



The Range-C Monitoring Handbook

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About the Cover

Monitoring rangeland soils at Pepperwood Preserve, Santa Rosa, CA (credit: Erika Foster)

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Introduction

The Rangeland Carbon Monitoring Program (hereafter called The Range-C Program) aims to help practitioners conduct transparent fit-for-purpose monitoring of aboveground and belowground carbon in response to rangeland management. It provides guidance on the selection of monitoring designs, sampling protocols, and laboratory methodologies to evaluate the influence of management practices on carbon. In addition, it provides technological support to help land stewards interpret and communicate their findings. At the same time that it supports efforts at the ranch scale, The Range-C Program is designed to evaluate management effects on carbon at regional scales using the aggregated network-wide dataset.

The Range-C Program includes robust but accessible protocols and decision-support tools to monitor and interpret changes in carbon in response to seven commonly recommended rangeland management practices, as well as conversion from row crop agriculture to rangeland. It was developed collaboratively by scientists and practitioners for use by technical service providers, land stewards, scientists, and others managing rangelands who are interested in detecting the impact of a particular management practice over time.

This handbook starts by introducing important concepts as they relate to The Range-C Program, beginning with background information, guidance on indicator selection, sampling frequency, point selection, and sampling density. It then moves on to provide practice-specific guidance before introducing detailed methodology for all of the carbon indicators. We recommend following the handbook from start to finish, but users should also feel free to navigate through the sections in whatever way is most useful.

Why Rangelands?

Rangelands are vast and diverse landscapes that include uncultivated terrestrial areas where domestic and wild animals can graze (Briske 2017). More specifically, calling on a widely adopted definition in the U.S. (Bedell 1998), rangelands are: “land on which the indigenous vegetation is predominantly grasses, grass-like plants, forbs, or shrubs and is managed as a natural ecosystem. If plants are introduced, they are managed similarly. Rangelands include natural grasslands, savannas, shrublands, many deserts, tundra, alpine communities, marshes, and wet meadows.” Globally, rangelands account for 28% of the land cover (Herrick et al. 2017) and are generally found in semiarid and arid regions with relatively low productivity and/or on steep terrain where crop production has historically been restricted. Typically, these lands are managed extensively, rather than intensively, with minimal inputs from irrigation or fertilizer.

Rangelands provide a plethora of critical ecosystem services, including supporting, regulating, provisioning, and cultural functions, which can be amplified or diminished via

human management (Millennium Ecosystem Assessment 2005, Plieninger et al. 2012). These include food production, water filtration and storage, flood management, nutrient cycling, carbon sequestration, wildlife habitat, recreational opportunities, and the socioeconomic foundation for ranching communities (Sala et al. 2017, Teague and Barnes 2017). Unfortunately, land conversion, energy generation (e.g., oil and gas or solar), climate change, and other stressors threaten the continued provisioning of many of these ecosystem services (Cameron et al. 2014; Herrick et al. 2012; Roche et al. 2021) at the very same time that societal demands from each acre are increasing. Stewardship is thus critically important and monitoring can help ensure stewardship decisions are efficient and effective while supporting ranchers' livelihoods and cultural values.

Why Monitor Carbon?

As the basic building block of life, carbon exists in “pools” (e.g., soil, plants, air) and it flows between aboveground and belowground ecosystems, serving as an indicator of biological response to environmental change and management. Protecting and rebuilding carbon through stewardship is an important part of the climate solution (Bossio et al. 2020). Beyond this, carbon stewardship offers a myriad of other benefits including, for instance, helping yields recover following drought (Bradford et al. 2019). Measurement of ecosystem carbon can provide insights into forage productivity and soil organic matter, nutrient availability, water infiltration and storage, and even wildlife habitat, all key aspects of ecosystem health and resilience (Figure 1). Given the importance of carbon for soil functioning, climate change mitigation, and adaptation, a growing number of government, private, and not-for-profit programs focus on protecting and rebuilding carbon as a primary goal (Bradford et al. 2021). This expanded interest in rangeland carbon creates an unprecedented need and opportunity to assess the benefits of rangeland stewardship through monitoring.

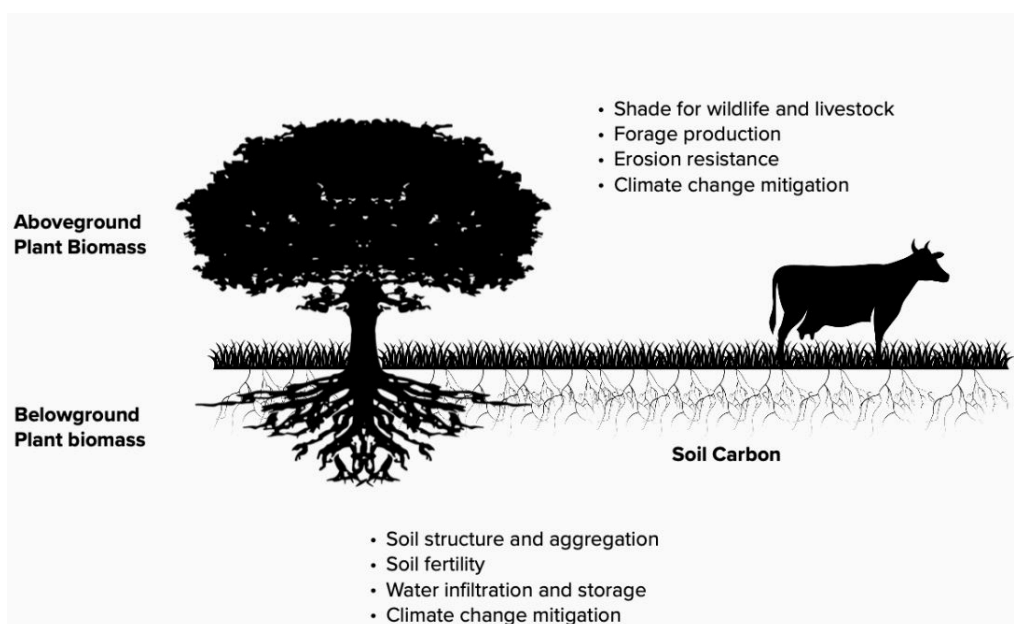


Figure 1. Rangelands provide critical ecosystem services, many of which are linked directly or indirectly to carbon storage in plants and soil.

About The Range-C Program

The Range-C Program was developed via a collaborative process with scientists, practitioners, and agency staff representing over 25 institutions. The Technical Working Group was composed of experts in carbon and soil health¹ research, monitoring, modeling, and management. Members of The Technical Working Group helped to develop and review key design aspects, such as minimum standards and recommended methodologies, through participation in five meetings. The Practitioner Working Group brought together ranchers, technical service providers, and other stakeholders interested in managing and monitoring carbon. This Group provided input on the utility and feasibility of The Range-C Program through participation in two meetings. The OpenTEAM Carbon Group was composed of additional experts in carbon and soil health research, monitoring, modeling, and management. Through twelve meetings, The OpenTEAM Carbon Group provided feedback on key design aspects that was considered and relayed to the other groups for further discussion. All groups were allowed the chance to provide written feedback on *The Rangeland Carbon Program: Handbook of Field Methods*, resulting in the final product that is presented here (referred to hereafter as the *The Range-C Handbook*).

The Range-C Program includes robust but accessible protocols to monitor changes in rangeland carbon over time. To account for the variety in management approaches being applied to rangelands today, The Range-C Program includes sampling design and protocol options that map onto specific practices. These practices are:

- prescribed grazing
- compost amendment
- range planting
- upland tree planting (i.e., silvopasture)
- hedgerow and windbreak establishment
- riparian forest buffer/restoration

¹ We define soil health as the capacity of the soil to function as a vital living ecosystem that maximizes provision of multiple ecosystem services within ecosystem boundaries in a sustainable way.

The Range-C Program also includes considerations for conversion from row crop agriculture into rangelands (Figure 2).

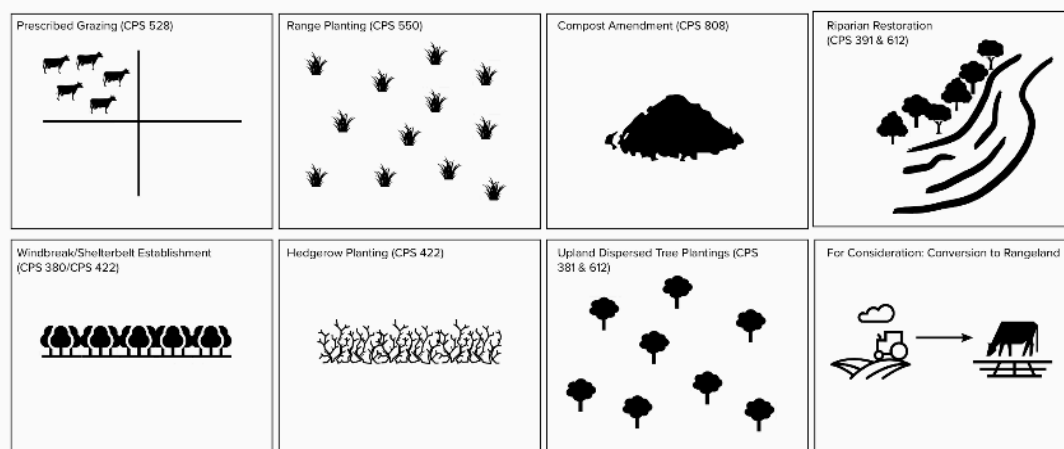


Figure 2. The Range-C Program includes specific protocols to monitor seven common categories of rangeland management that can be implemented (although not necessary) with Natural Resource Conservation Service Conservation Practice Standards (NRCS CPS). The Range-C Program also includes considerations for monitoring crop systems that convert into rangelands.

To complement the growing interest in carbon monitoring, The Range-C Program provides a ‘menu’ of options to meet the needs of technical service providers and land stewards who may have a variety of different monitoring objectives (Figure 3). Indeed, there are many different motivations and overlapping interests related to carbon stewardship and monitoring on rangelands (e.g., economic gains, ecosystem services, scientific understanding). These motivations and interests are supported by a growing number of funding streams and programs, including 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. While *The Range-C Handbook* was not designed to directly match current requirements for any specific program, the protocol development process took into account the current monitoring landscape and *The Range-C Handbook* is designed with enough flexibility to allow users to collect measurements in a transparent way that fits their individual needs. It also offers opportunities for programs to create and recommend *Range-C* ‘roadmaps’ for their participants to follow. However, it is important to note that measurement, reporting, and verification for voluntary carbon markets is beyond the scope of The Range-C Program, and therefore monitoring recommendations and protocols have not been developed with carbon offsets in mind.

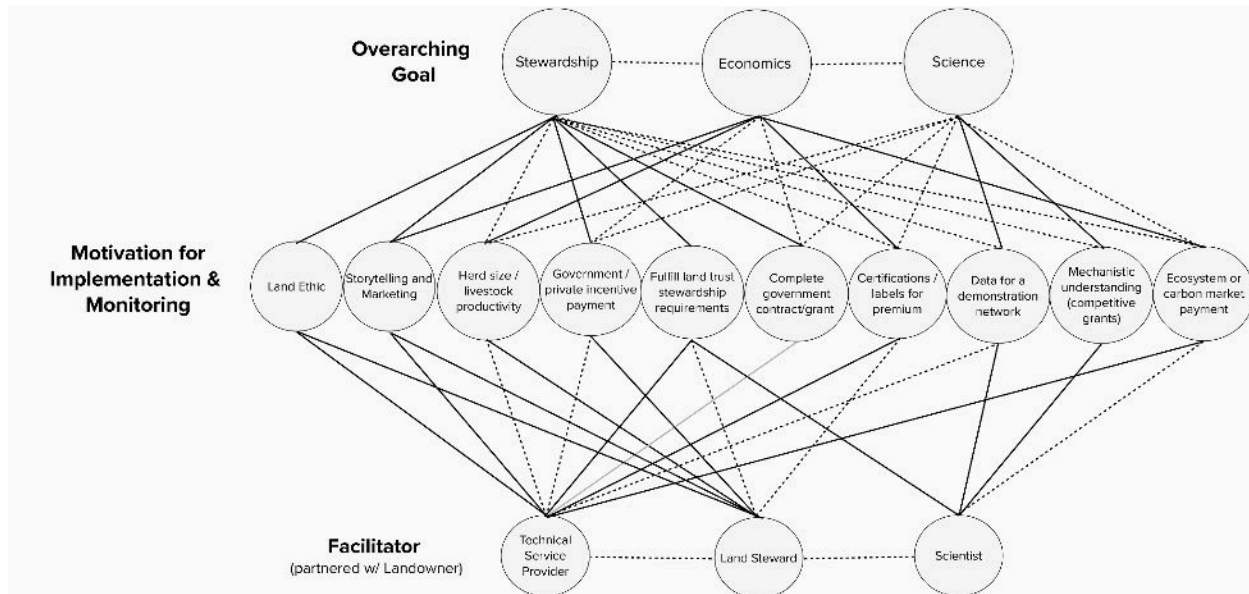


Figure 3. A conceptual framework for motivations, supporting mechanisms, and primary facilitators involved in soil carbon monitoring. Solid lines represent direct connections between entities and dotted lines represent indirect connections. The Range-C Program aims to directly or indirectly support all monitoring motivations except carbon offset markets, which require special attention and consideration for Measurement, Reporting, and Verification.

Use of The Range-C Program is open to anyone managing or working on rangelands, particularly those interested in detecting the impact of a particular stewardship practice. Because carbon indicators will be monitored following consistent methodologies, data gathered using *The Range-C Handbook* protocols can be aggregated across projects and practices, thus facilitating assessment both on-ranch and at regional scales for use by land managers, conservation planners, government programs, and researchers alike.

Monitoring Objectives

The Range-C Program objectives are to:

Provide blueprints for technical service providers and land stewards to monitor changes in carbon associated with commonly-recommended rangeland management practices. The Range-C Program is designed for a wide range of users with varying motivations for managing and monitoring carbon, including soil health, rangeland productivity, and climate change mitigation. However, protocols directly supporting carbon markets are outside the scope of this work given the special requirements for carbon market monitoring, reporting, and verification, as well as ongoing investment in the offset space by others (Oldfield et al. 2022).

Support the development of a network-wide dataset to assess changes in carbon with management. By applying a consistent monitoring framework and associated protocols, data collected as part of the Range-C Program can be combined into a large-scale

dataset to analyze management effects across locations and practices. This aggregated dataset can be used to evaluate predictive models, underpin decision-support tools, guide selection of effective practices by region, and set priorities for programs aiming to conserve and rebuild rangeland carbon for multiple benefits.

About *The Range-C Handbook*

This handbook walks users step-by-step through the monitoring process, providing background information and rationale, sampling schemes, recommended protocols, meta-data considerations, and useful references along the way. The handbook begins by introducing important concepts as they relate to The Range-C Program, such as indicator selection, sampling frequency, point selection, and sampling density calculations. It then transitions to consider practice-specific sampling densities and point selection methodologies before introducing detailed methodology for all of the carbon indicators. Throughout, the handbook includes highlighted “Decision Points” for consideration prior to the field sampling, creating a fit-for-purpose design.

There are many excellent resources on rangeland and carbon monitoring that have guided the development of this handbook, and which provide informative further reading. These include:

- *Rapid Carbon Assessment Project Procedures and Protocols for Field Data and Sample Collection* (Wills 2010)
- *Point Blue Rangeland Monitoring Network Handbook* (Porzig et al. 2018)
- *Monitoring Protocols: Options, Approaches, Implementation, Benefits in Rangeland Systems: Processes, Management and Challenges* (Karl et al. 2017)
- *Measurement Guidelines for the Sequestration of Forest Carbon* (Pearson et al. 2007)
- *Assessment, Inventory, and Monitoring* (various authors, BLM AIM Program <https://aim.landscapetoolbox.org>)
- *Monitoring Manual for Grassland, Shrubland and Savanna Ecosystems, Vols. 1 & 2* (Herrick et al. 2009 a & b)

The handbook is not designed to replace these resources. Rather, it aims to provide detailed guidelines for participation in The Range-C Program. In addition, it should be recognized that *The Range-C Handbook* is not a holistic guide to rangeland management and should not replace the conservation planning process. It does not make recommendations on goal setting or practice implementation, and does not comment on (or take into account) the wide array of co-benefits and potential trade-offs associated with different management interventions. Instead, The Range-C Program assumes these critical aspects of rangeland stewardship have already been carefully considered by the user, and that monitoring biodiversity and other ecosystem outcomes will be completed as necessary using separate, yet complementary protocols.

A Tiered Scoring Approach

The Range-C Program aims to support a diverse array of carbon monitoring motivations and needs that will provide different levels of insight into carbon dynamics and confidence in the findings. Indeed, the desired level of inference² for a project within The Range-C Program is expected to vary based on the context, goals, and the level of available resources, which will in turn affect monitoring decisions and the final monitoring design. The Range-C Program is built to account for this by embedding tiers that relate to key aspects of monitoring, such as:

- the number of indicators chosen
- the methods used to assess indicators
- the number of samples collected

Tiers are based on multiple criteria, but generally relate to the level of accuracy³, precision⁴, and statistical or ecological inference offered by a given decision. Readers are guided through “decision points” highlighted throughout the handbook that offer the opportunity to select from these different tiers, resulting in a fit-for-purpose approach. When possible, we recommend following Tier 1 approaches since these methods will help users make the strongest conclusions about changes in rangeland carbon with management.

Numerical rankings associated with each embedded tier are combined to provide an overall framework score on a scale from 0-100 that can be used to better understand and communicate the level of inference associated with each monitoring project (Figure 4). Decision points hold different weights, depending on how important they are for influencing inference. For instance, given that soil texture and pH are contextual variables whose main purpose is to help interpret carbon dynamics, their presence/absence from a monitoring design is weighted lower than carbon indicators and bulk density, which serve more integral roles in estimating carbon changes. As another example, for forage biomass, the difference in accuracy/precision between destructive harvesting (cutting plants at the base to measure weights) and visual estimation is expected to be large, and therefore the decision on methodology has a relatively strong influence on *The Range-C Inference Score* compared to, for instance, differences in tiered methodologies for soil organic carbon (SOC).

Higher overall scores denote a greater level of inference associated with the monitoring approach. Scores below 50 have relatively limited inference but may be sufficient for adaptive management and stewardship decision-making, scores between 50-75 have

² The level of inference refers to the strength and reliability of a conclusion about changes in carbon, and is based on available evidence from monitoring.

³ Accuracy describes how close a set of measurements are to the true value. Tiers that have higher accuracy methodologies or design decisions will lead to a closer approximation of the actual real value of carbon at a site. This metric is critical for assessing how much carbon is held within a landscape.

⁴ Precision refers to how similar measurements are to each other, and can reflect the reproducibility of a measurement and the value it produces. This metric is critical for estimating how carbon is changing over time within a landscape.

moderate levels of inference and will suffice for many programs and contexts, and scores greater than 75 have relatively strong inference to support those instances where high levels certainty are desired. This score should not be confused with a ranking of carbon stocks or sequestration rates; it does NOT rank the actual amount of carbon stored or sequestered. See [Appendix A](#) to access the scoring system and for more details.

Appendix A: Tiered Inference Scoring System Green = editable

Woody Biomass Plantings (Silvopasture/Tree establishment, riparian restoration)

Indicator Methodologies	Tier (1, 2, or 3) (enter 0 if NA)	Score	Tier descriptions*
Soil Organic Carbon	1	3	1 (Dry Combustion + Size Fractionation); 2 (Dry Combustion)
Soil Inorganic Carbon	1	3	1 (Pressure Calcimeter); 2 (Dry Combustion)
Herbaceous Root Biomass	1	3	1 (Standing Root Biomass)
Woody Root Biomass	1	3	1 (Conversion equation)
Aboveground Herbaceous Biomass	1	3	1 (Clipping & Dry Weight); 2 (Ocular estimation)
Aboveground Woody Biomass	1	3	1 (Height + DBH); 2 (DBH only)
Soil Texture	1	3	1 (Hydrometer); 2 (Texture by Feel)
Soil pH	1	3	1 (electrode in CaCl2); 2 (Portable meter in H2O)
Bulk Density	1	3	1 (Millet or hammer core); 2 (Length times width)
Sampling Design			Tier
Inclusion of Baseline Sampling and a Control	1	3	1 (Control + Baseline); 2 (Baseline but No Control -OR- No Baseline but Control); 3 (No Baseline or Control)
Point Selection	1	3	1 (QGIS or similar); 2 (Range-C Selector)
Point Density Methodology	1	3	1 (Power Analysis Tool); 2 (Range-C Look-Up Table)
Point Density	1	3	1 (High Certainty); 2 (Medium Certainty); 3 (Low Certainty)
SOC Sampling Depth	1	3	1 (> 12 in); 2 (12 in)

*Tier 1 offers greatest inference, then tier 2, and so on.

Inference Score (0-100)
100

The higher the better

Figure 4. This framework generates a tiered scoring system for participants to interpret and communicate the level of inference associated with their monitoring efforts.

Selecting Carbon Indicators

To achieve the objectives of The Range-C Program, we provide guidance for assessing aboveground carbon in plant biomass, belowground carbon in soil and root biomass, and contextual metrics such as soil texture and pH.

Soil organic carbon is critically important for mitigating and adapting to climate change on rangelands (Dass et al. 2018) and is linked to a suite of other co-benefits as well (Bradford et al. 2019). As such, this indicator forms the foundation of *The Range-C Program* and must be monitored with every project. We expect that all other indicators will vary by project and practice, being measured in some cases but not others (Table 1).

Table 1. Indicators included in The Range-C Program, the information that each provides, and the practices that are particularly relevant.

Carbon Indicators	Why Might you Measure this Indicator?	Relevant Practices
Soil organic carbon	Climate Change Mitigation; Soil Health Directly measures soil carbon sequestration and soil health, related to soil organic matter (SOM). Can be separated into particulate organic matter (POM) and mineral-associated organic matter (MAOM) fractions, which provides insight into permanence and can act as an early indicator of change.	All
Soil inorganic carbon	Climate Change Mitigation Relates to carbon sequestration via carbonate formation, particularly in dryland systems. Recommended only for soils with a pH over 7.	All
Herbaceous root biomass	Climate Change Mitigation; Soil Health Relates to SOC formation, carbon sequestration, and soil health.	Prescribed grazing; compost amendment; range planting; upland tree plantings; riparian restoration
Woody root biomass	Climate Change Mitigation; Soil Health Contributes to SOC formation, carbon sequestration, and soil health.	Riparian restoration; hedgerows; windbreaks/ shelterbelts; upland tree plantings
Aboveground herbaceous biomass	Forage Production Measures forage production in annual systems. A transient “pool” that can influence carbon sequestration, but is not itself a source of long-term carbon storage.	Prescribed grazing; compost amendment; range planting; upland tree plantings; riparian restoration
Aboveground woody biomass	Climate Change Mitigation Estimates carbon sequestration associated with long-term storage in woody plants.	Riparian restoration; hedgerows; windbreaks/ shelterbelts; upland tree plantings
Bulk density	Climate Change Mitigation, Soil Health Measures soil weight over volume related to compaction and aeration (pore spaces), which influence water infiltration, root penetration, and microbial habitat. This measurement is required to calculate tons of carbon per acre	All
Soil pH	Soil Health The acidity or alkalinity of soil alters the nutrient availability, microbes, and plant dynamics that in turn regulate the amount of carbon entering and	All

	cycling in the soil	
Soil texture	Climate Change Mitigation, Soil Health The proportion of sand, silt, and clay provides information on how soils potentially interact with and stabilize carbon	All

Decision Point: How many indicators will you monitor? Monitoring more indicators will strengthen your level of inference and your overall framework score. *Note on Scoring:* Carbon indicators are weighted more heavily than supporting indicators. Not all carbon indicators count towards all practices (see Table 1).

In most cases, there are numerous methods for assessing how a given carbon indicator changes over time. Each method varies in how accessible, established/validated, repeatable, cost-effective, and efficient it is. Below are methods supported by The Range-C Program for each indicator (Table 2). Note that some indicators have multiple (tiered) method options from which to choose. Tier 1 methodologies for each indicator should be used whenever possible as they will provide the most detailed, reliable information. Tier 2 and 3 indicators will provide lower confidence in the data (lower reliability), but may be acceptable depending on the context and goals of monitoring. Detailed information on how to collect, process, and analyze indicators using each method are provided in the Indicator Methodology section.

Table 2. Methods supported by The Range-C Program for each indicator and associated information on accuracy, precision, estimated labor and analysis costs, and recommended service laboratories. Relative method accuracy is defined as the correctness of a methodology (i.e., how close the results are to the actual value) and precision as the ability of a methodology to produce similar results (i.e., its repeatability). Recommended service laboratories include a few that participate in the North American Proficiency Testing Program; the list is non-exhaustive and could also include local universities or local extension-recommended labs. See the “Indicator Methodology” section for more details.

Carbon Indicator	Method	What does this Methodology Measure?	Relative Method Accuracy	Relative Method Precision	Estimated Labor/Sample	Lab Analysis Approx. Cost/sample -OR- Cost to Analyze In-house^a	Recommended Service Laboratories
Soil organic carbon (SOC)	Dry Combustion with optional acid pre-treatment and size fractionation (Tier 1)	Amount of total organic carbon, POM fraction, and MAOM fraction	High	High	Collection Labor: 5-15 min Processing Labor: 0-5 min	Service Lab: \$65 In-house: N/A	Cquester Analytics
	Dry Combustion with optional acid pre-treatment (Tier 2)	Amount of total organic carbon	High	High	Collection Labor: 5-15 min Processing Labor: 0-5 min	Service Lab: \$15-50 In-house: N/A	Ward Laboratories; UC Davis Analytical Lab; University of Idaho; Cquester Analytics
Soil inorganic carbon (SIC) (only for soils with pH > 7)	Pressure calcimeter (Tier 1)	Amount of soil inorganic carbon	High	High	Collection Labor: 0* min Processing Labor: 0	Service Lab: \$12 In-house: N/A	Cquester Analytics
	Dry Combustion with acid pre-treatment (Tier 2)	Amount of soil inorganic carbon, which is determined by subtracting soil organic carbon from total soil	Med	Med	Collection Labor: 5-15 min Processing Labor: 0-5 min	Service Lab: \$10-50 In-house: N/A	Ward Laboratories; UC Davis Analytical Lab; University of Idaho

		carbon)					
Herbaceous root biomass	Measurement of standing biomass at peak growth	Amount of roots in a soil core at the time of sampling, which can be converted to carbon equivalent using a conversion factor	High	Low-Med	Collection Labor: 30 min Processing Labor: 35 min	Service Lab: N/A In-house: \$585 one time, up front for equipment (sieves, drying oven, bucket, tins, scale)	In-house
Aboveground herbaceous biomass	Harvesting of standing biomass at peak growth from within grazing exclosures (<i>Tier 1</i>)	Biomass of ungrazed herbaceous plants at peak growth, which in annual rangelands is equivalent to total forage productivity	High	Med	Collection Labor: 10 min Processing Labor: 10 min	Service Lab: N/A In-house: \$476 one time, up front for equipment (paper bags, drying oven, scale)	In-house
	Ocular estimation of standing biomass at peak growth (<i>Tier 2</i>)	Biomass of ungrazed herbaceous plants at peak growth, which in annual rangelands is equivalent to total forage productivity	Low-Med	Low	Collection Labor: 5 min Processing Labor: 0 min	Service Lab: N/A In-house: N/A	In-house
Aboveground woody biomass & woody root biomass	Equations using measurements of tree width and height (<i>Tier 1</i>)	Tree height and diameter of the tree trunk is used in equations to estimate aboveground biomass and	High	Med-High	Collection Labor: 20 min Processing Labor: 5 min	Service Lab: N/A In-house: N/A	In-house

		carbon					
	Equations using measurements of tree width only (<i>Tier 2</i>)	Diameter of the tree trunk is used in equations to estimate aboveground belowground biomass and carbon	Med	Med	Collection Labor: 10 min Processing Labor: 5 min	Service Lab: N/A In-house: N/A	In-house
Soil Bulk Density	Slide-hammer method, recommended for > 12 in deep (<i>Tier 1</i>)	Soil weight for a given volume, needed to calculate total amount of carbon (stocks) ^b	Med-High	Med-High	Collection Labor: 5-15 min Processing Labor: 5-25 min	Service Lab: \$25 In-house: \$507 one time, up front for equipment (sieve, drying oven, tins, scale)	Ward Laboratories; Cquester Analytics; In-house
	Millet method, recommended for < 12 in deep (<i>Tier 1</i>)		Med-High	Med-High	Collection Labor: 10-15 min Processing Labor: 5-25 min	Service Lab: \$25 In-house: \$507 one time, up front for equipment (sieve, drying oven, tins, scale)	Ward Laboratories; Cquester Analytics; In-house
	Volume estimation by height and width (<i>Tier 2</i>)		Med	Med	Collection Labor: <5 min Processing Labor: 5-25 min	Service Lab: \$25 In-house: \$507 one time, up front for equipment (sieve, drying oven, tins, scale)	Ward Laboratories; Cquester Analytics; In-house
Supplemental Indicators							
Soil Texture	Hydrometer (<i>Tier 1</i>)	The relative proportion of sand, silt, and clay	High	Med	Collection Labor: 5-15 min Processing Labor: 5 min	Service Lab: \$12-20 In-house: N/A	Ward Laboratories; UC Davis Analytical Lab; Cquester Analytics
	By Feel (<i>Tier 2</i>)		Low	Med	Collection Labor:	Service Lab: \$5	Ward Laboratories;

					5-15 min Processing Labor: 5 min	In-house: \$0	In-house
Soil pH	By electrode in a 1:2 (w:v) CaCl ₂ solution (Tier 1)	The acidity or alkalinity of soil	High	High	Collection Labor: 0* min Processing Labor: 0	Service Lab: \$6 In-house: N/A	Ward Laboratories; UC Davis Analytical Lab; Cquester Analytics;
	Portable pH meter in a 1:1 (w:v) H ₂ O solution (Tier 2)		Med	Med	Collection Labor: 0* min Processing Labor: 5 min	Service Lab: N/A In-house: \$87 one time, up front for equipment (pH meter, calibration set, specimen cups)	In-house

^aAnalysis costs do not include cost of materials to collect samples or make measurements in the field. When labor and cost are presented as ranges for a given method, this is to account for differences in sampling depth and soil conditions (SOC and other soil properties) and lab fees (SOC, texture by hydrometer).

^bWe recommend calculating soil carbon stocks using equivalent soil mass, which is a technical way to say that carbon stocks are calculated by soil weight rather than soil depth. This approach helps to conduct apples to apples comparisons across different soil types and management regimes.

*Soil inorganic carbon, texture, and pH are given a collection labor estimate of 0, since it is assumed that soil used for SIC is subset from that which was collected for SOC and soil used for soil pH is subset from that which is collected for texture. Otherwise, estimates for time to collect soil for those indicators is 5-20 min/sample. If searching for additional service laboratories beyond the ones listed here, we suggest keeping to those that participate in the North American Proficiency Testing Program (<https://www.naptprogram.org/about/participants/all/>), which offers third-party checks of a laboratory's accuracy and reliability.

Decision Point: What methods will you use to monitor your indicator(s)?
For those indicators where more than one method is provided, choosing Tier 1 methods will strengthen your level of inference and your overall framework score.

Ensuring Data Quality

It is important to ensure the data are collected in a way that produces reliable results. Quality assurance and quality control are two processes that can help with this. Quality assurance is a proactive process that should be embedded into every step of the project, whereas quality control is the inspection process that occurs after data have been collected. Throughout the handbook, we offer quality assurance guidelines for different steps in the monitoring process. We also provide here some general guidelines to follow, adapted from MacDicken 1997 and Herrick et al. 2017 (Table 3).

Table 3. Quality assurance and control measures to keep in mind when monitoring using The Range-C Program.

To ensure projects are of the highest quality:
Read and follow the protocol carefully
Document and report all decision points, including any decisions that deviate from the protocol
Keep methods and analytical laboratories the same over time
Write legibly enough for yourself and others
Take all measurements carefully
Solicit technical assistance if needed
Describe and mark sampling points accurately enough to enable others to revisit in the future
Review data for completeness, including dates of all sampling activities; if errors are found return to sampling point to collect the correct data
Keep adequate records of all data, back them up with duplicated hard or electronic copies
Double check data entry for errors

Identifying the Study Area

The stewardship practices included in *The Range-C Program* often occur as discrete patches on the landscape, at the field or subfield scale. However, some, such as prescribed grazing, may span multiple fields or even be implemented ranch-wide.

The monitoring boundary should encompass, but not extend beyond, the entire area that received the management practice of interest (hereafter referred to as the “treated site”). Areas that received the same management practice at different times or with drastically different approaches should be considered as distinct management units and monitored separately.

Considering a Control Site

While not necessary, participants of The Range-C Program are encouraged to also monitor an untreated/unrestored control area when possible (hereafter referred to as the “control site”). Including a control site offers a number of benefits that help to create a better understanding of a practice’s effects. For instance, a control site helps to ensure changes in carbon that occur due to climate are not mistaken for changes due to management. This helps to strengthen inference both at the network scale and for individual projects. A control becomes even more important when baseline data (i.e., data collected prior to practice implementation) are not available, and when measuring indicators, such as forage productivity, that are highly responsive to year-to-year changes in rainfall.

With that said, for proper comparison, it is essential that control sites are well placed and carefully matched with conditions at the treated site. An improperly selected control site can result in drawing wrong conclusions, and in that way can be worse than not monitoring a control site at all. Important characteristics to keep consistent between the treated and control sites include vegetation at the onset of the project, soil type, topography, landscape position, and size of the study area.

If included, monitoring of the control site should mirror the treated site in the number of samples, approach to identify sampling points, and methods for measuring the selected indicators.

Control Site Checklist:

- Is the control site dominated by the same soil series and soil texture as the treated site (see [Appendix B](#) and [Appendix C](#))?
- Is the control site similar to the treated site in terms of topography (slope grade, aspect, catenal position [Figure 5])?
- Is the control site dominated by the same vegetation community (annual grasses, perennial grasses, briers, oak woodland, etc) as the treated site at the onset of the project?
- Is the control site approximately the same acreage?
- Is the control site as close to the treated site as possible, yet distinct? In other words, is there a ‘buffer zone’ in between the plots that helps exclude any effect from one plot on the other?

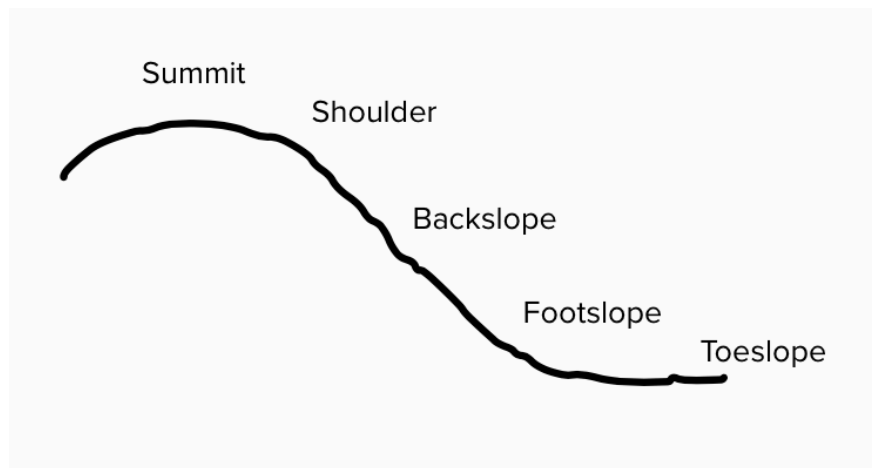


Figure 5. Catenal positions along a hillslope.

We provide two examples below to illustrate selection of a control.

Control Example 1: Compost was applied to a 10-acre pasture dominated by annual grasses with a <5% slope and Diablo clay soil. An ideal control would also be 10 acres, located within the same pasture or close by, and dominated by annual grasses, Diablo clay, and a slope <5%.

Control Example 2: A restoration team planted 100 native trees and shrubs on 0.5 acres along the east-facing bank of a creek. This area had been devoid of woody vegetation for over 30 years and encompasses everything from the summit to the footslope. An ideal control would also be 0.5 acres spanning the summit to the footslope along the east-facing bank of the creek. It would be located in an area that was devoid of woody vegetation for a similar amount of time, and preferably located nearby and upstream.

Decision Point: Will you monitor a control area in addition to the area that received management? Including a control area will strengthen your level of inference and your overall framework score.

Marking the Boundary

It is best practice to mark the boundary of a study area (treated site plus control site, if applicable) at the beginning of a project. Doing so helps to facilitate accurate measurements, repeat visits, and interpretation of the landscape over time. Walking the perimeter of the treated site and, if applicable, the control site is the most accurate way to delineate and document the study area boundary. Permanent markers (such as a T-post covered with PVC or a 12" bright orange plastic jumbo tent stake driven flush to the ground) can be used to mark the corners of the plot, or where feasible, the perimeter can be mapped

using a GPS unit or smartphone and free applications such as *GPS Fields Area Measure* or *Avenza Maps*. For larger areas across the landscape, spatial boundaries can also be identified and marked using aerial photographs, ranch maps, or satellite images. Use of GoogleEarth Desktop, USDA National Agriculture Imagery Program (NAIP), or USGS Earth Resources Observation and Science (EROS) Earth Explore can help facilitate this process.

Selecting Sampling Points

Monitoring requires finding efficient ways to collect a manageable amount of samples or measurements that accurately represent the study area. Carefully selecting sampling points is key to this process. The Range-C Program recommends measuring carbon from a subset of locations that are randomly selected. Random sampling, paired with a sufficient number of samples, helps to ensure that results are generalizable and representative of the entire study area. Simple random sampling forms the base of The Range-C Program sampling methodology. Where appropriate, users can also perform stratified random sampling, as described below. Please note that on specific tribal and federally owned lands, often a cultural or anthropological survey, permit, or active monitoring during sampling may need to occur.

Method for Picking Sampling Points

There are many ways to identify random sampling points. This program supports two approaches. Sampling points for The Range-C Program can either be selected prior to going out in the field using geographic information system (GIS)-based software or while in the field using a low-tech random sampling approach.

To select random samples prior to going out in the field, participants are encouraged to use QGIS, which is a free and open source GIS software. However, other software programs exist that could support this step as well. We provide detailed instructions on how to pick random points using QGIS in [Appendix D](#). This approach requires input of GIS shapefiles and will result in a list of coordinates that can be uploaded to a GPS or smartphone and used to find locations in the field. Because GPS accuracy for most handheld units is between 10-16 ft, if this method is going to be used for small areas (<0.25 acres) or practices that are narrow (<30 ft wide), we recommend the use of high-accuracy GPS receivers such as the [Bad Elf](#).

To select random samples in the field using limited technology, participants of the monitoring project should use The Random Sampling Point Selector Workbook ([Appendix E](#)). This worksheet takes into account the length and width of the study area, in addition to the number of samples for a given project. It is designed to be printed and used to locate one random point location in the field to the next. For ranch-wide practices such as

prescribed grazing, the worksheet can be used to identify points on a map or aerial photograph prior to locating them in the field (adopted from Herrick et al 2009). Additional instructions can be found in [Appendix E](#) and in each practice section below.

Decision Point: Will you use the QGIS (or other GIS software) or the Range-C Point Selector worksheet to identify sampling locations?

Subdividing the Study Area (Optional Stratification)

Improved sampling efficiency may be achieved by dividing the study area into sub-units (“strata”) with similar characteristics. This process, known as “stratification”, is not required but can lower the number of samples needed and thus the associated costs of collection and analysis. Stratification may increase the ability to detect changes over time, as it ensures that proportions of the site that may show early changes are sufficiently sampled (e.g., beneath planted trees). However, in some situations, stratification may not add any additional benefit; for instance, stratification may not be necessary when the study area is small or relatively uniform in topography, vegetation, management or soil type.

Consider Stratifying the Study Area if it:

- Is greater than one acre
- Is hilly
- Is adjacent to a waterbody (e.g., stream, river, pond)
- Has greater than one soil type (See [Appendix B](#))
- Includes a management practice where shrubs or trees were planted and are relatively spread out

When deciding whether and how to stratify, first visit the study area to make in-field observations and consider collecting aerial photographs and maps to assess the above criteria (topographic, soil, site potential; See [Appendix G](#)). Environmental characteristics that are most important to evaluate are those that are stable over time and likely to influence how carbon responds to management. Also note that subgroup importance may differ by carbon indicator; for instance, while proximity to a tree may be an important characteristic to group by for soil organic carbon, this subgrouping wouldn’t necessarily make sense for aboveground woody biomass. Common characteristics to group by include soil type, slope aspect, and vegetation community.

Another special type of environmental characteristic included in *The Range-C Program* is spatial proximity to another sample. Grouping by space to create a spatially-balanced design can be helpful when an indicator is expected to vary strongly across a study area but in an

unknown way. We provide guidance on how to balance sampling points across space using the Generalized Random Tessellation Stratified algorithm (GRTS) in [Appendix G](#).

Stratification Example 1: Figure 6 shows a landscape view of a planted and fenced riparian area. Both sides of the stream bank were restored, and the vegetation was planted along the hillslope. In this example, the study area could be grouped by slope aspect (the two sides of the streambank), catenal position (up- or downslope), and/or direct tree impact (beneath a tree canopy or in the interspace).

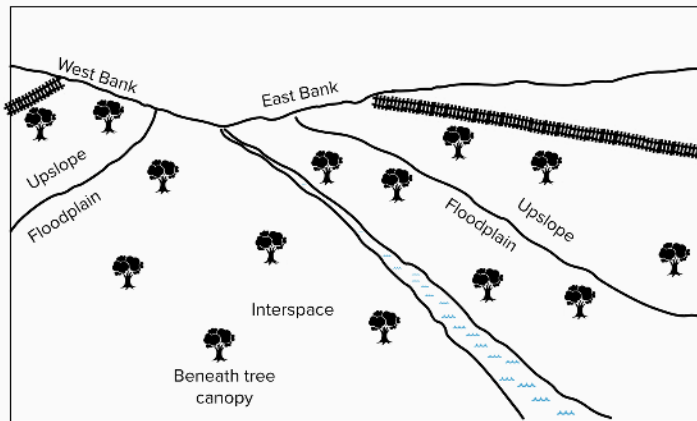
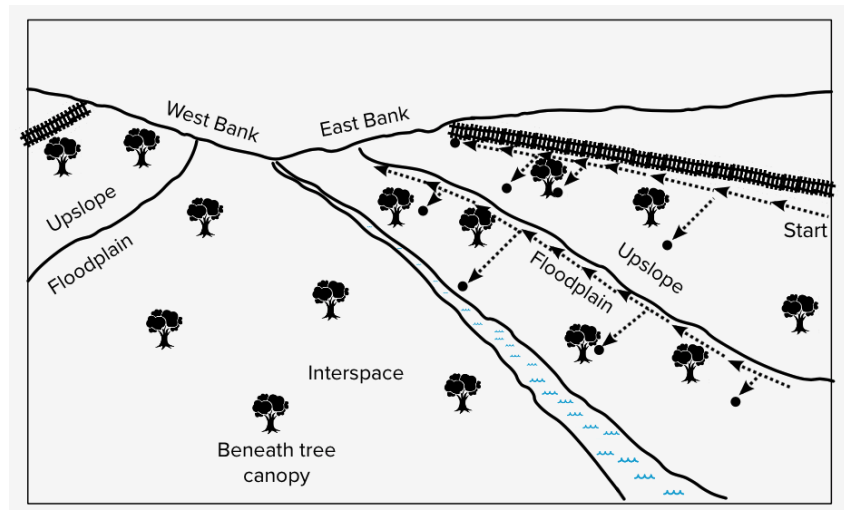


Figure 6. Landscape view of a restored riparian area and some potential subdivisions (“strata”). Someone might create strata for streambank aspect (West or East bank), landscape/catenal position (upslope or floodplain), and proximity to a tree (beneath canopy or interspace).

Once the strata have been identified, the number of samples that will be collected from within each subgroup can be calculated. We recommend allocating points (drawn from the total sample size) proportionally to each subgroup based on the area. If using GIS-based software to pick sampling points, this can be done by uploading GIS files and specifying how to allocate points ([Appendix G](#) and [Appendix H](#)). If using The Random Sampling Point Selector Workbook to select locations in the field, then use the stratification table in [Appendix H](#) to allocate the appropriate number of points to each stratum. With the pacing approach, simply reuse the worksheet to select points within each subgroup separately until the total number of samples for the study area have been located (Figure 7).

Figure 7. Example of using the Random Sampling Point Selector Workbook to select points within each subdivision (streambank aspect, landscape/catenal position, proximity to a tree). Only the point selection process along the east bank is shown; the same approach would also be used on the west bank.



Moving Points in the Field: Inaccessible Places & Areas to Avoid

During the initial setup phase, sampling points should not be moved unless absolutely necessary. However, there may be times when a sampling point must be rejected, and a new one selected. This can happen when a location:

- is dominated by poison oak or located in an erosion gully
- falls on a boulder or in an area that is prohibitively rocky
- occurs on a slope that exceeds a 50% grade or is otherwise unsafe to sample

If using QGIS or other GIS software to choose points prior to going out into the field, create 3-5 extra locations that can be used to substitute rejected points with a new one if necessary. If sampling from an extra or 'oversample' location from spatially balanced points (generated using GRTS), make sure to use the first one listed in the table (this ensures the points remain spatially balanced). When determining points in the field using the Random Sampling Point Selector Workbook, if a point must be rejected, go back to the primary line and navigate to the next point on the list. Similarly, if ranch-wide sampling points are being identified using a map or aerial photograph (see prescribed grazing section below), substitute the rejected point with one of the random extra 'oversample' points pre-identified during the point selection process. If a new sampling point must be chosen, record the reason on the protocol questionnaire.

Establishing Permanent Sampling Points

The Range-C Program recommends sampling from permanent locations over time. This approach increases the ability to detect change in carbon with a high degree of precision, and ensures differences due to space are not mistaken for differences due to time. To establish permanent locations, it is best to mark each sampling point within a study area using a GPS device as well as physical permanent markers. The physical markers are important given that GPS accuracy for most handheld units is only between 10-16 ft.

The most effective and non-intrusive permanent markers on rangelands are those that involve driving some sort of stake flush into the ground that can be found with the aid of a GPS later on. For example, a 2-3 foot galvanized wire can be tied to the top of an 18 inch concrete stake and driven underground at least 1-2 inches, such that the wire sticks aboveground and can be found during subsequent monitoring events. If GPS access is not available to locate points over time, then a T-stake with a pvc pipe covering can be installed or precise photos capturing landmarks from the exact sampling point can be used to relocate the point in the future.

Determining the Number of Samples

Once decisions around point selection have been made, it is time to determine how many samples to collect. The answer is ultimately going to depend on 1) the level of uncertainty one is willing to tolerate; 2) the size of the study area and the amount of variability within (Herrick et al. 2009); and 3) how much change is expected to occur, or how much change someone wants to be able to detect. Where pre-existing site-level data exist or reconnaissance efforts are feasible, we encourage calculating the number of samples needed for a given level of certainty using online resources such as “[Estimation and Inference for Soil Organic Carbon](#)” (Spertus 2020; Tier 1). In cases where this is not feasible, we have generated *Range-C Sample Size Look-Up Tables* for each practice that participants should use in order to determine the number of samples to monitor (Tier 2). We provide guidance below on how to evaluate project-specific needs and select a final number.

Decision Point: To determine the number of samples, will you use the custom site-specific sample density calculator (Tier 1) or Range-C Sample Size Look-Up Tables (Tier 2)? Using the custom approach will provide a more accurate estimate of sample density needs and will strengthen your overall framework score.

Certainty

How confident one wants to be that carbon has or has not changed following the implementation of a conservation practice will depend on the context and goals of the project. The amount of uncertainty a person is willing to tolerate can be defined using statistics. “Significance” is a term used to describe the chance of getting a false positive (i.e., mistakenly concluding there is a response of carbon to a given management practice when there is not). In contrast, “power” is a term used to describe the chance of getting a false negative (i.e., failing to detect an effect that actually exists). The Range-C Program sample size look-up tables are grounded in certainty levels that vary in both significance and power (Table 4; [Appendix F](#)).

Decision Point: How certain do you want to be that carbon did or did not change as a result of your management? Aiming for a higher certainty will increase your level of inference and overall framework score.

Study Area Variability

The number of samples needed for a project depends, in part, on the variability of the study area. All else equal, areas with higher variability are going to require more samples than areas with less variability (Herrick et al. 2009). Study areas with higher variability in carbon are likely to be those that are larger in size, and those which have complex topography, diverse soils, and varied historical management. Planting woody species through, for instance, upland tree plantings or riparian restoration, will also introduce variability into the landscape. In areas with high variability please also see the above section “Subdividing the Study Area” (Optional Stratification).

To determine whether the study area is expected to have high, moderate, or low variability in carbon dynamics, walk through *The Range-C Landscape Variability Assessment* (Figure 8). Put a check mark next to each bullet that describes the study area. Whichever category has the most bullets checked is what the site should be characterized as when determining the number of samples using *The Range-C Sample Size Look-Up Tables* below.

When determining the number of samples, be sure to locate the appropriate level of variability using the practice-specific *Sample Size Look-Up Tables* below. Each level of variability is associated with a given standard deviation (i.e., a measure of how much carbon sequestration is expected to vary across the study area), informed by the literature and existing monitoring data ([Appendix F](#)).

Expected Variation in Carbon	Landscape Characteristics
High	<ul style="list-style-type: none"> -High slopes -Greater than 3 soil types -Diverse vegetation assemblages (e.g., open grassland plus oak woodland) -Adjacent to a waterbody ✓ -Large area (> 25 acres) -Was planted with trees or shrubs ✓
Medium	<ul style="list-style-type: none"> -Moderate slopes ✓ -2-3 soil types -Similar vegetation assemblages, ✓ variables species (e.g., open grassland, different herbaceous species) -Not adjacent to a waterbody -Medium sized area (5-25 acres) ✓ -Was planted with trees or shrubs ✓
Low	<ul style="list-style-type: none"> -Flat -1 soil type ✓ -Uniform vegetation (e.g., open grassland, generally same species across study area) -Not adjacent to a waterbody -Small area (<5 acre) -Was not planted with trees or shrubs

Figure 8. Landscape variability assessment, including an example of how to conduct the assessment. See text for instructions. Adapted with permission from Regen Network.

Magnitude of Change

The size of the change that occurs with management (i.e., the management “signal”) is going to influence the number of samples needed to detect the change in carbon. If the management effect is large, fewer samples will be needed. The change in carbon that is expected to occur will vary across practices, indicators, environmental gradients, and time (Smith et al. 2004; Booker et al. 2013; Carey et al. 2020). For instance, practices like compost amendments and riparian restoration are thought to have a larger influence on soil organic carbon than prescribed grazing in semi-arid environments (Stanton et al. 2018; Buckley Biggs and Huntsinger 2021). These practice effects should accumulate for some fixed amount of time after implementation so that longer sampling intervals will lead to detection of higher changes in carbon.

In the practice-specific *Range-C Sample Density Look-Up Tables* below, we have generated sample number estimates that depend on the expected annual change for each practice and differ in the number of years between each resampling (smaller expected effect sizes

require more time to accrue before resampling). For any given practice, monitoring more frequently than recommended will result in a smaller signal and will require more samples than what has been calculated. Conversely, monitoring less frequently should result in a greater change between sampling events and will require fewer samples, all else equal.

Stratification

When conditions call for it, and when done right, subdividing the study area via stratification can reduce the number of samples needed by up to 25% (Worsham et al. 2012). The *Sample Size Look-Up Tables* were generated using a simple random (non-stratified) approach, so if participants stratify, they may actually achieve higher certainty for the same sample number.

Combining Samples

Some of the measurements in The Range-C Program require collection of physical samples. Namely, soil organic carbon, herbaceous root biomass, aboveground herbaceous biomass, bulk density, soil texture and pH. When this is the case, combining multiple samples into a single one (i.e., a composite) for analysis can be an effective approach to capture variability and obtain an accurate estimate of carbon change. The primary benefit of combining samples is to minimize cost of sample preparation and analysis. Using a composite sample can also help to ensure that each sample has sufficient weight or volume to conduct all of the analyses necessary. However, combining samples does have some drawbacks, including a lack of information about variability or “range” of values and thus the uncertainty of carbon estimates within the study area (Boone et al. 1999). These limitations are not a concern when samples are combined across areas where the variability is meant to be captured but not necessarily understood (e.g., within several feet of a single sampling point).

For The Range-C Program the number of sampling points and associated samples must align with the *Sample Density Look-Up Tables* or be informed by a separate power analysis. Combining samples within a sampling point does not mean that fewer sampling points can be used; compositing is supplemental and should be used only to ensure each individual sample is representative of the sampling point (important in areas that are patchy, such as grasslands with scattered areas of bare ground) and has enough weight or volume for the desired analyses (Figure 9).

Rules for combining samples:

- Requirements for the number of individual samples must be met even after combining. For instance, if 10 distinct samples are required to meet the desired level of certainty, there must still be ten final samples, even if those are formed by combining multiple subsamples at each sampling point.

- Keep the number of samples per composite the same across sampling points.
- Ensure that each subsample contributes an equal amount to the composite sample (i.e., the same mass or volume).
- Make sure the composite sample combines samples that are similar to each other. For example, subsample must be collected close to each other and from the same management unit or “stratum”.
- Each subsample that contributes to the composite sample should be taken from a random location near the main sampling point location (e.g., 1 foot north, south, east, and west of the point). In each subsequent sampling year, all of the subsamples must come from a slightly offset location, rather than directly on top of the previous sample.

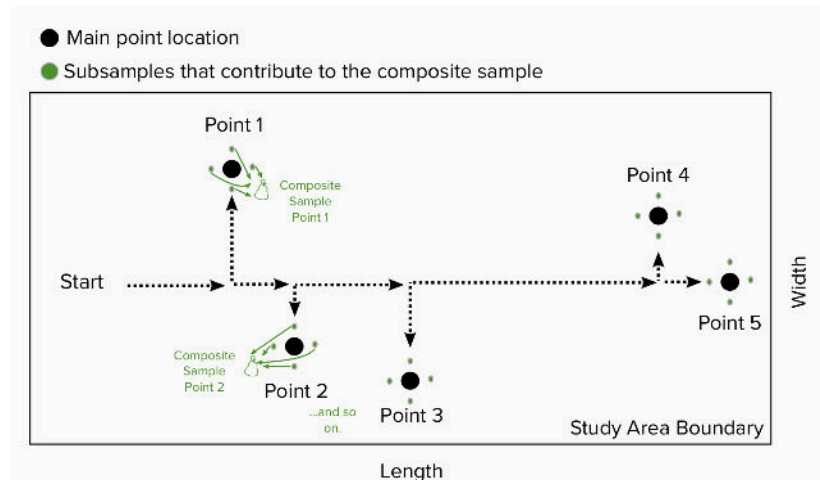


Figure 9. An example of collecting and compositing multiple subsamples (green dots) per point (black dot) and mixing them into a sample bag (green bag).

Practice-Specific Considerations

Whereas above we described general guidance irrespective of practice, here we build off and refine that guidance to take into account the uniqueness of each conservation practice.

Prescribed grazing

Number of Sampling Points: Use the following look-up table to determine how many samples to monitor. The numbers of samples were determined based on a 10-year resampling interval (i.e., allowing 10 years between each sampling event), and more information on their generation can be found in [Appendix F](#).

Number of Samples for PRESCRIBED GRAZING							
Soil Carbon				Herbaceous Biomass & Roots			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	6	14	Low	16	35	65
Med	4	11	26	Med	31	66	123
High	6	19	43	High	52	112	209
Bulk Density & Soil Texture				Soil pH			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	5	Low	3	4	7
Med	3	4	8	Med	3	7	12
High	3	6	14	High	5	11	20

Point Selection: To choose points using the QGIS random sampling option, follow the instructions in [Appendix E](#). To choose points without the aid of GIS software, place a ruler horizontally and vertically along a map or aerial photograph of the study area (Figure 10). Randomly select distances in inches from [Appendix E](#) “Landscape Level Practice” tab, and find the point where the two lines intersect. Repeat until all locations have been identified. Mark up to 5 random extra ‘oversample’ points, in case a main point is inaccessible or in an

area that should be avoided. Use the map to then find the sampling points in the field, take the appropriate samples and measurements, and mark the locations using a GPS and permanent field markers.

If there are subgroups (strata) to include, mark them on the map and subdivide the number of sampling points roughly proportional to the size of the subgroup area. While identifying randomly selected sampling points on the map, allocate the appropriate amount of points within each section, then skip over all subsequent random points that fall within it. Continue marking points on the map until the entire study area is filled out with the correct amount of total points.

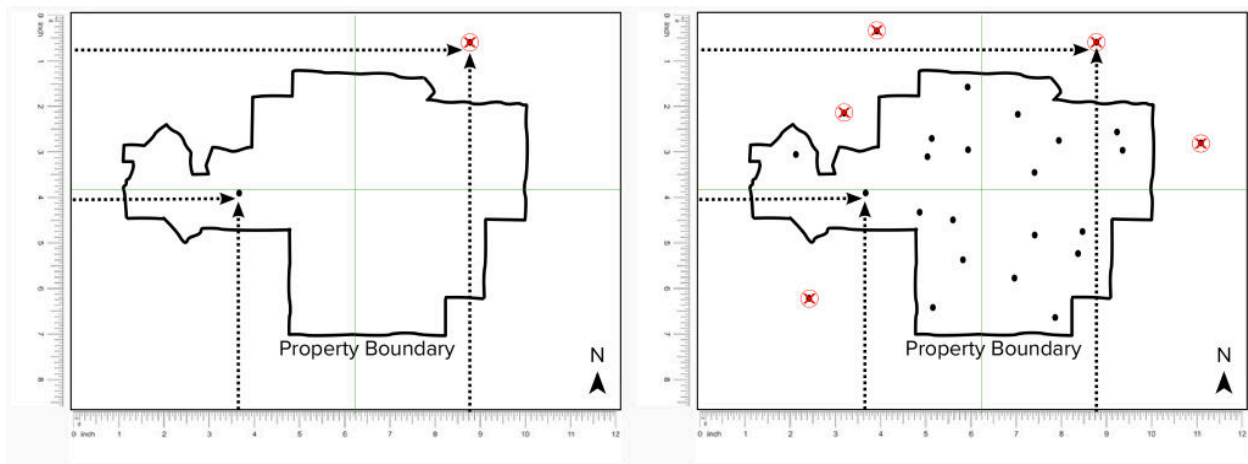


Figure 10. Ranch-wide sampling points can be selected using a map or aerial photograph, ruler, and random number generator spreadsheet. Choose points using random numbers for x (east to west), y (north to south) coordinates and keep only those that fall within the study area boundary (left panel). If seeking a spatially-balanced design (e.g., stratification by space), subdividing the map into quarters (as seen here with the green lines) can help allocate points proportionally. See right panel figure for complete example of a property with 20 points, five per subdivision.

To monitor smaller study areas that are being targeted by grazing for invasive plant management or other outcomes, fill in and print [Appendix E](#) for Dispersed/Uniform Practices. This will be used to identify points in the field (Figure 11). To do this, in the field, choose a random point toward the center of the shortest boundary edge. Consult the spreadsheet to determine the number of feet along and then off the primary line to the first sampling point. Walk the designated distance along what will be the primary line down the center of the study area, then turn the direction the spreadsheet indicates (left or right) and walk perpendicular to the primary line until the sampling point is reached. Take the necessary soil samples and plant measurements at the location and mark it with a GPS and permanent field marker.

Repeat this process by going back to the primary line and continuing on until all the sampling points have been identified. If the distance of the primary line extends beyond the practice boundary length, turn around when the edge is reached and head back along the primary line.

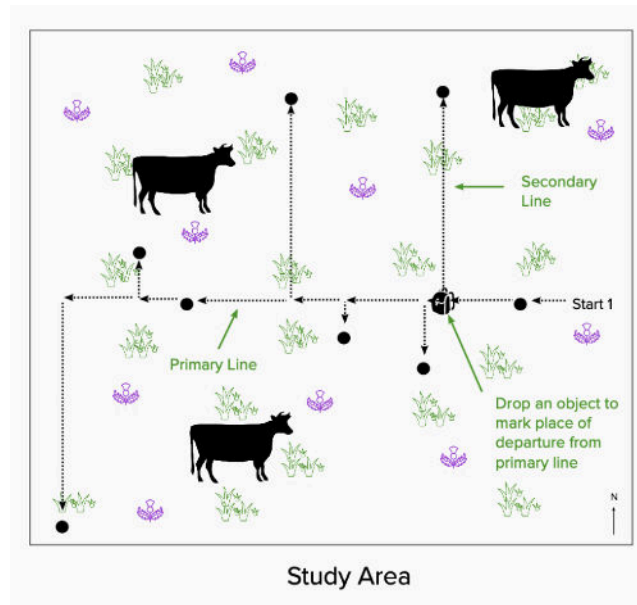


Figure 11. Sampling points for prescribed grazing can be selected in the field using the random number generator spreadsheet. To maintain walking in a straight direction along the primary line, consider using a compass or setting sight on an object on the horizon and maintain walking toward that. When walking perpendicular, mark the spot of departure from the primary line using an object such as an electric fence post wire or backpack placed on the ground. This will help to re-find the primary line each time and continue on to the next sampling point.

Compost amendment

Number of Sampling Points: Use the following look-up table to determine how many samples to monitor. The numbers of samples were determined based on a 1-year resampling interval, and more information on their generation can be found in [Appendix D](#).

Number of Samples for COMPOST AMENDMENT							
Soil Carbon				Herbaceous Biomass & Roots			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	6	Low	3	3	5
Med	3	5	10	Med	4	6	10
High	4	7	17	High	5	9	16
Bulk Density & Soil Texture				Soil pH			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	5	Low	3	4	7
Med	3	4	8	Med	3	7	12
High	3	6	14	High	5	11	20

Point Selection: To choose points using the QGIS random sampling option, follow the instructions in [Appendix E](#). To monitor areas that were amended with compost using the Random Sampling Point Selector Workbook, fill in and print [Appendix E](#) for Dispersed/Uniform Practices. This will be used to identify points in the field. Then, in the field, choose a random point toward the center of the shortest boundary edge (Figure 12). Consult the spreadsheet to determine the number of feet along and then off the primary line to the first sampling point. Walk the appropriate distance along what will be the primary line down the center of the study area, then turn the direction the spreadsheet indicates (left or right) and pace perpendicular to the primary line until the sampling point is reached. Take the necessary soil samples and plant measurements at the location and mark it with a GPS and permanent field marker.

Repeat this process by going back to the primary line and continuing on until all the sampling points have been identified. If the distance of the primary line extends beyond the practice boundary length, turn around when the edge is reached and head back along the primary line.

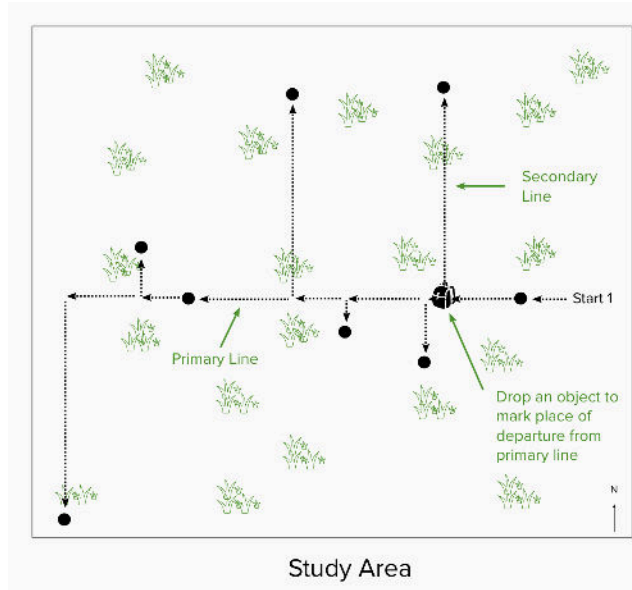


Figure 12. Sampling points for compost amendments can be selected in the field using the random number generator spreadsheet. To maintain walking in a straight direction along the primary line, consider using a compass or setting sight on an object on the horizon and maintain walking toward that. When walking perpendicular, mark the spot of departure from the primary line using an object such as an electric fence post wire or backpack placed on the ground. This will help to re-find the primary line each time and continue on to the next sampling point.

Range planting

Number of Sampling Points: Use the following look-up table to determine how many samples to monitor. The number of samples were determined based on a 5-year resampling interval, and more information on their generation can be found in [Appendix F](#).

Number of Samples for RANGE PLANTING							
Soil Carbon				Herbaceous Biomass & Roots			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	9	23	Low	6	12	19
Med	5	17	44	Med	11	22	36
High	7	28	74	High	18	38	61
Bulk Density & Soil Texture				Soil pH			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	5	Low	3	4	7
Med	3	4	8	Med	3	7	12
High	3	6	14	High	5	11	20

Point Selection: To choose points using the QGIS random sampling option, follow the instructions in [Appendix E](#). To monitor range planting areas using the Random Sampling Point Selector Workbook, fill in and print [Appendix E](#) for Dispersed/Uniform Practices. This will be used to identify points in the field. Then, in the field, choose a random point toward the center of the shortest boundary edge (Figure 13). Consult the spreadsheet to determine the number of feet along and then off the primary line to the first sampling point. Walk the appropriate distance along what will be the primary line down the center of the study area, then turn the direction the spreadsheet indicates (left or right) and pace perpendicular to the primary line until the sampling point is reached. Take the necessary soil samples and plant measurements at the location and mark it with a GPS and permanent field marker.

Repeat this process by going back to the primary line and continuing on until all the sampling points have been identified. If the distance of the primary line extends beyond the practice boundary length, turn around when the edge is reached and head back along the primary line.

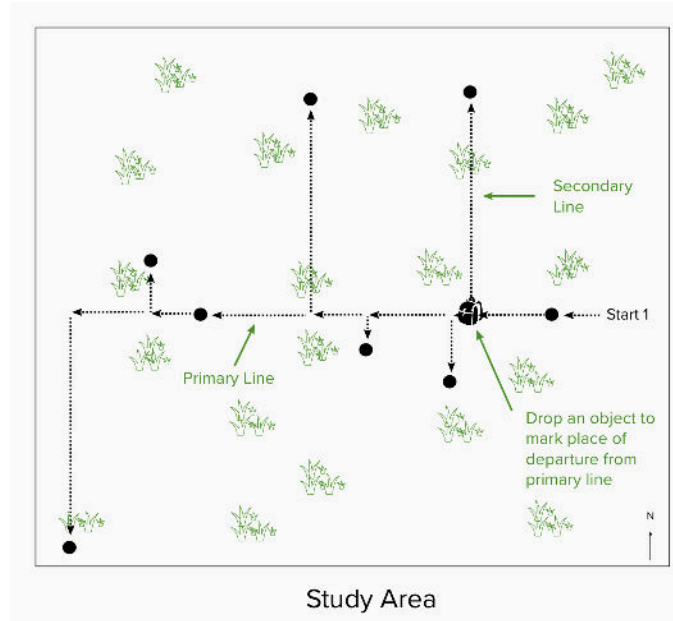


Figure 13. Sampling points for range planting can be selected in the field using the random number generator spreadsheet. To maintain walking in a straight direction along the primary line, consider using a compass or setting sight on an object on the horizon and maintain walking toward that. When walking perpendicular, mark the spot of departure from the primary line using an object such as an electric fence post wire or backpack placed on the ground. This will help to re-find the primary line each time and continue on to the next sampling point.

Upland tree planting (e.g., silvopasture)

Number of Sampling Points: Use the following look-up table to determine how many samples to monitor. The number of samples for low density plantings were determined based on a 10-year resampling interval, and for high density plantings were determined based on a 1-year resampling interval. More information on their generation can be found in [Appendix F](#).

Number of Samples for UPLAND TREE PLANTINGS - Low Density							
Soil Carbon				Herbaceous Biomass & Roots			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	9	17	Low	53	78	137
Med	5	16	31	Med	101	149	259
High	7	27	53	High	172	252	440
Bulk Density & Soil Texture				Soil pH			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	7	Low	3	3	3
Med	3	5	13	Med	3	3	4
High	4	7	21	High	3	4	7
Woody Biomass (if using Point Center Quarter Method below)							
	Study Area Variability						
Certainty	Low	Med	High				
Low	3	3	3				
Med	3	3	3				
High	3	3	4				

Number of Samples for UPLAND TREE PLANTINGS - High Density (tree lots)							
Soil Carbon				Herbaceous Biomass & Roots			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	4	10	Low	3	5	10
Med	3	7	19	Med	5	8	18
High	4	11	31	High	8	14	30
Bulk Density & Soil Texture				Soil pH			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	7	Low	3	3	3
Med	3	5	13	Med	3	3	4
High	4	7	21	High	3	4	7
Woody Biomass (if using Point Center Quarter Method below)							
	Study Area Variability						
Certainty	Low	Med	High				
Low	3	3	3				
Med	3	3	3				
High	3	3	4				

Point Selection: To choose points using the QGIS random sampling option, follow the instructions in [Appendix E](#). To monitor areas that were planted with trees or shrubs using the Random Sampling Point Selector Worksheet, fill in and print [Appendix E](#) for Dispersed/Uniform Practices. This will be used to identify points in the field. Then, in the field, choose a random point toward the center of the shortest boundary edge (Figure 14). Consult the spreadsheet to determine the number of feet along and then off the primary line to the first sampling point. Walk the appropriate distance along what will be the primary line down the center of the study area, then turn the direction the spreadsheet indicates (left or right) and pace perpendicular to the primary line until the sampling point is reached. Take the necessary soil samples and plant measurements at the location and mark it with a GPS and permanent field marker.

Repeat this process by going back to the primary line and continuing on until all the sampling points have been identified. If the distance of the primary line extends beyond the practice boundary length, turn around when the edge is reached and head back along the primary line.

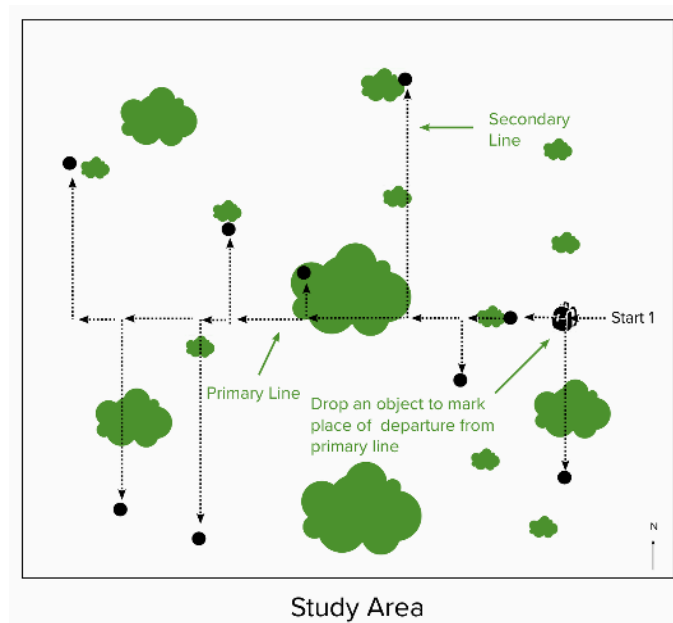


Figure 14. Sampling points for upland tree plantings can be selected in the field using the random number generator spreadsheet. To maintain walking in a straight direction along the primary line, consider using a compass or setting sight on an object on the horizon and maintain walking toward that. When walking perpendicular, mark the spot of departure from the primary line using an object such as an electric fence post wire or backpack placed on the ground. This will help to re-find the primary line each time and continue on to the next sampling point.

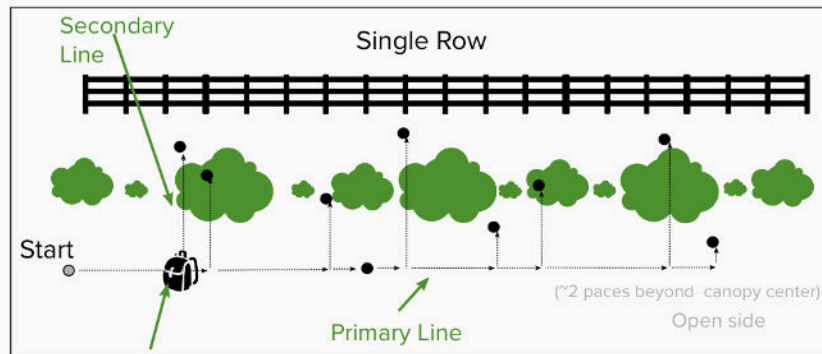
Hedgerow and windbreak establishment

Number of Sampling Points: Use the following look-up table to determine how many samples to monitor. The number of samples were determined based on a 3-year resampling interval, and more information on their generation can be found in [Appendix F](#). Woody biomass is estimated at the stand level as described in the indicator methodology section, therefore does not have a sample size recommendation.

Number of Samples for HEDGEROW AND WINDBREAK ESTABLISHMENT							
Soil Carbon				Herbaceous Biomass & Roots			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	5	Low	3	3	4
Med	3	5	9	Med	3	5	8
High	3	8	15	High	5	8	13
Bulk Density & Soil Texture				Soil pH			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	7	Low	3	3	3
Med	3	5	13	Med	3	3	4
High	4	7	21	High	3	4	7

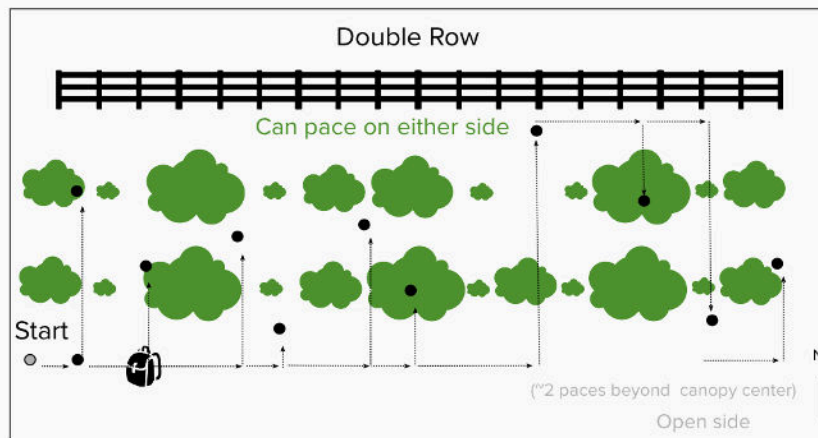
Point Selection: To choose points using the QGIS random sampling option, follow the instructions in [Appendix D](#). To monitor a hedgerow or windbreak using the Random Sampling Point Selector Worksheet, fill in and print [Appendix E](#) for Linear Practices. In the field, choose a random point toward one end of the planted row that is approximately two paces (~2 yards) out from the center of the canopy on the open side (Figure 15). Consult the spreadsheet to determine the number of feet along and then off the primary line to the first sampling point. Walk the appropriate distance along the primary line down the edge of the study area, then turn into the hedgerow and pace perpendicular to the primary line until the sampling point is reached. Take the necessary soil samples and plant measurements at the location and mark it with a GPS and permanent field marker.

Repeat this process by going back to the primary line and continuing on until all the sampling points have been identified. If the distance of the primary line extends beyond the practice boundary length, turn around when the edge is reached and head back along the primary line.



Drop an object to mark place of departure from primary line

Study Area



Study Area

Figure 15. Sampling points for hedgerows can be selected in the field using the random number generator spreadsheet. Follow the edge of the hedgerow, maintaining a consistent distance (2 paces from the canopy center) when walking the primary line. When walking perpendicular, mark the spot of departure from the primary line using an object such as an electric fence post wire or backpack placed on the ground. This will help to re-find the primary line each time and continue on to the next sampling point.

Riparian forest buffer/restoration

Number of Sampling Points: Use the following look-up table to determine how many samples to monitor. The number of samples were determined based on a 5-year resampling interval, and more information on their generation can be found in [Appendix F](#).

Number of Samples for RIPARIAN FOREST BUFFER/RESTORATION							
Soil Carbon				Herbaceous Biomass & Roots			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	5	13	Low	3	6	10
Med	3	9	25	Med	6	11	19
High	5	15	42	High	8	19	32
Bulk Density & Soil Texture				Soil pH			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	7	Low	3	3	3
Med	3	5	13	Med	3	3	4
High	4	7	21	High	3	4	7
Woody Biomass (if using Point Center Quarter Method below)							
	Study Area Variability						
Certainty	Low	Med	High				
Low	3	3	3				
Med	3	3	3				
High	3	3	3				

Point Selection: To choose points using the QGIS random sampling option, follow the instructions in [Appendix E](#). To monitor restored riparian areas using the Random Sampling Point Selector Worksheet, fill in and print [Appendix E](#) for Linear Practices. This will be used to identify points in the field. If both sides of the waterway (stream or river) have been restored, we recommend splitting the number of samples proportionally so that each side is monitored. In the field, choose a random point toward one end of the riparian area that is along the fence line (Figure 16). Consult the spreadsheet to determine the number of feet along and then off the primary line to the first sampling point. Walk the appropriate distance along what will be the primary line down the edge (i.e., fence line or equivalent) of the study

area, then turn into the riparian area and pace perpendicular to the primary line until the sampling point is reached. Take the necessary soil samples and plant measurements at the location and mark it with a GPS and permanent field marker.

Repeat this process by going back to the primary line and continuing on until all the sampling points have been identified. If the distance of the primary line extends beyond the practice boundary length, turn around when the edge is reached and head back along the primary line. Repeat on both sides of the waterway if necessary.

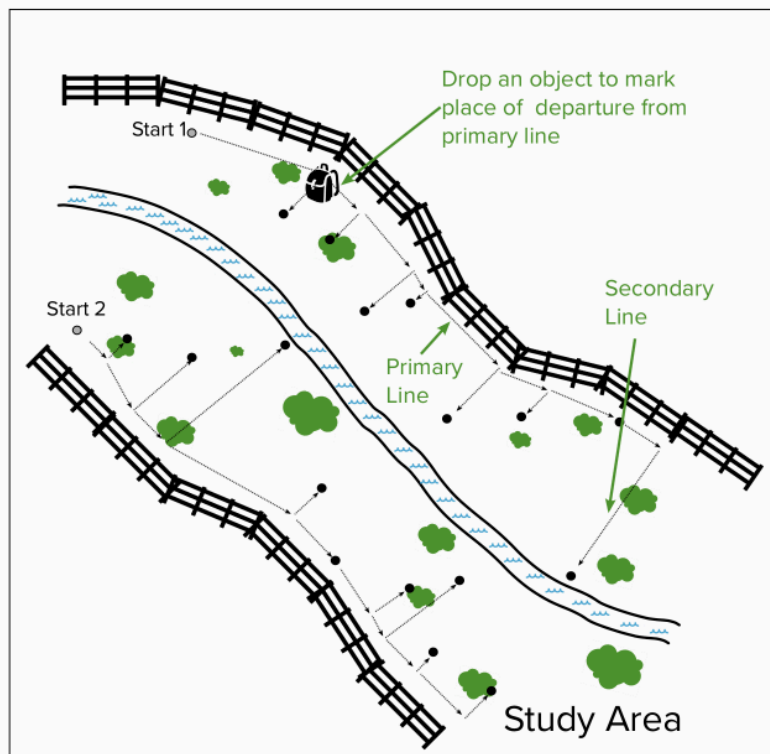


Figure 16. Sampling points for riparian restoration can be selected in the field using the random number generator spreadsheet. Follow the fence line (or equivalent) when walking the primary line. When walking perpendicular, mark the spot of departure from the primary line using an object such as an electric fence post wire or backpack placed on the ground. This will help to re-find the primary line each time and continue on to the next sampling point.

Conversion to rangeland from cropland

Number of Sampling Points: Use the following look-up table to determine how many samples to monitor. The number of samples were determined based on a 3-year resampling interval, and more information on their generation can be found in [Appendix E](#).

Number of Samples for CONVERSION TO RANGELAND							
Soil Carbon				Herbaceous Biomass & Roots			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	5	Low	3	4	5
Med	3	5	10	Med	4	6	9
High	4	8	16	High	6	10	15
Bulk Density & Soil Texture				Soil pH			
	Study Area Variability				Study Area Variability		
Certainty	Low	Med	High	Certainty	Low	Med	High
Low	3	3	5	Low	3	4	7
Med	3	4	8	Med	3	7	12
High	3	6	14	High	5	11	20

Point Selection: To choose points using the QGIS random sampling option, follow the instructions in [Appendix E](#). To monitor landscape-level conversion from cropland (or some other land use type) into rangeland using the Random Sampling Point Selector Worksheet, first place a ruler horizontally and vertically along a map or aerial photograph of the study area (Figure 10). Randomly select distances in inches from the [Appendix E](#) Landscape Level Practice spreadsheet, and find the point where the two lines intersect. Repeat until all locations have been identified. Mark up to 5 random extra ‘oversample’ points, in case a main point is inaccessible or in an area that should be avoided. Use the map to then find the sampling points in the field, take the appropriate samples and measurements, and mark the locations using a GPS and permanent field markers.

If there are subsections (strata) to include, mark them on the map and subdivide the number of sampling points approximately proportional to the size of the area. While identifying randomly selected sampling points on the map, allocate the appropriate amount of points to each subgroup, skipping over any subsequent random points that fall within that subgroup.

Continue marking points on the map until the entire study area is filled out with the correct number of total points.

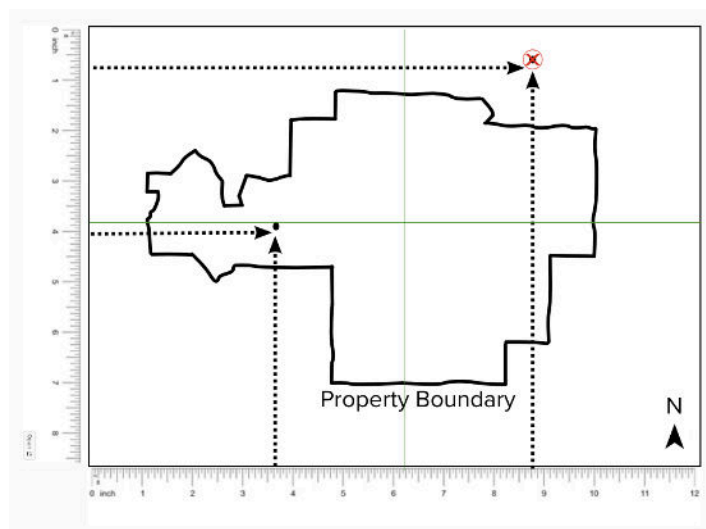


Figure 17. Ranch-wide sampling points can be selected using a map or aerial photograph, ruler, and random number generator spreadsheet. Choose points using random numbers for x (east to west), y (north to south) coordinates and keep only those that fall within the study area boundary. If seeking a spatially-balanced design (e.g., stratification by space), subdividing the map into quarters (as seen here with the green lines) can help allocate points proportionally.

To monitor smaller study areas (e.g., pasture- or sub-pasture level) that are being transitioned out of crop production using the Random Sampling Point Selector Worksheet, fill in and print [Appendix E](#) for dispersed/uniform practices. This will be used to identify points in the field (Figure 18). In the field, choose a random point toward the center of the shortest boundary edge. Consult the spreadsheet to determine the number of feet along and then off the primary line to the first sampling point. Walk the appropriate distance along what will be the primary line down the center of the study area, then turn the direction the spreadsheet indicates (left or right) and pace perpendicular to the primary line until the sampling point is reached. Take the necessary soil samples and plant measurements at the location and mark it with a GPS and permanent field marker.

Repeat this process by going back to the primary line and continuing on until all the sampling points have been identified. If the distance of the primary line extends beyond the practice boundary length, turn around when the edge is reached and head back along the primary line.

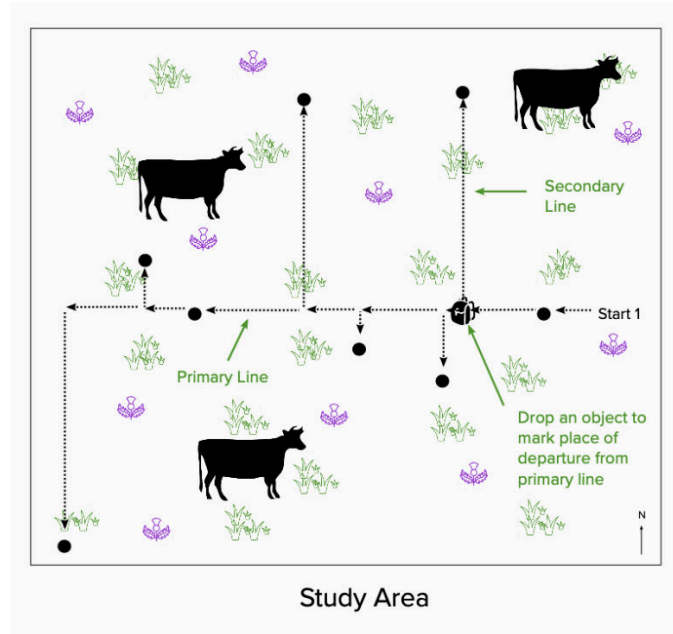


Figure 18. Sampling points for smaller targeted projects can be selected in the field using the random number generator spreadsheet.

Indicator Methodology

Materials for each of the Indicator Methods are grouped in [Appendix I](#) with web links provided for more specialized equipment.

Soil Organic Carbon and Soil Inorganic Carbon

When to Sample: Whenever possible collect baseline samples prior to practice implementation and be consistent over time. For instance, if baseline samples are collected in April, collect all subsequent samples in April as well. Sampling when soils are moist but not saturated will ease collection.

Materials & Supplies:

- Bucket auger or step probe
- Resealable polyethylene gallon-sized bags (e.g., Ziplocs)
- Permanent writing marker (e.g., Sharpie)
- Ruler or similar
- Long screwdriver or similar
- Soil knife (e.g., hori-hori)
- Clippers/shears or similar
- Bucket (optional)

How to Collect a Sample: Find the sampling point and use shears or clippers to cut away any plants at the soil surface, leaving roots intact. Brush away any plant litter or debris from the surface with a hori-hori. Be careful not to remove or disturb the mineral soil itself. When sampling from a compost-amended area, avoid collecting the compost itself with the sample; this will artificially spike the soil carbon values. Use a bucket auger, step probe, or sharp shooter to sample to at least 12 inches depth. If collecting bulk density using the slide-hammer method described below, those samples can be used for soil organic or inorganic carbon measurement in lieu of using a step probe, bucket auger, or sharp shooter. The minimum 12 inch depth must be reached, although the maximum depth may be decided by combining expected depth of management impact with local knowledge of soil layers. If local knowledge is limited, users can examine the recorded soil profile using the USDA Web Soil Survey (“Depth to Any Soil Restrictive Layer” section in the “Soil Properties and Qualities” Tab).

Regardless of the collection method, keep the probe as vertical as possible during the collection process, and be mindful not to lose any soil as the probe is removed from the ground. Place the soil sample in a pre-labelled resealable gallon-sized bag; use the screwdriver to help loosen the soil from the probe if necessary. The soil can be first emptied into a bucket and then transferred to a Ziploc bag if helpful. If subsamples at a location are being collected to make a composite sample, combine them in the same bag. Keep depth increments separate when sampling more than one depth.

Sample Handling and Storage: Keep soil samples out of the sun while in the field, and bring them back to a cool, dry location as soon as possible. Open up each resealable bag with soil in it, break up the soil slightly, and allow them to air-dry. To speed up this process, lay the samples out on newspaper or butcher paper for a couple of days, being sure to keep each sample separate. After the samples are dry, package and send to one of the recommended service laboratories where they will be passed through a 2-mm sieve and prepped for analysis.

Analysis:

Soil Organic Carbon: For Tier 1 methodology, request soil carbon analysis via size fractionation and automated dry combustion with an acid pre-treatment to remove inorganic carbon if an HCl test deems inorganic carbon is present. Tier 2 methodology, request only analysis via automated dry combustion with optional acid pre-treatment. If interested in estimating carbon stocks (e.g., tonnes of carbon per acre), soil bulk density must also be measured and we recommend reporting values on an equivalent soil mass basis as listed in [Appendix M](#).

Soil Inorganic Carbon: If measuring soil inorganic carbon, request analysis via the modified pressure calcimeter method. A Tier 2 option is also available, which is to request analysis of total carbon and total organic carbon via dry combustion, and using the difference to estimate inorganic carbon concentrations.

Quality Assurance: Make sure each sample is collected to the same depth. Soil organic carbon concentrations vary considerably by depth, so it is important to be consistent and precise during the collection process. When using a sharp shooter, it is critical to ensure there is even coverage along the depth profile. If the targeted depth cannot be reached due to e.g., rocks, or if an appreciable amount of soil is lost during transfer out of the ground into the resealable bag, then “waste” the sample and go 6 inches to the north and try again. If there are still issues reaching the desired depth, then keep the sample and make note of this on the data collection sheet.

Methodology Citation(s): (1) Robertson G.P., et al. (eds.), 1999. Standard soil methods for long-term ecological research (Vol. 2). Oxford University Press. (2) Ellert, B.H., Janzen, H.H., VandenBygaart, A.J., and E. Bremer. 2006. Measuring change in soil organic carbon storage. In: Soil Sampling and Methods of Analysis, 25-38. (3) Wendt, J., and S. Hauser. 2013. An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. European Journal of Soil Science (64): 58-65. (4) Miller, R.O., Gavlak, R., and D. Horneck. 2013. Soil, plant, and water reference methods for the Western Region, 4th edition. WREP 125.

Decision Point: How deep will you sample for SOC? Going beyond the minimum sampling depth of 12 inches will strengthen your level of inference and overall framework score.

Herbaceous Root Biomass

When to Sample: During peak plant biomass, e.g., around April or May for California Mediterranean-type rangelands. Be consistent over time.

Materials & Supplies:

- Battery-operated cordless drill with >2 long-lasting batteries
- Hole saw with pilot drill bit
- Resealable polyethylene gallon-sized bags (e.g., Ziplocs)
- Permanent writing marker (e.g., Sharpie)
- Soil knife (e.g., hori-hori)
- Clippers/shears or similar
- Optional: Bucket (flexible to collect samples)
- 2 x No. 40 sieve (8-in diameter; 0.017-in mesh opening)
- 5 quart plastic bucket with 8-in diameter and pour spout
- Flexible plastic cutting board
- Baking sheet (8 x 13 inch)
- Aluminum baking tins
- Compressed air cans
- Flat blade (e.g., spatula or butter knife)
- Drying oven (preferably forced-air convection)
- Scale (0.01 g precision)

How to Collect a Sample: Collect the root core from within 3 feet of where soil organic carbon was collected. Use shears or clippers to cut away any plants at the soil surface, leaving roots intact. Brush away any plant litter or debris from the surface with a hori-hori. Be careful not to remove or disturb the mineral soil itself. Use the hole saw to collect samples to at least 6-in depth. Keep the saw as vertical as possible during the collection process. Place the sample in a pre-labelled polyethylene bag. If subsamples at a location are being collected to make a composite sample, combine them in the same bag.

Sample Handling and Storage: Keep the samples out of the sun while in the field, and bring them back to a cool, dry, and safe location as soon as possible. If they can be processed within a week, allow the samples to air-dry in the bags by opening the seal. If not, keep them sealed and store immediately in a freezer until analysis. With frozen samples, remove samples prior to analysis and allow them to thaw. This will ensure roots do not break during the sieving process.

Analysis: To analyze a sample for root biomass, first separate the roots from the soil by placing the sample in a No. 40 sieve outfitted with a flexible plastic barrier (e.g., plastic table placemat) inserted around its edge. This plastic barrier serves to extend the sieve wall upward so that no roots inadvertently get sprayed out during the cleaning process. Rinse the root sample with water, allowing the wet root-free soil to drain from the sieve. Once most of the soil has passed through the sieve, transfer any partially rinsed roots that have collected on the sieve into a 5 qt bucket with a pour spout. Do this by turning the sieve over and rising the backside with water. Once all organic material has been transferred, spend a fixed amount of time (at least 3 minutes) removing any non-root debris from the samples, such as plant leaves and sticks, which may be floating at the top of the bucket.

Next, place a clean No. 40 sieve below and to the side of the 5-quart plastic bucket, aimed to catch water that overflows out of the bucket's pour spout. Gently run water into the bucket and stir for approximately 1.5 minutes, allowing roots and water to overflow from the pour spout into the second sieve. Then, carefully pour all the water from the bucket into the sieve. Repeat the process if there are still roots in the bottom of the bucket.

Concentrate the roots in the center of the sieve using a gentle water stream and let sit for 2 minutes. Turn the sieve upside down and use a compressed air can to help transfer all the roots onto a baking sheet. Use a flat blade to move the roots one final time from the baking sheet to a pre-weighed aluminum baking tin. Place the sample and tin in an oven at 150 °F for at least 48 hours, or until constant weight. Remove the tin and spend another three minutes per sample discarding any pieces that are conspicuously not roots (e.g., buried bark). Weigh to the nearest 0.01 gram. Use [Appendix J](#) to calculate root biomass as grams/meter².

Quality Assurance: Removing as much of the aboveground plant shoots/stems before sampling is important so that they do not get mistaken for roots later on in the process. Using gardening shears or a soil knife to give the sampling point a clean “cut” prior to sampling roots is important.

Ensure the soil and roots stay within the hole saw when they are extracted from the hole; if an appreciable amount of soil or root mass is lost during this step, “waste” the sample and collect a new one 6 inches north of the previous hole.

During the root washing process, be careful not to lose roots by inaccurately placing the spout or splashing water as it pours from the bucket to the second sieve.

Methodology Citation(s): (1) Byrne, K.M., 2021. A Rapid Method to Estimate Root Production in Grasslands, Shrublands, and Forests. *Rangeland Ecology & Management* (76): 74-77.

Woody Biomass (Aboveground and Root)

When to Sample: Whenever possible, but be consistent over time. For example, if baseline samples are sampled in April, collect all subsequent samples in April as well.

Materials & Supplies:

- Rope or yard stick
- Measuring tape
- Compass
- Caliper or diameter tape
- Clinometer, clinometer phone app, or laser rangefinder (if measuring height)
- Paint marker or tree tags (Optional)

How to Take Measurements:

High-Density Plantings (Point-Center Quarter Method): For riparian restoration and upland tree plantings with higher densities (>10% cover), use the same random point locations that were identified for soil organic carbon to conduct the point-center quarter method (PCQM). This method estimates tree density, basal area, and biomass, which can be used to calculate carbon stocks in woody vegetation. With the soil organic carbon sampling point location as the center, mark out four quadrants by laying an object like a rope or a yard stick pointing North-South and then East-West, or if applicable upstream-downstream and then perpendicular. The quadrants should extend 15 feet in all four directions from the point center (creating a 15 ft radius circle; Figure 19). Within each quadrant, the tree closest to the point center should be measured; only include those trees with a > 2 inch diameter at breast height (DBH; 4.5 feet from the tree base) (CARB 2014b). At each sampling point, there will be measurements of up to 4 trees.

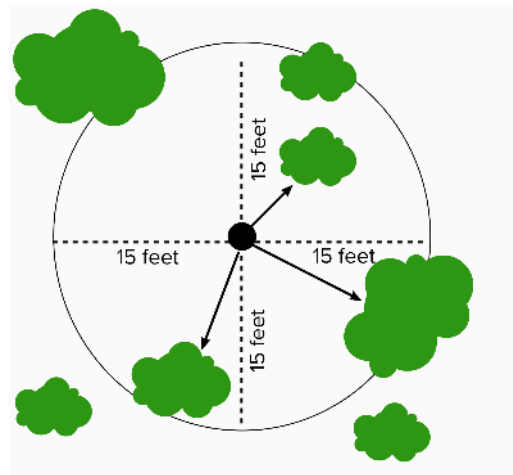


Fig 19. Illustration of the point center quarter method technique. Within each of the quadrants, the closest tree to the point center over 2 inch diameter at breast height is sampled. In this example, sampled trees have an arrow pointing toward them. The tree in the upper left quadrant is not sampled as the trunk falls outside of the circle.

For the focal trees in each quadrant that have greater than a 2 inch diameter at breast height⁵, measure the diameter at breast height using a caliper or diameter tape. For plants with multiple stems, such as willow or junipers, only include those individuals where the total biomass of all measurable stems would be equal to or greater than a single-stemmed tree with a 2 inch diameter at breast height. However, for these often shrubby trees, only actually measure and record the three largest diameter stems; this information will be used to estimate their total biomass using equations in [Appendix K](#) (“PCQM-DBH only or PCQM-DBH+Height tab”).

In each instance, also measure the distance from the center quadrant to each focal tree. Record the values in [Appendix K](#) and follow instructions on how to calculate aboveground and belowground root carbon stocks as tons C/acre. If no trees with the minimum diameter at breast height fall within a quadrant, record “NA” (not applicable).

In some cases, a tree may grow at an angle out of the ground, or be located on a slope (Fig. 20). Always locate diameter at breast height (DBH at 4.5 feet):

- from the ground on the uphill side of the slope if on a hill
- from the ground along the underside of the trunk if sloped
- by moving up and along the trunk to reach 4.5 feet when the trunk is curved

If two of the above criteria compete, choose the option that will move the DBH farthest from the base of the tree (i.e., highest up the trunk).

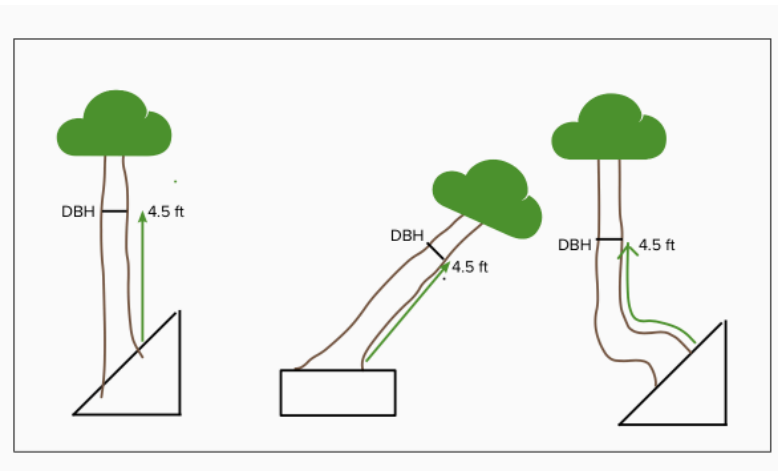


Fig 20. How to locate diameter at breast height (DBH, 4.5 ft) on trees that are not growing straight out of flat ground. Adapted from Dybala (in prep).

It is also possible that the trunk will fork or “split” below 4.5 feet, resulting in two or more stems. If this happens for any tree besides shrubby plants (see above), measure each stem that is at least 0.5 inches in diameter and add them together when inputting into [Appendix K](#).

⁵ Woody biomass trees and shrubs with DBH less than 2 inch—along with semi-woody species such as blackberry—will be left unmeasured. While these may contribute most of the woody material immediately after restoration, they are challenging to measure and in the long run their biomass makes up a small proportion of the total aboveground carbon.

To measure height (Tier 1 methodology), walk at least one tree-length distance away from the base of the tree. In other words, walk away from the tree so that if it fell over it would not hit you. Measure the distance from the base of the tree using a field tape, rangefinder, or equivalent. Use the scale on the clinometer (% or degrees) and record the value at the top and base of the tree. Enter the distance and clinometer data into [Appendix K](#).

Low-Density Plantings (Plot-Based Method): For uniformly distributed and low density plantings (<10% canopy cover), the PQCM will not be the most effective approach for monitoring woody biomass. Instead, plot-based methods should be used. Establish a 70x70 ft square and measure all trees rooted within the plot following diameter of breast height and height instructions above. Record the values in [Appendix K](#) (“Plot-Based Method - DBH only” or “Plot-Based Method - DBH + Height” tab).

Hedgerow Plantings (Volume-Based Method): For well-established hedgerow plantings, it can be difficult to discern one plant from another thus making it challenging to measure individual plants as part of this practice. We therefore recommend using a volume-based approach to estimating aboveground carbon stocks at the hedgerow scale. Measure total length, width, and height of the hedgerow and record the values in [Appendix K](#) (“Hedgerow Biomass” tab). If the hedge has variation in width and height, then take multiple random measurements and report the average. Then, estimate the density of the hedgerow by calculating percent cover by laying a tape measure or rope with regularly marked intervals (we suggest every 5 feet, but distance can vary depending on how long the hedgerow is) along the length of the hedgerow (Fig. 21). Record whether the hedgerow canopy covers each marked interval, and record the number of points covered (i.e., the number of “hits”) in [Appendix K](#) (“Hedgerow Biomass” tab). This information will be used to estimate total aboveground and belowground biomass using this approach.

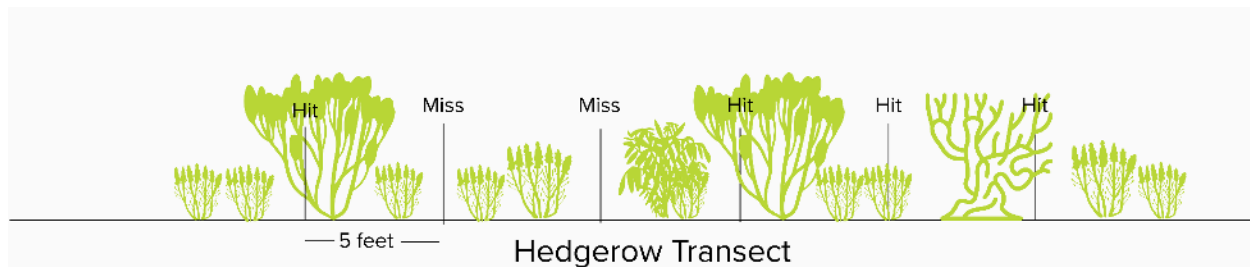


Fig 21. Measure the length, width, and average height of the hedgerow. Then, use a tape measure or rope to determine cover of the hedgerow. This information will be used to estimate above and belowground biomass.

Sample Handling and Storage: N/A

Analysis: Use the in-field measurements to run calculations in [Appendix K](#) that will result in aboveground and belowground root carbon stocks as tons carbon/acre.

Quality Assurance: Small differences in placement of the diameter tape or calipers over time can result in error to the estimates. To help minimize this, mark the tree where initial

measurements were made (at diameter at breast height) using paint or a permanent tree tag. When taking measurements, ensure the diameter tape and calipers are squarely perpendicular to the tree and that the tape is snug all around. If there is a knot, scar or other anomaly, move the tape above slightly and make a note of this on the datasheet.

Methodology Citation(s): (1) Dybala, K.E. In Prep. Protocol for evaluating the multiple benefits of riparian zones in California. Version 0.X. Point Blue Conservation Science, Petaluma, CA. (2) Merritt DM, Manning ME, Hough-Snee N, eds. 2017. The National Riparian Core Protocol: A riparian vegetation monitoring protocol for wadeable streams of the conterminous United States. Gen. Tech. Rep. RMRS-GTR-367. Fort Collins, CO: USDA Forest Service. (3) Black et al. 2022. Biomass pools in intensively managed hedgerows can be a net emission of carbon dioxide. Research Square.

Decision Point: Will you measure woody biomass using the Point Quarter Center Method, the Plot-Based Method, or the Volume-Based Method? The approach should be defined by practice and project details and does not affect your overall inference score.

Aboveground Herbaceous Biomass

When to Sample: During peak plant biomass, e.g., around April or May for California Mediterranean-type rangelands

Materials & Supplies:

Biomass Harvesting (Tier 1):

- Hog panel or similar (16 feet long)
- T-post x 2
- T-post driver
- 6.5" diameter ring (e.g., hose clamp) x 2
- Paper grocery bags
- Clippers/shears or similar
- Ruler or similar
- Drying oven (preferably forced-air convection)
- Scale (0.01 g precision)

Ocular Estimation (Tier 2):

- Hula hoop

How to Take Measurements: If estimating biomass via harvesting, install a grazing enclosure within 30 feet of the soil organic carbon sampling point. To choose a random location nearby, stand at the point center and throw an object in a random direction. Set up the grazing enclosure here at the beginning of the growing season (e.g., fall in a California mediterranean climate). Bend a hog panel into a circle and secure it to the ground with at least two t-posts. This will serve to exclude domestic and wild herbivores from consuming any of the herbaceous vegetation. Near the time of peak plant biomass, remove the grazing enclosure and take two randomly placed forage samples from inside. These random sampling locations within the enclosure should be chosen by throwing an object, like a metal ring, pen or pencil within the enclosure footprint. Then, to collect each sample, place the 6.5" diameter ring on the ground, making sure all plants with a root inside of the ring are pulled into the ring for clipping. For all forage rooted within the ring, cut the plant flush with the ground, and place the clipped forage into a pre-labelled paper bag. If some species have begun to dry out, but you know that they are this years' growth, then include those plants in the sample. Combine the two replicates into the same bag. Be sure to fold the top of the bag closed when done so the sample is not lost.

If estimating biomass visually, toss a hula hoop in a random direction from the main soil organic carbon point location and estimate biomass from within the area where it lands. Do this at least three times around a single point by either 1) counting the number of plant species occurring with the hoop and using pre-established weight estimates for each species to determine total forage biomass (by adding all estimated plant weights together); or by 2) using a Robel Pole to determine plant density and estimate biomass. Record

measurements in [Appendix L](#). Note that both these methods require careful initial calibration with actual plant weights (via comparison with destructive harvesting). If using visual estimate methods without an enclosure, these plants may have been grazed, resulting in a measurement of net forage biomass

Sample Handling and Storage: Air-dry the harvested forage in the paper bags for up to 2 days in a cool/dry place, then move the samples and paper bags into a laboratory grade oven* to dry at 140 °F for 24-48 hours. *A laboratory grade oven is preferred over a conventional oven because using the latter poses a fire risk.

Analysis: For the harvesting method, use a scale that provides at least two decimal places to weigh and record the weight of the bag + dried plant samples in [Appendix L](#). Do this shortly after removal from the oven, so that moisture is not taken back up by the sample. Empty the bag by removing all of the plant biomass into a compost bin or some other receptacle, and record the weight of just the bag. The bag weight should be fairly standard, but it is nevertheless most accurate to record the weight of each. Use the weight measurements to feed calculations in [Appendix L](#) that will result in forage production estimates.

Quality Assurance: When harvesting biomass, the weight of the forage samples will be affected by where the samples are cut in relation to the ground; it is therefore important to keep the harvest height consistent across enclosures. In addition, ocular estimation of forage biomass is subjective; therefore, in order to be accurate using this approach, it should only be done by observers that are carefully trained and skilled at estimating weight of forage using their senses (sight, touch) in the field. Training requires repeated estimation of plant weights by species followed by a confirmation of the weight via harvesting.

Methodology Citation(s): (1) University of California, 2018. Rangeland management series: Annual forage production. ANR Publication 8018. (2) Abbot, L. The Landscape Toolbox Learning Center: Vegetation Measurement and Monitoring, Harvest and Estimation Methods. Accessed: December 2020. (3) USDA NRCS, 2006. National Range and Pasture Handbook: Inventory and monitoring grazing land resources.

Decision Point: If you are assessing herbaceous biomass, which method will you use? Using the harvesting method (Tier 1) will strengthen your level of inference and overall framework score.

Soil Bulk Density

When to Sample: At the same time as soil organic carbon sampling, preferably during peak plant biomass, e.g., around April or May for California Mediterranean-type rangelands. Sampling when soils are moist but not saturated will ease collection. Be consistent over time.

Materials & Supplies:

Millet Method (Recommended if sampling to 12 in depth) (Tier 1):

- Thick nylon stocking, cut to appropriate height (height of sampling depth + 5 inches)
- Long screwdriver or similar (This is used to help the stocking conform to the sampling cavity -- it should be narrow enough to easily fit in the cavity and long enough to reach the bottom while still being retrievable)
- Funnel with at least 1 in diameter hole at the base
- 1 kg millet in a Ziploc bag; ensure seeds are not viable, so if in the environment they cannot grow
- Large measuring cup (2 cups)
- Resealable polyethylene gallon-sized bags (e.g., Ziplocs)
- Permanent writing marker (e.g., Sharpie)
- Aluminum baking tins (if conducting in-house)
- Drying oven (if conducting in-house)
- 2-mm sieve (if conducting in-house)
- Scale (0.01 g precision; if conducting in-house)

Slide-hammer Method (Recommended if sampling below 12 inch depth) (Tier 1):

- Slide-hammer core sampler with thin-walled metal sleeves (AMS Inc., diameter selected based on amount of soil needed for analyses)
- Kitchen knife or similar
- Resealable polyethylene gallon-sized bags (e.g., Ziplocs)
- Permanent writing marker (e.g., Sharpie)
- Aluminum baking tins (if conducting in-house)
- Drying oven (if conducting in-house)
- 2-mm sieve (if conducting in-house)
- Scale (0.01 g precision; if conducting in-house)

Ruler Method (For any depth) (Tier 2):

- Ruler or similar (A survey flag with pre-marked measurement delineations also works well)

How to Collect a Sample:

Millet method: Bulk density will be calculated by measuring the volume of the hole excavated by an auger or corer for the soil carbon sample. If sampling multiple consecutive depths, the millet method must be conducted separately for each integrated depth (e.g., 0-6 in, 0-12 in). To begin, place a screwdriver or other weighted object into the stocking and drop it into the hole from the soil carbon sample. Pour the millet seed through the funnel and into the stocking with the screwdriver in place. This allows the millet to conform to the shape of the hole. Carefully remove the screwdriver when the millet has filled up approximately half the hole; a swirling motion helps the millet fill in the hole's edges. Gently tamp down the millet to fill any irregular cavities in the auger hole. Continue filling the hole until the millet is flush with the surface. Carefully pull the stocking out of the hole and pour the millet into a graduated cylinder. Gently shake the cylinder to level out the millet. Record the value in your data sheet.

Repeat this process one more time in the same hole and record the second volume accordingly. Repeating the measurement increases the precision of the metric. Be sure to pour the millet back into its original container before taking the second measurement. Pouring a previously measured volume back into the hole does not increase precision. If the difference between the two volumes is greater than 10% of the smaller volume, repeat the process twice more for a more precise measurement.

Slide-hammer method: Collect the bulk density sample from within 3 feet of where soil for soil organic carbon was collected. If using the slide-hammer sample for soil carbon itself, then collect it at the exact location designated for the soil carbon sample. Gently brush away any plant litter from the soil surface, being careful not to disturb the soil. Drive the slide-hammer core to the desired depth, keeping a firm downward pressure on the sampler during the process. Lift out the slide hammer. Be sure soil is not lost from the bottom of the ring by placing the soil knife or trowel underneath during removal from the hole. Remove the cylinder from the sleeve, and use a knife to cut the soil flush with the bottom of the cylinder. If collecting multiple depths, cut the soil flush with the top of each section as well. Place the bulk density sample in a pre-labelled resealable bag; use the screwdriver to help loosen the soil from the core if necessary. If subsamples at a location are being collected to make a composite sample, combine them in the same bag. Keep depth increments separate when sampling more than one depth.

Ruler method: Using this method, bulk density will be calculated by measuring the depth of the hole excavated for the soil carbon sample using a ruler or other implement. If sampling multiple consecutive depths, this must be done separately for each integrated depth (e.g., 0-6 in, 0-12 in). Take four depth measurements at discrete locations along the edge of the hole and record in [Appendix M](#). These values, along with the width of the auger or probe will be used to calculate volume.

Sample Handling and Storage: Keep the samples out of the sun while in the field, and bring them back to a cool, dry, and safe location as soon as possible. Allow the samples to air-dry in the bags by opening the seal.

Analysis: Work each air-dried sample through a 2-mm sieve. Large rocks will not pass through the sieve. Place the sieved soil in a pre-weighed aluminum baking tin and oven-dry at 221 °F for at least 36 hours. Record the sample + tin weight in [Appendix M](#) and follow the instructions to calculate bulk density as grams/cm³.

Quality Assurance: If using the slide-hammer method, when inserting the slide hammer core into the ground, check to see if the soil inside is the same level as outside. If it is noticeably lower inside the slide hammer, then compaction has occurred during the process. Should this be the case, discard the sample and collect a new one 6 inches north of the previous hole. If it continues to happen, then consider coming back when conditions are a bit drier. For the millet method, consider that on a slope, the millet should be added such that the top edge matches the shape of the slope when pressed down in the stocking by hand. Also note that excessive shaking will cause the millet to become increasingly compact in the measuring container, affecting the measurement, so be consistent with how the millet is shaken and measured each time. During sieving and weighing of the samples, be sure to transfer all soil carefully and fully from one container to the next; bulk density is derived from the weight that is in the sample, so anything that is lost will lead to an underestimate of bulk density.

Methodology Citation(s): (1) Elliott, E.T., Heil, J.W., Kelly, E.F. and Monger, H.C., 1999. Soil structural and other physical properties. Standard soil methods for long-term ecological research., pp.74-85. (2) Throop, H.L., Archer, S.R., Monger, H.C. and Waltman, S., 2012. When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. *Journal of Arid Environments*, 77, pp.66-71. (3) Porzig, E., Seavy, N.E., DiGaudio, R. T., Henneman, C., and Gardali, T., 2018. *The Rangeland Monitoring Network Handbook V2.0*. Point Blue Conservation Science, Petaluma, California.

Decision Point: If you are assessing bulk density, what method will you use and how deep will you sample? Using the millet or slide hammer method will increase accuracy of this measurement and strengthen your overall inference score.

Soil Texture

When to Sample: Whenever possible. Soil texture remains relatively constant, but is most convenient to pair with sampling for soil organic carbon. Only needs to be sampled once; repeat sampling over time is typically unnecessary.

Materials & Supplies:

Lab Texture by Hydrometer (Tier 1)

- 40-100g soil is required per each sample location
- Resealable polyethylene gallon-sized bags (e.g., Ziplocs)
- Permanent writing marker (e.g., Sharpie)

Field Texture by Feel (Tier 2)

- 25 g soil per each sample location
- Water to wet soil (in a small bottle works well; if conducting in house)
- Ruler or similar (if conducting in house)
- Small bucket or Polyethene (Ziploc) bag (if conducting in house)

How to Collect a Sample: Collect a soil sample with the same method (e.g., auger) and to the same depth(s) as the organic carbon sample, and within 1 foot of the main sampling point.

Sample Handling and Storage: Soil texture by feel can be determined in the field or on air-dried samples in the lab. For lab analysis of soil texture, the samples should be collected, handled, and stored the same as for soil organic carbon collection.

Analysis: For textural analysis by a service laboratory (by hydrometer [Tier 1] or by feel [Tier 2]), ship the soil within the same sample bag as the organic carbon sample or take subsample and ship separately, but ensure the amount of sample meets lab requirements.

For texture-by-feel in the field ([Appendix C](#)), take a bit of soil from the organic carbon sample or collect soil adjacent to the main soil organic carbon sampling point and mix it well within a bucket or ziplock bag. Place about 25 grams of the soil (walnut-sized) into your hand and wet it to a putty-like consistency. Try to roll it into a ball to test for sandy soils. Then, use that soil ball and try to create a ribbon by pushing the soil between the thumb and forefinger, assessing how long the ribbon gets before it breaks. Add more water to the soil to create a paste and feel for grittiness or smoothness. Follow the flow chart in [Appendix C](#) to determine the texture type and percent of sand, silt and clay. Record results in [Appendix N](#).

Quality Assurance: Repeating each texture-by-feel test 2-3 times on a different subsample can check the precision of the assessment.

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<https://smallholder-sha.org/protocol-1/texture-by-feel/>.

Decision Point: If you are assessing soil texture, which method will you use?
Using the hydrometer method (Tier 1) will strengthen your level of inference and overall framework score.

Soil pH

When to Sample: Anytime when the soils are not saturated with water. Be sure to be consistent over time. If baseline samples are sampled in January, collect all subsequent samples in January as well. It will be most convenient to pair with sampling for soil organic carbon and texture.

Materials & Supplies:

Lab pH measurement (Tier 1)

- Approximately 15g (1 tablespoon) soil per each sample location
- Resealable polyethylene gallon-sized bags (e.g., Ziplocs)
- Permanent writing marker (e.g., Sharpie)

In-field pH measurement (Tier 2)

- Approximately 15g (1 tablespoon) soil per each sample location
- Distilled or bottled water (2 tablespoons per sample)
- Handheld field pH meter
- pH buffer solution of two levels (pH 7 & either pH 4 or pH 10, whichever is closer to the soil's pH)
- Resealable polyethylene gallon-sized bags (e.g., Ziplocs)
- Permanent writing marker (e.g., Sharpie)
- Plastic or paper sample cups (e.g., dixie cups)
- Kitchen knife or similar

How to Collect a Sample: Take a subsample of soil from the well-mixed soil texture sample or follow the soil organic carbon sampling guidelines to take a new sample to a specific depth of interest, within 1 foot of the main organic carbon sampling point.

Sample Handling and Storage: For in-house analysis of soil pH using a pH meter, measurements are conducted field-moist with a handheld instrument. For analysis of soil pH at an analytical lab, the samples should be treated the same as for soil organic carbon, which includes being air-dried and stored in a cool, dry place.

Analysis:

Laboratory pH with CaCl₂: To conduct pH analysis from an analytical lab (Tier 1), air-dried soil can be shipped within the same sample bag as the soil texture sample or subsetted and shipped separately. Make sure there is an adequate amount per lab requirements. Indicate and confirm with the analytical lab that the pH desired is a 1:2 soil sample to solution of calcium chloride (CaCl₂), which helps with measurement consistency.

In-field with water: For in-field pH analysis (Tier 2), first calibrate the pH meter with two pH buffer solutions (either pH 7 and pH 4 or 10) as per the manufacturer instructions. At

minimum, do this at the start of every field day. If the meter has not been used for a while, soak it in tap water for 5 minutes.

Mix the soil sample in a ziplock bag or small bucket well. Place a tablespoon of soil into a clean sample cup. Add two tablespoons of distilled water and then mix the soil and water into a paste. Wait 10 minutes prior to measuring the sample paste using the pH meter. After 10 minutes have elapsed, insert the entire bulb of the probe into the surface of the paste. Wait up to 30 seconds for the reading to stabilize and then record the results in [Appendix M](#).

Quality Assurance: It is important when subsetting/splitting a sample to ensure the sample is well-mixed such that a representative sample is partitioned for each subsample. In-house pH analysis using a pH meter and H₂O results in a less accurate estimate, so repeating a test 2-3 times on multiple subsamples from the same sample can help with accuracy and precision; the data can be calculated into an average. In addition, ensure that between samples the pH meter is rinsed thoroughly and lightly dabbed (not rubbed) dry.

Methodology Citation(s): (1) USDA and Soil Quality Institute Staff. 2001. Soil Quality Test Kit: Soil pH Test. Accessed Jan. 7, 2022. (2) Robertson, G.P., Sollins, P., Ellis, B.G. and Lajtha, K., 1999. Exchangeable ions, pH, and cation exchange capacity. Standard soil methods for long-term ecological research, 2, p.462.

Decision Point: If you are assessing soil pH, which method will you use? Using the pH electrode in CaCl₂ (Tier 1) will strengthen your level of inference and overall framework score.

Record Monitoring and Management Information

Collecting accurate and detailed information on the monitoring protocol used and the management practice implemented is key to achieving the second objective of this framework. It is also best practice to collect such information for individual projects at the ranch level, so a practice and project can be fully understood and repeated in the future if desired.

We have generated a practice and protocol questionnaire to record monitoring and management information, in addition to other important contextual information, in [Appendix P](#). Be sure to fill this out during the monitoring process.

Data Management and Interpretation

Data management applications and interpretation tools are forthcoming. For inquiries regarding data sharing policies, data management, and interpretation intentions for the program, please contact RangeC@pointblue.org.

Appendices

[Appendix A: Tiered Scoring System](#)

[Appendix B: Determining Soil Type](#)

[Appendix C: Estimating Soil Texture by Feel](#)

[Appendix D: Using QGIS to Select Random Sampling Points](#)

[Appendix E: Random Sampling Point Selector Worksheets](#)

[Appendix F: Calculating Sample Size by Practice](#)

[Appendix G: Stratification Resources](#)

[Appendix H: Stratification Table](#)

[Appendix I: Materials List for All Methodologies](#)

[Appendix J: Root Biomass Data Collection Worksheet](#)

[Appendix K: Woody Biomass Data Collection Worksheets](#)

[Appendix L: Herbaceous Biomass Data Collection Worksheet](#)

[Appendix M: Bulk Density & Carbon Stocks Data Collection Worksheet](#)

[Appendix N: Soil Texture Data Collection Worksheet](#)

[Appendix O: Soil pH Data Collection Worksheet](#)

[Appendix P: Practice and Protocol Questionnaire](#)

[Appendix Q: Decision Brief](#)

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Example Roadmap for Using the Range-C

The Range-C Monitoring Program offers opportunities for programs or projects to set unique requirements for their participants in a way that offers interoperability with others in the broader program. Here we provide an example of how a fictional incentive program could provide specific *Range-C Monitoring* guidelines for participants in their program.

Fictional Incentive Program Guidelines:

All participants of *The Fictional Incentive Program* are expected to follow the Range-C Monitoring Program guidelines as part of their monitoring compliance requirements. Participants should specifically make the following decisions:

- **Decision Point 1:** Only soil organic carbon content is required, but participants are also encouraged to measure soil texture and pH.
- **Decision Point 2:** Use automated dry combustion for soil organic carbon, and if measuring soil texture and pH send the samples out to an analytical laboratory to be analyzed via hydrometer and electrode in 1:2 w/v solution, respectively.
- **Decision Point 3:** Monitoring a control is not necessary. However, monitoring baseline conditions prior to implementation is necessary.
- **Decision Point 4:** Use the Random Sampling Point Selector Workbook to identify sampling points in the field.
- **Decision Point 5:** Stratification is not necessary.
- **Decision Point 6:** Use the Range-C Sample Size Look-Up Tables.
- **Decision Point 7:** A medium level of certainty is required.
- **Decision Point 8:** Soil organic carbon (and if applicable, soil texture and pH) should be sampled to 12 inches.