For example, total plant biomass increased 4-fold (966,809 kg/ha) from 2007 to 2013 in Shortgrass Prairie that was prescriptively grazed in 2010 (Fig. 2). However, gains were highly dependent on precipitation patterns as evidenced by sensitivity of remotely-sensed productivity over the 7-year period in question (SD ± 951,308 kg/ha; Fig. 2, S2AS2A). Abrupt shifts in productivity across whole pastures were apparent at pixel-level scales in the high-resolution imagery (Fig. 2). For example, a more mesic gully consistently produced 1,000 kg/ha more plant biomass than a nearby dry upland (Fig. 2) despite underlying disparities in productivity over the 7-year evaluation. Collectively, the nuances that we can now explore show the value of new technologies for quantifying spatially heterogeneous outcomes at conservation-relevant scales (Fig. S1). Availability of accurately archived management histories now present more of a constraint than productivity mapping to quantify outcomes in rangeland conservation.

When management history data are available, as in our study, we show how leveraging long-term datasets can provide multi-decadal before-after inference (Fig. 3; Fig. S3). To illustrate, when compared to previous decades, tree removal in sagebrush steppe resulted in a 21% increase in one pasture's productivity (Fig. 3A) and an 18% decline in another (Fig. 3B). This aligns with recent evidence showing divergent outcomes from removal of pinyon-juniper trees in the upper Colorado River Basin (Fick et al., 2022) and with examinations of tree removal in the Great Plains (Scholtz et al., 2021). The temporal extent of these datasets enables benefits that resulted from treatments (Fig. 3A) to be differentiated from apparent successes that, when compared to previous decades, exhibited no positive outcomes in plant biomass attributable to woodland management (Fig. 3C and possibly 3 B). Moreover, technology permits the parsing of high interannual variability (SD ± 32,340 and 174,555 kg/ha) amongst pastures for the 34-year period for which we estimated trends (Fig. 3 A & B). Importantly, because we focused only on areas where conservation was implemented, we limit our inference to areas where before and after treatments were applied (Fig. 3A–C). However, because RAP-based productivity (as well as other similar datasets) covers the entirety of US rangelands, control sites can easily be selected to mirror treatment site edaphic factors and added into study designs as evidenced for tree removal in the intermountain West (Rigge et al., 2020; Reeves , 2020; Fick et al., 2022). This means the effects of conservation practices on plant biomass can now be assessed via the gold standard of ecological impact assessments—randomized control trials—across all US working lands (Larsen et al., 2019).

Our pasture-scale findings demonstrate how land managers can use new technologies to analyze their actions at biologically relevant scales, identify successful treatments, and either adapt their management or replicate beneficial outcomes in other landscapes. For instance, we show Loess Canyons private landowners used high intensity prescribed fires to fully restore plant biomass in a management unit formerly infested with eastern redcedar (*Juniperus virginiana*) (Figs. S1B, S3A). This echoes recent field-based research in the Loess Canyons showing extreme prescribed fire can reverse state transitions from grasslands to woodlands and restore herbaceous biomass (Bielski et al., 2021). Conversely, capturing undesirable responses at the treatment-scale facilitates rapid learning and adaptive management (Scholtz et al., 2021). To illustrate, plant biomass may not have responded to early fire treatments because, in areas heavily infested prior to burning, eastern redcedar has been

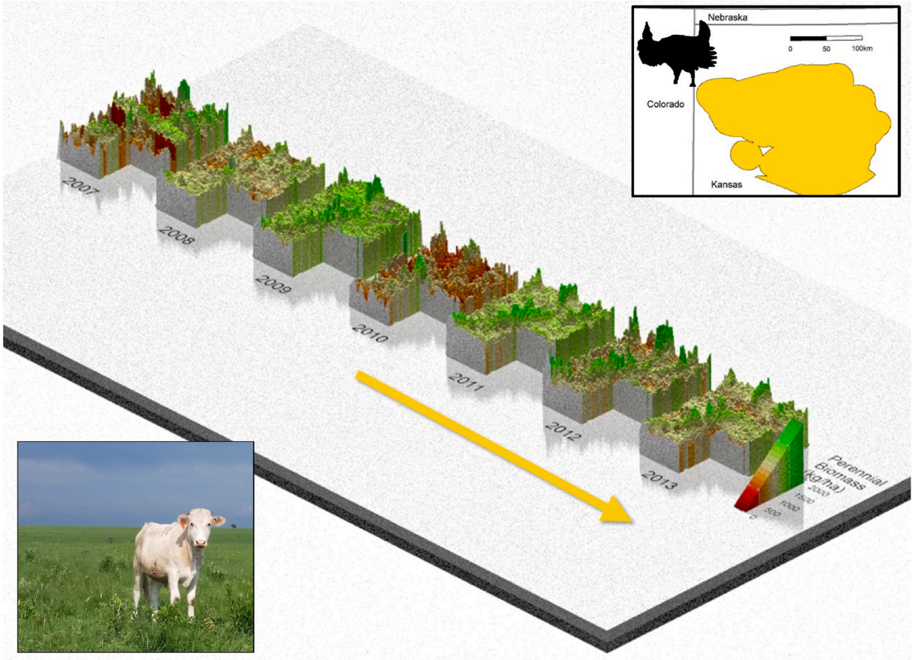

Fig. 2. Three-dimensional images depicting spatial complexity of perennial above ground herbaceous biomass (kg/ha) for all 30 × 30 m pixels within a 408 ha pasture that received prescribed grazing in the Lesser Prairie Chicken Initiative Shortgrass Prairie Focal Area. Pixel color and height indicate plant productivity. Yellow arrow indicates prescribed grazing occurred from 2010 onward. Photo credit: Christine Bielski.

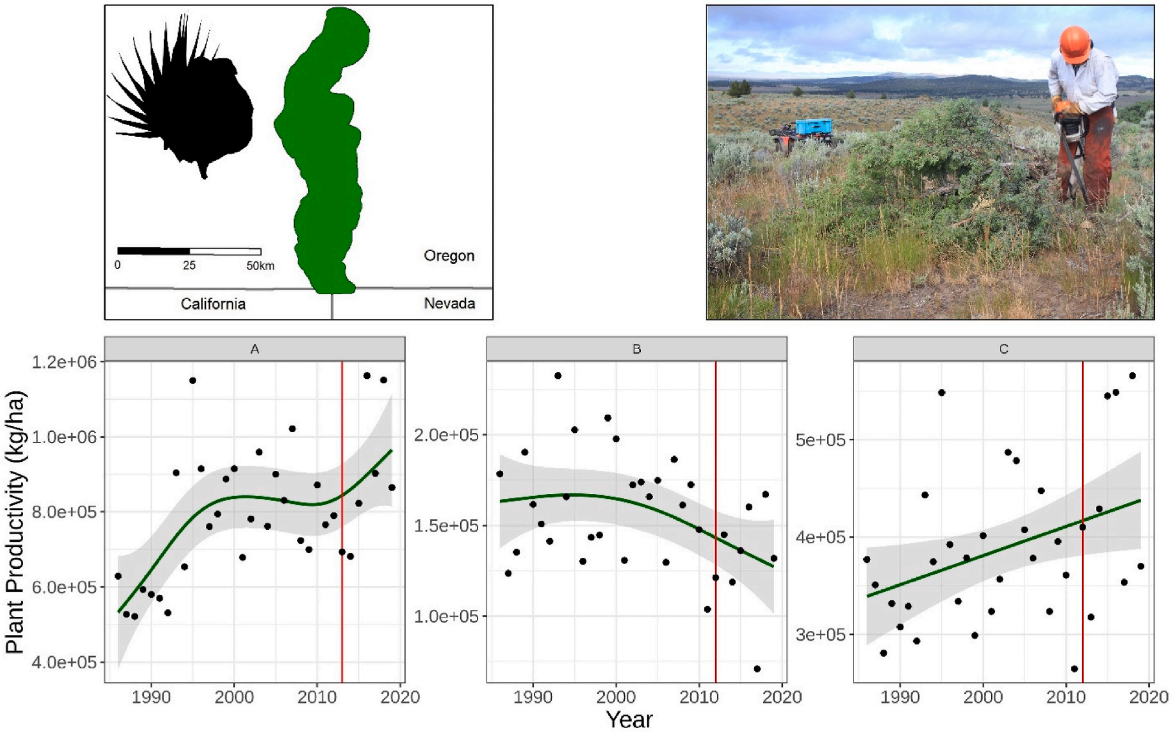

Fig. 3. Differential outcomes in plant productivity for three focal pastures that received mechanical tree removal in the Warner Mountains, Oregon, USA. Red vertical lines indicate the year when tree removal occurred. Figures show estimated above-ground perennial herbaceous biomass (kg/ha; black dots), trends (generalized additive model predictions; colored lines), and 95% confidence limits (grey ribbons). Photo credit: Jeremy Roberts.

shown to rapidly re-invade grasslands post-fire (Fogarty et al., 2021). Given that these data stretch back decades and are annually updated, we show outcomes can be assessed even one- or two-years post-fire.

3.2. Pixel-scale conservation outcomes

At the 30 × 30 m pixel scale, spatiotemporal perennial and annual plant biomass outcomes met expectations based on management history and aerial imagery (Fig. 4, S4). Prescribed fire in the Loess Canyons provided the clearest example: we successfully detected complete restoration of plant biomass as a result of prescribed burning (Fig. 4). Specifically, perennial plant biomass initially declined 80% in the pixel invaded by trees that was prescriptively burned, but then biomass rebounded post-fire, a 492% recovery from nadir (1,622 kg/ha regained; Fig. 4). In contrast, the pixel that was invaded but unburned declined by 84% in perennial plant biomass (1,648 kg/ha lost); and the pixel that was uninvaded and unburned remained relatively constant (+90 kg/ha or a 5% increase; Fig. 4). Interestingly, biomass of annual plants was similar between burned, invaded, or uninvaded pixels (Fig. 4), and across the entirety of the Loess Canyons despite it receiving large, intense, and consistent prescribed burning (Fig. S5; Roberts et al., 2022). This contrasts with studies from other western US rangelands showing extreme or intense fire exacerbates exotic annual grass invasions (Keeley and McGinnis, 2007; St. Clair and Bishop, 2019; *but see* Porensky and Blumenthal, 2016).

Our pixel-scale results highlight our ability to move past simplistic comparisons like “burned vs. unburned” or even powerful before-after-impact-control comparisons when assessing rangeland management outcomes and explore nuance in unprecedented ways (Hiers et al., 2020; Twidwell et al., 2020). As we show by differential outcomes between pixels (i.e., 30 × 30 m areas) that both received tree removal treatments (Fig. S4A) and pixels that all received the same prescribed grazing regiment (Fig. S4C), we can now directly quantify how spatiotemporal heterogeneity emerges from treatments. This means we can enact the call put forth by Fuhlendorf et al. (2006) for heterogeneity to become the foundational metric of rangeland conservation. We can ask questions like “is a treatment producing sufficient heterogeneity to increase rangeland biodiversity?” and “is a treatment producing sufficient heterogeneity to hedge bets for livestock forage during drought?” (McGranahan et al., 2016; Fuhlendorf et al., 2017).

4. Conclusions

Responses of plant productivity to prescribed grazing, mechanical tree removal, and prescribed fire are scale-dependent. Our findings corroborate other studies showing that conservation practices produce divergent and complex outcomes (Archer and Predick, 2014; Reinhardt et al., 2020; Fick et al., 2022) and that tracking outcomes at a single scale will almost certainly lead to spurious conclusions (Levin, 1992; Lindborg et al., 2017; Bielski et al., 2018). Working lands initiatives like those included here (i.e., Sage Grouse Initiative, Lesser Prairie-Chicken Initiative, and Nebraska Natural Legacy Project) intentionally saturate whole watersheds with conservation practices anticipating that desirable outcomes will emerge at ecoregion-scales. For example, Sage Grouse Initiative tree removal efforts in the Warner Mountains resulted in a 12% increase in growth rate for the resident imperiled sage-grouse population (Olsen et al., 2021). Similarly, large-scale prescribed fires in the Loess Canyons led to a significant increase in American burying beetle abundance (Ludwig et al., 2021) and ecoregion-scale increases in grassland bird diversity (Roberts et al., 2022). The new generation of remote sensing products we discuss here provides unprecedented opportunities to quantify if and how divergent outcomes at pasture- and pixel-scales coalesce into regional benefits in plant biomass (Allred et al., 2021). This also creates enormous opportunities for investigating emergence and scaling behaviors from the lens of panarchy theory (Allen et al., 2014; Twidwell et al., 2022), which is already motivating and shaping conservation strategies across biomes like the North American Great Plains (Garmestani et al., 2020; NRCS, 2021a).

Although new technologies obviate the need to extrapolate intensive fine-scale sampling to broader scales, field-based studies are still critical for quantifying conservation outcomes. Clearly, field data are needed to validate and improve models that estimate biophysical variables derived from remote sensors (e.g., plant biomass, vegetation cover, ecohydrological variables, etc.). Just as importantly, results from remote sensing

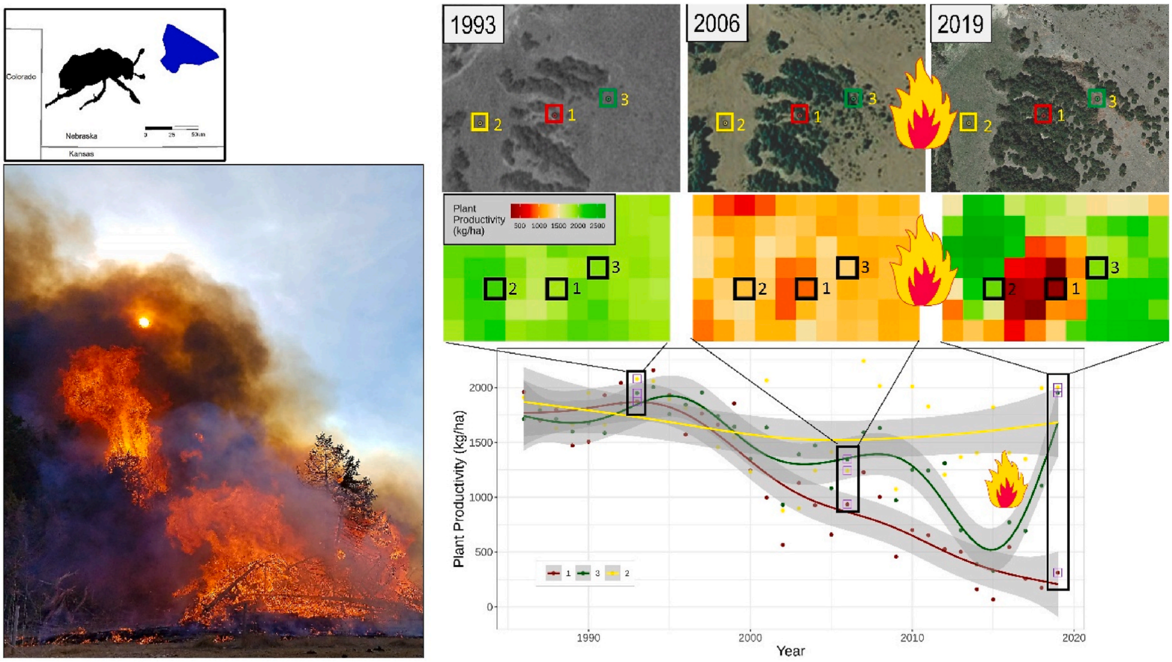

Fig. 4. Comparison of management history data, aerial imagery, and plant productivity trends. Images and maps depict temporal trends and spatial patterns at and surrounding three 30 × 30 m focal pixels (pixel 1: invaded and not burned; pixel 2: not invaded and not burned; pixel 3: invaded and burned) within the Loess Canyons Experimental Fire Landscape, Nebraska, USA. The focal pixels are shown in 1) three aerial photographs taken at the same location in three different years, with focal pixels denoted as colored squares, 2) three raster images corresponding to each aerial image, with focal pixels outlined in black and colored according to plant productivity (kg/ha) estimates, and 3) line graphs, with colored dots indicating yearly perennial biomass (kg/ha) for each pixel, colored lines indicating trends for each pixel estimated via generalized additive models, and grey ribbons indicating 95% confidence limits. Prescribed fire occurred in 2016. Photo credit: Christine Bielski. Aerial images were provided by the USDA Farm Production and Conservation Geospatial Enterprise Operations and the U.S. Geological Survey.

and field-based studies can inform each other and inspire new hypotheses. For instance, in our study, the divergent results we found in individual pixels could lead to new field-based trials to determine finer-scale causes. Results from field-based experimental studies (e.g., diversity-stability studies, herbivory exclosure studies, drought studies, etc.) can be tested at larger scales via remote sensing products (McGranahan et al., 2016; Bielski et al., 2018). Similarly, satellite data can make field-based trials more efficient by helping choose homogeneous sites to conduct experiments (Jones et al., 2020).

Datasets and technologies capable of quantifying biome-scale conservation outcomes are continually growing and evolving. Here, we focused on the plant biomass dataset from the Rangeland Analysis Platform, but other datasets that produce similar estimates are also freely-available (e.g., Reeves, 2020). There are also multiple datasets at similar spatiotemporal resolutions that estimate fractional vegetation cover by functional group: Allred et al., (2021) produced fractional vegetation cover by coarse functional groups such as tree, shrub, annual forb and grass, litter, etc., and Rigge et al. (2020) created a fractional vegetation cover dataset that includes more specific vegetation types such as sagebrush cover. Datasets such as Landsat's and MODIS's Leaf Water Stress or Normalized Difference Vegetation Indices have long histories of quantifying prescribed grazing and fire outcomes for vegetation (Zhou et al., 2017; Steiner et al., 2020). Additionally, given how much conservation threats such as woody plant encroachment and climate change affect water availability in arid systems (Polley et al., 2017; Zou et al., 2018), datasets that estimate aspects of ecohydrology such as soil moisture (Vergopolan et al., 2020) and evapotranspiration (OpenET, 2022) will play increasingly important roles for quantifying conservation outcomes in working lands.

New technologies for quantifying management outcomes help create a shared vision for working lands conservation initiatives and diverse stakeholders. Shared visions help build the trust necessary to realize durable, large-scale conservation success across landscapes with mixed public and private ownership (Briske et al., 2017; Burger et al., 2019; Naugle et al., 2019). In this article, we showcased how new datasets can communicate conservation outcomes in ways that are meaningful for stakeholders interested in economic and wildlife habitat results (NRCS, 2021b; Sullins et al., 2021). The ability to communicate outcomes via a key ecosystem service like plant biomass can unite people with different goals and have positive conservation effects at the scale of biomes (Naugle et al., 2020). This will stand working lands conservation initiatives in good stead for confronting the biome-scale conservation challenges of our time.

Credit author statement

Caleb P Roberts: Conceptualization, Methodology, Analysis, Writing, Reviewing, Editing, Data curation, Software. David E Naugle, Dirac Twidwell: Funding acquisition, Writing, Reviewing, Editing, Supervision. Brady W Allred, Victoria M Donovan, Dillon T Fogarty, Matthew O Jones, Jeremy Maestas, Andrew Olsen: Data curation, Writing-Reviewing and Editing, Software.

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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Appendix A. Supplementary data

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