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DATA ARTICLE

The USA National Phenology Network's Buffelgrass Green-up Forecast map products

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Abstract

1. Buffelgrass (*Cenchrus ciliaris* syn. *Pennisetum ciliare*) was introduced to Sonoran Desert in the early 20th century and has become widespread at low elevations. This perennial bunchgrass accumulates abundant biomass that can carry fires through ecosystems not adapted to fire, resulting in devastating impacts for native cacti and other plant and animal life.
2. Buffelgrass is most effectively managed through the application of herbicide when the grass is at least 50% green. Because the grass rapidly greens up following summer monsoon rainfall, it is possible to forecast green-up using daily rainfall measurements.
3. In 2019, the USA National Phenology Network (USA-NPN) released daily Buffelgrass Green-up Forecast maps for the state of Arizona based on the PRISM 4 km daily total precipitation product. The daily digital Buffelgrass Green-up Forecast maps are a freely available data product and meet the FAIR principles of findability, accessibility, interoperability and reusability. They are permanently archived and publicly accessible as raster and image layers from the USA-NPN website.
4. These map layers support planning the timing of management activities to maximize buffelgrass treatment efficacy and researchers seeking to incorporate daily estimates of buffelgrass greenness in their analyses.

KEYWORDS
buffelgrass, Cenchrus ciliaris, forecast, Pennisetum ciliare, phenology

Spanish Abstract

1. Cenchrus ciliaris (syn Pennisetum ciliare, Buffelgrass) fue introducido en el desierto de Sonora a principios del siglo XX y ahora se distribuye ampliamente en las elevaciones bajas. Este pasto racimoso perenne acumula abundante biomasa que puede transportar incendios a través de ecosistemas que no son adaptados al fuego, lo cual resulta en tremendos impactos para los cactus nativos y otros plantas y animales.

2. C. ciliaris se controla de manera más efectiva mediante la aplicación de herbicidas cuando el pasto es al menos 50% verde. Debido a que la hierba reverdece rápidamente después de las lluvias monzónicas de verano, es posible pronosticar el reverdecimiento utilizando mediciones de lluvia diaria.
3. En 2019, la Red Nacional de Fenología de EE. UU. (USA-NPN) publicó pronósticos ecológicos de C. ciliaris para el estado de Arizona basados en el producto de precipitación total diaria de 4 km de PRISM. Los pronósticos ecológicos están disponibles gratuitamente y cumplen con los principios FAIR de búsqueda, accesibilidad, interoperabilidad y reutilización. Se archivan permanentemente y son disponibles como imágenes y rásteres desde el sitio web de la USA-NPN.
4. Los pronósticos apoyan a la planificación de las actividades de manejo para maximizar la eficacia del tratamiento del pasto C. ciliaris y los investigadores que buscan incorporar estimaciones diarias del verdor del pasto C. ciliaris en sus análisis.

1 | INTRODUCTION

Invasive species can substantially alter the functioning and diversity of ecological systems (Ehrenfeld, 2010). Buffelgrass (*Cenchrus ciliaris* syn. *Pennisetum ciliare*), a perennial grass native to Africa, was originally introduced to the Sonoran Desert in the southwestern United States and northwest Mexico for erosion control and as forage for cattle (Franklin et al., 2006). In recent decades, buffelgrass has rapidly spread throughout the southwestern United States and beyond at elevations below 3000′ (Cox et al., 1988; Franklin & Molina-Freaner, 2010). As buffelgrass abundance increases, the amount of dry biomass to fuel fires accumulates, leading to devastating impacts to ecosystems that are not fire adapted (Jarnevich et al., 2019; Olsson et al., 2012). For example, Saguaro cacti (*Carnegiea gigantea*) populations are at extreme risk from widespread fires in the region. In addition, buffelgrass invasion alongside a positive buffelgrass–fire feedback cycle results in altered ecohydrology and soil microbiomes and increases in buffelgrass dominance, leading to irreversible shifts in vegetation composition and loss of biodiversity (Castellanos et al., 2016; Gornish et al., 2020).

While buffelgrass has undergone substantial spread throughout the region, there is evidence that populations can be controlled and eliminated with sufficient targeted effort and resources. Buffelgrass is most effectively controlled through the application of broad-spectrum herbicides when the grass is green – ideally, at least 50% greenness – and prior to flowering and seed development. Wallace et al. (2016) used imagery collected by the Moderate-resolution Imaging Spectroradiometer (MODIS) satellite, climate data and in situ observations of greenness in this species to establish the amount of precipitation that must fall to result in at least 50% greenness in buffelgrass. Wallace et al. (2016) demonstrated that buffelgrass greens up more rapidly following rainfall than native vegetation. This information can be used in planning for and prioritizing lands for treatment, particularly during the summer monsoon period where the frequency and size of seasonal rainfall events are the driving factor promoting phenological shifts rather than temperature (Martin-R et al., 1995).

The USA National Phenology Network (USA-NPN) is a national-scale monitoring and research initiative that produces and distributes data, information and forecasts to support natural resource management and decision-making (Schwartz et al., 2012). The USA-NPN offers a growing suite of daily maps that support management by predicting the status of life cycle stages in important species (Crimmins et al., 2020), such as buffelgrass. To support buffelgrass management efforts in Arizona, USA, we established a workflow to generate daily digital maps indicating locations where buffelgrass will be sufficiently green to be effectively treated with herbicide. These maps use a relationship established by Wallace et al. (2016) between accumulated precipitation and buffelgrass green-up. The daily digital Buffelgrass Green-up Forecast maps are a freely available data product and meet the FAIR principles of findability, accessibility, interoperability, and reusability. They are permanently archived and publicly accessible as raster and image layers from the USA-NPN website. These maps are publicly available as image files for managers to reference in control efforts and as raster files for use by others in research and analysis.

2 | MATERIALS AND METHODS

The data product being generated daily is the current day's forecast map of anticipated green-up in buffelgrass across the state of Arizona based on sufficient accumulated precipitation. Buffelgrass Green-up Forecast maps are generated for the extent of the state of Arizona based on a rolling 24-day window of precipitation accumulation using Parameter-elevation Relationships on Independent Slopes Model (PRISM) gridded daily total precipitation layers (PRISM Climate Group, Oregon State University [http://prism.oregonstate.edu]). These products are generated to highlight both precipitation thresholds associated with 50% greenness in buffelgrass established by

Wallace et al. (2016), with the higher threshold offering a conservative value for the region.

Wallace et al. (2016) coupled precipitation data with in situ observations of buffelgrass and 8-day composites of MODIS imagery to determine that buffelgrass achieves 50% greenness after receiving sufficient rain over three 8-day periods (24 days). The amount of rain necessary to achieve at least 50% greenness in buffelgrass varied in two mountain ranges near Tucson, Arizona evaluated by Wallace et al. (2016): in the Tucson Mountains adjacent to Tucson, buffelgrass reaches 50% greenness 8–16 days after 1.0″ of rain has fallen within a 24-day period, and in the Catalina Mountains north of Tucson, buffelgrass reaches 50% greenness after 1.7″ of rain has fallen within a 24-day period. These different thresholds likely reflect differences in substrate, with the Tucson Mountains composed of mafic volcanic material and the Catalina Mountains composed of felsic granites and gneiss, as well as differences in aspect, with study sites in the Tucson versus Catalina Mountains along north and east slopes versus south and west slopes. Both thresholds are used to produce the USA-NPN's Buffelgrass Green-up Forecasts.

In a nightly process, the USA-NPN ingests the previous day's 4 km total precipitation layer for the conterminous United States from PRISM's data services. The layer is cropped to the extent of Arizona. Forecast maps are then generated by totalling precipitation values for the preceding 24 days on a pixel-by-pixel basis using raster math. Maps are presented categorically, depicting locations where the precipitation threshold for green-up has not been met (less than 1.0 inches of precipitation have fallen in the preceding 24 days), where green-up may occur in the next 8–16 days (1.0–1.7 inches of precipitation has fallen in the preceding 24 days) and where it is likely to occur in the next 8–16 days (more than 1.7 inches of precipitation has fallen in the preceding 24 days).

The Buffelgrass Green-up Forecast maps are generated using PRISM layers, which are not stable until approximately 6 months past the map date (PRISM, 2021). During the nightly process, the USA-NPN downloads precipitation layers for previous dates up to 6 months in the past. If more stable data have become available, daily Buffelgrass Green-up Forecast maps are updated accordingly. Once daily Buffelgrass Green-up Forecast maps have been regenerated using 'stable' PRISM precipitation data (PRISM, 2021), the maps are not regenerated and are maintained as a stable USA-NPN data product. Daily Buffelgrass Green-up Forecast maps are available from 1 January 2019 to present.

2.1 | Map validation

To evaluate the accuracy of the Buffelgrass Green-up Forecast maps, we compared predictions of green-up to ground observations contributed through three mechanisms: (1) *Nature's Notebook* (www.naturesnotebook.org), the USA-NPN's plant and animal phenology monitoring program (Rosemartin et al., 2014); (2) a one-time buffelgrass reporting form on the USA-NPN's website (buffelgrass.usanpn.org); and (3) iNaturalist (www.inaturalist.org) in the months of June–September 2019, 2020 and 2021.

Nature's Notebook uses 'status' protocols, meaning that on each date an observation of an individual plant or animal is made, the status of a phenophase, or life cycle stage, is recorded – 'yes' if it was occurring and 'no' if it was not (Denny et al., 2014). The protocols also incorporate measures of intensity that reflect the proportional expression of a phenophase (e.g. proportion of canopy with green leaves). Approximately half of individuals submitting observations to *Nature's Notebook* are volunteer citizen scientists and the other 50% are professionals (scientists, researchers, agency professionals).

The one-time buffelgrass reporting form was developed as an alternative way for acquiring reports of buffelgrass greenness status because repeated observations of an individual plant over the season – as is encouraged through *Nature's Notebook* – are not possible or practical for plants that are treated with herbicide once they are located. This simple form asked observers to report the location of the plant under observation, the date of the observation, whether leaves were present on the plant under observation and the percentage of the plant that is green (<5%, 5%–24%, 25%–49%, 50%–74%, 75%–94% or 95% or more). At the beginning of the 2020 season, representative photographs for each buffelgrass greenness category were added to the form to aid observers.

Observations of buffelgrass contributed to *Nature's Notebook* and the one-time buffelgrass reporting form were classified as either <50% green or >50% green based on the intensity category reported by observers.

We also accessed all available observations with photos of buffelgrass documented through the iNaturalist nature app for the summer monsoon period (15 June to 30 September) of 2019 and 2020. For each photo where the majority of the plant was visible, we assessed the percentage of the plant that is green following the method used for *Nature's Notebook* described above (either <50% green or >50% green).

To evaluate forecast performance, we compared observations of buffelgrass greenness as reported to *Nature's Notebook*, the one-time buffelgrass reporting form, and iNaturalist to the forecasts made for the date on which the observations were collected. We compared forecast predictions of green-up to 113 observations contributed to *Nature's Notebook*, 96 observations contributed through the one-time buffelgrass reporting form and nine observations contributed to iNaturalist. An observation was for a single plant on a single date. In all, we compared observations to forecasts on 124 unique dates (45 in 2019, 49 in 2020 and 30 in 2021). Observations were concentrated in the Tucson, Arizona, region. Points were classified as true positives, where the grass was predicted to be green and reported green; false positives, where the grass was predicted to be green and reported not green; true negatives, where the grass was predicted to not be green and was reported not green; and false negatives, where the grass was predicted to not be green and was reported green. Accuracy was calculated as (true positives + true negatives) / total observations.

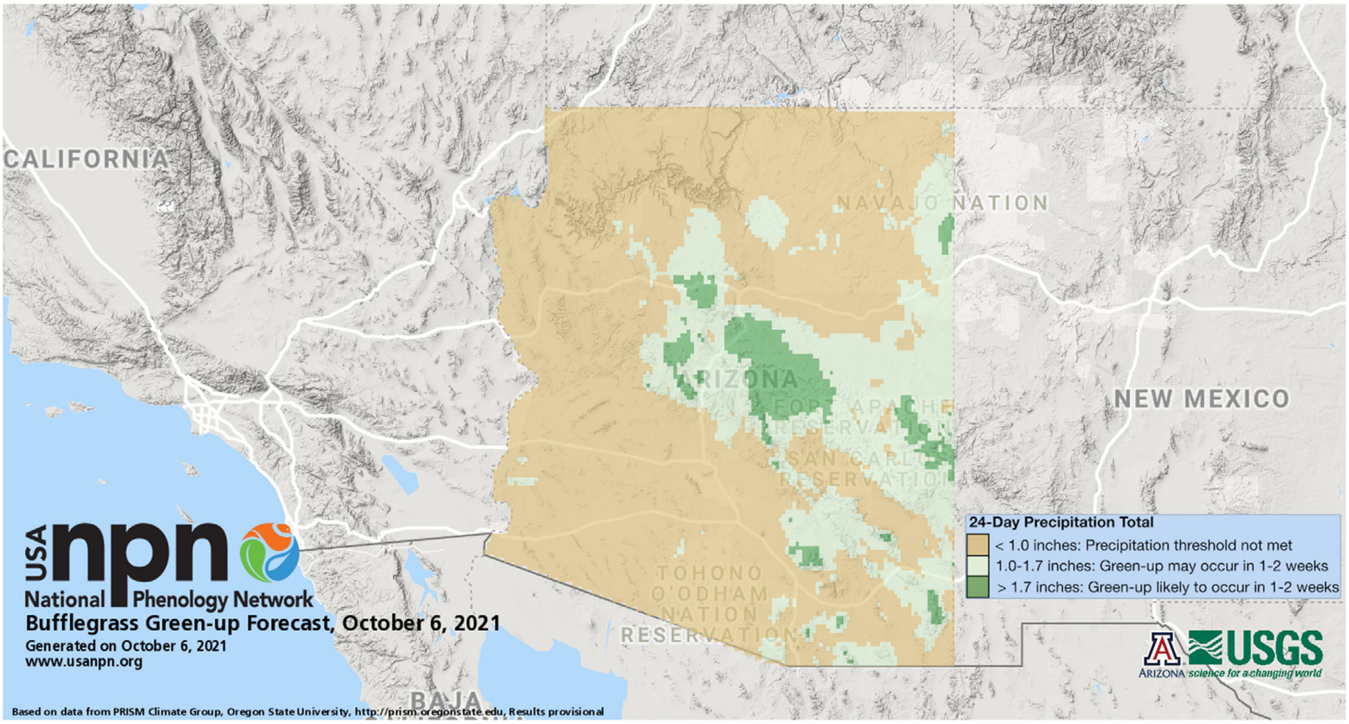

FIGURE 1 Buffelgrass Pheno Forecast Map for 6 October 2021 reveals where the precipitation threshold for 50% green-up in buffelgrass has not been met (tan), where green-up may occur in next 1–2 weeks (light green) and where it is likely to occur in the next 1–2 weeks (dark green)

TABLE 1 Agreement between in situ buffelgrass observations and USA-NPN buffelgrass greenness forecasts

	7 days forecast					14 days forecast				
	True positives	False positives	True negatives	False negatives	Accuracy	True positives	False positives	True negatives	False negatives	Accuracy
2019	7	23	26	22	56%	7	10	36	32	58%
2020	0	0	12	69	20%	0	0	12	67	23%
2021	38	0	12	4	93%	27	1	11	15	72%

Note: True positive – predicted green, reported green; false positive – predicted green, reported not green; true negative – predicted not green, reported not green; false negative – predicted not green, reported green. Accuracy calculated as (true positives + true negatives) / total observations.

3 | USAGE NOTES

All code used to generate the maps is available on the USA-NPN repository at https://github.com/usa-npn/gridded_models and is archived in Switzer and Marsh (2021).

4 | GENERAL PATTERNS

4.1 | Buffelgrass green-up forecasts

Maps show, on a daily basis and at 4-km spatial resolution, locations where the precipitation threshold for 50% green-up in buffelgrass has not been met (tan), where green-up may occur in next 1–2 weeks (light green) and where it is likely to occur in the next 1–2 weeks (dark green; Figure 1).

Spatial and temporal patterns in green-up depicted in the daily forecast maps clearly reflect patterns in rainfall preceding the date for which the map is generated.

4.2 | Forecast validation performance

When Buffelgrass Greenness Forecasts were compared with ground observations of buffelgrass greenness status, agreement varied. In general, forecasts suffered from a higher rate of false negatives, where forecasts failed to predict green-up in plants that was reported by observers, than by false positives (Table 1).

We expect that the high rate of false negatives is the result of many of the ground observations originating along roadsides and near paved paths. Buffelgrass frequently grows in road medians and along road edges, and because of surface runoff from impervious surfaces, the plants on roadsides are far more frequently green than plants near but not in close proximity to road edges (J. Rogers, pers. comm., 2020). Because plants along roadsides and paved paths are readily observed, they are more likely to be reported. Forecast accuracy was highest in 2021 and lowest in 2020 (Table 1). Summer precipitation was especially low in both 2019 and 2020, the years with the lowest accuracy values, in the Tucson area. Specifically, summer 2019 was the second hottest on record, with only a little over half of the average summer rainfall (National Weather Service, 2019), and summer 2020 was the hottest and seventh driest on record, receiving only 35% of average summer rainfall (National Weather Service, 2020). In contrast, forecast accuracy was much higher in 2021, which was the second wettest summer on record (National Weather Service, 2021). It appears that in years with very limited precipitation, the maps frequently predict a lack of green-up in the plants, regardless of their location. Because buffelgrass plants situated on roadsides benefit from concentrated runoff, the Buffelgrass Green-up Forecasts can underpredict greenness in these plants. Forecast accuracy could likely be improved by validating the maps with points collected farther from road edges. Low accuracy rates may also be the result of the coarse resolution of the daily precipitation data layers used to generate the forecasts. Summer monsoon precipitation events in the Sonoran Desert are highly spatially variable and events can be much smaller than the 4-km resolution of the PRISM precipitation data used in the Buffelgrass Green-up Forecast maps (Comrie & Broyles, 2002). In addition, interpolated products such as gridded precipitation data maps can vary in accuracy as a result of factors such as elevation, coastal effects, slope and aspect, riparian zones and land use/land cover that complicate estimation across space (Daly, 2006; Daly et al., 2008). Finally, the simple moving window model for predicting buffelgrass green-up may not fully account for the nuance in soil moisture necessary to plants to trigger green-up.

Despite the limitations of the forecasts, local land managers have shared that they use the maps to plan their treatment activities (Rosemartin et al., under revision). These maps were created in response to managers' requests for such a product. At present, they simply depict accumulated rainfall amounts and highlight two thresholds, allowing managers to calibrate these data to their specific landscape. Future efforts to improve the maps could address several current limitations, including low forecast accuracy in close proximity to road edges and coarse precipitation data. In addition, it would also be worth further evaluating the generality of the two precipitation thresholds established by Wallace et al. (2016) across broader geographic areas and considering the role that additional variables such as substrate, aspect and temperature might play in triggering greenness.

5 | RELATED WORKS

Interaction with land managers and stakeholders that inspired the creation of the Buffelgrass Greenup Forecasts is described in Rosemartin et al. (under revision). The workflow implemented in the generation of the USA-NPN's Buffelgrass Green-up Forecast maps follows that used to generate short-term forecasts of insect pest activity based on gridded daily minimum and maximum temperature maps, described in Crimmins et al. (2020).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

TMC, KLG, EEP and CSAW conceived the maps. RLM and JS developed the maps. TMC and EEP collected ground observations. TMC performed validation analyses. TMC led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

All data offered by the USA National Phenology Network are freely available for unrestricted use under a Creative Commons 4.0 (Attribution License). The map layers are publicly accessible through a number of mechanisms to maximize accessibility and usability. The USA-NPN's Buffelgrass Greenup Forecast map layers (2018–present) can be accessed and downloaded as raster files using the R package *rnpn* v1.1.1 (Marsh et al., 2020) and the USA-NPN's Geoserver Request Builder, an online raster query interface (www.usanpn.org/geoserver-request-builder); when accessed through these mechanisms, the layers are referred to as 'Pheno Forecasts, Buffelgrass'. The maps can also be accessed as image files via the USA-NPN website (www.usanpn.org/data/forecasts/Buffelgrass). Regardless of the access mechanism used, users will receive the same data layer for the same date.

The layers are stored on physical servers maintained by USA-NPN and backed up to Amazon Web Services.

Metadata for these layers is stored at ReDATA (USA National Phenology Network, 2021).

PEER REVIEW

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