Rapidly quantifying drought impacts on aid reseeding strategies

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On the Ground

- Remote sensing for rapid estimation of forage losses.
- Cross referencing forage losses from drought with ecological sites can aid seeding decisions.
- Drought monitors, by themselves, do not necessarily reflect extent and scope of forage losses.
- Partnering with multiple agencies and stakeholders can enhance the overall response to drought.

Keywords: Ecological sites, Reseeding, Drought remote sensing

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Introduction

Conceptually, drought is a water shortage due to reduced rainfall compared to long-term, normal baseline conditions specific to geographical extents with ecological, social, and economic consequences.[1,2] Objective and operational definitions of drought depend on perspective. Meteorological definitions are based on temporary departures from climate averages as measured by metrics including the Standard Precipitation Index,[3] which is based on low rainfall relative to average precipitation. Similarly, the Palmer Drought Severity Index[4] approximates the long-term balance between precipitation and water use based on precipitation and temperature but does not identify short-term or developing drought. The Evaporative Demand Drought Index[5] and the Standardized Precipitation Evapotranspiration Index[6] can be computed for multiple time scales and can detect both fast-developing droughts (flash droughts of weeks to months) and seasonal and long-term droughts (months to years), but produce variation depending on estimation methods.[7] Meteorological definitions of drought are modified for impacts on economic, social, and ecological sectors, although definitions are not mutually exclusive and can co-exist.[1] Hydrological drought has effects on water flows and snowpack, measured by the Surface Water Supply Index, for example.[1] Agricultural drought affects short-term soil moisture conditions for crop growth and is quantified with metrics such as the Crop Moisture Index (CMI).[8] Socioeconomic drought measurements are used when water supplies do not meet demands for different goods, services, or activities.[9] Because ecosystems are complex, ecological drought definitions currently are more conceptual than operational (e.g., "an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems").[10] Identification of drought and drought characteristics depends on the drought definition and metric being sought.[11]

Drought impacts vegetation differentially across space, time, and among species.[12] Reduced soil water content causes stress to plants and potential mortality.[13] Plant stomata regulate carbon dioxide and water vapor, and when soil moisture levels drop, closure of stomata reduces the supply of carbon dioxide to photosynthesis necessary for plant growth, reproduction, and survival. Soil moisture is depleted from increasingly deeper soils, affecting short-rooted species before long-rooted species.[13] Drought that results in loss of vegetation cover reduces current forage quantity and potentially future forage yield, due to soil erosion that degrades water-holding capacity and fertility.[14] Spatial gradients in moisture, arising from factors such as soils and topography, may generate differential productivity. Drought effects are variable on forage quality, although drought may increase the amount of dead plant material and after loss of preferred forage, cattle may shift to lower quality options (e.g., less protein, more fiber).[15,16]

Reduced soil moisture affects annual net primary productivity (ANPP), which impacts land managers and producers throughout the United States. Proactive planning for drought management is restricted in part due to drought complexity, resources limitations, financial assistance that occurs after drought, and limited availability of drought monitoring information, including onset of drought conditions.[11] Drought metrics such as the United States Drought Monitor (USDM)[17] have informed relief programs for livestock producers (https://droughtmonitor.unl.edu/) since 1999. Similarly, the Vegetation Drought Response Index (VegDRI) identifies vegetation stress due to drought (https://vegdri.unl.edu/). New tools such as the Grass-Cast (http://grasscast.agsci.colostate.edu/) and Fuelcast (www.fuelcast.net) incorporate remote sensing data and weather information to provide projections of current growing season total herbaceous production. Although many drought metrics exist, none directly quantify forage losses, which is the actual response of interest to producers, rather than drought. To provide a direct measure of drought effects on forage for livestock producers and range managers, we developed the Rangeland Production Monitoring Service (RPMS),[18] which quantifies aboveground ANPP. Indeed, we may consider reductions in ANPP a measure of ecological drought, particularly important for rangeland agroecosystems.

Traditional assessment of the most affected lands to determine which producers and what areas might be eligible for assistance is costly, time consuming, and covers only a fraction of the affected area. Advancements in technology coupled with decreasing costs of remotely sensed data have resulted in applications of remote sensing in ways previously not possible.[19] In this vein, the USDA Natural Resources Conservation Service (NRCS) and Forest Service teamed up for rapid identification of areas that had the greatest reductions in ANPP relative to the long-term average. Subsequently during March 2019, Secretary of Agriculture Perdue designated three Arizona counties as primary natural disaster areas due to drought. During May 2019, the USDA NRCS announced producer assistance to aid recovery would be available for areas affected by drought.[20] This drought assessment then allowed development of a northeastern Arizona drought responsive seeding strategy, to aid evaluation of eligibility for financial assistance to agricultural producers.[21] This joint project offers significant promise for future efforts where rapid quantification of forage losses is needed. Here, we document the simple but rapid and effective two-phase process in response to drought. The first phase includes an assessment of vegetation production across ecological sites in the three-county region of Arizona, and the second phase includes a ranking process to determine which landscapes and ownerships are available to receive assistance. Financial assistance programs aimed at reseeding directly require estimates of forage losses, and this new approach using the RPMS can save time and money while adding objectivity and repeatability for any rangelands in the United States.

Methods

Study area

Our study area for developing this process includes the counties of Coconino, Navajo, and Apache in northeastern Arizona near the Four Corners region (Fig. 1). These were the three counties designated as primary natural disaster areas. To identify rangelands within the study area, we used spatially explicit data developed by Reeves and Mitchell.[22] Rangelands identified in these three counties, represent 5.1 million hectares (12.6 million acres) and the top 10 vegetation types occupy 96% of the rangeland area (Fig. 1).

Quantifying vegetation performance during the 2018 drought

The goal of this assessment was to quantify the reduction in ANPP in the three-county region in northeastern Arizona in the heart of the drought declaration area. To accomplish this, we compared the 2018 estimates of ANPP to the average production from 1984 to 2017 using the formula:

(1)PctDiff2018=ANPP2018-ANPP8417/ANPP8417100

where $PctDiff_{2018}$ is the change in ANPP in 2018 relative to the 34-year baseline, $ANPP_{2018}$ is the estimated ANPP in 2018, and $ANPP_{8417}$ is the 34-year average estimated ANPP from 1984 to 2017.

The ANPP data used to evaluate vegetation performance and quantify drought effects came from the RPMS. The RPMS is a database of annual production estimates for US rangelands from 1984 to present. The RPMS was created primarily to help managers and producers rapidly determine trends in ANPP that can enhance management decisions. The data used to derive the estimates of ANPP come from the Thematic Mapper suite of sensors including the Landsat 5, 7, and 8. These data are offered at a native resolution of 30 m but we resampled to 250 m.

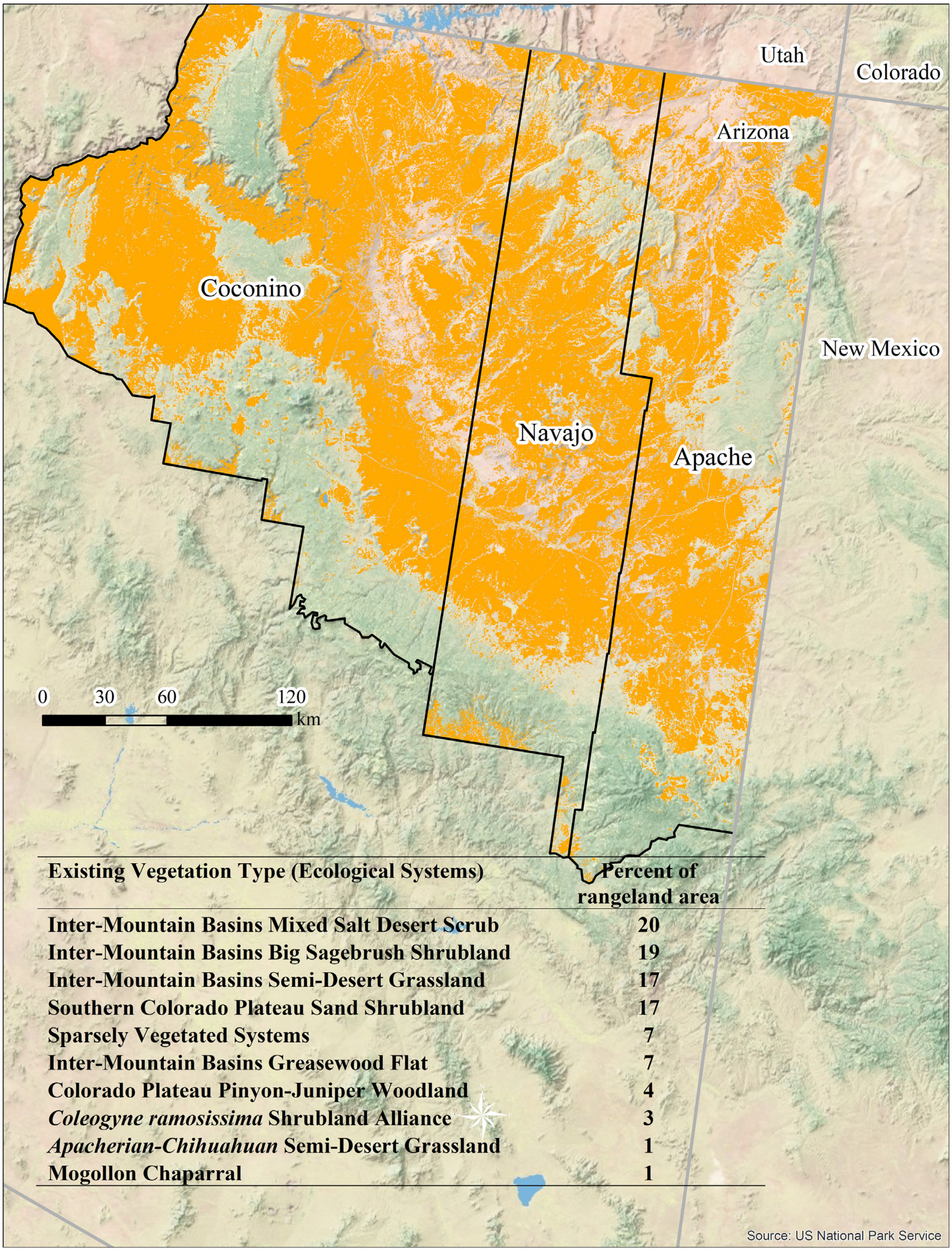
These data were converted to the commonly used Normalized Difference Vegetation Index (NDVI). The NDVI is formulated as:

(2)NDVI=NIR--Red/NIR+Red

where Red and NIR stand for the spectral responses acquired in the red (visible) and near-infrared regions (band passes),[23] respectively. The annual maximum NDVI for each year from 1984 to 2017 formed the basis for estimating rangeland ANPP of the conterminous United States. The freely available RPMS, including tools and tutorials can be found at RPMS,[24] and Reeves et al.[18] offers methodology of estimating ANPP from NDVI data.

Pixel level data describing the percentage reduction in 2018 were then overlain with soil ecological sites, or spatial units in the Soil Survey Geographic Database.[25] The average ANPP response across each ecological site was quantified. The reductions in ANPP were then divided based on four classes of reductions in ANPP. The classes were Class 1; ANPP > 0% (no reduction in ANPP), Class 2; 0% <= ANPP > 50%, Class 3; 50% > ANPP > 80%, and Class 4; 80% <= ANPP >= 100%. These reductions in ANPP were also represented in contiguous blocks of 202 hectares (500 acres) or more.

In addition, the USDM[17] was evaluated for 2018. The USDM offers data in polygon format, each week throughout the year, where each polygon is coded in classes of D0, D1, D2, and D3, and D4. To quantify drought, these thematic categories were numerically coded as 0, 1, 2, and 3 and 4 for the D0, D1, D2, and D3, and D4 categories, respectively.



Existing Vegetation Type (Ecological Systems)	Percent of rangeland area
Inter-Mountain Basins Mixed Salt Desert Scrub	20
Inter-Mountain Basins Big Sagebrush Shrubland	19
Inter-Mountain Basins Semi-Desert Grassland	17
Southern Colorado Plateau Sand Shrubland	17
Sparsely Vegetated Systems	7
Inter-Mountain Basins Greasewood Flat	7
Colorado Plateau Pinyon-Juniper Woodland	4
Coleogyne ramosissima Shrubland Alliance	3
Apacherian-Chihuahuan Semi-Desert Grassland	1
Mogollon Chaparral	1

Figure 1. The three-county study area in Northeastern Arizona. The areas in orange are rangelands in the area that were considered in the drought analysis. In addition, the dominant rangeland types are listed in Table 1 along with their respective proportional coverage.

These numeric codes were then summed over the year to get an estimate of cumulative drought for all 52 weeks in the analysis. These data were used to corroborate or help communicate and describe the estimated ANPP response.

Results

In the three-county study area, we estimated 2%, 60%, 27%, and 11% of the total area was occupied by the ANPP reductions of class 1 (ANPP > 0%), class 2 (0% <= ANPP > 50%), class 3 (50% > ANPP > −80%) and class 4 (−80% <= ANPP >= 100%), respectively (Fig. 2A). These proportional areas were tantamount to 0.1, 3.0, 1.0, and 485,623 hectares (0.25, 7.4, 2.5, and 1.2 million acres), respectively (Fig. 2A). Average response also varied by ecological site (Fig. 2B). The time series of ANPP across the Sandy Upland ecological site, covering the largest amount of area in the study area, reveals that 2018 exhibited the lowest ANPP since 1984 (Fig. 2C). Error bars about each of these time series represent one standard deviation about the mean ANPP response. In this manner they represent spatial variability of ANPP across the sites.

Likewise, the USDM analysis indicated that, in 2018, Navajo and Apache counties experienced the highest level of drought since 2000, whereas Coconino county was not as severe (Fig. 3). According to the USDM, in Coconino County the cumulative drought in 2018 has been surpassed in 3 years including 2002, 2003, and 2004. In contrast, reductions of ANPP were greater in 2000 and 2009 in all three

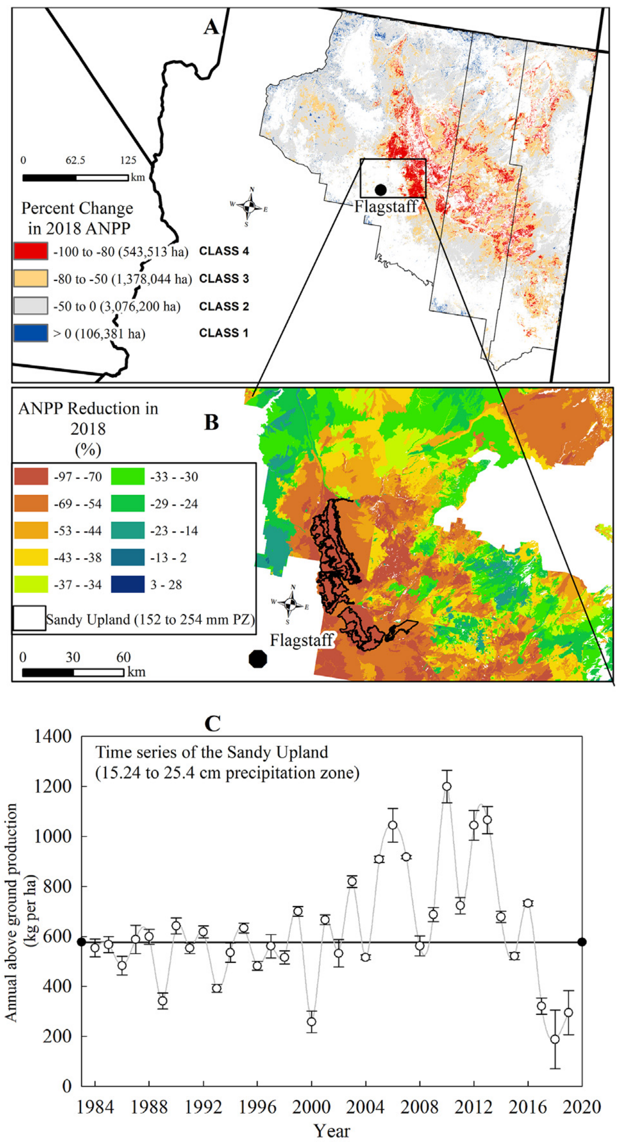


Figure 2. Spatial and temporal trends of ANPP across the study area. A, Demonstrates the results of the comparison of 2018 ANPP to the 34-year average (1984–2017) from the Rangeland Production Monitoring Service. The values have been binned into categories according to the selection criteria for resource assistance as outlined by the USDA, NRCS. B, Demonstrates how the pixel level ANPP reductions in 2018 were aggregated (scaled up) to ecological sites. The link to ecological sites was needed so that appropriate seed mixture could be chosen for lands deemed eligible. A portion of the Sandy Upland (15.2–25.4 cm [6–10 inch] precipitation zone) ecological site, which is common throughout the study area, is shown in black outline. C, Shows the time series of ANPP exhibiting the significant reduction of ANPP in 2018 experienced by this section of the Sandy Upland (15.2–25.4 cm [6–10 inch] precipitation zone) ecological site. The time series of ANPP was derived using the Rangeland Production Monitoring Service (https://www.fs.usda.gov/rmrs/projects/development-rangeland-production-monitoring-service-could-improve-rangeland-management). Based on this assessment, at the county level, Coconino County exhibited the greatest overall reduction compared with the 34-year average (1984–2017).

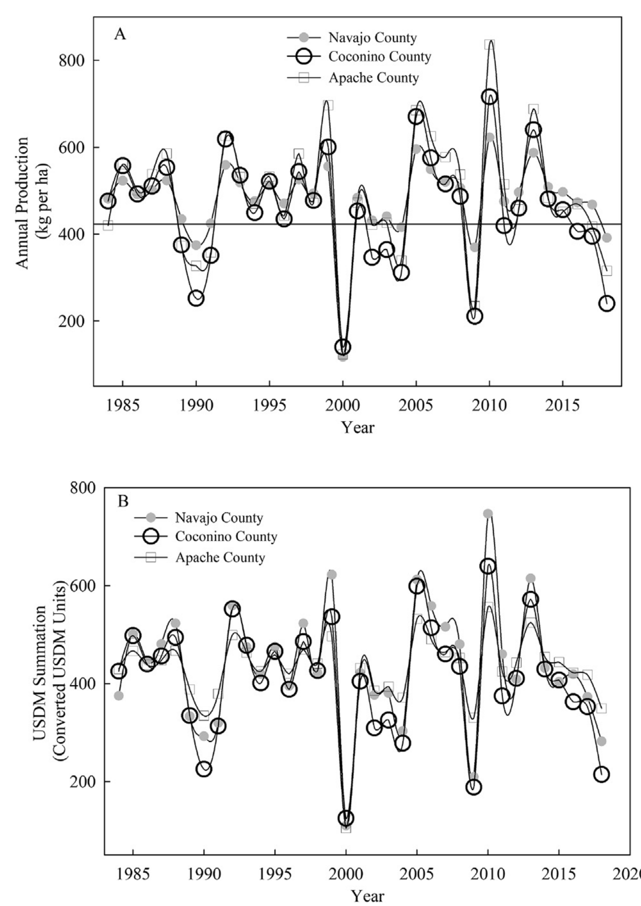


Figure 3. Time series of ANPP and USDM across the three-county study area in northeastern Arizona. A, Demonstrates the time series of ANPP for each of the three counties designated as primary disaster areas. Although 2018 was considerably lower than most other years, some years such as 2009 and 2000 were lower in terms of annual production. Despite this broad pattern many sites within these counties were unquestionably much lower than in all previous years since 1984. B, Demonstrates the accumulated response of the USDM across all three counties designated as primary disaster areas. In this case, because the drought monitor values were accumulated during the year, a higher score indicates a greater amount of accumulated drought.

counties overall (Fig. 3). These observations highlight the importance of long time series and site-specific information because offering estimates of drought and drought impacts over large areas can be somewhat misleading depending on the scale of analysis. In this vein, these broad averages bely the subregional patterns or site level responses that occurred in 2018 (e.g., Fig. 2A). This also points to the disjunctive nature of rainfall patterns that often occur in this region during the monsoon period. As revealed by the RPMS, some areas experienced >95% losses in productivity, which was corroborated by resources such as photographs taken throughout the study area, one of which showed that blue grama (*Bouteloua gracilis*) has largely died back (Fig. 4).

Figure 4. A representative picture showing the impact of drought on *Bouteloua gracilis* (blue grama) where die backs were visibly extensive (2019, photo courtesy of I. Burden). The black arrows show patches of blue grama that died in response to the drought.

Determining eligibility for recovery resources

Based on these results, seeding assistance was available through the NRCS Environmental Quality Incentive Program (EQIP). Priority was given to areas with >80% reductions in forage because large-scale die-off of native vegetation and/or severely reduced productivity increases the risk of soil loss, particulate matter, and non-native species invasion. Here we only quantified the reduction in forage but did not test if widescale dieback of perennial vegetation was due to drought. After we identified which sites exhibited the greatest ANPP reductions, we applied criteria to prioritize the areas eligible to receive seeding assistance and associated resources. Producers demonstrating or documenting prescribed grazing practices before seeding implementation were given priority. In addition, screening included the following questions:

- Can the producer demonstrate access control of domestic livestock and feral animals?
- Is the producer willing and able to defer grazing the seeded area two growing seasons (of spring, summer, fall) each year for 2 years?
- Is the producer willing and able to have their animal/forage balance (i.e., stocking rate) in line with current conditions?
- Can the producer show the seed quality test/label from the seed vendor?

After the priority areas were identified, the USDA NRCS Plant Material Center in Tucson, Arizona recommended seed mixtures based on the precipitation zones of the affected areas. The most affected areas usually fell into the 15.2 to 25.4 and 25.4 to 35.6-cm (6-10 and 10-14-inch) annual precipitation zones. The Plant Material Center recommended seeds for

Table 1. Recommended seed mix, rates, percentage mix, and pure live seed needed per acre for (15.2–25.4 cm [6–10 inch] and 25.4–35.6 cm [10–14 inch]) precipitation zone.

Seed mix	PLS aerial seeding rate	PLS seeding rate	Mix proportions
	(kg per ac)		%
15.2 to 25.4 cm precipitation zone:	10.31	5.16	50
Indian Ricegrass *(Achnatherum hymenoides)*	0.45	0.22	50
Sand Dropseed *(Sporobolus cryptandrus)*	0.00	0.00	
25.4 to 35.6 cm precipitation zone:	16.81	3.36	20
Quick Guard (Sterile Cereal Grain)	10.31	2.06	20
Indian Ricegrass *(Achnatherum hymenoides)*	0.45	0.22	50
Sand Dropseed *(Sporobolus cryptandrus)*	4.93	0.49	10
Globemallow *(Sphaeralcea spp.)*	10.31	5.16	50

Note: When applying aerially, seed rates are always doubled due to the potential for increased chances of seed loss to environmental factors otherwise not present when seed is drilled into the soil.
PLS indicates pure live seed.

both precipitation zones that were cost effective, readily available on the open market, and had the best chances of success (Table 1). The seeds were recommended, but as conditions change, seed mix alterations (e.g., price fluctuations and availability) to implement the reseeding strategy may be needed. Overall, the reseeding effort is presently scheduled to involve aerial re-seeding given the large extent of the drought effected area. All seeding rates are doubled when seed is applied through aerial application due to increased chances of loss due to additional environmental factors compared with conventional seeding techniques such as drilling.

Discussion

Our goal was to rapidly quantify losses in ANPP due to drought and identify the most affected areas that could be eligible for assistance with reseeding efforts to improve the resilience and re-growth in prioritized areas. This joint project between USDFA NRCS and the Forest Service offers significant promise for future efforts where rapid quantification of forage losses is needed to provide information for management. Using traditional ground-based reconnaissance this process would take much longer (i.e., months) to complete over such a large area, and likely cost far more, to conduct vegetation sampling along transects to evaluate production relative to a long-term baseline. Likewise, using drought metrics alone, forage losses must be inferred. In comparison, using the process we developed here, we accomplished our main objective in about 5 days. Even this short turn-around time could be reduced to just a few days or even hours depending on the area being observed and the availability of ecological site information.

Other benefits of this process include objectivity and repeatability, which are especially important because financial aid is being prioritized using this process. Identifying drought-related impacts to annual production has been limited historically to inferences by using drought monitors, based on a variety of methods, that may not be repeatable or well-documented. The precision, speed, objectivity, and quantitative nature of our analysis suggests that one of the preferred next steps is automation of this process so that anyone can invoke the algorithms and transparently generate results. Automating this process would greatly reduce the workforce required to perform ground-related reconnaissance and form a repeatable assessment process that should stimulate even better analytical processes in the future.

Additionally, this method can examine post-drought recovery of production. Recovery during 2019 was based on production and field observations, and additionally, seasonal drought remains in effect (Figs. 2 and 4). In general, the observed post-drought response has been an influx of primarily native forbs and non-native forbs, specifically, kochia (*Neokochia americana*), globe mallow (*Sphaeralcea ambigua;* see Fig. 4), primrose (*Coreopsis sp.*), tansymustard (*Descurainia pinnata*), and tumble mustard (*Sisymbrium altissimum*). The primary perennial grass to respond was squirreltail (*Elymus elymoides*) with little to no response from other native perennial grasses. No non-native perennial or annual grasses were observed in the area pre or post drought. A future step will be to evaluate the effectiveness of the seeding strategy and aerial seeding.

The small increase in ANPP during 2019, however, does not offer evidence for, or against, resilience. As shown in the present work, evaluating ANPP losses on an annual basis relative to a baseline is possible and not difficult but identifying post-drought resilience is an area of future research and beyond the analysis presented here. One approach to quantifying post-drought resilience is to quantify different levels of drought by using one of the numerous drought monitors available (like the USDM), and then evaluating vegetation response through time after the drought has subsided.

Drought metrics are a surrogate for loss of vegetation production. Rather than using drought monitors to infer forage losses, we now can directly assess forage losses using the RPMS in conjunction with spatially explicit data describing the location of ecological sites. The NRCS guidelines developed in the Northeastern Arizona Drought Responsive Strategy prioritized re-seeding using forage loss levels (50–80% and >80%).[21] The novel manner in which we used remotely sensed estimates of ANPP could be replicated to inform decisions for mitigation in response to future drought. After prioritizing areas, the NRCS determined where resources were most needed for restoration purposes, particularly soil protection. It is important to realize, however, that losses of production not only represent drought effects but also any other processes that can reduce photosynthesis and plant production. For example, it is possible that some losses in production detected by the RPMS were not only related to drought but also herbivory, for example, by wild or native ungulates and insects such as locusts (*Locusta* spp.) or grasshoppers (*Melanoplus* spp.). Despite this possibility it is likely that the overwhelming cause for the reduced ANPP is drought as generally indicated by the USDM.

Our results indicated a notable difference in ANPP for Coconino County when comparing the USDM and the RPMS. This is likely because these two systems apply different measurement approaches. The USDM is a generic metric of drought that can reflect water shortages, forage losses, and low stream flows.[17] This generalized viewpoint of drought, therefore, should not be expected to behave synchronously with the RPMS, which measures vegetation performance directly.[18] Our analysis is most closely aligned with the concept of ecological drought, whereas the USDM can be more generally interpreted for other types of drought. Alternatively, tools such as VegDRI[26] may be more closely aligned with the RPMS results because both use remote sensing information.

This framework informs management response to drought, through a systematic process at a landscape scale. This type of rapid drought assessment may be critical for improvement of state drought programs, by meeting needs for monitoring and predicting drought followed by evaluation of post-drought recovery. Although most western states have drought plans, few states conduct post-drought or impact assessments and many states lacked indicator data at spatial and temporal scales needed for effective monitoring.[27] Our method can help provide clear and relevant drought indicators and monitor progress of drought recovery. The assessment was reactive, but also can be proactive in pointing out developing drought conditions through productivity declines.

Conclusions

This work represents an effort by the NRCS and USFS to rapidly quantify the impact of drought on vegetation production across large areas to inform a reseeding strategy for affected areas. As a result of this collaboration 1.5 million hectares (3.7 million acres) in three counties were identified as exhibiting 50% losses in production or greater. During future drought declarations, this technology may be deployed to rapidly determine the impacts of the drought and identify the hardest hit areas. Additionally, RPMS can be applied to identify areas developing drought conditions and recovering from drought. Information produced by this process can be an important component to management strategies, adding to manager expertise and drought plans.[14] When used in conjunction with other sources of information, such as drought monitors, this process provides a rapid, cost-effective, transparent solution to a long-standing problem and demonstrates a unique way that multiple agencies can team together to help producers and land managers in the western United States. This type of analysis is inherently multijurisdictional and embraces the "Shared Stewardship"[28] vision and leverages multiagency resources from the NRCS and USFS to combat the effects of drought.

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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