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Statistical considerations of using the 1-ft^2 quadrat for monitoring peak standing crop and residual dry matter on California annual rangelands

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On the Ground

- Peak standing crop (PSC) and residual dry matter (RDM) are the primary measures of production and grazing intensity on California's annual rangelands.
- One of the most common methods of monitoring forage metrics is to clip 1-ft^2 quadrats. The USDA Forest Service, Bureau of Land Management, universities, and other land managers have been using this methodology since the 1930s.
- We used best linear unbiased predictors (BLUEs) to determine 95% confidence intervals for PSC and RDM. For both PSC and RDM, as the number of samples taken increased from 1 to 10, the predictive ability also significantly increased. We found no evidence of increased predictive power past 10 samples.

Keywords: residual dry matter, peak standing crop, environmental monitoring, bare ground, quadrat.

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Introduction

Environmental monitoring is a critical part of policy, regulatory, and management activities aimed at sustainable natural resource use.[1-3] Monitoring to determine rangeland production metrics is a decades-old process. There are recent technologies emerging that are bringing renewed interest in accurate assessments of rangeland peak standing crop (PSC) and residual dry matter (RDM). For example, recent applications of remote sensing to quantify forage production used regional-scale data to calibrate and validate detection algorithms and generate thousands of temporal and spatial data points.[4-5] Collecting on-the-ground data is necessary to validate and calibrate detection algorithms.[6,7] Also, trend monitoring for environmental assessments, such as desertification, erosion control, and carbon sequestration, with respect to climate change and land-use change, requires accurate biomass measurements at the regional scale. Furthermore, the United States Department of Agriculture (USDA), Farm Service Agency rangeland drought disaster program requires an accurate assessment of drought-year forage production for comparison to long-term average production rates.[8] Finally, at the ranch scale, forage biomass monitoring is a key parameter for deciding grazing stocking rates and targeting end-of-season RDM for achieving erosion control and nutrient cycling goals.[9] Each of these monitoring objectives (e.g., baseline, best management practice implementation effectiveness, trend, compliance, and validation) requires monitoring protocols that vary in frequency, duration, and intensity of analysis to obtain the necessary statistical objectives.[10]

Sampling of quadrats serve as one standard method for determining PSC and RDM levels on rangelands.[9-11] Clements[12] created the term "quadrat", which was defined as the basic sampling unit with an area of 1 m^2 (10.7 ft^2). He noted that under some circumstances there could be smaller "subquadrats." For example, to measure mosses, a 2 × 2 dm subquadrat would work well.

In California, a 0.03 m (12 in) by 0.03 m (12 in) steel frame, commonly referred to as 1-ft^2 quadrat, is often employed as the standardized quadrat size. The 1-ft^2 (0.093 m^2) quadrat was used as early as 1936 at the USDA Forest Service, San Joaquin Experimental Range in Madera County (Fig. 1). The earliest known use of a 1-ft^2 quadrat, reported in the literature

Figure 1. H.H. Biswell explained the research at the US Forest Service San Joaquin Experimental range in 1936 while a young man from the Civilian Conservation Corp clipped the residual dry matter from a 1-ft^2 quadrat.

by researchers was in 1937.[13] It was quickly adopted as the standard protocol for California rangelands, although there has been continued debate over how plot size and shape affect the statistical efficacy on annual rangelands.[14] H.H. Biswell, a trained range scientist, and Vasilios Papanastasis rigorously examined the sampling error produced by plots ranging in size from 0.0625 to 1 m^2 on annual grasslands.[15] They found, as expected, error in estimating standing biomass decreased with increasing plot size, but the increased speed of sampling strongly favored the smaller plots. They also found plot shape was unimportant and grazed plots had more sampling error than ungrazed plots.[15]

Currently, square, or circular plots of 1 ft^2 are predominantly used to measure either PSC or RDM and are deemed convenient, repeatable, and fast, especially in California's annual grasslands. The herbage in a 1-ft^2 quadrat can be harvested in less than 5 minutes. Once the herbage is harvested, dried, and weighed in grams, it is then multiplied by 96 to obtain pounds per acre (kg/ha). At the end of the summer, when RDM is dry in California's Mediterranean climate, the biomass can be weighed in the field after harvesting a quadrat.

The small size and ease of harvesting a 1-ft^2 quadrat allows for rapid processing, but it may not capture the inherent variability present in a larger sample area. The major statistical concern regarding quadrat biomass monitoring is "what is the minimum number of samples required to meet the monitoring accuracy objectives?" There is no single answer to this question, as it will change with differences in vegetation type, soil type, aspect, slope, elevation, annual precipitation variation, and grazing intensity. The best method for determining the number of quadrats to accurately predict PSC and RDM at the landscape scale is not well defined. In practice, the recommended number of samples should generally be determined after taking many samples and calculating the variance. To optimize the number of replicate quadrats necessary to achieve a given statistical objective, a rigorous pilot study would be needed on each landscape unit before initiation of the actual measurement regime. This is a huge effort when working at scales larger than a few individual landscape units and can be challenging for many rangeland owners and managers.

Other researchers have discussed this sample-number concept, and its importance in determining the sampling accuracy and confidence because incorrect assessments can be misleading, especially in the context of meeting regulatory compliance objectives.[16] Inaccurate assessments can lead to overgrazing and incorrect insurance payments, which play a role in the economic viability of a grazing operation. Developing a standard protocol ensures the accuracy of the data collected in any monitoring program.[16] There are many combinations of accuracy standards and statistical confidence levels to evaluate the number of samples required to effectively predict PSC and RDM levels. In fact, an inadequate monitoring program that does not achieve reasonable accuracy criteria produces meaningless data and wastes time and resources.[16] The standard recommendation for determining the sample size for a utilization study is to do preliminary sampling to determine the variance and adjust sampling intensity based on study goals and precision.[17] However, in practice, this approach is rarely adopted, and land managers often only collect a few samples, as time and funding permits.

For our study, we analyzed 1-ft^2 quadrat data collected from 43 sites distributed throughout Monterey, San Luis Obispo, and Santa Barbara Counties with different rainfall zones, soil types, aspects, and slopes on the Central California Coast to assess the minimum number of quadrat samples needed to meet a given statistical objective. In rangeland monitoring, the true population value will never be known; however, to judge how well a sampling protocol estimates the true population a confidence interval is calculated.[10] The confidence interval is a range of values expected to include the true population size.[18] Using this approach, we provide an estimate of the number of replicate samples required to meet the given statistical objective. Our study addresses specific sample size questions for real-world rangeland biomass monitoring and fills a critical knowledge gap for annual rangeland monitoring programs.

Methods

Each year during 2014 to 2020, we measured forage PSC in the spring and RDM in the fall at 43 sites in Monterey, San Luis Obispo, and Santa Barbara Counties on the Central Coast of California (Fig. 2). This corresponded to 239 site-year combinations (i.e., environments). Rainfall at each site changed each year. Each site was between 0.5 and 2 ha (1.24-4.94 acres) in size. Elevation, slope, aspect, and soil type were the same at each site. Average annual rainfall amounts ranged from 250 to >1,000 mm (9.8 to >39.4 inches).

In October during 2014 to 2020, four 7.2 m^2 (77.5 ft^2) exclosures (3.05 m diameter [10 feet]) were randomly located on each site. Within each of the four exclosures, three, 1-ft^2 quadrats were randomly sampled, by clipping all herbage, for a total of 12 samples per site. Exclosures were randomly moved 9 to 15 m (29.5 to 49.2 feet) in a random direction but re-

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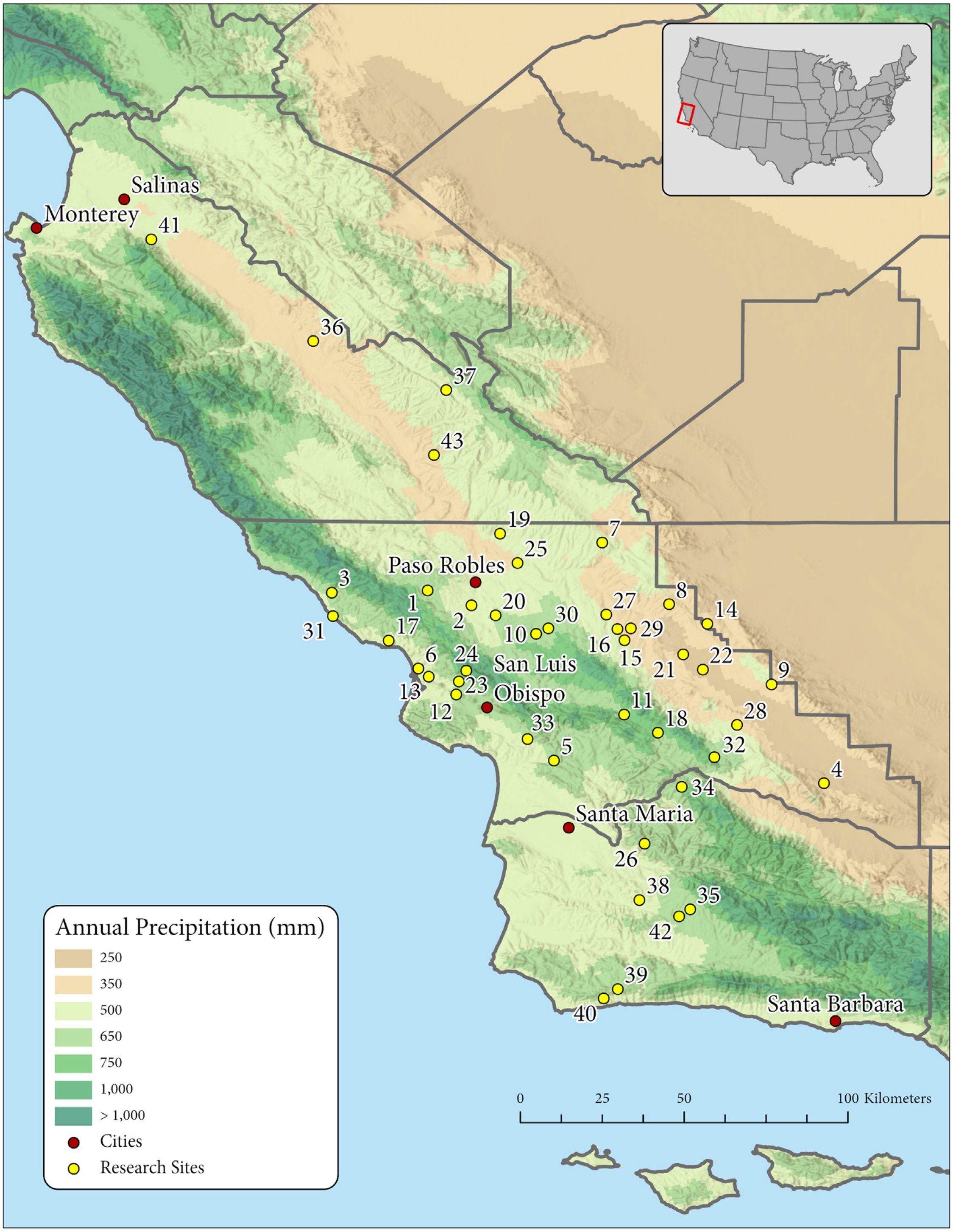

Figure 2. Distribution and average annual rainfall (mm) for our 43 sampling locations in Monterey, San Luis Obispo, and Santa Barbara Counties along the California Central Coast, United States.

mained within the same site conditions of soil type, slope, aspect, and elevation. Samples were taken to the lab and dried at 60°C (140°F) for 48 hours, weighed, and converted to kg/ha for statistical analysis. In addition, the average herbage height, bare ground, and percent rodent disturbance contributing to bare ground were visually estimated for each quadrat. The herbage height was measured with a ruler as a continuous value. Bare ground was estimated as a percent starting with 1% to 3%, 5%, then continuing in 5% increments. Rodent disturbance was estimated by looking at bare ground caused by rodent activity, and given a value of 0 (none), 1 (<10%), 2 (10-30%), or 3 (>30%).

Within each environment, PSC and RDM data were analyzed as mixed models.[19-21] The site was considered fixed, and samples (i.e., quadrats) were considered random. We obtained best linear unbiased predictors (BLUEs) and 95% con-

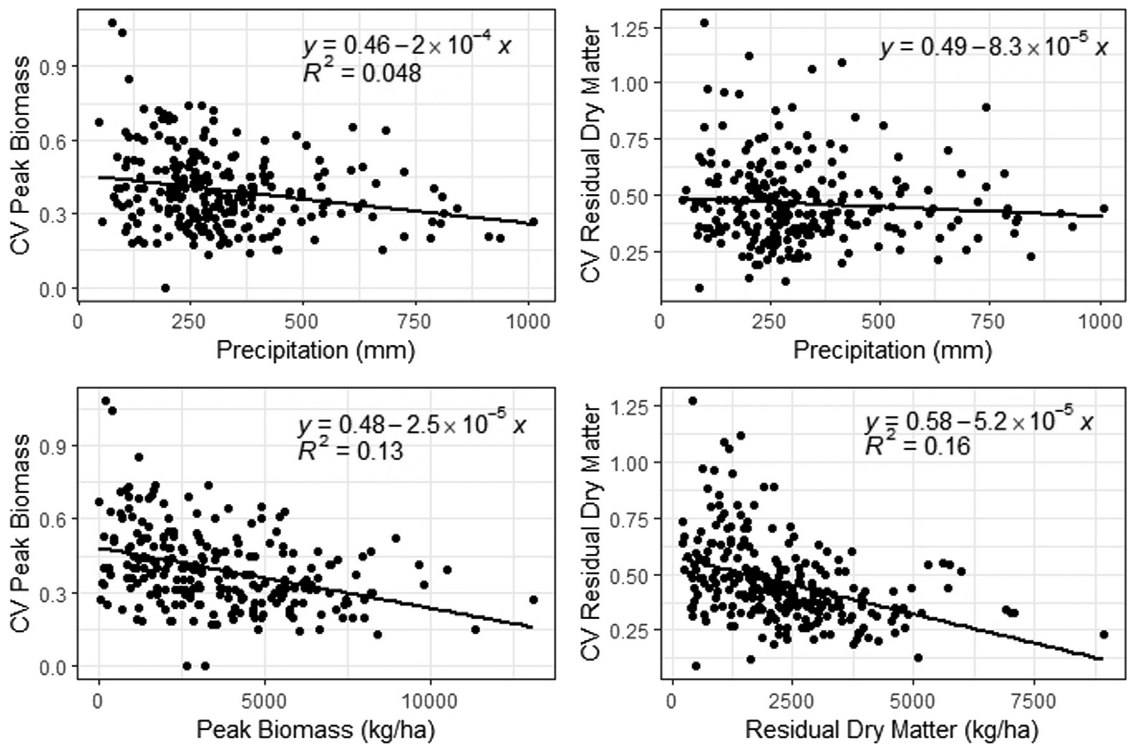

Figure 3. Relationship of coefficient of variation for peak biomass (peak standing crop) and residual dry matter relative to precipitation and total forage production (i.e., Peak biomass and residual dry matter).

fidence intervals for PSC and RDM corresponding to each site. The resulting BLUEs for PSC and RDM were considered as the "reference values" for the subsequent resampling analysis. We recognize these reference values are not true mean values. We cannot obtain the true reference biomass values without harvesting the herbaceous matter from the entire study site. However, our intent was to determine if herbage estimates were inaccurate without multiple samples from each site, therefore we only needed to have estimated herbage reference values.

Multiple years of data from a given site had different rainfall amounts and forage productivities, hence each site × year combination was considered as an environment. We also estimated the coefficient of variation (CV) for PSC and RDM within each environment. We used regression analysis of the corresponding CV against precipitation, PSC, and RDM in each site to determine the change in variation based on changes in precipitation and biomass.

The 12 individual samples collected from each environment were used for the resampling analysis. A subsample of samples (i.e., anywhere from 1 to 12), were resampled 10,000 times with replacement values for each environment. For each sample, the mean of the 10,000 samples was compared to the corresponding environment's reference value. If the value was within ±20% of the reference value it was coded as a 1, otherwise, it was coded as a 0. The coded data were analyzed within each environment to determine if differences among the number of samples were observed for the proportion of times; they fell within ±20% of the reference value.

Results

Environmental BLUEs ranged from nearly 0 to 12,000 kg/ha (0 to 10,706 lbs/acre) PSC and from 0 to 10,000 kg/ha (0 to 8,922 lbs/acre) RDM. Greater amounts of biomass were associated with coastal environments during wetter years and lesser amounts were associated with inland locations during drier years (data not shown). Additionally, we found a high correlation between herbage height and PSC ($r = 0.84$, $P < 0.0001$). Correlations between herbage height and RDM, bare ground and PSC, and bare ground and RDM were lower and of less predictive value ($r < |\pm 0.60|$). We found no relationship between PSC and RDM, or with rodent activity and RDM. The regression analysis of CVs showed a tendency for PSC variation to decrease with increasing precipitation and increasing PSC. The same analysis showed RDM variation decreased with increasing RDM values. However, R^2 values for these analyses were <0.20 and explained little of the variation (Fig. 3).

Based on analysis of the resampling data, we found significant differences among the number of quadrat samples collected and the proportion of times those samples were expected to be within ±20% of the true reference value for both PSC and RDM. A single sample has a probability of ~40% of being within ±20% of the true reference value for PSC and ~35% for RDM. These probabilities increased until achieving values of ~80% and 85% for PSC and RDM with 10 samples. There was no increased predictive improvement beyond 10 samples for any of the environments (Fig. 4).

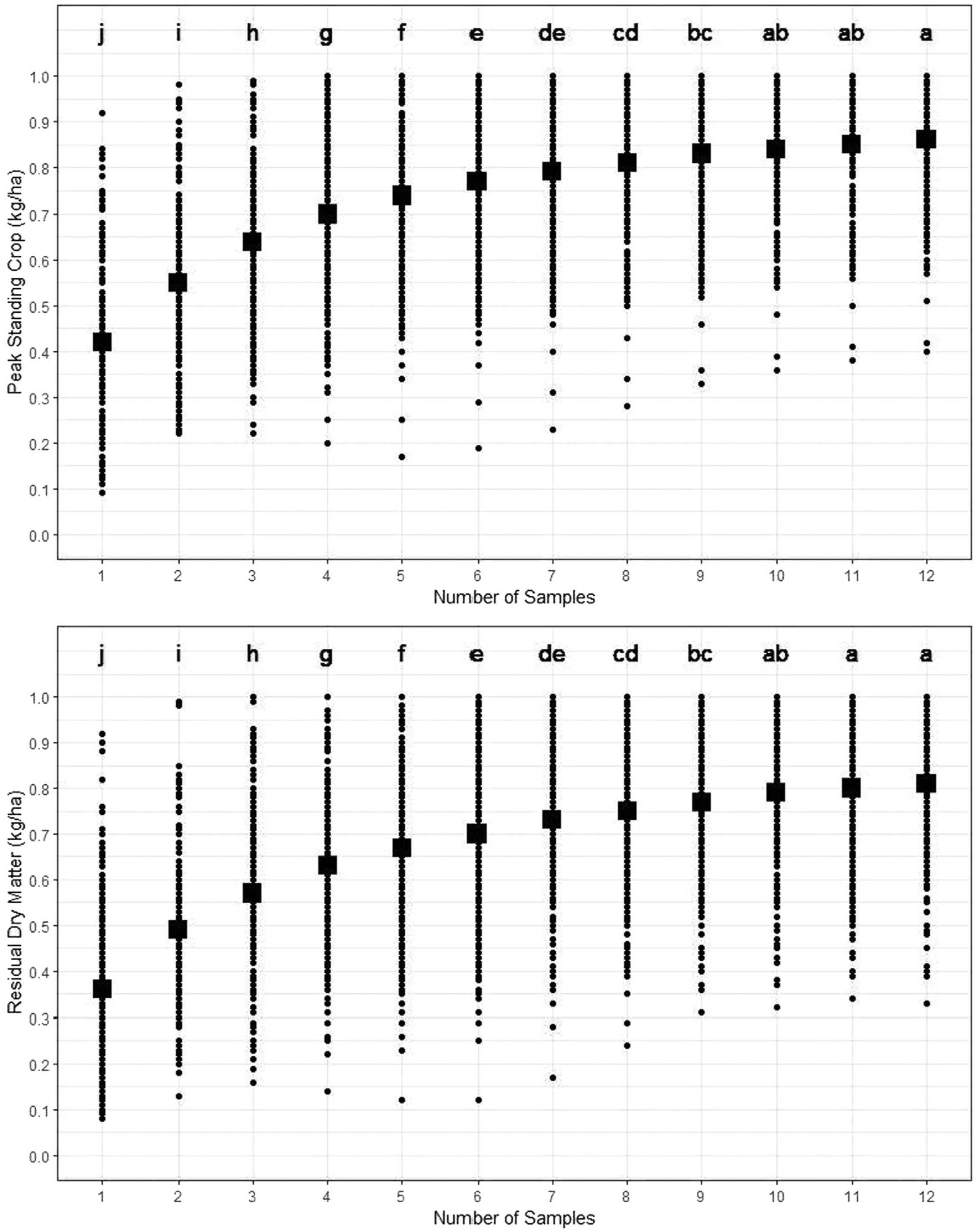

Figure 4. Probability that the number of quadrat samples will result in a biomass estimate within ±20% of the true reference value for peak standing crop (PSC) and residual dry matter (RDM). Values with different letters significantly differ at $P < 0$.

Discussion

Monitoring to meet management and public policy goals has increased in recent decades. While clipping a few quadrats will yield a result, it may not meet sample size requirements to meet accuracy standards in management or regulatory protocols. Depending on the management goals, a small number of samples may be adequate. Historically the US Department of Interior Bureau of Land Management guidelines for utilization studies suggested a sample size of 25, but later this guideline was changed to a recommendation to complete a pilot study to determine site-specific number of samples.[17,22] Many managers and agencies may not have enough time to determine the number of samples required to meet their goals. Variation can be high among small quadrats (e.g., 1 ft^2), and may yield broad confidence intervals. In our study, we sampled 0.5 to 2 ha areas (1.2 to 4.9 acres). Our sites were constrained by selecting sites within an area with similar slope, aspect, soil type, rainfall, and microclimate. Our study showed that the predictive power increased as sample numbers increased up to 10 samples for sites with similar environmental conditions. Our sampled areas were up to 2 ha (4.9 acres) and did not cover large heterogeneous pastures because they would likely require more samples to ensure similar levels of confidence. Moreover, the actual number of samples depends on the goals and accuracy level required to meet the monitoring objectives of the study.

Surrogate measures of herbage height and bare ground had limited predictive value for PSC and RDM. Only the correlation between PSC and herbage height was >0.80. Thus, herbage height may serve as a potential proxy for PSC during sampling. Factors leading to higher variation in RDM may include herbage laying down on the ground surface versus standing erect and increased bare soil due to disturbance. The RDM height and density can be influenced by grazing and trampling, summer weathering losses, and other abiotic and biotic factors.[23] Bare ground may be initiated by grazing and/or rodent or other wildlife activity.[15] Additionally, extended rodent activity over the summer is a potential factor that may increase variability for RDM relative to PSC because of an increase of bare ground and removal of vegetation, but further targeted studies are required for verification.[24] We also found that increasing precipitation and biomass may have a small effect on the sample variation for PSC and RDM, but the effect is small and not significant.

Sampling important rangeland traits, such as PSC or RDM, on large landscapes requires considerable resources. And the time and cost of estimating PSC and RDM increases with the size and heterogeneity of the landscape being sampled. Double sampling methods, such as the comparative yield method, have been used to overcome the costs of clipping quadrats on California's annual rangelands.[17,25,26] It is important to follow consistent protocol when using any sampling methods.

Recently, remote sensing techniques have been successfully applied to obtain frequent (i.e., annual, monthly, or even biweekly) biomass estimates, which are publicly available online.[27] Such datasets allow unprecedented detail and improve the ability to monitor rangeland resources. Where more spatial detail is required, estimates of biomass using unmanned aerial vehicles in conjunction with satellite imagery have been reported in the literature.[4,28] There is also active development of calibration and validation databases for biomass estimation using satellite-based Light Detection and Ranging (LIDAR) technology.[29] This development has important ramifications for other remote sensing studies to determine how many quadrats are needed to meet calibration requirements. Because satellite-borne LIDAR can cover large landscapes continuously, multiple environments (rangelands included) can be assessed in short spans of time. Indeed, using satellite-based remotely sensed estimates of biomass in rangelands is expanding. Estimates of biomass will benefit from these comprehensive datasets as data for customized validations from new approaches are developed and made available to the public.[30] Until satellite-based approaches become more routinely feasible, the take-home message of our research is simple—multiple samples taken across the landscape are necessary to confidently estimate biomass.

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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