Estimating rangeland fractional cover and canopy gap size class with Sentinel-2 imagery

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Abstract

Rangelands are extensive ecosystems, providing important ecosystem services while undergoing continuous change. As a result, there is a need for improved monitoring technologies that better characterize vegetation changes over space and time. Satellite remote sensing has proven effective in this regard, tracking vegetation dynamics at both broad and fine scales. Advancements in technology provide the opportunity to improve monitoring efforts and to better capture subtle yet ecologically significant changes. We leveraged the enhanced spatial, spectral, and temporal resolution of Sentinel-2 satellites to estimate fractional cover and the size distribution of plant inter-canopy gaps across rangelands of the western United States. We developed a one-dimensional convolutional neural network, trained on extensive field data, to predict cover of plant functional types and select genera, and canopy gap size classes. We produced annual, 10 m resolution estimates from 2018 to 2024, providing an unprecedented resource for monitoring rangeland condition and assessing the effectiveness of management strategies.

Background and Summary

Rangelands are diverse, heterogeneous ecosystems that contain a variety of plant communities, including grasslands, shrublands, woodlands, and savannas. Covering approximately half the earth's land surface[1], rangelands support a wide array of biodiversity and provide important ecosystem services. Due to their vast coverage and use by humans, monitoring rangeland conditions has been a primary objective for decades[2]. Since the beginning of satellite remote sensing, scientists and engineers have actively pursued mapping and quantifying rangelands at broad scales[3–6]. In recent years, research has focused on estimating fractional cover, i.e., estimating the proportion of an area (commonly the area of a pixel) covered by vegetation or other land cover types[7,8]. Compared to traditional categorical or thematic vegetation classifications, fractional cover estimates better represent the sub-pixel complexity and landscape heterogeneity that dominates rangelands and have become a standard indicator for monitoring ecological state change and the effectiveness of management strategies[9].

Decomposition and unmixing methods successfully produced fractional cover estimates of general cover classes, including photosynthetically active and inactive vegetation[10–12]. The increased collection of vegetation data across broad scales–particularly in the United States–resulted in the ability to empirically model fractional cover and similar metrics[13]. Estimates may be aggregated to specific plant functional types/groups, genera, or remain at the individual species level[14–16]. While the use of satellite imagery is widespread and permits estimates across spatiotemporal scales, aerial imagery can also be used to produce finer resolution cover estimates[17,18], albeit with limited spatial and temporal scope. While empirical methods vary, regression trees and neural networks are frequently employed due to their robustness and ability to successfully learn diverse metrics[19,20].

Rangeland fractional cover estimates (at broad scales) have historically been derived from the MODIS and Landsat satellite collections[12,15]. While images from these collections are now considered spatially coarse (250 m and 30 m spatial resolution, respectively), their advantage is an unmatched historical record that permits unique time series analysis[21–23]. Newer satellites and sensors, however, offer improvements that enable the detection of more subtle changes in rangeland condition and facilitate the exploration of new research and management questions. The Sentinel-2 mission currently consists of three satellites (2A launched June 2015, 2B launched March 2017; 2C launched September 2024 and is planned to replace 2A), producing optical imagery at a finer spatial resolution of 10 to 60 m and at a shorter nominal revisit time of 10 days. An increased number of spectral bands, combined with finer resolution and quicker revisit times (relative to Landsat satellites), may improve fractional cover estimates over rangelands and provide greater understanding of both ecological processes and the impacts of land management.

While fractional cover provides valuable information regarding rangeland vegetation, it does not fully capture the spatial arrangement of plants. Canopy gap, which quantifies the size and distribution of openings between plant canopies, is an important indicator for many ecosystem processes, including wind erosion, water infiltration, and wildlife habitat[24,25]. Estimating canopy gap distributions alongside fractional cover of plant functional types may improve the characterization of rangeland vegetation structure and increase the value of these datasets for understanding and responding to structural ecosystem change.

We explored the use of Sentinel-2 satellites in estimating fractional cover across the United States. We built upon the methods and models from Allred et al.[19] and constructed a model to estimate the fractional cover of common plant functional types and select genera, and to estimate canopy gap size classes. Using this model, we produced estimates characterizing rangeland vegetation, soil, and canopy gap cover across the western United States for the time period 2018 through 2024.

Methods

Vegetation data

We used field data collected by various programs across the conterminous United States (CONUS; Table 1) to train a model capable of estimating fractional cover and canopy gaps. Vegetation was sampled on private and public rangelands using line point intercept (LPI) and canopy gap methods in 47 states within CONUS. Species cover, litter cover, and bare soil were calculated using LPI first hit and aggregated into various plant functional types or genera (Table 2; Figure 1). Canopy gaps were measured and aggregated into classes (Table 2; Figure 2). We limited vegetation data to years 2018 through 2024 (Figure 3), corresponding with the bulk of the Sentinel-2 satellite record in the United States. We only used samples in which vegetation cover and canopy gap measurements were available. We used the R package terradactyl[26] for cover and gap calculations. Stratifying by US state and year of vegetation data collection, we

divided vegetation data into training, validation, and testing sets (85%, 5%, and 10%, respectively); we used a total of 47,833 vegetation samples aggregated and harmonized in the Landscape Data Commons[13].

We aimed for our model to provide estimates in naturally vegetated areas only, excluding areas that were cropland, developed, or water. While this can be accomplished after the fact through pixel masking, we wanted our model to be independent and self-reliant. Ideally, our rangeland dataset would be combined with a cover dataset representing these additional areas (i.e., croplands, developed, and water) for our time period and spatial resolution; sadly, no such dataset exists. To substitute, we used additional data from the Cropland Data Layer[27], a medium-resolution (30 m) classification dataset that covers the United States. Stratifying across years 2018 through 2022, we randomly selected point locations across CONUS that were classified as cultivated, developed, or open water. To match the continuous measurements of the vegetation data, each location was given a value of 100 according to its classification (i.e., cultivated croplands, development, or water) and a value of 0 for all other groups. While simplistic, the inclusion of these data were to inform the model what is not rangeland, not to accurately estimate fractional cover in cropland, developed, or water areas. This additional dataset was separated into training, validation, and testing (85%, 5%, and 10%, respectively); we used a total of 9,938 additional samples and combined them with the vegetation data.

Satellite data

We used Sentinel-2 (satellites 2A and 2B) top of atmosphere reflectance as satellite input. We masked pixels with a Cloud Score+[28] usability value less than 0.65. For a given calendar year, we created 29 sequential 10-day timesteps, beginning on day of year 041 and ending on day 330, to best capture the growing season and to limit data processing. For each timestep, we calculated the median reflectance value for the visible (bands 2-4), near infrared (bands 5-8), and short wave infrared (bands 11-12) bands. Missing reflectance values within a timestep (due to clouds or missing data) were filled using forward fill (i.e., the value from the previous timestep). Reflectance values were natural log normalized. We also calculated the normalized difference vegetation index (NDVI) and normalized burn ratio two (NBR2) using standard formulas. Sentinel-2 bands at resolutions greater than 10 m were resampled to 10 m using nearest neighbor. Spatial location (X,Y coordinates) was calculated in an equal area coordinate reference system (EPSG:5070) and normalized between zero and one using the maximum and minimum coordinates of CONUS. Image processing was performed in Google Earth Engine[29].

Model

We employed a one-dimensional convolutional neural network (1D CNN) architecture, generally following the approach outlined in Allred et al.[19], with modifications to the temporal sequence and the number of units in certain layers. The input features consisted of the log normalized reflectance values, reflectance vegetation indices, and spatial location (X,Y coordinates). We processed reflectance values and vegetation indices through two separate convolutional streams. Each stream had three consecutive 1D convolutional layers with 64 units, a kernel

width of three, rectified linear unit (ReLU) activation, and dilation rates increasing exponentially from one to four with each successive layer. A dropout layer with a dropout rate of 0.2 was applied after each convolutional layer. Final convolutional layers were reduced using average pooling and concatenated, along with a dense layer output of spatial location information. This combined vector was passed through a dense layer with 512 units, followed by a dropout layer of rate 0.2. The final layer contained 16 units with linear activation. We trained the model with a loss of mean squared error, a learning rate of 0.0001, an Adam optimizer, and a batch size of 64. Model performance was evaluated with root mean square error (RMSE), mean absolute error (MAE), and the coefficient of determination (r^2) of the testing dataset.

Data Records

Fractional cover and canopy gap estimates were produced for the western United States. Data are available as GeoTIFFs at http://rangeland.ntsg.umt.edu/data/rangeland-s2/. GeoTIFFs are estimates of fractional cover or canopy gap, and stored as 8-bit integers, with a no data value of 255. Dataset size is approximately 2 TB.

Technical Validation

Model performance

We produced a robust model for rangeland fractional cover and canopy gap sizes. Performance metrics revealed good model fit and strong relationships between predicted and observed values (Table 3; Figures 4 and 5). Overall model performance was similar to or better than Landsat-based predictions of the same plant functional types from the Rangeland Analysis Platform cover dataset (v3), with RMSE of annual forb and grass, perennial forb and grass, shrub, and tree decreasing 1.6, 1.3, 1.0, and 0.4, respectively; MAE of the same groups decreased 1.6, 2.2, 1.2, and 0.3, respectively. Relative to an independent evaluation of the same dataset[30], RMSE of annual forb and grass, perennial forb and grass, shrub, and tree decreased 1.3, 1.8, 1.9, and 1.0, respectively; MAE of the same groups decreased 1.3, 2.0, 2.0, and 0.7, respectively. RMSE of canopy gap size classes 25-50 cm and >200 cm decreased by 0.9 and 2.2, respectively, compared to available Landsat-based predictions[16].

Usage Notes

We developed a model capable of producing fractional cover and canopy gap estimates across United States rangelands at an unprecedented 10 m spatial resolution. The greater spatial, temporal, and spectral resolution of Sentinel-2 imagery improves the monitoring of common plant functional types (i.e., forbs and grasses, shrubs, and trees) as well as more specific vegetation groups. The inclusion and improvement of estimates for sagebrush, invasive annual

grasses, pinyon-juniper, and canopy gap–all in a single model–presents a significant step forward in the ability to monitor rangeland vegetation structure and composition.

A key strength of Sentinel-2 lies in its ability to capture finer scale spatiotemporal heterogeneity. The 10 m spatial resolution allows for improved detection of small yet ecologically significant features, such as subtle changes in vegetation composition, isolated shrub or tree patches, or management actions (e.g., Figures 6 and 7). These details, which are often lost at coarser resolutions, can help inform condition assessments and management decisions. For example, managers can use improved and finer resolution estimates to evaluate the effectiveness of invasive species treatments[31], reclamation efforts[32], and other management actions. Moreover, the more frequent revisit time of Sentinel-2 satellites provides greater temporal resolution, enhancing the ability of the model to use phenology and other temporal dynamics in distinguishing vegetation characteristics. This may be particularly important for vegetation groups such as invasive annual grasses, encroaching coniferous trees, or shrubs which often have very different phenologies compared to surrounding vegetation.

Important considerations

While this model represents an advancement in estimating fractional cover and canopy gap, it is crucial for users to understand limitations and employ the data responsibly. These considerations are not shortcomings of the model itself, but rather factors to account for when interpreting and applying the data.

The Sentinel-2 imagery used in this model covers a relatively recent time period. For analyses requiring long-term historical trends, datasets based on Landsat imagery[16,19,33] may be more appropriate. While harmonization between Sentinel-2 and Landsat-derived cover estimates is a promising area of research, the exploration and testing of such work has yet to be completed.

While the model demonstrates strong overall performance, certain vegetation groups presented unique challenges. Understanding these challenges is vital for accurate interpretation.

Distinguishing sagebrush from other shrub species, particularly rabbitbrush (*Ericameria nauseosa*) in the Great Basin, proved challenging, sometimes leading to overestimation of sagebrush (but see also Figure 4). Conversely, we noticed good discrimination between sagebrush and greasewood (*Sarcobatus vermiculatus*) in the Great Basin, whereas in the Northern Great Plains, the model struggled to differentiate sagebrush from greasewood, particularly in riparian areas. Critically, sagebrush estimates are only reliable within the known sagebrush biome[34,35]; estimates outside this range should be interpreted with caution and considered uncertain.

Invasive annual grasses often have unique characteristics compared to native annual or perennial grasses that lend themselves to identification with satellite remote sensing, for example earlier green up and senescence, multiple germinations or die-off, and increased response to precipitation[36–38]. Care should be taken, however, to corroborate that native annual

forbs and grasses are not being misidentified as invasive. For example, in very dry years in the Great Plains, the native annual grass *Vulpia octoflora* can exhibit similar growth patterns as invasive annual grasses, and we noticed that large patches of *V. octoflora* were sometimes categorized as invasive annual grass. Comparing predictions of invasive annual grass cover to annual forb and grass cover, and to local expertise and knowledge, may help mitigate misidentification.

Pinyon-juniper woodlands are notoriously difficult to characterize with satellite data[39–41]. The model captures general spatiotemporal trends in pinyon-juniper cover, but the estimates should not be interpreted as a definitive presence/absence of pinyon-juniper. Therefore, estimates are only valid within established pinyon-juniper ranges[42]. Predictions of pinyon-juniper cover in dry forests, semidesert shrublands, or ecotones between these systems and pinyon-juniper woodlands should be treated with caution; for example, the model estimates cover of pinyon-juniper throughout the dry forests of the central Sierra-Nevada mountains where pinyon-juniper is generally absent.

Due to the model's methodology and species aggregation (see Table 1), understory herbaceous or woody vegetation may not be well-represented, especially in areas with dense overstory canopies (e.g., southern Texas Tamaulipan thornscrub, Rocky Mountain forests). Additionally, users should be aware that woody vegetation groups (shrubs and trees) may exhibit year-to-year variability, between or within groups, potentially due to noise. Thus it may be helpful for the user to examine and combine woody vegetation groups to better understand variability.

Riparian and wetland areas also presented unique challenges. Mischaracterization of vegetation (e.g., attributing herbaceous cover to trees or shrubs) and nonsensical estimates (e.g., attributing vegetated areas to developed) were observed in some cases. These challenges are partly due to riparian and wetland areas exhibiting unique phenological patterns compared to upland systems, with different timing of green-up, senescence, and vegetative responses to seasonal changes[43]. Because these systems are often under-sampled in field surveys, the model's understanding of their dynamics may be limited. Careful inspection of the data in these areas, informed by local expertise, is essential.

Best practices

These considerations highlight the importance of using these data in conjunction with other sources, including local knowledge, field data, and other relevant information. Integrating diverse data sources is crucial for accurate interpretation and informed decision-making[44]. By understanding the model's capabilities and limitations, and by applying local expertise, users can effectively leverage these data for rangeland management and research.

Code Availability

The model architecture and weights are available on GitHub (https://github.com/allredbw/rangeland-s2-cover-gap).

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Contributions

Allred performed data retrieval, modeling, testing, inference, and wrote the manuscript. McCord performed data retrieval, testing, and wrote the manuscript. Morford performed testing and wrote the manuscript. Assal, Bestelmeyer, Boyd, Brooks, Cady, Fuhlendorf, Green, Harrison, Jensen, Kachergis, Mattilio, Mealor, Morford, Naugle, O'Leary, Olsoy, Peirce, Reinhardt, Shriver, Smith, Tack, A. Tanner, E. Tanner, Twidwell, and Webb performed testing, assisted with the manuscript, and provided intellectual guidance.

Ethics declarations

Competing interests

The authors declare no competing interests.

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Tables

Table 1. Datasets used for model training. Vegetation data were collected using line point intercept methods and span private and public rangelands across the conterminous United States.

Program / Source	**Number of samples**
Bureau of Land Management Assessment, Inventory, and Monitoring[45]	39,024
Bureau of Land Management Assessment, Inventory, and Monitoring - Riparian and Wetland[46]	407
Bureau of Land Management Beartrap RX Burn Monitoring Data	6
United States Forest Service Crooked River National Grassland Ecological Site Descriptions	19
Jornada Experimental Range	200
Nevada Department of Wildlife	304
National Park Service Inventory and Monitoring	224
Natural Resources Conservation Service National Resources Inventory[47]	7,318
National Wind Erosion Research Network	109
University of Idaho Rinker Rock Creek Ranch	58
United States Geological Survey Post Fire Paired Plots[48]	164
National Agricultural Statistics Survey Cropland Data Layer[27]	9,938

Table 2. Categories and descriptions of fractional cover predictions and data sources.

Fractional cover category	**Description**	**Source**
Annual forb and grass	The cover of annual forbs and grasses in the sampling plot, not including forbs and grasses that have cover above them.	Vegetation field data
Bare ground	The cover of soil that has no additional cover above it. Rocks, mosses, and lichens are not included in this category.	Vegetation field data
Litter	The cover of total litter, both herbaceous and woody, in the sampling plot, not including litter that has cover above it.	Vegetation field data
Perennial forb and grass	The cover of perennial forbs and grasses in the sampling plot, not including forbs and grasses that have cover above them.	Vegetation field data
Shrub	The cover of shrubs and sub-shrubs in the sampling plot, not including shrubs that have cover above them.	Vegetation field data
Tree	The cover of trees in the sampling plot, not including trees that have cover above them.	Vegetation field data
Invasive annual grass	The cover of *Bromus tectorum, B. arvensis, B. rubens, B. hordeaceus, Eremopyrum triticeum, Schismus spp., Taeniatherum caput-medusae,* and *Ventenata dubia* in the sampling plot, not including these species that have cover above them.	Vegetation field data
Pinyon-juniper	The cover of *Juniperus monosperma, J. occidentalis, J. osteosperma, J. scopulorum, Pinus edulis,* and *P. monophylla* in the sampling plot, not including these species that have cover above them.	Vegetation field data
Sagebrush	The cover of *Artemisia arbuscula, A. cana, A. nova, A. tridentata,* and *A. tripartita* in the sampling plot, not including these species that have cover above them.	Vegetation field data
Canopy gap		
Gaps 25-50 cm	The percentage of the sampling plot's soil surface covered by gaps between perennial and annual plant canopies that are from	Vegetation field data

	25-50 cm in size.	
Gaps 51-100 cm	The percentage of the sampling plot's soil surface covered by gaps between perennial and annual plant canopies that are from 51-100 cm in size.	Vegetation field data
Gaps 101-200 cm	The percentage of the sampling plot's soil surface covered by gaps between perennial and annual plant canopies that are from 101-200 cm in size.	Vegetation field data
Gaps > 200 cm	The percentage of the sampling plot's soil surface covered by gaps between perennial and annual plant canopies that are greater than 200 cm in size.	Vegetation field data
Other		
Cropland	Value of 0 or 100% cultivated cropland cover, determined by the USDA NASS Cropland Data Layer.	Cropland Data Layer
Developed	Value of 0 or 100% developed, determined by the USDA NASS Cropland Data Layer.	Cropland Data Layer
Water	Value of 0 or 100% water, determined by the USDA NASS Cropland Data Layer.	Cropland Data Layer

Table 3. Model performance metrics (mean absolute error, MAE; root mean squared error, RMSE; coefficient of determination, r^2). Metrics were calculated using testing data (10%) held out from training and validation. Coefficients of determination were omitted for cropland, developed, and water as there were only two possible observed values and provided little relevance.

Category	**MAE (%)**	**RMSE (%)**	**r^2**
Annual forb and grass	5.4	9.4	0.60
Bare ground	5.9	9.6	0.71
Litter	4.9	7.4	0.52
Perennial forb and grass	8.0	12.7	0.76
Shrub	5.0	7.8	0.64
Tree	2.3	6.3	0.67
Sagebrush	3.2	5.6	0.64
Invasive annual grass	3.4	7.1	0.60
Pinyon-juniper	1.3	4.1	0.65
Gaps 25-50 cm	2.6	3.9	0.50
Gaps 51-100 cm	3.3	4.9	0.58
Gaps 101-200 cm	3.7	5.8	0.57
Gaps > 200 cm	6.6	12.2	0.65
Cropland	2.2	10.1	-
Developed	2.5	10.6	-
Water	0.7	5.7	-

Figures

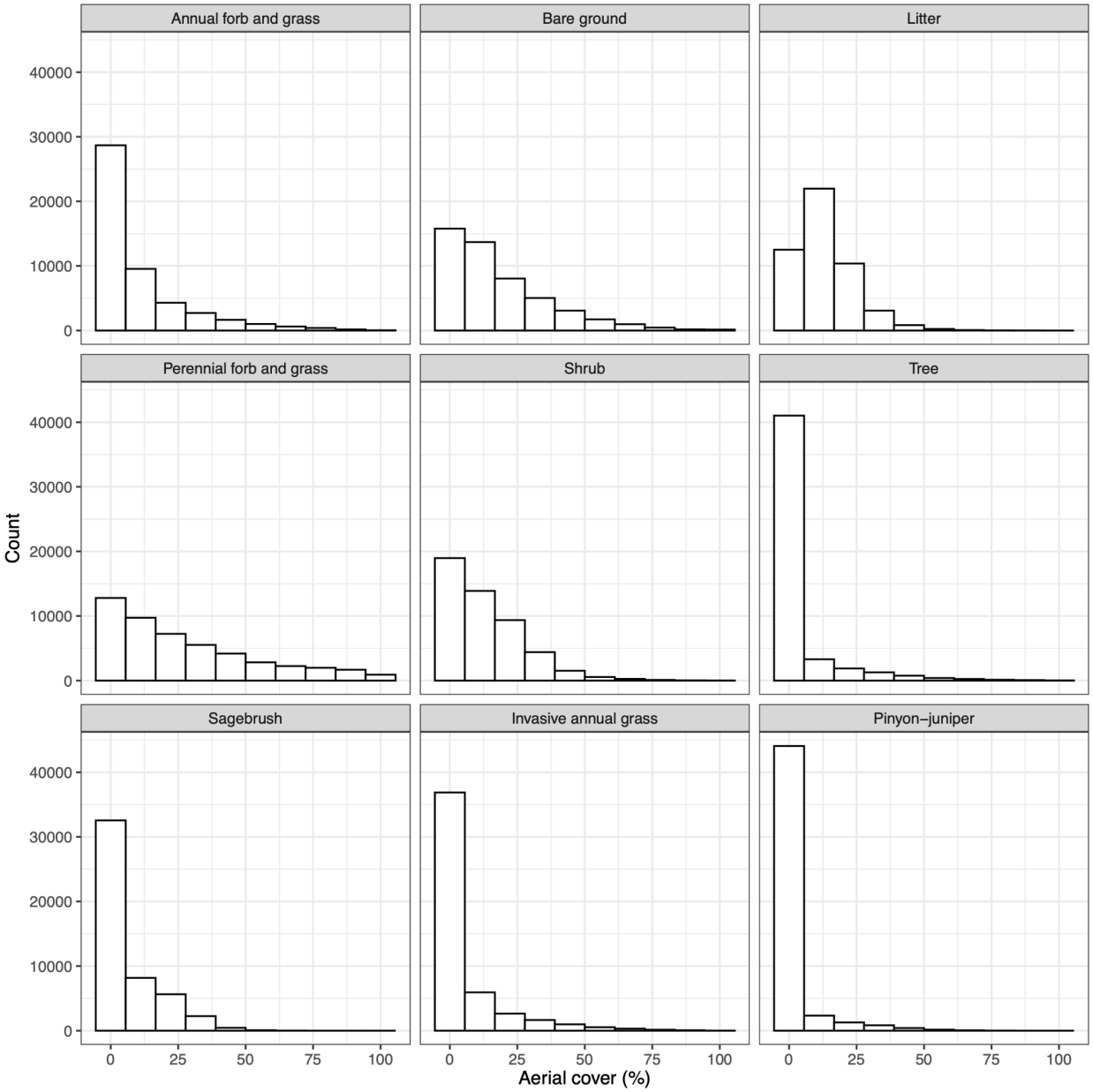

Figure 1. Frequency of cover measurements for the vegetation field data. Vegetation categories are described in Table 2.

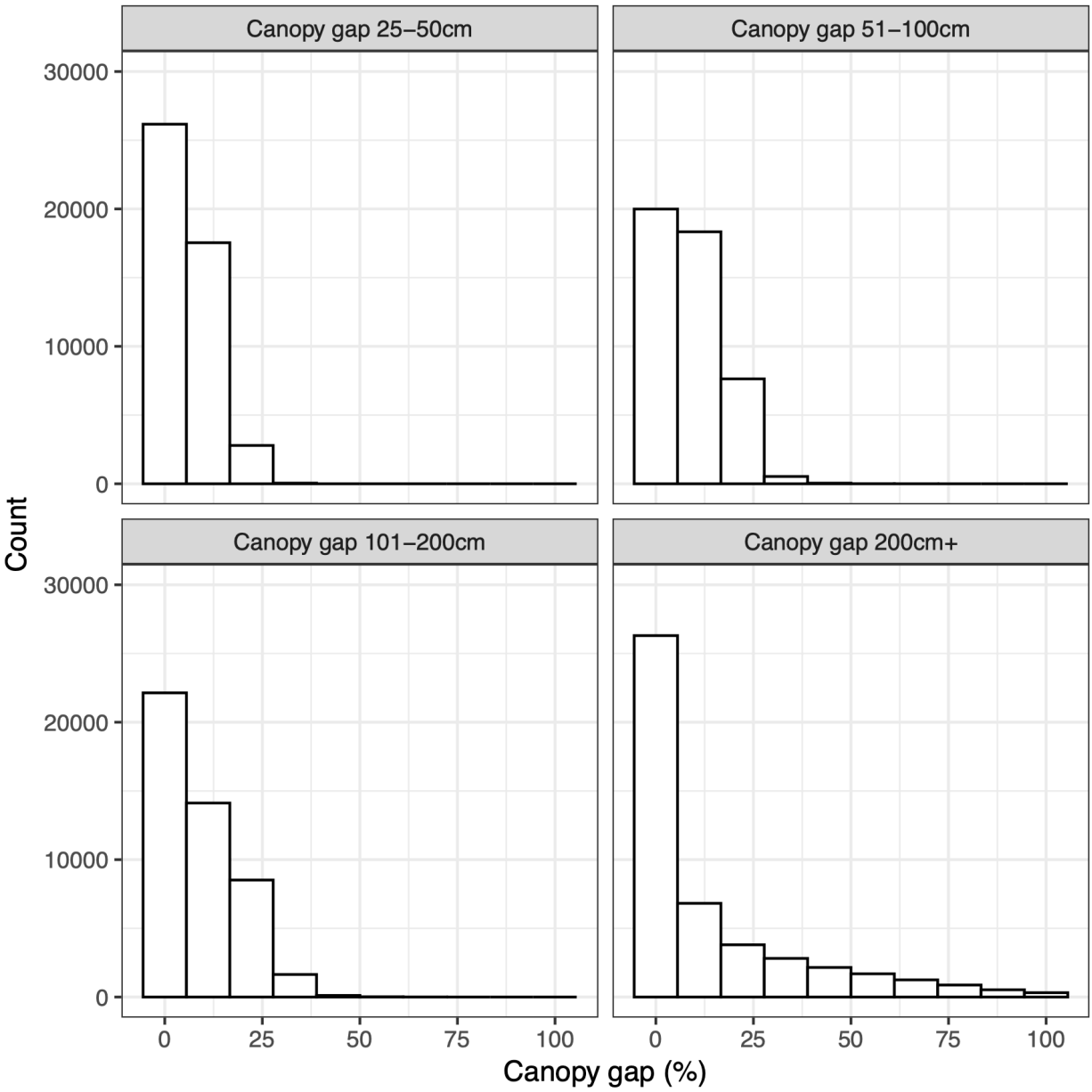

Figure 2. Frequency of canopy gap measurements for the vegetation field data. Canopy gap classes are described in Table 2.

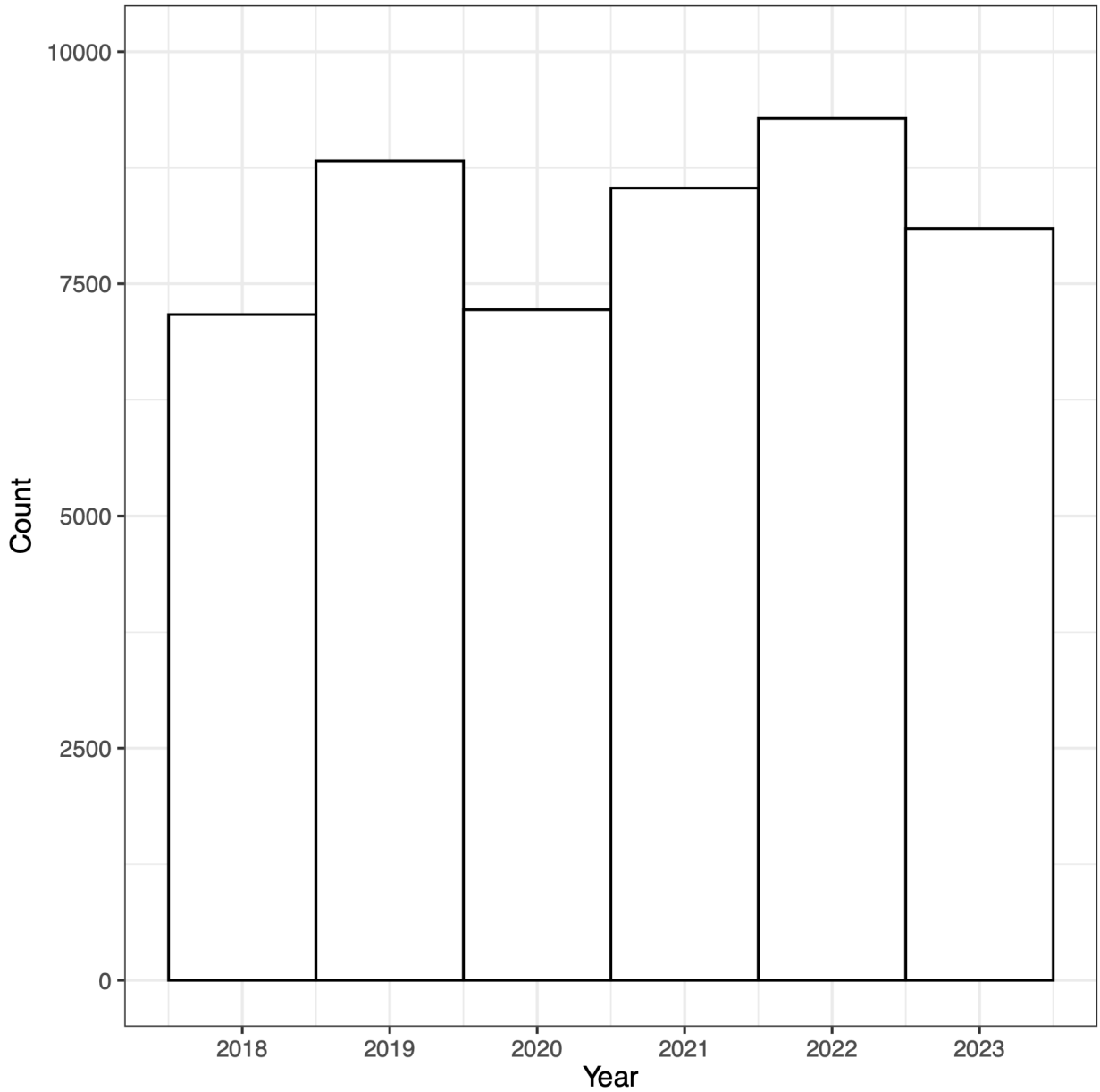

Figure 3. Temporal distribution of sampling plots from the vegetation field data used in model training. Vegetation datasets are listed in Table 1.

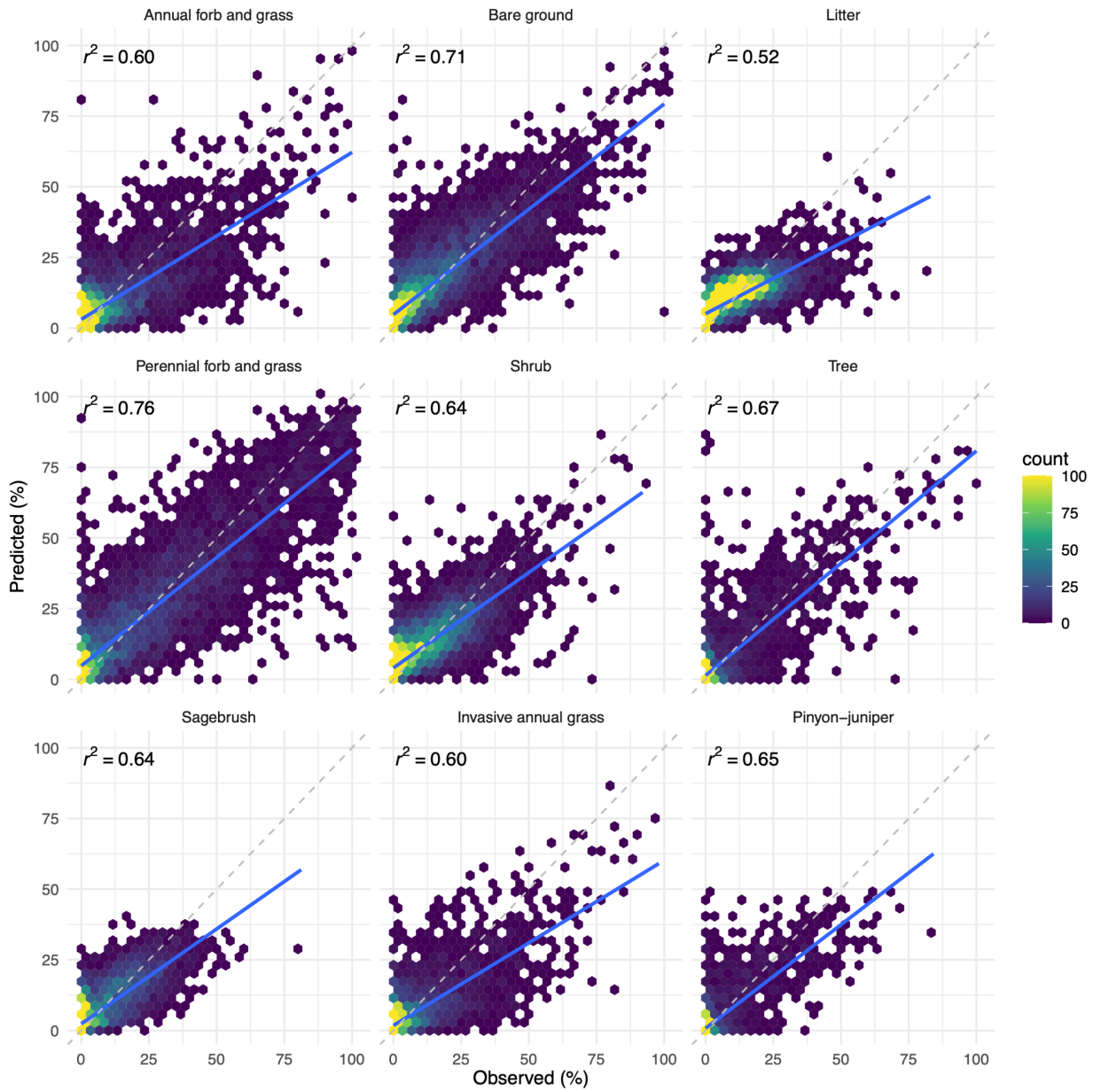

Figure 4. Predictions of fractional cover relative to observed for the testing set. The dashed gray line represents a 1:1 relationship; the solid blue line is the linear fit between predicted and observed. See also Table 3.

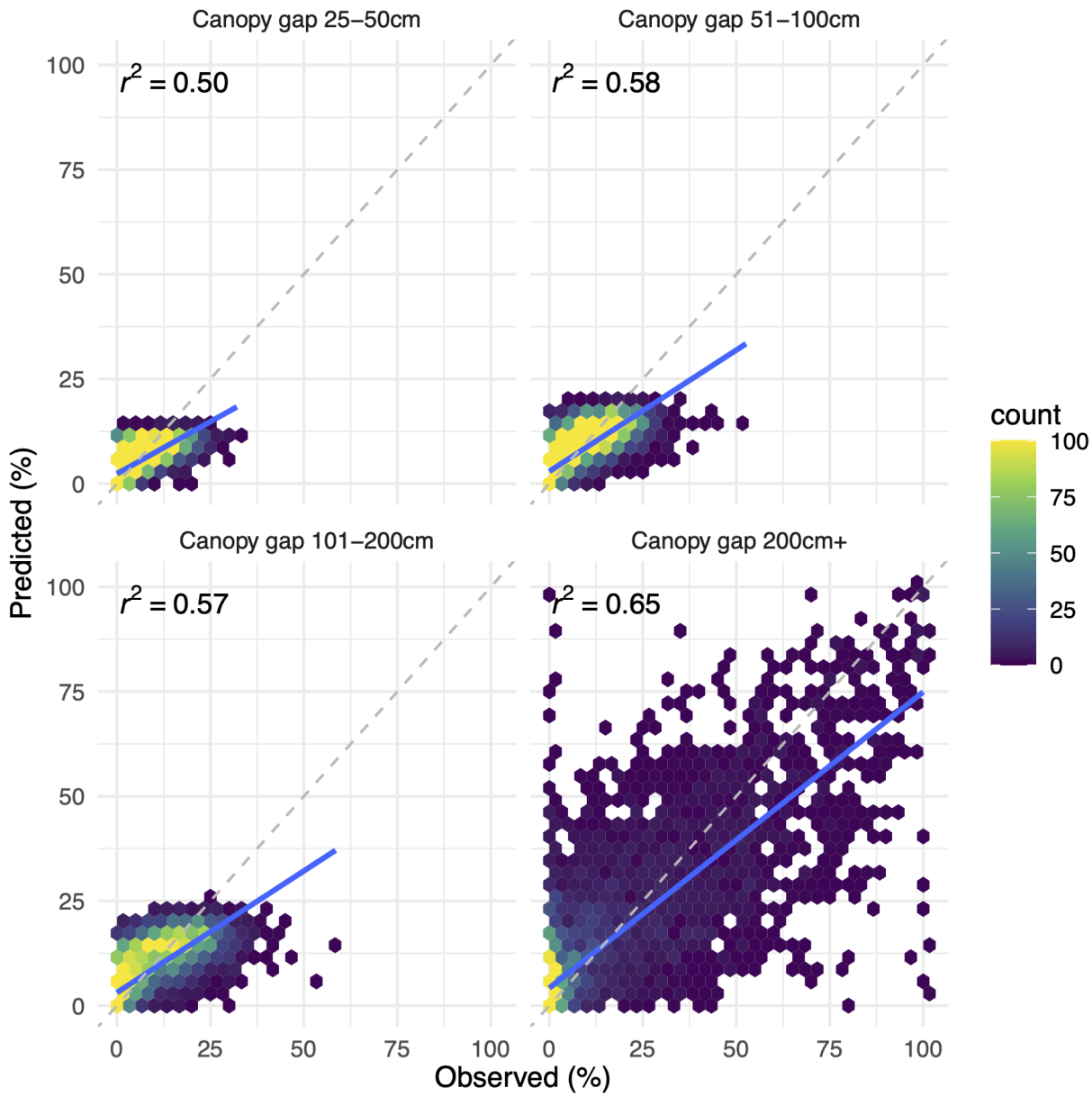

Figure 5. Predictions of canopy gap relative to observed for the testing set. The dashed gray line represents a 1:1 relationship; the solid blue line is the linear fit between predicted and observed. See also Table 3.

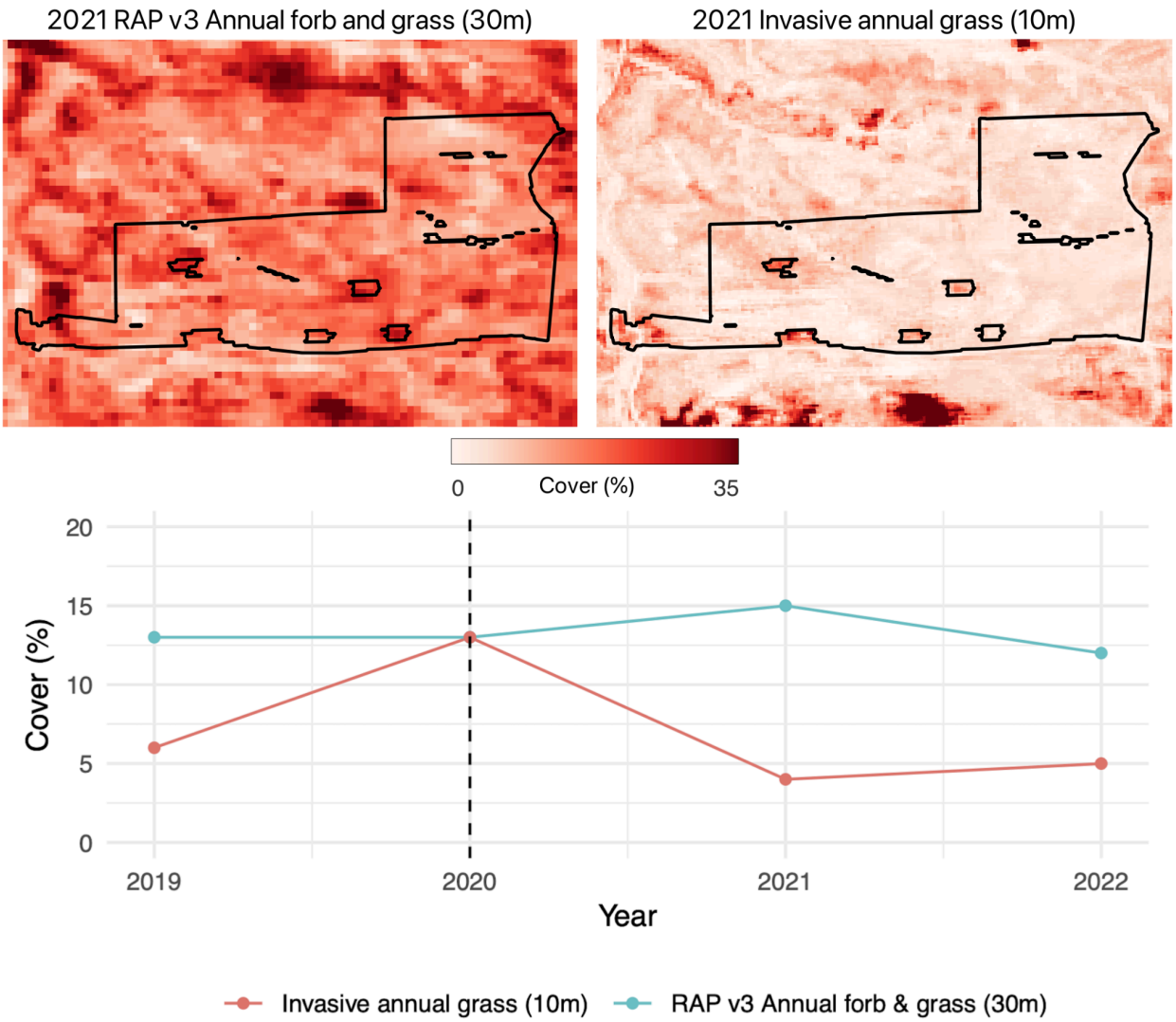

Figure 6. Comparing remotely sensed estimates of Landsat-based fractional cover for annual forb and grass (RAP v3, 30 m resolution)[19] and Sentinel-2 based invasive annual grass (10 m resolution, described in this paper) for an herbicide treatment of invasive annual grasses. Visuals display estimated fractional cover one year post herbicide treatment. Time series represents the average across the treatment for each year; dashed line indicates the year of treatment. The 10 m, Sentinel-2 based estimate of fractional cover detects immediate reductions of invasive annual grasses and correctly highlights areas that were not treated (small inholdings within the treatment). Although cover values do not reach zero, the Sentinel-2 based estimate more closely reflects the near total eradication of invasive annual grasses post treatment (Mealor, personal communication, February 21, 2025). Treatment is near Sheridan, Wyoming, USA and is approximately 97 ha.

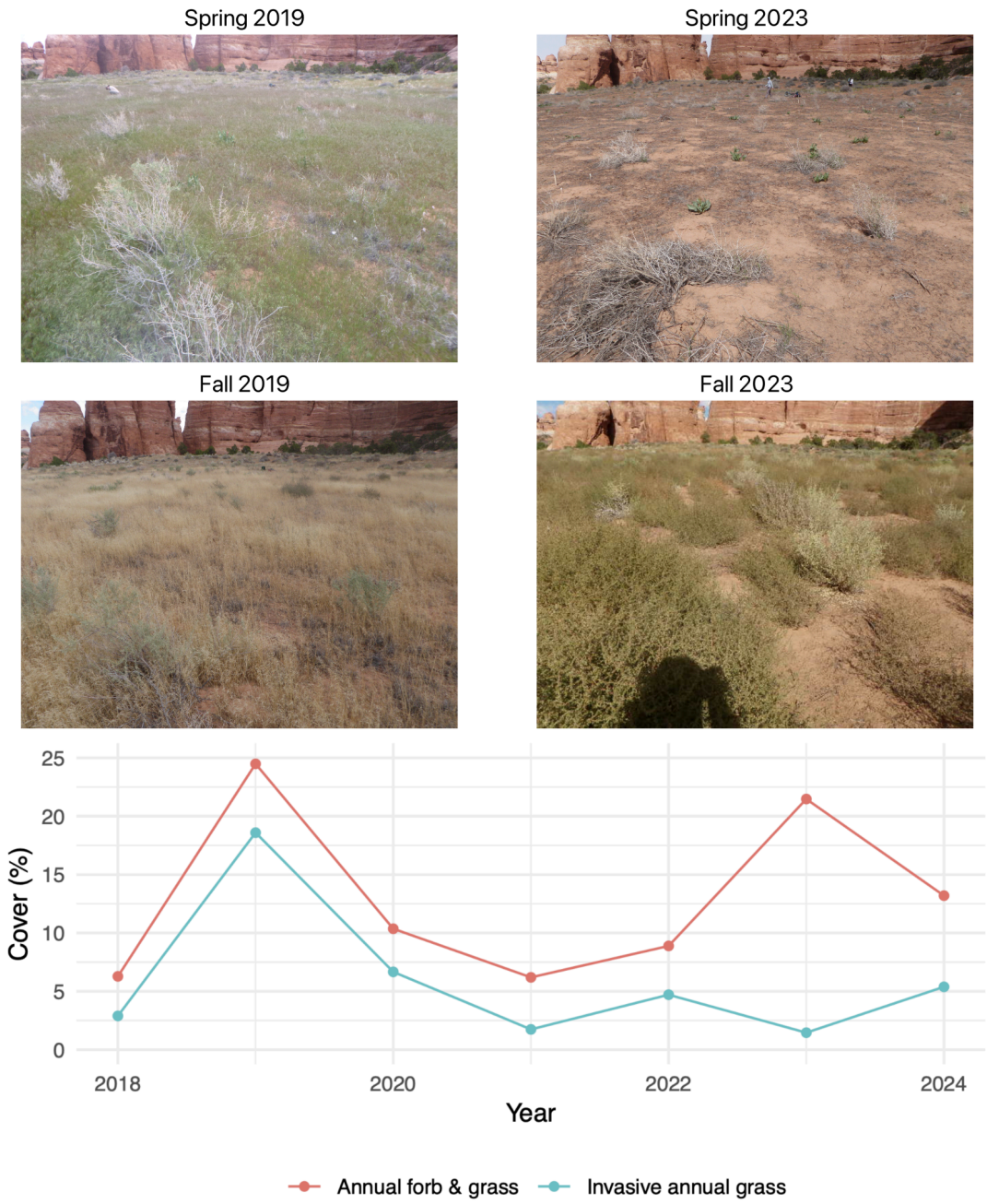

Figure 7. The increased temporal resolution of Sentinel-2 satellites allows the fractional cover model to distinguish between similar plant types with different phenological patterns. The four photographs were taken from the same location in Canyonlands National Park, UT, USA. Spring and fall 2019 photographs show high cover of *Bromus tectorum*, an invasive annual grass species that completes its life cycle during the spring and early summer. Spring and fall 2023 photographs show the same location in a year dominated by *Salsola tragus*, an introduced annual forb that reaches peak biomass in mid- to late summer. The predicted cover for this location shows high cover of annual forb and grass in both of the years pictured, but correctly estimates high cover of invasive annual grass species only in 2019.