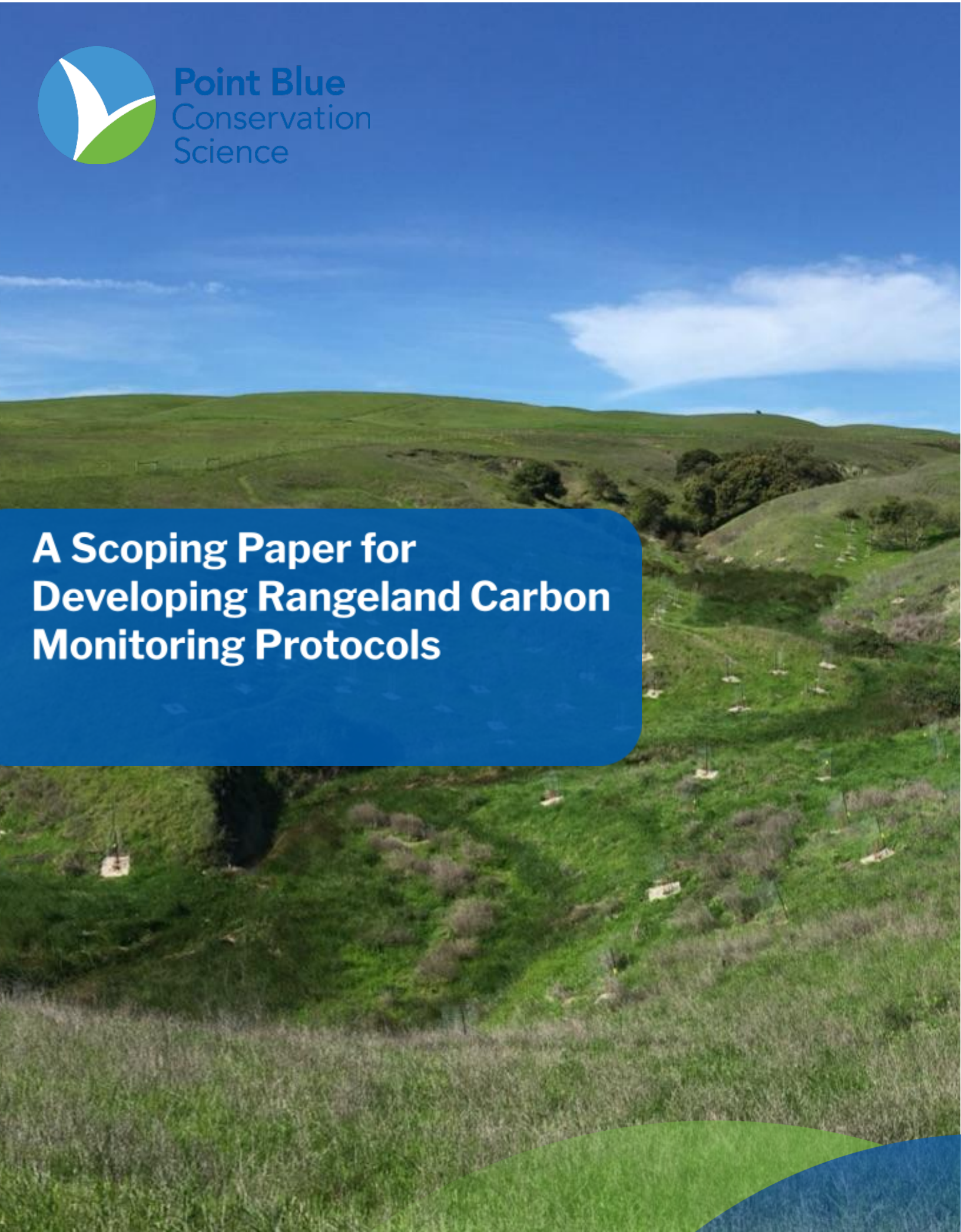
Point Blue
Conservation
Science

A Scoping Paper for Developing Rangeland Carbon Monitoring Protocols



At a Glance: Rangeland Carbon Monitoring Framework

Overarching Goal	-Detect impact of practice on above and belowground carbon to inform on-ranch needs and conduct science at scale
Ecosystem	-Rangeland (initial deployment in California, and expanding to western US states)
Study Areas	-Location on ranch where management practice is implemented (and a control site if possible)
End-users (who will collect data)	-Land managers (e.g., ranchers, land trusts, other land stewards) -Technical service providers
Targeted data use	-Adaptive rangeland management -Direct-to-consumer storytelling -Compliance/performance monitoring for incentive programs -Applied scientific research

A Scoping Paper for Developing Rangeland Carbon Monitoring Protocols

September 2021

Prepared by

Point Blue Conservation Science

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Suggested citation:
Foster, E.J. and Carey, C.J.* 2021. A scoping paper for developing rangeland carbon monitoring protocols. Point Blue Conservation Science (Contribution No. XXXX), Petaluma, CA.

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Acknowledgements: We'd like to thank Libby Porzig for providing comments on an earlier version. We are grateful to collaborators from Colorado State University and Mad Agriculture, in addition to the Technical Working Group members and End-User Focus Group members, who agreed to provide their time and expertise to help make this monitoring framework a reality. We'd also like to thank the OpenTEAM Carbon Series group participants for providing thought-provoking discussions around many of the concepts covered in the document. Funding for this work was provided by the Foundation for Food and Agriculture Research, TomKat Ranch Educational Foundation, The Battery, and an anonymous donor.

Cover photo:
A landscape-level look at a riparian area in Tolay Lake Regional Park, Petaluma, California that has been actively restored by Point Blue Conservation Science's Students and Teachers Restoring a Watershed (STRAW) program. The white squares are plants installed by volunteers, including coast live oak, buckeye, coffeeberry, California rose and more. Photo credit: Isaiah Thalmayer, Point Blue.

Point Blue Conservation Science – Point Blue's 160 scientists work to reduce the impacts of climate change, habitat loss, and other environmental threats while developing nature-based solutions to benefit both wildlife and people.

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Summary

This report is written for technical experts and practitioners to help design a robust and accessible protocol for carbon measurements on rangelands in California and beyond. With carbon farm plans, healthy soils incentives, and growing interest in regenerative management covering vast areas of rangeland, a great need and opportunity exists to assess and monitor changes on the ground. Rangelands are social-ecological systems that are predominantly managed for livestock production, encompass a globally significant proportion of land area, and are increasingly valued for their role in the terrestrial carbon cycle. In partnership with collaborators at Colorado State University and Mad Agriculture, Point Blue Conservation Science aims to create a robust monitoring framework to measure carbon above and belowground in response to commonly recommended rangeland management practices. This monitoring framework will include a handbook of protocols for use by ranchers, technical service providers, and other managers to aid in land stewardship evaluation and other on-site needs. The protocols will be designed to create an aggregated database for addressing scientific questions about the rate and magnitude of carbon change in response to rangeland stewardship.

The document includes a broad overview of the rangeland carbon monitoring goals, important sampling design aspects, core indicators and methods for monitoring aboveground and belowground carbon, and considerations of common rangeland conservation practices. This report does not include detailed protocol steps, exhaustive summaries, a systematic review of all existing rangeland protocols, nor prioritization of which practices or sites sequester more carbon; this information is not for direct implementation by ranchers or other practitioners. We provide background information for protocol development to monitor aboveground and belowground carbon in support of rangeland stewardship.

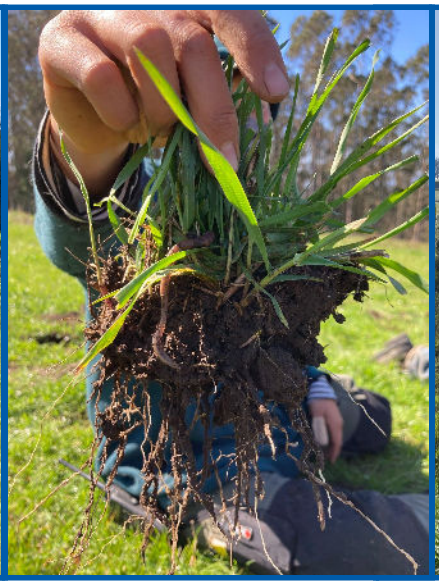




Photo Credit: Chelsea Carey, Point Blue

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INTRODUCTION

Rangeland Extent, Significance, and Management

Rangeland ecosystems are a vast and diverse land classification that broadly include uncultivated terrestrial areas where domestic or wild animals can graze (Briske 2017). Rangelands support a plethora of critical ecosystem services that can be amplified or diminished to varying degrees with human management (e.g., Millenium Ecosystem Assessment,2005; Plieninger et al. 2012). These services include food production, water capture, filtration, and storage, flood management, nutrient cycling, carbon sequestration, habitat both above and belowground, and cultural and economic support for ranching communities (Sala et al. 2017; Teague and Barnes 2017).

Globally, rangelands account for 28% of global land cover and contain primarily grassland, shrubland, and savannah ecosystems, but also include desert, wetlands, and other types of woodland (Herrick et al. 2017). In California alone, rangelands cover approximately 57 million acres, with Mediterranean-type grasslands, shrublands and woodlands accounting for 30% of this estimate (FRAP 2018). Rangelands are typically found in semiarid and arid regions, relatively less productive soils, and/or on steep terrain where crop production has historically been restricted. Typically, these rangelands are managed extensively, rather than intensively, as they receive minimal inputs such as irrigation or fertilizer. The biological composition, productivity, and cycling of rangeland carbon is largely driven by climate conditions and underlying geology, which are highly variable—and the ability to influence certain aspects of rangeland soil health through management activities like planned grazing is thought to be more limited or nuanced than in croplands or intensively managed pastures (e.g., Briske et al. 2008; Booker et al. 2013; Buckley Biggs and Huntsinger 2021). However, the growing list of management practices and approaches considered for rangelands provides new opportunities to support private ranchers and public land managers who desire, or are expected, to optimize the full array of services provided by these landscapes.

The Role of Science and Monitoring

Momentum is building in California and across the Western US to support multi-benefit rangeland stewardship; thus, engaging networks of ranchers, scientists, and agency staff to conduct relevant science and ecological monitoring will help to ensure actions are effective and efficient. Indeed, while some frameworks such as ecological site descriptions and state-and-transition models help predict management impacts on ecosystem outcomes (e.g., Brown and MacLeod 2011; Ratcliff et al. 2018), an empirical large-scale dataset that captures effects of multiple rangeland management practices may prove invaluable for informing and refining best management practices. As rangelands are highly dynamic, stewardship decisions often have to be made despite variability and uncertainty in practice impact. Therefore, collecting data that can build a large-scale verifiable dataset of practice impact, while also supporting immediate on-ranch adaptive management and other rancher needs would be even more powerful.

Put another way, as rangeland research expands and includes data from ranchers and technical service providers collected in a rigorous, repeatable way, the cumulative information can support stewardship of individual ranches and simultaneously assess impact at larger scales (Toevs et al., 2011). When consistent protocols are implemented, the effects of management can be analyzed on a regional, state or national scale, especially when protocols are easy-to-use, flexible between sites and management contexts, and consistent enough to harmonize into a central database. In rangelands across the Western US existing monitoring efforts can inform protocols to determine practice impact on rangeland ecosystem services (Karl et al., 2017; Kleinman et al., 2018; Porzig et al., 2018).

Narrowing the Scope: Managing and Monitoring Rangeland Carbon

We propose the development of a monitoring framework that serves multiple purposes, focused on carbon in aboveground vegetation and belowground roots and soils. As the basic building block of life, carbon exists in pools and flows between aboveground and belowground ecosystems, serving as an indicator of biological response to environmental changes. Beyond the potential value of protecting and rebuilding[1] carbon as one mechanism for climate change mitigation, carbon stewardship offers a myriad of other benefits (Bradford et al. 2019). Measurement of ecosystem carbon can provide insights into forage production, soil organic matter content and associated soil functioning (e.g., water infiltration, nutrient cycling), and system resilience to stressors like drought (Figure 1).

Given the importance of carbon as an ecosystem property, it is quickly becoming foundational in rangeland management discourse with a growing number of programs focusing on protecting and rebuilding carbon as a primary goal. We believe that managing carbon must be weighed in the context of other outcomes such as biodiversity, with co-benefits maximized wherever possible. Widespread rangeland management practices that aim to rebuild carbon and support other ecosystem benefits create an unprecedented opportunity to assess practice impact across these working landscapes (Dybala et al. 2019). Carbon monitoring protocols must be designed to map onto various practices, be accessible to ranchers and technical service providers, and harmonize across projects, and thus facilitate assessment both on-ranch and at regional scales.

[1] We intentionally use the words protect and rebuild in this context. Protecting existing carbon is a critical strategy for ecosystem management of rangelands (Sanderson et al. 2020), and efforts to increase carbon should focus on places from which it has been lost. This is particularly true for those rangeland systems where increasing carbon might not be desirable, or would come with tradeoffs. A classic example is the serpentine grassland, which is characterized by inherently low productivity and low soil carbon, but which provides critical refugia for native plants and pollinators.

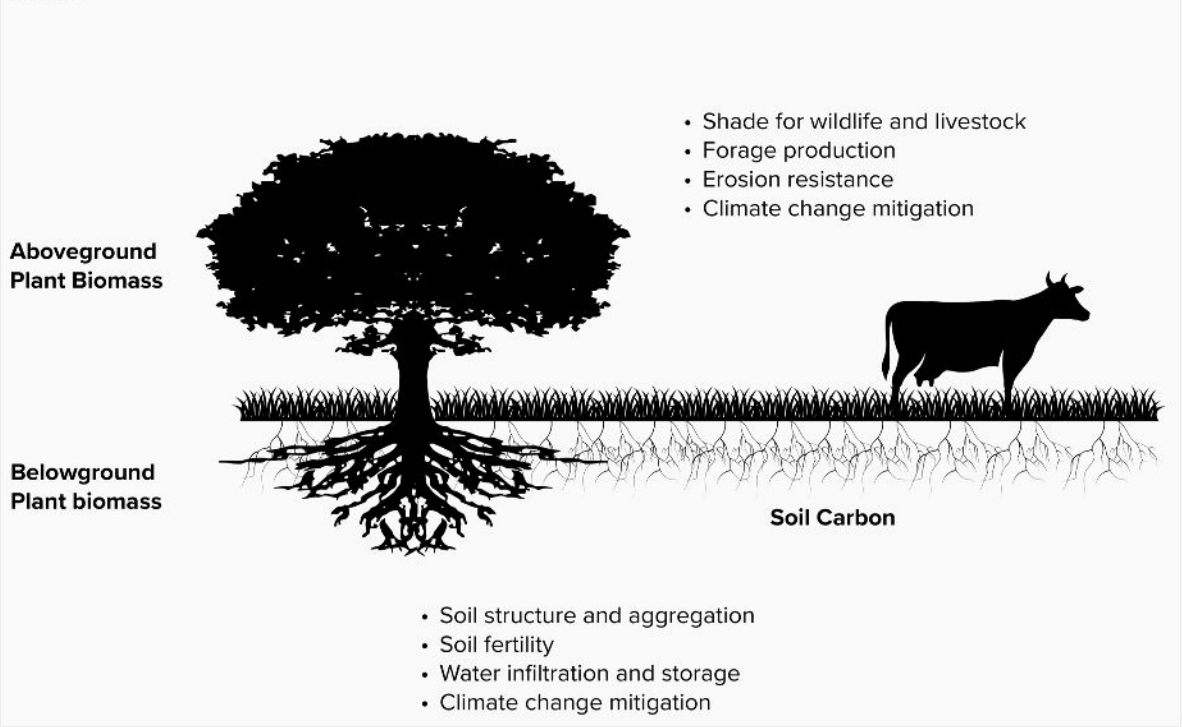


Figure 1. Rangelands provide critical ecosystem services, many of which are linked directly or indirectly to carbon storage above and belowground.

Monitoring Objectives

At its highest level, this monitoring framework will help to track changes in above and belowground carbon after implementation of rangeland management practices. Multiple complementary mechanisms exist or are emerging to facilitate the management and monitoring of rangeland carbon related to soil health, rangeland productivity, and climate change mitigation. Groups such as ranchers, landowners, policy-makers, and scientists may be motivated by different or overlapping interests (e.g., economic gains, ecosystem services, scientific understanding), which are supported by a growing number of funding streams and programs. These mechanisms that support changes in management include certifications, regenerative labels, direct-to-consumer storytelling, carbon farm plans, protected lands stewardship initiatives, incentive programs, existing monitoring networks, and government contracts or grant programs. We will develop protocols that pair with multiple of these support mechanisms by using a tiered approach (Billings et al. 2021), designing methods to serve multiple purposes in the context of today's carbon management and monitoring landscape (Toevs et al. 2011; Figure 1). Doing so will help to broaden the support that these protocols can provide, and will ultimately help to build a more robust dataset to assess practice impact across rangelands of the West. To clarify, given the special requirements for carbon market monitoring, reporting, and verification, and the ongoing investment in this space by others (e.g., CAR Soil Enrichment Protocol; Oldfield et al. 2021), direct market support is outside the scope of this work.

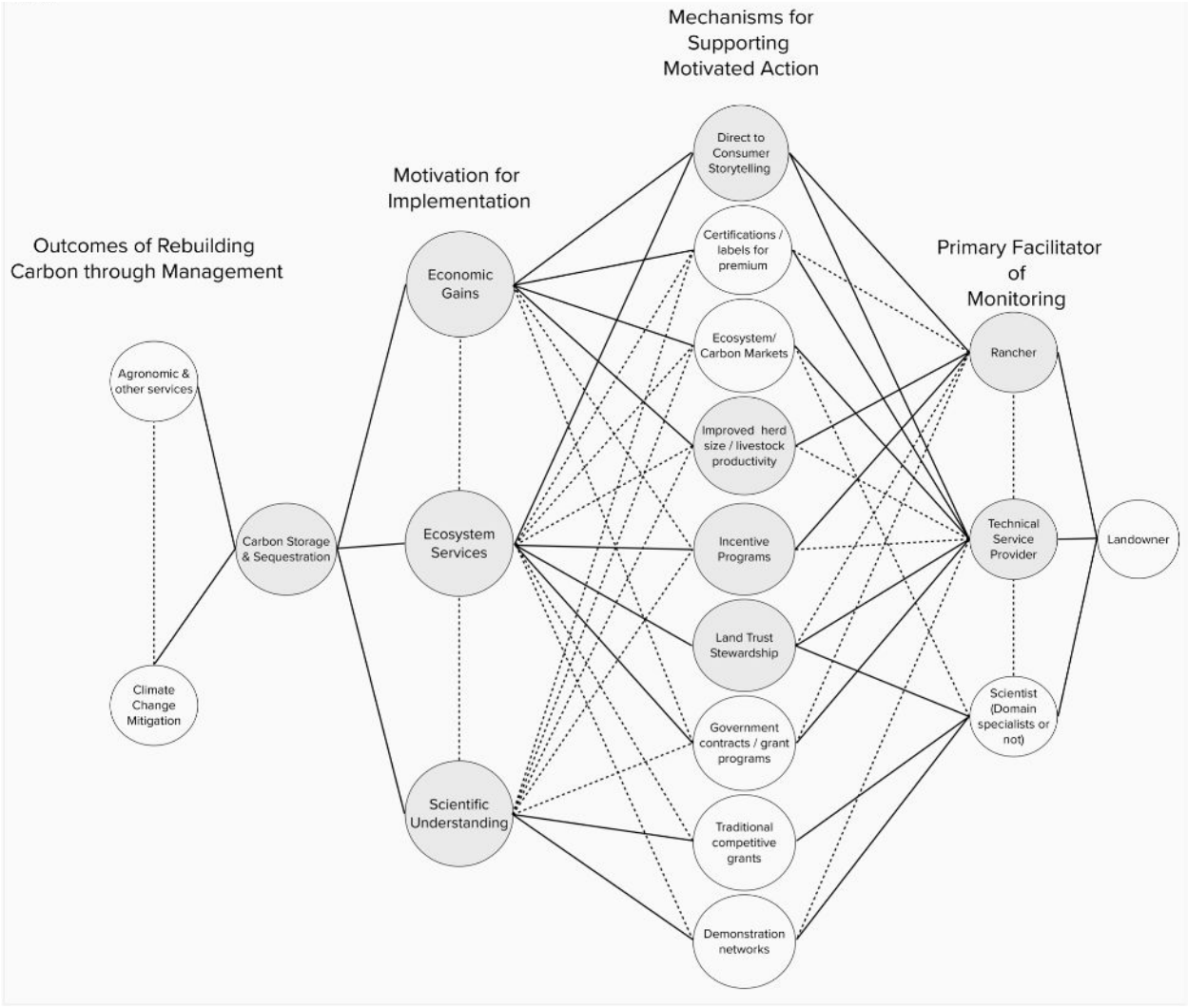


Figure 2. A conceptual framework for existing outcomes, motivations, supporting mechanisms, and primary facilitators involved in soil carbon monitoring. Solid lines represent direct connections between entities and dotted lines represent indirect connections. Although rangeland carbon monitoring includes all of these factors and more, the development of this carbon monitoring framework focuses on the shaded circles. The final protocol may also tangentially inform the other supporting mechanisms (e.g., certifications or grants) or use by other facilitators (i.e., scientists or landowners).

Within this context, the proposed objectives of the monitoring handbook (subject to modification based on our Working Group feedback) are to:

1. Provide blueprints for land managers and technical service providers to monitor changes in carbon with the implementation of commonly-recommended rangeland management practices.[2]

2. Support a large-scale verifiable dataset documenting changes in carbon with management that can be used to reduce uncertainty and inform future planning and prioritization for stewardship.

While some monitoring frameworks aim to capture broad scale or ranch-wide changes in carbon associated with forage and soils (e.g., Point Blue's Rangeland Monitoring Network (RMN); Savory's Ecological Outcomes Verification)—and a number of scientific publications have documented ways to measure carbon in response to rangeland management (e.g., Matzek et al. 2020; Ryals et al. 2014)—we are unaware of a framework to-date that aggregates protocols for multiple commonly-recommended practices such as compost additions, windbreaks, and silvopasture. Each of these practices have unique considerations for monitoring and thus will benefit from separate monitoring guidelines. We will therefore develop protocols to capture changes with different management practices, referencing the National Resource Conservation Service (NRCS) Conservation Practice Standards (CPS), as they represent rangeland management across the western US and are widely promoted by other programs like carbon farm planning, county-level climate action plans, and the California Department of Food and Agriculture's Healthy Soils Program. Below is an illustration of the major practice categories and their associated NRCS Conservation Practice Standard codes (Figure 2). We will also consider touching on conversion from other land use types to rangeland, which has the possibility of significantly influencing carbon. Two teams, a Technical Working Group and End-User Focus Group, will provide feedback on the protocol scope and objectives and help to develop protocols that effectively serve the objectives.

> "Monitoring and assessment data collected to meet the local management needs should also contribute to regional and national monitoring and assessment efforts." Toevs et al. 2011

[2] Modified from original wording 'Provide blueprints for ranchers and technical service providers to track changes in carbon with the implementation of practices as part of the adaptive management process' based on interpretation of feedback from Technical Working Group Meeting 1.

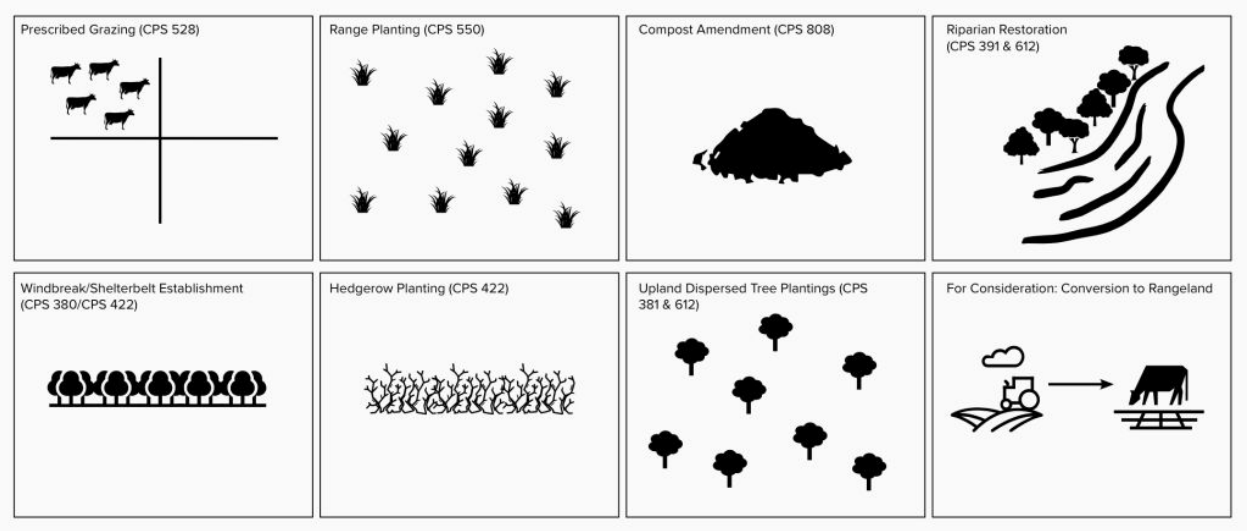


Figure 3. The carbon monitoring framework in development aims to include specific protocols to implement with seven common categories of rangeland management that match the above NRCS Conservation Practice Standards (CPS), as well as considerations for monitoring landscapes that convert into rangelands.

Carbon Monitoring Design

Defining on-ranch management and monitoring objectives is a critical first step to guide subsequent decisions around the design of a carbon monitoring project. As described above, the motivations and supporting mechanisms to implement and monitor rangeland practices to protect or rebuild carbon vary widely, and, concomitantly, associated decisions around sampling design will also vary. There are a number of existing resources and organizations that provide guidance through the planning process, which includes identifying resource concerns and setting objectives. These include the Carbon Farm Planning process, the NRCS Conservation Planning process, the Holistic Management International planning program, and the Bureau of Land Management's Assessment, Inventory, and Monitoring (AIM) program. We therefore posit that the initial goal-setting step is beyond the scope of this work, and focus our efforts on developing flexible but robust guidelines that help to monitor carbon in response to rangeland management once objectives have been set. A tiered system that offers a menu of design options, indicators, and recommended methods can help to support this kind of approach (e.g., Billings et al. 2021). Below we describe key design aspects that require careful consideration by the Technical Working Group and End-User Focus Group when creating the monitoring framework.

Study Area

It is our expectation that protocols included in this monitoring framework will be designed to map onto the specific management practices mentioned above. The study area will thus be

predefined based on where a practice is implemented, informed by a planning process that includes identification of resource concerns and setting of goals by the rancher, landowner, or resource manager. In order to ensure the monitoring data can be scalable (Toevs et al. 2011), we suggest the entire implementation area (save for areas that physically inhibit monitoring, like strong slopes or poison oak patches) be made available to take samples using some form of randomized approach (see sampling layout below for more on point selection; Karl et al. 2017). This will ensure the data are not systematically over- or underestimating reality and has the added benefit of helping to assuage concerns around 'gaming the system'. When describing study area delineation in the protocols, recommendations around GPS mapping and marking the boundaries will be important to make in order to capture an acreage estimate, facilitate efficient repeat sampling, and to pair covariate measurements in the final data analysis.

Wherever possible, we would like to encourage the monitoring of a control (i.e., an untreated/unrestored) area as well. This will offer the maximum amount of inference to disentangle management impacts from other drivers of temporal change, such as precipitation, both at the network scale and for individual projects (Kimiti et al. 2020). Having a paired treated and control area also helps to minimize issues with observer bias and laboratory measurement uncertainties downstream by allowing for analysis of paired differences, assuming information from both areas is collected by the same person(s) and processed in the same lab. However, delineating and sampling from a control area is not without its challenges. One primary concern is identification of areas that are similar in size, vegetation, soil type, topography and other characteristics at the onset of the project. This is not trivial, but issues with imperfect site selection can be minimized by taking baseline measurements across both areas in a before-after control-impact design (Christie et al. 2019). Of course, more resources are needed to monitor two areas as opposed to one, and in some cases it may not be amenable to the rancher or landowner to set aside land as a control. In those cases, it may be worth considering whether a smaller control area or some other creative design option (e.g., sampling from the treatment study area perimeter) could be recommended.

Sampling Design

Sampling design informs the collection of measurement data within the study area and careful consideration of key design aspects is critical to the development of an informative, rigorous, and scalable monitoring plan (Toevs et al. 2011). At the broadest level, one must contend with choosing between a probability (i.e., random) versus non-probability (i.e., non-random) based sampling approach. Unlike probability sampling, non-probability sampling uses subjective judgement to determine sampling locations and therefore not all locations within the study area have a guaranteed chance of being sampled. This creates issues around representativeness, making it difficult to generalize findings and evaluate precision of estimates (EPA, 2002). We therefore recommend a probability sampling approach for this monitoring framework, of which there are a few.

Probability-based sampling strategies include simple random sampling, spatially balanced random sampling, systematic sampling, and stratified sampling. Other sampling strategies exist, such as adaptive sampling (Huang et al., 2020), which we do not cover here given their intensive, iterative nature. Simple random sampling chooses sampling locations within the study area completely by chance and is most appropriate when the study area under consideration is relatively homogenous (Ellert et al., 2007; Chang et al., 2016). This approach lends itself to easy statistical analysis; however, because all points are equally likely to be selected for sampling, it is possible that the sampling locations could by chance be irregularly distributed in space (i.e., non-representative, particularly for small sample sizes), which is one limitation of this approach (Willis et al. 2018). It also tends to be less efficient than other methods of probability-based sampling, requiring more samples to achieve a given level of precision (EPA, 2002). Only 11% of monitoring schemes in Europe use simple random sampling (van Leeuwen et al. 2017), reflecting a broader consensus that this approach falls short of providing the efficiency needed especially when monitoring larger landscapes.

Spatially balanced random sampling can overcome some of the limitations of simple random sampling by identifying random locations that are evenly dispersed over the study area. This enhances representativeness and efficiency, particularly when strong spatial trends are present (Kermorvant et al. 2019). One of the most widely used spatially balanced designs in natural resource monitoring is Generalized Random Tesselation Stratified (GRTS) sampling (Stevens and Olsen 2004), which underpins the sampling design for Point Blue's RMN and the Bureau of Land Management's AIM program. It has been shown to be more helpful for increasing precision than stratification in some cases (see below for more on stratification; Lackey and Stein 2013), and may be a good sampling strategy to consider for this monitoring framework, especially for practices that cover relatively large areas.

Systematic sampling via use of a predetermined regularized pattern (with random starting point) is another way to address some of the limitations of a simple random sampling approach (Bijleveld et al. 2012). Grid sampling and transects are common examples of systematic approaches, but patterns may take other shapes (e.g., triangular; Willis et al. 2018). In general, this approach should outperform simple random sampling, garnering a more representative sample due to its uniform spatial coverage (Tan, 2005). Indeed, systematic sampling is commonly deployed in precision agriculture and soil monitoring networks, with approximately 44% of monitoring schemes in Europe using some form of systematic approach (van Leeuwen et al. 2017). One limitation of this approach, however, is that an unbiased estimate of design variance does not exist, making it challenging to calculate reliable confidence intervals for estimated population parameters (Opsomer et al. 2012; Magnussen et al. 2020). Still, because of its relative simplicity and ability to provide more precise estimates compared to simple random sampling (Mostafa and Ahmad 2018), systematic sampling may be another sampling strategy to consider, especially for practices that cover relatively small areas.

> "If no suitable ancillary variables are available for stratification, one may consider stratification on the basis of spatial coordinates." de Gruijter et al. 2006

In heterogeneous areas, stratification prior to sampling can help ensure representativeness of the data and greater precision particularly compared to a simple random sample of the same size. Stratified sampling involves subdividing the whole study area into smaller homogeneous units via geography, landscape features, soil type, vegetation, management, or any other characteristic that moderates indicator variability (EPA 2002; Donovan, 2013). Sampling locations are then identified within each strata and combined to create a stratified sample. Many national soil monitoring networks use stratification (van Wesemael et al. 2011) with approximately 26% of soil monitoring schemes in Europe stratifying in some way (van Leeuwen et al. 2017). Even for field-scale assessments, this approach has been described as not only superior, but necessary (e.g., Brus et al. 1999). However, stratification requires considerably more expert knowledge and preparation to execute effectively, which if done wrong can make sampling actually less efficient. Stratification also requires use of more complex analyses/calculations post hoc to produce mean and variance estimates. Presumably for these reasons, the Bureau of Land Management's AIM program recommends against stratifying for terrestrial monitoring projects unless necessary. The usefulness of stratification for enhancing efficiency may also decrease as the size of the study area decreases, something that may be particularly relevant for this monitoring framework.

With the goal of repeat sampling to detect changes longitudinally, another important consideration is how samples will be collected over time. Options include selecting new random sampling locations, sampling from permanent locations, or sampling from a rotating panel of locations. Selecting new random sampling locations has the benefits of increasing information on spatial variation in addition to temporal variation (de Gruijeter et al. 2006) and allowing for improved stratification over time as new information becomes available (de Grujiter et al. 2016). However, this kind of design has lower power to detect temporal trends than other approaches. Instead, sampling from permanent locations is commonly used to detect trends over time (Allen et al. 2010; Spencer et al. 2011; Smith et al. 2020), including by Point Blue's RMN, FAO's Global Soil Organic Carbon (GSOC) MRV, and Verra's Soil Carbon Quantification Methodology (Oldfield et al. 2021). This approach offers greater precision than selecting new points each time, decreases the minimum detectable difference, and helps to ensure spatial and temporal differences are not confounded (Herrick et al. 2009; Allen et al. 2010); it is also arguably simpler, since sampling locations only have to be identified once. A hybrid approach also exists, where some proportion of new and existing locations are resampled in a rotating panel (Nieuwenbroek 1991). This approach helps to maximize spatial representation while also capturing temporal variability and is used by the National Park Service and the Bureau of Land Management for inventory and monitoring.

> "It is usually wise to avoid highly complex sampling designs, because the theoretical gain in efficiency compared with simpler solutions is easily outweighed by the practical difficulties." de Gruijter et al. 2006

We recommend the working group carefully consider spatial and temporal sampling strategies during the monitoring design process, taking into account the purpose of monitoring (to precisely detect change in mean carbon values within the study area over time), the common study area size (< 1 acre to 100s of acres) and implementation design (linear, dispersed, or uniform impact) for each practice. The costs/limitations that may inhibit adoption and proper use of each approach at scale (e.g., requirement of expert knowledge or special software) should also be weighed against the potential benefits.

Sample Timing and Frequency

In addition to sampling design, sampling duration, frequency, and seasonality are also important to consider in relation to monitoring objectives. Because we would like to explore developing protocols that can be used widely and serve multiple purposes in today's carbon management and monitoring landscape, we recommend a fit-for-purpose approach that includes some level of guidance or recommendations to help land managers make sound decisions. This guidance could relate to how quickly changes are expected to accumulate for different carbon pools (e.g., herbaceous biomass versus total soil organic carbon) and what season is most feasible or appropriate to take different measurements. Minimum requirements could also be suggested, including taking repeat measurements within a project at approximately the same time.

Statistical Power and Sample Size

Of course, throughout the design process, a question that sits front and center for most is: how many samples is enough to reliably detect temporal trends despite inherent levels of uncertainty in the system (Field et al. 2004)? The answer to this question is ultimately going to depend on 1) how "reliably" is defined—in other words, the level of uncertainty one is willing to tolerate; 2) the effect size of interest; and 3) the size of, and amount of variability within, the study area (Herrick et al. 2009). As discussed above, sampling design can also help increase efficiency (i.e., decrease sample size), which is key given that resources and funding are often limited. For this framework, there are two scales at play when thinking about power and sample size; one is at the ranch level and requires collecting enough data within a study area to sufficiently meet land manager needs. The other is at the network level and requires collecting enough data across projects to sufficiently support scientific inquiry at scale.

Although not always the case (Herrick et al. 2009), reliability or sufficiency is commonly determined using a significance level, alpha (α), of 0.05 and statistical power (1-β) of 0.8 or higher. Here, significance is the probability of rejecting the null hypothesis while it is true (Type I error or "false positive") and power is the probability of rejecting the null hypothesis while it is false (a "true positive"). To optimize monitoring for decision-making, these values can be modified to reflect real or perceived costs (economic or ecological) associated with a Type I or Type II error (Field et al. 2007). Using the goal of this monitoring framework as an example, a Type I error would mean mistakenly concluding there is a response of carbon to a given management practice when there is not, and could result in incentivizing or relying on practices to manage carbon that are not actually effective. In contrast, a Type II error would mean failing to detect an effect that actually exists and may result in removing effective practices from the carbon management "toolbox". We believe that, given the growing number of rangeland practices in said toolbox and the imperative to successfully stewards these landscapes for climate mitigation and adaptation, a Type I error has greater repercussions than a Type II error in this case; however, we would be interested to hear from the working group on this, as the conclusion may differ between end-user groups and between the two objectives of the framework (on-site support and science at scale).

Another important piece of the puzzle when determining the number of samples needed is the expected effect size or the desired minimum detectable difference (MDD). The expected effect size associated with rangeland management can be informed by existing data and published literature, and is likely to vary across metrics, practices, environmental gradients, and time (Smith et al. 2004; Booker et al. 2013; Carey et al. 2020). For instance, across California's rangelands, practices like compost amendments and riparian restoration are thought to have a larger influence on total soil carbon than grazing strategy (Stanton et al. 2018; Buckley Biggs and Huntsinger 2021); these effects should accumulate for some fixed amount of time after practice implementation so that longer sampling intervals will lead to greater effects. In the practice-specific section below, we highlight literature-derived effect sizes for each of the rangeland practices considered in this framework, and below we provide results from a power analysis across a range of effect sizes typical for soil carbon in California (Figure 4).

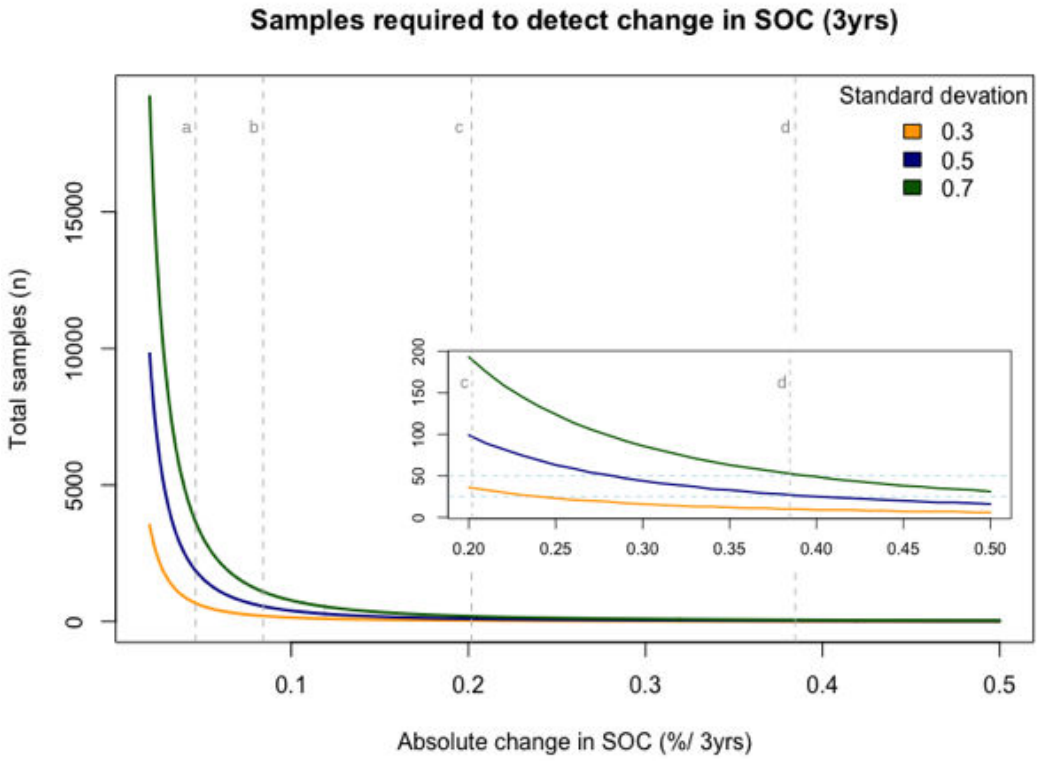


Figure 4. A simple power calculation estimating the number of soil samples needed based on the expected absolute change in soil organic carbon (SOC) over a three year period across Rangeland Monitoring Network sites in California. A range of standard deviations is used, although the observed standard deviation of the RMN samples for SOC was 0.55 (denoted by the blue line). The analysis was conducted similarly to Oldfield et al. (2021), using the R software pwr () package two tailed t-test with an α set at 0.05 for a Type I false-change error rate and β of 0.20 for a Type II missed-change error rate (i.e., a power of 0.80). The first two dotted lines represent estimated absolute changes in SOC (%) over a 3 year period from peer-reviewed literature in California rangelands: (a) 0.046 from Matzek et al. 2020[3] and (b) 0.08 from Dahlgren et al. 1997[4]. The inset is meant to help show the number of samples needed to detect SOC change in RMN data, with dotted gray lines at (c) representing the mean change of -0.20 % SOC from 0-10 cm (and converted to absolute change) and (d) the mean RMN SOC from only sites that gained carbon, equal to 0.38 % from 0-10 cm. The inset also includes two horizontal dotted lines as a reference at a sample size of 25 and 50.

In addition to the above considerations, the variability in the metric of interest will influence the number of samples required to detect a given level of change. All else equal, areas with higher variability are going to require more samples than areas with less variability (Herrick

[3] From Matzek et al. 2020, the soil carbon gains for the upper bank (1.12 Mg C ha^{-1} y^{-1}) reported in text was converted to % SOC using the average bulk density values for the upper bank (1.44 g cm^{-3}), and then multiplied by three to estimate change over three years.

[4] From Dahlgren et al. 1997 Table 4 the values were reported for oak planting without grazing (66 g C kg^{-1}) and grassland without grazing (25.1 g C kg^{-1}). The difference of the two was then divided by the average age of an oak (90 y; which assumes a linear trend over time) to arrive at 0.279 g C kg^{-1} y^{-1}. This was then multiplied by three years to estimate change over that time period (0.837 g C kg^{-1} $3y^{-1}$). Finally to convert to % SOC the value was divided by 10.

et al. 2009)—and in general, rangelands have a considerable amount of spatiotemporal variability that at once makes them special and challenging to study (Table 1). The amount of variability is often related to scale of measurement (e.g., the size of the study area; Fuhlendorf et al. 2017; Conant and Paustian 2002), and is driven by differences in climate, management, and underlying topo-edaphic characteristics. The scale of measurement, or spatial footprint, associated with each of the rangeland management practices in this framework is going to differ by practices and projects; however, most are implemented at the sub-field scale. Practices such as hedgerow planting and riparian restoration will tend to have a smaller footprint than a practice like prescribed grazing. Indeed, a quick glance at the projects awarded by the CDFA's HSP in 2018 shows that one riparian restoration project totalled 1.5 acres while another project focused on prescribed grazing covered close to 5,000 acres. Most projects on the list that provide acreage estimates are less than 75 acres, with many falling closer to 5-10 acres.

Table 1. Coefficients of variation for rangeland datasets derived from California

	Field/Sub Field Scale	Ranch Scale	Statewide Scale	Source	Description
Bulk Density (g/cm3, 0-7.5 cm)	NA	10.0	12.8	Porzig et al. 2018; Carey et al. 2020b	Observational rangeland monitoring; upland, grazed sites
Soil Carbon (%, 0-10 cm)	NA	31.1	46.2	Porzig et al. 2018; Carey et al. 2020b	Observational rangeland monitoring; upland, grazed sites
Soil Carbon (%, 10-40 cm)	NA	30.7	67.2	Porzig et al. 2018; Carey et al. 2020b	Observational rangeland monitoring; upland, grazed sites
Δ Bulk Density (g/cm3, 0-7.5 cm)	NA	224.2	679.5	Porzig et al. 2018	Observational rangeland monitoring; upland, grazed sites
Δ Soil Carbon (%, 0-10 cm)	NA	186.1	274.8	Porzig et al. 2018	Observational rangeland monitoring; upland, grazed sites
Δ Soil Carbon (%, 10-40 cm)	NA	276.4	481.8	Porzig et al. 2018	Observational rangeland monitoring; upland, grazed sites
Δ Woody Biomass Carbon (Mg C ha-1)	10.4-53.7*	NA	NA	Dybala et al. 2019	Riparian restoration, Cosumnes River Preserve
Δ Soil Carbon (Mg C ha-1,	18.5-43.6*	NA	NA	Dybala et	Riparian restoration,

0-12 cm)				al. 2019	Cosumnes River Preserve

**We estimated CVs by first calculating the standard deviation from sample number and standard error, then dividing the standard deviation by the estimated average annual rate of change for aboveground carbon and soil carbon associated with planted and naturally regenerating restored riparian areas.*

Various approaches to determine sample size exist, which take into account the aforementioned information in different ways. On the one hand, site level information and reconnaissance sampling can be used to calculate project-specific numbers using appropriate equations (Willis et al. 2018). This has the benefit of ensuring each project has an adequate number of samples for inference, but is time-consuming and requires a level of technical expertise that may be a barrier to scaling. On the other hand, generalized numbers can be selected based on local or regional information derived from studies on replication requirements. This has the benefit of being easy-to-use and thus scalable, but falls short of offering site-specific information to ensure adequate sample size. We recommend that the working group carefully consider whether the protocols developed for this framework could offer multiple options for deciding on sample size that range from needing site-specific information to choosing from pre-populated tables (as in Herrick et al. 2009). We also suggest carefully discerning the per-project sampling requirements from the sampling requirements needed across the network to answer scientific questions at scale.

Sample Compositing

Sample compositing is a commonly used approach to capture local variability and is a key decision-point for monitoring. The primary benefit is reduced analysis cost, but it has some limitations including a lack of information about range and uncertainty of properties within the study area (Willis et al. 2018). However, these limitations should not be a concern if the end-user composites across areas where they want to capture, but not necessarily understand, variation (e.g., at the point scale). We would like to explore whether the decision to compost samples should be offered as an option based on project-specific needs, and to discuss as a working group what that might look like.

Indicators and Methods

Carefully selecting and describing indicators and associated methodology is critical to ensure the data that are produced from this monitoring framework are reliable and have the ability to aggregate across the network and possibly with other programs. Karl et al. (2017) offer over a dozen criteria to help select a core set of indicators for monitoring; these include usability, signal-to-noise ratio, quality assurance, use by other monitoring programs, and applicability to policy and management. Consistent methodology must support monitoring of selected indicators, and methods that are quantitative, repeatable and efficient, objective, well-established, easy-to-implement, and used in other programs should be prioritized for consideration (Karl et al. 2017).

For this monitoring framework, we propose to focus on empirical field-based indicators and methodologies. We recognize that rapid advancements in remote-sensing technologies offer promising new ways to monitor rangeland dynamics. However, we posit that exploring these options is beyond the scope of the framework, and instead suppose that the collected data could be used to ground truth remote sensing information as it becomes available (Al-Bukhari et al., 2018; Liu et al., 2021).

In this section, we highlight carbon indicators that we would like to discuss with the technical working group and consider for inclusion in the framework. These include aboveground carbon pools in woody and herbaceous biomass, belowground carbon pools in root biomass and soil, and contextual indicators like soil texture and pH. We expect that indicator selection will vary by project and practice depending on context and goals, but that we could offer consistent options from which end-users of the protocols can choose. In this section, we also describe a number of methods for each indicator that may be relevant and worth discussing during the protocol development process.

Aboveground Woody Biomass

Aboveground woody biomass is a highly relevant indicator for carbon sequestration associated with a number of practices in this monitoring framework, including riparian restoration, hedgerows, windbreaks/shelterbelts, and upland dispersed tree plantings. In the most direct manner, the measurement of woody biomass requires destructive sampling and analysis of plant carbon content. However, destructive sampling is time consuming, costly, logistically challenging, and poses risks to the success of management projects by harvesting individuals that were invested in during implementation (Chieppa et al. 2020). Because of this, allometric equations are commonly used to estimate aboveground woody biomass (Beets et al. 2012; Cifuentes Jara et al. 2014) and associated carbon stocks using relationships derived from the literature or from a small number of targeted destructive sampling events (e.g., Dybala et al. 2019; Matzek et al. 2020; Chieppa et al. 2020).

Relatively straightforward measurements, including plant height, diameter at breast height (DBH), and stand density (stems/ha), can facilitate estimation of larger trees. For example, Matzek et al. (2020) recorded DBH for woody and semi-woody individuals larger than 2.5 cm at DBH and used that information to determine biomass using generalized equations for riparian trees and woody shrubs. Of course, using allometric equations is not without its limitations, a primary one being the applicability (or lack thereof) for estimating biomass during the early stages of growth and development (i.e., seedling stage; Geudens et al. 2004). In addition, wood density is often assumed to be constant within a species, which could introduce errors into carbon estimates (Babst et al. 2014)—and the accuracy of allometric estimates may be compromised in heterogeneous environments where tree growth is highly variable and dimensions deviate from the norm (McPherson et al. 2016). However, these latter limitations can be at least partially addressed by using local- or regions-specific equations (e.g., Karlik and Chojnacky 2014).

A number of resources exist that are widely used to facilitate calculation of aboveground plant biomass, which could be considered for use in this framework. These include global databases like GlobAllomeTree (Henry et al. 2013; Cifuentes Jara et al. 2014), national databases as in Jenkins et al. (2003), and regional databases such as the one used by The California Air Resource Board (CARB 2014). Should allometric equations be deemed an appropriate fit by the technical working group, we suggest adopting regional equations wherever possible in an effort to provide more accurate estimates while complementing existing programs. We also encourage the working group to discuss whether and how aboveground biomass can be measured with ease and accuracy in the years immediately following establishment when woody plants are small.

Aboveground Herbaceous Biomass

Aboveground herbaceous biomass is another highly relevant indicator related, in this case, to forage production. It will be most applicable to practices such as prescribed grazing, compost amendments, range seeding, upland dispersed tree plantings, and possibly also riparian restoration. Estimation of herbaceous biomass is most directly measured via destructive sampling, and unlike with aboveground woody biomass, this approach is commonly used by ranchers, technical service providers, and scientists alike. One of the most widely used approaches to estimate biomass production entails clipping forage at or near maturity in small plots (exclosures) that have not been grazed during the growing season (Becchetti et al. 2016). Collecting and processing the samples is relatively simple, requiring clipping and removing plants from a given area, placing them in a paper bag, then air-drying or oven-drying at 65℃ to produce biomass estimates. While destructively harvesting vegetation from exclosures is a direct and relatively reliable way to estimate forage production, in some cases establishing exclosures may be unfeasible and will create a barrier to adoption. Other approaches of destructive harvesting, such as those used by the NRCS, rid the need of installing grazing exclosures by measuring or estimating utilization of vegetation to include in biomass calculations (NRCS 2006). A limitation of this latter approach is that measuring utilization rates requires multiple visits, while estimating utilization occularly requires training and experience, which if done improperly or inconsistently could lead to substantial errors in derived values.

Non-destructive methods for determining aboveground herbaceous biomass exist as well. Visual obstruction measurements using a Robel Range Pole, for instance, determine plant height and density and can be used to quickly estimate standing plant biomass (Robel et al. 1970). A rising plate meter is another method that estimates plant biomass by measuring the height of compressed vegetation, and electric gauges estimate biomass by measuring electrical capacitance (Sanderson et al. 2001). These and other non-destructive methods require local calibration with harvested samples (López Diaz et al. 2011), and have been found to lack accuracy and precision by some (Sanderson et al. 2001) but not others (Robel et al. 1970; Moffet et al. *unpublished;* Flombaum and Sala 2007). Because these approaches

are simple, quick, and cheap, it is possible to collect many more samples than destructive methods, and together the two approaches can be paired to conduct a double-sampling scheme should that be desirable.

We suggest recommending some minimal level of destructive sampling for this framework that could possibly be supplemented or paired with nondestructive estimation methods. However, we'd like to discuss the pros and cons of each approach for estimating aboveground herbaceous biomass with the technical working group and focus group to determine a final recommendation strategy.

Fine Root Production

Plant roots play a big role in sequestering carbon out of the atmosphere and enhancing soil properties such as aggregation and structure (Angers and Caron 1998; Rasse et al. 2005). The production of fine roots is therefore a relevant indicator that relates to carbon sequestration and soil health-related properties, and changes in this indicator may be expected to occur to some degree across all practices in this framework. While this indicator is not commonly included in monitoring networks because of methodological challenges, both standardized and emerging approaches exist for estimating fine root production that may be relevant for inclusion here (Fahey et al. 1999; Byrne 2021).

Two of the most common methods, sequential coring and root ingrowth cores, have the benefit of not requiring expensive instrumentation, but often present challenges related to standardization and effort (Fahey et al. 1999; Byrne 2021). Sequential coring entails sampling root biomass multiple times over the growing season using a coring device, then separating, drying, and weighing the root biomass. Root ingrowth cores estimate fine root production by removing a volume of soil and replacing it with a root-free medium like sand; after a set amount of time, the medium is removed from the soil and roots that have grown into it are separated, dried, and weighed. This approach is relatively simple, but introducing root-free medium to the surrounding soil creates an artificial environment that may affect the behavior and growth of roots in that area (Fahey et al. 1999). Modifications to these methods were proposed for rangeland systems by Byrne (2021) to help minimize the amount of effort that is required to collect and process samples. These modifications focus on use of a cordless drill and hole saw for field sampling and describing root washing methods that can be conducted by hand in a common laboratory sink.

Minirhizotrons are one other method for estimating fine root production worth noting. A minirhizotron system includes a miniature video camera that is installed in transparent soil access tubes, which can estimate fine root production via the collection of repeated, non destructive observations over time. Primary limitations of this approach include the high cost of hardware and software, and the high degree of effort and technical skill required to digitize images (Majdi 1996).

If the technical working group is in favor of including fine root production as an indicator, we suggest considering the use of sequential coring, root ingrowth cores, or both, as modified by Byrne (2021). Guidance on sampling depth and frequency will have to be made and will therefore benefit from discussion during the protocol development process.

Soil Carbon

Rangeland soils store a substantial amount of carbon in both organic (soil organic carbon; SOC) and inorganic (soil inorganic carbon; SIC) forms (Follet and Kimble 2001). Soil organic carbon influences soil structure and aggregation, water infiltration and storage, and nutrient cycling, and is seen as a central indicator related to carbon sequestration and soil health for most agricultural lands (Trivedi et al. 2018). Changes in SOC will be relevant to all the practices in this framework, although almost certainly to varying degrees. In dryland environments, soil inorganic carbon as $CaCO_3$ offers additional opportunities for sequestering carbon out of the atmosphere (Monger and Martinez-Rios 2001). For the purposes of this scoping paper, we focus on measurements related to SOC as an indicator, but encourage the working group to discuss whether and how SIC should also be considered in the framework.

Soil organic carbon can be estimated in-situ or by collecting samples and sending them to a laboratory for analysis via wet or dry combustion (Chatterjee et al. 2009). Currently, the latter approach (direct measurement on collected samples) is required to ensure accuracy (Paustian et al. 2019). During the collection, handling, and processing of soil samples, a number of key decisions have to be made prior to analysis. These include deciding on the appropriate sampling tool (soil probes, shovels), sampling depth, storage, and processing steps. Because SOC measurements across different depths can be harmonized post-hoc (Maynard et al. 2019), we recommend a fit-for-purpose approach that includes a minimum sampling depth requirement and some level of guidance or recommendations to help land managers make sound decisions around additional depth increments; however, it will be important to discuss this as a working group. It is also likely that as a working group we will recommend SOC samples be dried, crushed, sieved, and ground prior to analysis using one of the methods described below, but appreciate the opportunity to discuss this during protocol development.

Of the direct measurement options, dry combustion methods are more widely used than wet combustion, and include weight-loss-on-ignition (LOI) and automated combustion. The LOI method oxidizes soil organic matter (SOM) in a sample by heating it to a very high temperature, and then measures the mass difference to produce a value for SOM that can be converted to SOC using the standard conversion factor of 0.58. However, this method can decompose inorganic carbon constituents and remove water that may be remaining in the sample, effectively overestimating SOM content (Sollins et al. 1999). Despite this limitation, LOI-derived measurements of SOM content have been shown to correlate strongly with direct measurement of SOC content via automated dry combustion

(Chatterjee et al. 2009)—which is considered the superior method for routine analysis (Sollins et al. 1999; Paustian et al. 2019).

While we recommend including automated dry combustion as the standard option across protocols, we would be interested to hear from the technical working group whether the LOI method has a place in our framework especially given its popularity among ranchers.

Additional Indicators

We recommend at least three additional indicators for consideration that are either important contextual variables for understanding carbon response to management (soil pH and texture) or important for calculating stocks (bulk density). It will be important for the technical working group to consider the pros and cons of methods supporting each indicator and determine which are most appropriate to recommend given the objectives of the framework.

Meta-data and Management Information

Meta-data is information about the primary data that is important for tracking, documentation, and analysis purposes. It can include information like geographic location, soil depth, and protocol used. Collecting meaningful meta-data will be critical to facilitate aggregation and study of data across the network, especially if and when fit-for-purpose approaches to data collection are recommended as part of the framework. Collecting meaningful management data beyond the level of presence/absence will also be key to help answer questions around practice impact. We provide potentially relevant practice-specific management below to consider for inclusion by the technical working group and focus group.

Practice-Specific Considerations

For the seven rangeland management practices included in this framework, we have compiled and synthesized the following information in order to facilitate productive discussion on practice-specific monitoring needs:

Definition: The practice definition for each relevant Conservation Practice Standard, as listed in the NRCS Field Office Technical Guide.

Relevant NRCS CPS Code(s): A direct link to the practice standard.

Study Area Size: A range of possible study area sizes, derived from acreage estimates for funded CDFA HSP Incentive projects in 2018 (CDFA Incentives Projects 2018) and acreage recommendations from a number of Carbon Farm Plans.

Implementation Design & Impact: A description of the spatial impact pattern expected for each practice. Options include uniform, irregular, dispersed, or linear.

Sampling Considerations: Practice-specific considerations for designing protocols and sampling aboveground and belowground carbon, including unusual caveats/challenges or unique sources of variability.

Management Information: Practice-specific management information, some of which may be worth collecting and including in the database to fulfill objective two of this framework.

Expected Effect Size: The expected annual impact on above and belowground carbon based on COMET-Planner Dry/semiarid estimates (Swan et al. 2015, COMET-Planner Report).

Relevant Protocols & Publications for Study Design: A non-exhaustive list of existing protocols and relevant peer-reviewed literature for practice-specific study designs.

Prescribed Grazing



Photo Credit: Chelsea Carey, Point Blue

Definition: "Managing the harvest of vegetation with grazing and/or browning animals with the intent to achieve ecological, economic, and management objectives" -NRCS

Relevant NRCS CPS Code(s): CPS 528

Study Area Size: Pasture to Ranch level (~1 to 2,000 ha)

Implementation Design & Impact: Uniform and/or irregular

Sampling Considerations: Relatively large spatial footprint; Size and characteristics of control areas; Whether to avoid sampling from sensitive or uniquely impacted areas.

Management Information: Livestock type, stocking density, rotation frequency, seasonality.

Expected Effect Size: 0.01 - 0.04 Mg C ha^{-1} y^{-1}

Relevant Protocols & Publications for Study Design: ; Conant and Paustian 2002; USDA 2006; Herrick et al. 2009, 2017; Willis and Benham 2010; Donovan 2017; Porzig et al. 2018; Savory Institute, 2019; Carey et al. 2020b; Wang et al. 2021

Range Planting



Photo credit: TomKat Ranch (left); Alicia Herrera, Point Blue (Right)

Definition: "Establishment of adapted perennial or self- sustaining vegetation such as grasses, forbs, legumes, shrubs and trees." -NRCS

Relevant NRCS CPS Code(s): CPS 550

Study Area Size: Sub-Pasture to Pasture level (~2 to 40 ha)

Implementation Design & Impact: Uniform, linear, or dispersed

Sampling Considerations: Difference in spatial configuration due to planting style (broadcast or drilled); Possible lag time in establishment.

Management Information: Species selection; Site preparation; Planting density and style (broadcast or drilled); Planting date and depth; Site maintenance.

Expected Effect Size: 0.02 - 0.08 Mg C ha^{-1} y^{-1}

Relevant Protocols & Publications for Study Design: NRCS 2007; Hardegree et al. 2011; Herrick et. al. 2017

Upland Dispersed Tree Planting



Photo Credit: Drought-Tolerant Oaks Project, Point Blue

Definition: "Establishment and/or management of desired trees and forages on the same land unit. Establishing woody plants by planting seedlings or cuttings, by direct seeding, and/or through natural regeneration." -NRCS

Relevant NRCS CPS Code(s): CPS 381 and CPS 612

Study Area Size: Sub-Pasture to Pasture level (~2 to 20 ha)

Implementation Design & Impact: Dispersed

Sampling Considerations: Management increases landscape heterogeneity; Presence/absence of woody plantings as a possible stratification layer; Design needs based on planting density.

Management Information: Species selection; Planting density and style (e.g., seed, container); Planting date and depth; Site maintenance.

Expected Effect Size: 0.05 - 0.14 Mg C ha^{-1} y^{-1}

Relevant Protocols & Publications for Study Design: Dahlgren and Singer 1997; Waddell and Barrett 2005; Herrick et. al. 2017

Hedgerow Planting



Photo Credit: Pam Krone, NOAA (left); Goldridge RCD (right)

Definition: "Establishment of dense vegetation in a linear design to achieve a natural resource conservation purpose." -NRCS

Relevant NRCS CPS Code(s): CPS 422

Study Area Size: Sub-Pasture to Pasture level (500 to 1,200 meters)

Implementation Design & Impact: Linear

Sampling Considerations: Hedgerow depth; Possible access issues over time (with dense growth); Relatively small total area, but can cover a long distance.

Management Information: Species selection; Planting density and style (e.g., seed, container); Planting date and depth; Site maintenance.

Expected Effect Size: 0.05 - 0.13 Mg C ha^{-1} y^{-1}

Relevant Protocols & Publications for Study Design: Earnshaw 2004; Long 2010; Thiel 2014; Van Den Berge et al. 2021

Windbreak/Shelterbelt Establishment



Photo Credit: Alicia Herrera, Point Blue

Definition: "Windbreaks or shelterbelts are single or multiple rows of trees or shrubs in linear configurations." - NRCS

Relevant NRCS CPS Code(s): CPS 380

Study Area Size: Sub-Pasture to Pasture/Small Ranch level (500 to 2,000 meters)

Implementation Design & Impact: Linear

Sampling Considerations: Species growth rate for sampling frequency; selection of specific trees to monitor or systematic sampling via transects or plots; Direct measurement of biomass possible; Allometric equations can estimate biomass from height/DBH; Consider estimation of belowground biomass.

Management Information: Species selection; Planting density and style; Planting date and depth; Site maintenance.

Expected Effect Size: 0.10 - 0.40 Mg C ha^{-1} y^{-1}

Relevant Protocols & Publications for Study Design: NRCS 2004; Pousso 2016

Riparian Restoration



Photo Credit: Chelsea Carey, Point Blue

Definition: "An area predominantly trees and/or shrubs located adjacent to and up-gradient from watercourses or water bodies." - NRCS

Relevant NRCS CPS Code(s): CPS 391 and CPS 612

Study Area Size: Pasture level (~0.2 to 8 ha)

Implementation Design & Impact: Linear or dispersed

Sampling Considerations: Description of (or stratification based on) sample position relative to the water body; sample placement must consider seasonal variation in water level; belowground carbon accrual versus deposited sediment; Separation of living and dead biomass for C estimation; depth of soil and horizons may change across riparian transects

Management Information: Species selection; Planting density and style (e.g., seed, container); Planting date and depth; Site maintenance.

Expected Effect Size: 0.04 - 0.18 Mg C ha^{-1} y^{-1}

Relevant Protocols & Publications for Study Design: Health et al. 2010; Young-Mathews et al. 2010; Lewis et al. 2015; Dybala et al. 2019; Matzek et al. 2020

Compost Amendment



Photo Credit: Alicia Hererra, Point Blue (Left, Center); Bill Millot, TomKat Ranch (Right).

Definition: "Using amendments derived from plant or animal residues to improve the physical, chemical, and biological properties of the soil." - NRCS

Relevant NRCS CPS Code(s): CPS 808

Study Area Size: Sub-Pasture to Ranch level (~0.4 to 405 ha - mean of 30 ha)

Implementation Design & Impact: Uniform

Sampling Considerations: Removing or subtracting addition of compost carbon to calculate practice impact.

Management Information: Application rate, date(s), and method (e.g., surface application); Compost chemistry (C, N, pH, moisture content for dry application rate).

Expected Effect Size: ~2.99 Mg C ha^{-1} y^{-1}

Relevant Protocols & Publications for Study Design: Gravuer 2016; Haden et al. 2014; Larchevêque et al. 2006; Silver et al. 2018

Conclusion

In this scoping paper, we have aimed to provide relevant and useful information that will guide the protocol development process. This includes providing a broad overview of the rangeland carbon monitoring goals, highlighting important sampling design aspects, offering core indicators and methods for monitoring aboveground and belowground carbon, and illustrating considerations of common rangeland conservation practices. We look forward to considering many of these topics with the technical working group and end-user focus group as we work together to create a monitoring framework that will meaningfully support rangeland carbon stewardship across California and beyond.

Photo Credit: Chelsea Carey, Point Blue

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