Point Blue

The Crop-C Monitoring Handbook

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G.S.R. led the working group process and wrote the original drafts of the handbook. C.J.C. conceptualized and secured project funding. E.J.F and A.C. supported the working group process, led the editing process and provided critical feedback on the framework. L.E. supported literature review and computations for sample density recommendations, wrote appendix sections, and provided a final in depth review..

Point Blue Conservation Science:
Point Blue's 160 staff and scientists develop nature-based solutions to climate change, habitat loss, and other environmental threats to benefit wildlife and people. We conserve birds, other wildlife, and ecosystems through science, partnerships, and outreach. Visit Point Blue on the web www.pointblue.org.

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https://www.pickpik.com/strawberry-bushes-green-plant-garden-nature-bush-142843
Inside Cover Image: A view of alfalfa above- and belowground, a commonly used cover crop in farmland, Erika Foster.

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Monitoring Plan - Quick Form

This printable page summarizes key decisions for developing a Crop-C monitoring plan. See the referenced pages to further evaluate options and how the choices influence data quality. After collecting samples, fill out Appendix P and submit it to CropC@pointblue.org to document your choices in the secure Point Blue database.

What management practices are being studied?

☐ *Crop Rotations* ☐ *Soil Carbon Amendments* ☐ *Livestock Integration* ☐ *Mulching*

☐ *Cover Crops* ☐ *No- or Reduced-Tillage* ☐ *Living Groundcover* ☐ *Hedgerow/Windrow*

☐ *Tree/Shrub/Vine Establishment* ☐ **Other:* _____

**If you don't see your desired management practice, see Practice Specific Considerations section (pg. 40) for instructions.*

Which carbon indicators do you plan to sample? (pg. 19)

☐ *Soil organic carbon* ☐ *Soil bulk density* ☐ *Woody biomass* ☐ *Soil pH*

☐ *Soil inorganic carbon* ☐ *Soil texture* ☐ *Aboveground herbaceous biomass* ☐ *Herbaceous root biomass*

What methods do you plan to use to measure these indicators? (pg. 21-24, and pg. 51-62)

Indicator	*Method*	*# Samples**

**use the Sample Size Lookup Tables (pg. 42-50), or conduct power analysis with existing data (Appendix G, section 6)*
**if multiple management practices are applied simultaneously, use the one with the highest expected impact (pg. 40)*

Soil sampling depth increments (pg. 53-54): _____ *(0-12 in. is standard for Crop-C)*

Selecting Sampling Points

Choose your target for certainty level (pg. 36): ☐ *Standard* ☐ *Advanced* ☐ *Academic*

How are you selecting sampling points? (pg. 28)

☐ *Simple Random Sampling* ☐ *Stratified Random Sampling* ☐ *Spatially Balanced Sampling*

Yes or No?

___ Sampling points will be created using mapping software (versus the Crop-C Point Selector worksheet) (pg. 29)

___ (Recommended) Baseline samples will be taken *before* a new mgmt. practice is implemented (pg. 16, Table 1)

___ This project includes a control site (pg. 25)

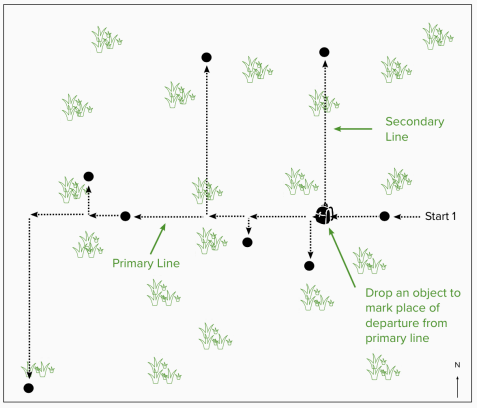
___ The *Sample Size Lookup Tables* helped determined how many samples to take (vs. a power calculator) (pg. 34)

Requirements:

Sample from the same locations within a field, across all project years
Do not combine samples from different parts of a field (pg. 37)
Use the same lab(s) and test methods across all project years
Follow the sampling intervals when using the Sample Size Lookup Tables (pg. 42-50)

Quick Form (continued): Selecting Points From Within the Field

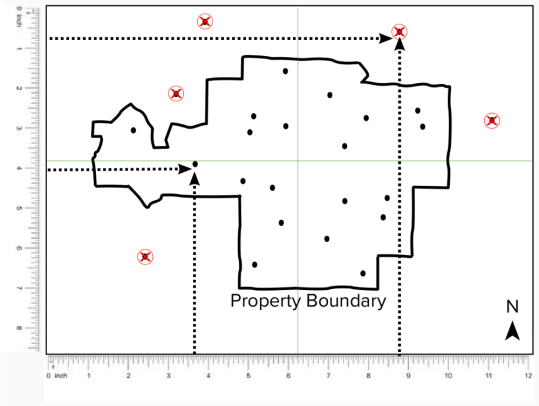
SKIP this page if you are using GIS or other mapping software to randomly select points.
READ this page if using the analog Crop-C Point Selector worksheet (Appendix F).



Study Area

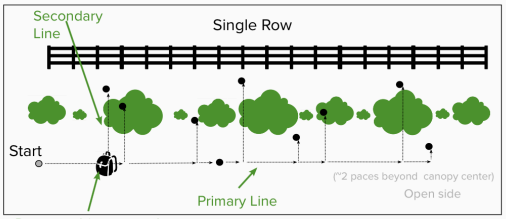
Field-Scale Practices (works for ≤ 10 acres)

Sampling points for field-scale practices can be selected while 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 your sight on an object on the horizon to walk toward. 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.

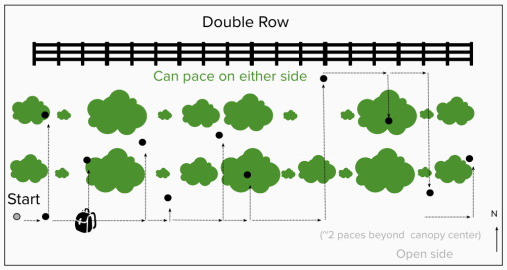


Property-Wide Practices (usually > 10 acres)

When monitoring impacts across a larger field or property, 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, subdividing the map into quarters can help allocate points proportionally. This figure shows a property with 20 points, five per subdivision.



Study Area



Study Area

Hedgerows / Windbreaks / Vegetative Strips*

Sampling locations for practices that form a line on the landscape can be selected in the field using the random number generator spreadsheet. Start at one end and follow the edge of the planted row, 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.

**vegetative strips may include buffer strips, filter strips, grassed waterways, herbaceous wind barriers.*

Introduction

Why Croplands?

Croplands are a critical source of food, feed, fiber and fuel as well as culture, livelihood, and connection to natural systems. Covering approximately 12% of global land area (~3 billion acres), farm management has the power to improve and/or degrade the health of terrestrial and aquatic ecosystems by affecting the quality of soil, water, and air, and thus overall ecosystem services (Sanaulla et al. 2020; DeClerck et al. 2023).

The past decade has seen a rapid expansion of incentive programs for regenerative agriculture[1] and soil health[2]. These approaches to farming focus on ecological principles that enhance the agronomic productivity of a farming system, and often use carbon as a key indicator of ecosystem vitality. Carbon is an essential building block for all living organisms, and the amount and cycling of carbon within soils and plants is a strong metric of agroecosystem health. Soils with higher levels of organic carbon tend to have increased fertility, water holding capacity, and disease suppression (Bradford et al. 2019; Lal 2020). As such, soils richer in organic carbon provide crops with improved resilience to extreme weather like flood events, heatwaves, and drought. In addition, carbon in agricultural soils and biomass is directly drawn down from the atmosphere via photosynthesis and can be considered an important climate mitigation strategy (Pramanick et al. 2021). For these reasons, carbon sequestration through agriculture is potentially a win-win solution and creates opportunities for collaboration across farming communities, conservationists and policy makers alike.

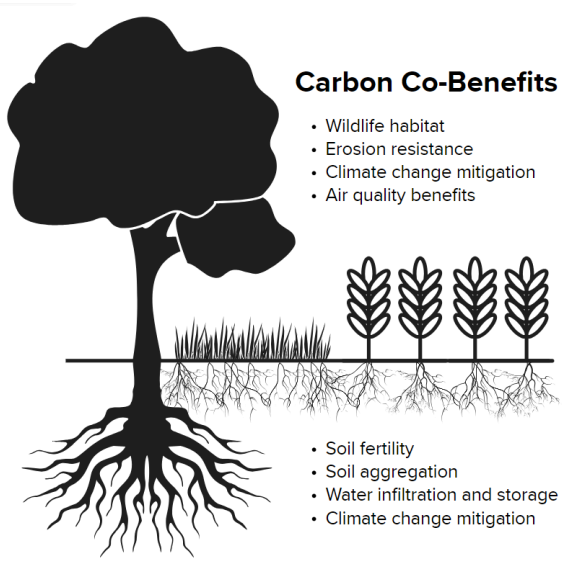


Figure 1. Croplands provide critical ecosystem services, many of which are linked directly or indirectly to carbon storage in plants and soil.

As momentum builds in support of increasing on-farm carbon levels, numerous programs have "cropped up" to advance the adoption of conservation practices by providing technical service and financial support. Yet, while many of these programs offer recommendations for *what* to measure when it comes to carbon, there is often insufficient guidance and/or flexibility regarding *how* to take these measurements. This is what the Crop-C Monitoring Handbook aims to provide.

[1] Regenerative agriculture is a holistic approach to farming and ranching that strives to enhance social, ecological and agronomic conditions through regionally-appropriate farming practices.
[2] We define soil health as the capacity of the soil to function as a vital living ecosystem that maximizes provision of ecosystem services within ecosystem boundaries in a sustainable way.

Purpose of Crop-C

The Crop-C Monitoring Program has two main objectives:

Provide flexible blueprints for technical service providers and land stewards to effectively monitor changes in carbon resulting from cropland management practices (as listed in Fig. 2). This science-based and accessible guide is designed to support the process of monitoring changes in carbon. To account for the variety of management approaches being applied to croplands today, The Crop-C Program includes sampling design and protocol options that map onto specific practices.

Support the development of a network-wide dataset to assess changes in carbon resulting from cropland management. At the discretion of Crop-C users, data submitted to the Crop-C Program will be combined into a large-scale dataset to analyze management effects across regional scales, soil types, locations and practices. This aggregated dataset can be anonymized by users and will meet high security standards in order to support evaluation of predictive ecosystem models, underpin decision-support tools, guide selection of effective practices by region, and set priorities for programs aiming to conserve and rebuild cropland carbon for multiple benefits. The program focuses on carbon as a main indicator of cropland productivity and health, rather than for carbon market participation, which is detailed elsewhere (see Oldfield et al. 2022).

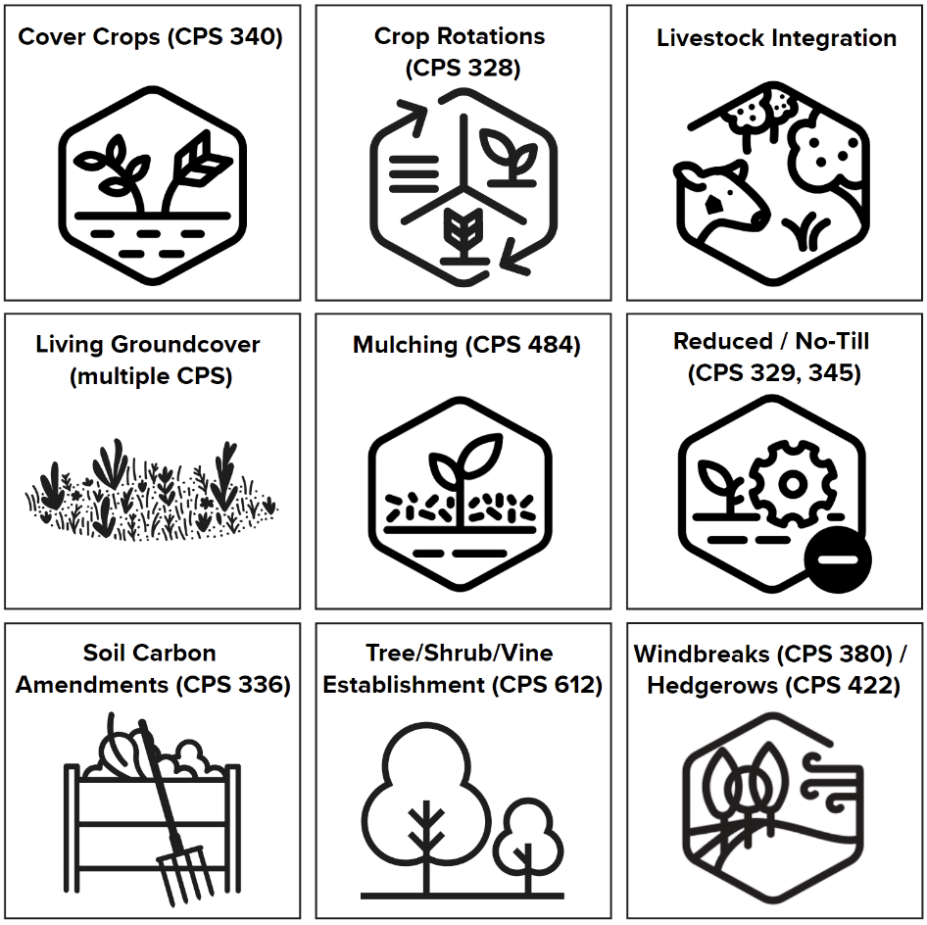


Figure 2. The Crop-C Program provides protocols for monitoring specific management practices, listed above. These can be implemented (although not necessary) within existing Natural Resource Conservation Service Conservation Practice Standards (CPS).

The Crop-C Program serves to meet many of the motivations behind carbon stewardship and monitoring on croplands (Fig. 3). Measurement, reporting, and verification (MRV) for carbon markets, however, is beyond the scope of The Crop-C Program.

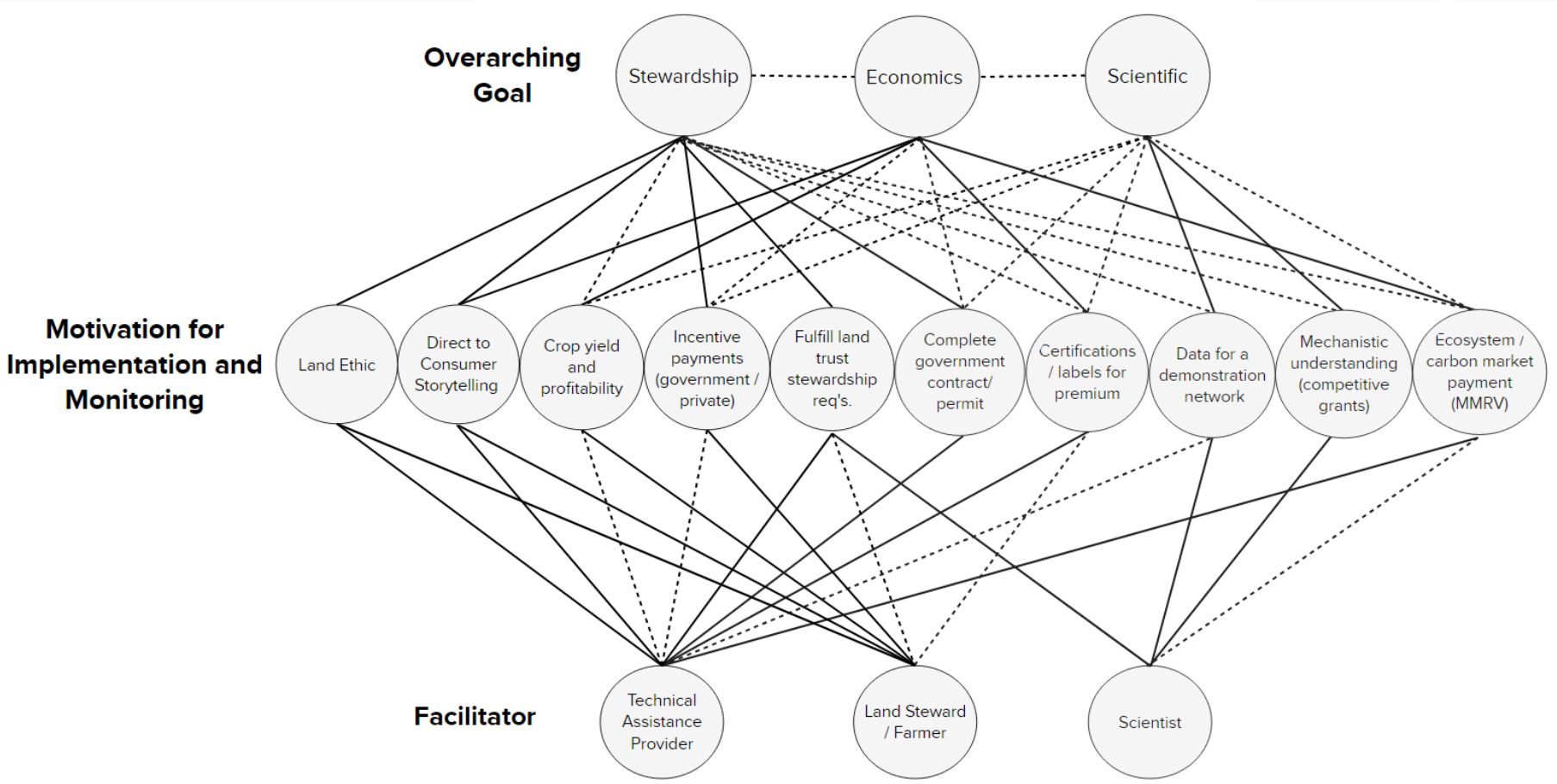


Figure 3. Full range of motivations, supporting mechanisms, and primary facilitators involved in the vast landscape of soil carbon monitoring. Solid lines represent direct connections between entities and dotted lines represent indirect connections. Crop-C design excludes monitoring to meet carbon market standards (far right).

Developing this Guide

The Crop-C Program is a key pillar of Point Blue Conservation Science's Agriculture Carbon (Ag-C) Monitoring Program and builds on the previous success of Range-C.

The Crop-C Handbook was developed via a collaborative process, with generous input from technical science advisors and members across the farming community (see pg. 4). These partnerships helped to ensure that this guide is both accessible and practical while meeting strong scientific standards.

The handbook is designed to merge best practices from existing resources, scientific literature, and expert opinions. Excellent resources on cropland carbon monitoring can complement this guide and provide informative further reading, including:

- *Monitoring Soil Carbon: A Practical Field, Farm and Lab Guide (Soil Carbon Project, 2021)*
- *Measuring Soil Carbon Change: A Flexible, Practical, Local Method (Soil Carbon Coalition, 2013)*
- *Soil Organic Carbon Stock Monitoring - CEMA 221 (USDA, 2023)*
- *A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes - GSOC MRV (FAO, 2020)*
- *U.S. Soil Enrichment Protocol (SEP) v 1.1 (Climate Action Reserve, 2022)*
- *Rapid Carbon Assessment Project Procedures and Protocols for Field Data and Sample Collection* (Wills, 2010)

The Crop-C Handbook is not a holistic guide to cropland management and should not replace the conservation planning process. It does *not* make recommendations on goal setting or practice implementation, and does currently measure the wide array of co-benefits (creation of habitat, protection of biodiversity, augmentation of water storage etc) and potential trade-offs associated with different management interventions. Instead, The Crop-C Program assumes these critical aspects of cropland stewardship have already been carefully considered by the user. Monitoring of biodiversity and other ecosystem outcomes can be overlaid using separate, yet complementary protocols.

How to Use *The Crop-C Handbook*

This document will guide you through the process of creating a scientifically sound monitoring plan. If this is your first time using Crop-C, we recommend following the handbook from start to finish, focusing on your specific management practice(s). Otherwise, begin with the Quick Form on pg. 7 and reference the below sections as needed.

Note that this guide is based on current scientific understanding and many hours of careful deliberation. Because each site is unique, project design approaches and methods herein can serve only guidelines for best practices. There are cases where it will be up to users' discretion to determine what is appropriate. The most important aspect of monitoring is to be consistent over time and provide adequate documentation. Crop-C users are welcome to email Point Blue Conservation Science at CropC@pointblue.org with questions pertaining to their carbon monitoring projects.

Tiered Scoring System

Because the Crop-C Program provides users with flexibility in designing their monitoring plans, it also scores key decisions based on the level of accuracy[3], precision[4], and statistical or ecological inference it generates. "Decision points" are featured throughout the handbook, highlighting key opportunities to influence data quality through monitoring choices. These are consolidated into the Quick Form on pg. 6. Examples include:

- How many carbon indicators (e.g. soil, plant biomass) will be measured?
- What methods will be used for the measurements?
- How many samples will be collected from the study area?

When resources allow, we recommend following the top Tier 1 approaches. These methods will help users make the strongest conclusions about changes in cropland carbon and increase the likelihood of detecting practice impacts.

Numerical rankings associated with each tier are combined to provide an overall Crop-C Inference[5] Score on a scale from 0-100. These can be used to better understand and communicate the level of interpretation possible for each monitoring project. Decision points hold different weights, depending on the degree that they influence inference: Higher weights are assigned to more durable (i.e. persistent) carbon pools and to indicators that can be influenced more readily by management. Certain aspects of monitoring designs aid with interpretation of results such as control sites and baseline sampling and therefore also contribute to *The Crop-C Inference Score*. See Appendix A to access the scoring system and for more details.

Higher overall Inference Scores denote a greater level of confidence in the data and the ability of that data to describe changes in carbon over time as a result of management. Scores below 50 have relatively limited inference but may be sufficient for guiding farm management decisions, scores around 50-75 have moderate levels of inference and may suffice for many contexts, including incentive programs. Scores greater than approximately 75 have relatively strong inference. **This Inference Score does NOT evaluate the *amount* of carbon sequestered in the system, but describes how certain we can be about conclusions drawn from the data.**

[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.
[5] The level of inference refers to the strength and reliability of data to describe changes in carbon, and is based on available evidence from your monitoring approach.

Pre-Assessment

Monitoring carbon can involve significant investment of time and resources. This section is a checkpoint to help Crop-C users think critically about whether they are likely to obtain meaningful results. Before proceeding, we recommend using this flow chart to assess whether sampling carbon makes sense for you.

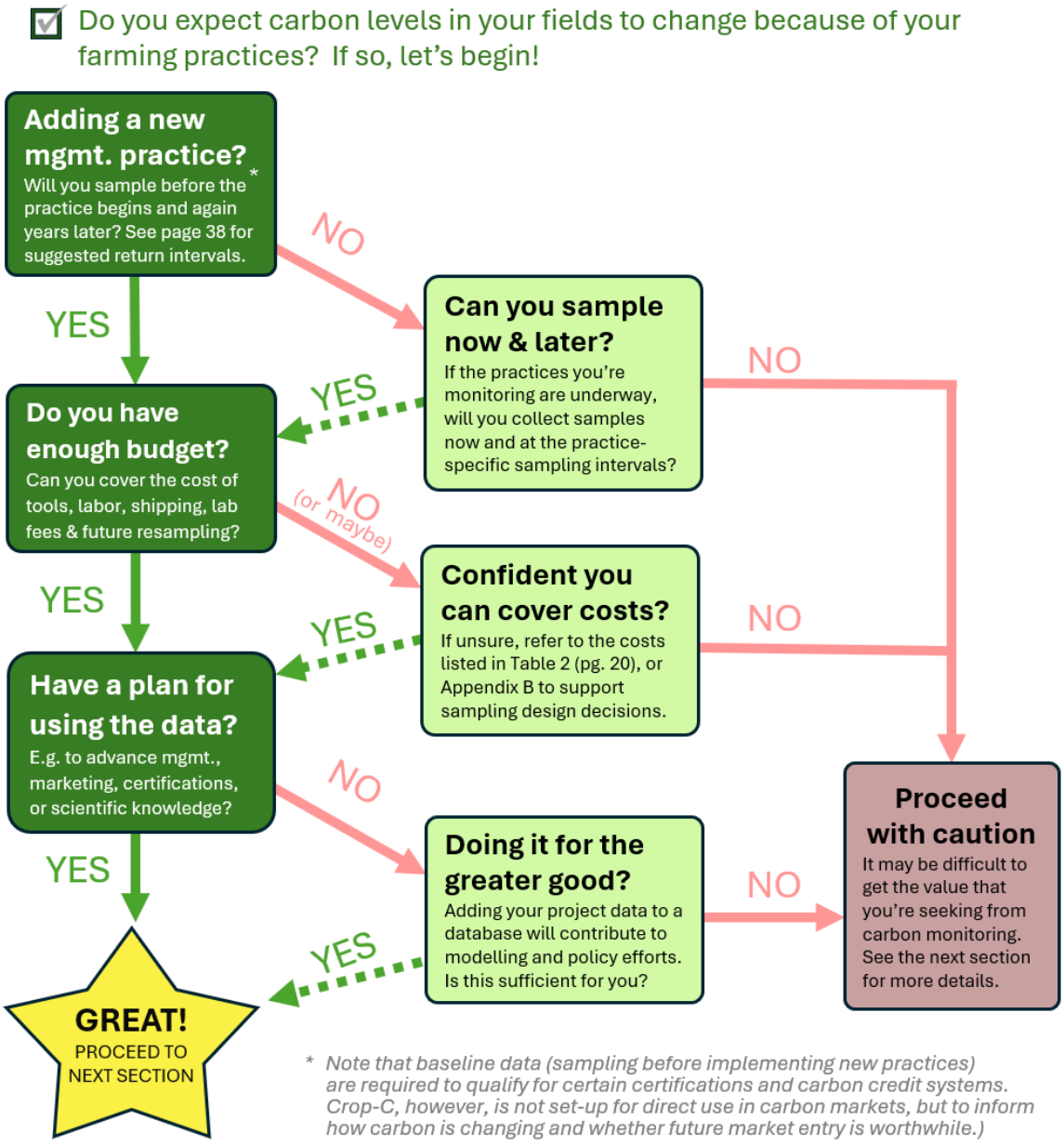


Figure 4. This flow chart provides a point of reflection for Crop-C users to evaluate whether they are poised to receive the intended benefits of monitoring carbon. Explanations for navigating situations that end up at the red "Proceed with caution" box are provided on the next page.

Interpreting: "Proceed with Caution"

Sampling "Now and Later":

If you cannot collect samples at two distinct time points, it is very difficult to accurately monitor changes in carbon. Even if you are comparing a control site to a field with many years of beneficial management, sampling only once is limiting. It is not possible to understand the directionality of change over time (Sanderman, 2010): imagine a situation where the treatment and control areas both lose carbon but at different rates. Only measuring once might give the perception that one has gained carbon. In addition, this scenario makes a big assumption that the two fields started with the same carbon levels.

The recommended way to track changes in carbon over time is to take a baseline measurement documenting field conditions before practices are implemented. (This is sometimes necessary to qualify for certifications or carbon markets[6]). It is possible to track changes after a practice has begun by taking a sample, for example, in year three of a practice and revisiting in year eight. Adding a control site to either scenario improves inference but is not required by the Crop-C Program.

Table 1 - Distinctions between baseline sampling, resampling, and control sites.

	Description	Purpose
Baseline sampling (Recommended)	Take samples prior to practice implementation and again after the recommended interval.	Quantify "full" impact of management practice on carbon over time.
Resampling "Now-and-Later" (No Baseline)	Take samples after practice implementation, and again after the recommended interval.	Quantify partial impact of management practice on carbon over time.
Control Site	As an add-on to the two options above, also monitor a nearby second site with very similar field conditions and mgmt. history, but without the new practices implemented.	Untangle effects of climate on the site (e.g. drought) from the impacts of the management practice.

Budgeting and Costs:

At this early stage of the process, it may be difficult for you to know the exact costs of monitoring carbon for this project. Carbon sampling can be expensive when adding up equipment and materials, labor, shipping and lab fees; therefore, it is important to keep your budget in mind when making sampling decisions. Table 4 (pg. 21) offers basic guidance on the investments required for monitoring, and the Crop-C Project Cost Calculator can be adjusted for your project.

[6]Reminder: Crop-C is not set up for direct use in carbon markets. There are additional considerations (e.g. permanence, additionality) that go beyond the scope of monitoring change over time.

Applying Results:

It can be helpful to define how the data from your project will advance broader goals, prior to embarking on data collection. Figure 3 (pg. 10) highlights a range of motivations for carbon sampling on croplands that can help to clarify the value of carbon monitoring for you. A useful exercise is to run through scenarios where the data from your project shows desirable, neutral, or mixed results, and to consider how you might use that information, as well as what qualifies as a significant change. Even if the data is not directly useful to you, all data submitted to the Crop-C database will contribute to a broader understanding of how management decisions influence carbon in cropping systems. If it is not clear how tracking carbon will help you to meet your goals, and if contributing this data for broader learning is not sufficient, then there's reason to ask whether it is worth pursuing monitoring in the first place.

Ensuring Data Quality

It is important to collect data in a way that produces reliable results. Follow all protocols and instructions[7] as closely as possible to ensure data standardization.

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 various steps in the monitoring process. We also provide general guidelines to follow here, adapted from MacDicken 1997 and Herrick et al. 2017 (Table 2).

Table 2. Quality assurance and control measures to keep in mind while monitoring with Crop-C.

To ensure projects are of the highest quality:
Read and follow the protocol carefully
Describe and geolocate sampling points to enable others to revisit them in the future
Write legibly enough for yourself and others
Keep methods and analytical laboratories the same over time
Only use laboratories that meet industry standards for quality, and that offer the carbon measurements recommended by Crop-C
Take all measurements carefully
Document and report all decision points, including any decisions that deviate from the protocol
Solicit technical assistance if needed
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

We reiterate that it is strongly advised to use the same laboratory throughout your project for data quality assurance. This is important as each lab has slightly different processing techniques, equipment, and protocols from one another. If you are in a position where you need to change laboratories and are uncertain how to strategically do so, you may contact CropC@pointblue.org for advice and recommendations.

[7] If it is necessary to stray from the protocols, record these changes at the bottom of Appendix P before submitting this form to CropC@pointblue.org.

Selecting Carbon Indicators

This section provides guidance on which indicators or forms of carbon to monitor, whether above or belowground, and in plant biomass or in soils. Additional indicators are included that provide useful contextual understanding, such as soil texture and pH.

Because soil organic carbon is critically important to ecological function and both mitigating and adapting to climate change on croplands (Pramanick et al. 2021, Bradford et al. 2019), it forms the foundation of The Crop-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 3. Carbon indicators included in The Crop-C Program, motivation for monitoring, and the relevant practices for which they apply.

Carbon Indicators	**Why might you measure this indicator?**	**Relevant Practices**
Soil organic carbon (SOC)*	**Climate Change Adaptation & Mitigation; and Soil Health** As a key component of soil organic matter, carbon contributes directly to healthy soil function. Soil organic carbon can be separated into particulate organic matter (POM) as a proxy for fertility and mineral-associated organic matter (MAOM), which provides insight into persistence for climate change mitigation.	All
Soil inorganic carbon (SIC)	**Climate Change Mitigation** Relates to carbon sequestration via carbonate formation, particularly in dryland systems. Recommended only for soils with a pH over 6.5.	All
Herbaceous root biomass	**Climate Change Adaptation & Mitigation; and Soil Health** Supports soil aggregation - enhancing water holding capacity and site productivity while reducing compaction - and formation of more stable carbon.	Cover crops; crop rotations; livestock integration; mulching; reduced-/no-till; soil organic amendments; living groundcover
Woody root biomass (calculated)	**Climate Change Adaptation & Mitigation; and Soil Health** Supports soil aggregation - enhancing water holding capacity and site productivity while reducing compaction - and formation of more stable carbon.	Windbreak / hedgerow establishment; tree / shrub / vine establishment
Aboveground herbaceous biomass	**Plant Productivity** Primarily in annual systems. A transient “pool” that can influence carbon sequestration, but is not itself a source of long-term carbon storage.	Cover crops; crop rotations; livestock integration; mulching; reduced-/no-till; soil organic amendments; living groundcover

Aboveground woody biomass	**Climate Change Adaptation & Mitigation** Estimates carbon storage associated with long-term storage in woody plants.	Windbreak / hedgerow establishment; tree / shrub / vine establishment
Bulk density*	**Climate Change Adaptation & Mitigation; and Soil Health** Measures soil weight over volume related to compaction and aeration (pore spaces), which influence water infiltration, root penetration, and 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 cycling in the soil.	All
Soil texture	**Climate Change Adaptation & Mitigation; and Soil Health** The proportion of sand, silt, and clay provides information on how soils potentially interact with and stabilize carbon. This is not expected to change over time, so can be measured once.	All

**To calculate changes in soil organic carbon stocks (e.g. tons/acre), it is necessary to measure both soil organic carbon levels (%) and bulk density (g/cm^3).*

The minimum sampling depth for Crop-C is 0-12 in., but you may want to sample deeper and/or collect cores from multiple depth intervals. While short-term carbon increases tend to be concentrated in the topsoil, each farming practice can influence soil depths differently.

Decision Point: Select indicators to measure

How many indicators will you monitor? Monitoring more indicators will strengthen your Inference Score.

Each carbon indicator is scored independently; see Appendix A for details.

Summary of Measurement Methods

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 Crop-C Program for each indicator (Table 4). Note that some indicators have multiple (tiered) options of methods from which to choose. Tier 1 methodologies for each indicator should be used whenever possible as they will provide the most detailed and reliable information. Tier 2 and 3 indicators will provide lower confidence in the data (lower reliability), but may be preferable depending on the context and goals of monitoring. Basic information on how to collect, process, and analyze indicators using each method are provided in the Indicator Methodology section.

Table 4. Methods supported by The Crop-C Program for each indicator and associated information on accuracy, precision, estimated labor and analysis costs, and examples of 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). The recommended service laboratories are examples and non-exhaustive. Crop-C users are advised to use laboratories in the North American Proficiency Testing Program (https://www.naptprogram.org/about/participants/all/), which may include local universities or extension-recommended facilities. 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 for Crop-C User	Approximate Cost per Sample[a]	Recommended Service Laboratories
Soil organic carbon (SOC)[b]	Size fractionation and dry combustion with optional acid pre-treatment	Amount of total organic carbon fractions (particulate and mineral- associated organic carbon)	High	High	Collection Labor: 5-15 min Processing Labor: 0-5 min	Service Lab: $75 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: $16.50 - $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 > 6.5)	Measure CO_2 from SIC directly (eg., pressure calcimeter) *(Tier 1)*	Amount of soil carbon in mineral form (e.g. carbonates)	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 carbon	Med	Med	Collection Labor: 0* min Processing Labor: 0-5 min	Service Lab: $18 - $50 In-house: N/A	Ward Laboratories; UC Davis Analytical Lab; University of Idaho

Carbon Indicator	Method	What does this Methodology Measure?	Relative Method Accuracy	Relative Method Precision	Estimated Labor/Sample for Crop-C User	Approximate Cost per Sample[a]	Recommended Service Laboratories
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: See Row 24 of Crop-C Project Cost Calculator, one time purchase upfront ($$) for equipment (sieves, drying oven, bucket, tins, scale)	In-house
Aboveground crop and/or herbaceous biomass	Harvesting of standing biomass at peak growth (if grazed, must use exclosures) *(Tier 1)*	Biomass of crops and/or herbaceous plants at peak growth	High	Med	Collection Labor: 10 min Processing Labor: 10 min	Service Lab: N/A In-house: See Row 24 of Crop-C Project Cost Calculator, one time purchase upfront ($$) for equipment (scale, drying oven, paper bags)	In-house
Aboveground woody biomass & woody root biomass	Equations using measurements of tree width (T*ier 1*)	Tree dimensions used in equations to estimate aboveground biomass and carbon	High	Med-High	Collection Labor: 20 min Processing Labor: 5 min	Service Lab: N/A In-house: $0	In-house

Carbon Indicator	Method	What does this Methodology Measure?	Relative Method Accuracy	Relative Method Precision	Estimated Labor/Sample for Crop-C User	Approximate Cost per Sample[a]	Recommended Service Laboratories
Soil Bulk Density	Equivalent Soil Mass (ESM) to calculate carbon stocks, after sampling. by sampling at ≥2 depths *(Tier 1)*	Soil weight for a given volume, needed to calculate total amount of carbon (stocks)[c]	High	High	Collection Labor: 10-20 min Processing Labor: 10-45 min	Service Lab: $30 per sample In-house: See Row 24 of Crop-C Project Cost Calculator, one time purchase upfront ($$) for equipment (scale, drying oven, tins)	Ward Laboratories; Cquester Analytics; In-house
	Slide-hammer method, recommended for < 12 in deep (*Tier 2*)		Med-High	Med-High	Collection Labor: 5-15 min Processing Labor: 5-25 min		Ward Laboratories; Cquester Analytics; In-house
	Millet method, recommended for ≤ 12 in deep (*Tier 2*)		Med-High	Med-High	Collection Labor: 10-15 min Processing Labor: 5-25 min		Ward Laboratories; Cquester Analytics; In-house
	Volume estimation by height and width (*Tier 3*)		Med	Med	Collection Labor: <5 min Processing Labor: 5-25 min		Ward Laboratories; Cquester Analytics; In-house
Supplemental Indicators							
Soil Texture	Hydrometer method (*Tier 1*)	The relative proportion of sand, silt, and clay	High	Med	Collection Labor: 5-15 min Processing Labor: 5 min	Service Lab: $16.50 - $25 In-house: N/A	Ward Laboratories; UC Davis Analytical Lab; Cquester Analytics
	By Feel (*Tier 2*)		Low	Med	Collection Labor: 5-15 min Processing Labor: 5 min	Service Lab: $7 In-house: $0	Ward Laboratories; 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: $7 In-house: $0	Ward Laboratories; UC Davis Analytical Lab; Cquester Analytics;
	Portable pH meter in a 1:1 (w:v) H_2O (*Tier 2*)		Med	Med	Collection Labor: 0* min Processing Labor: 5 min	Service Lab: N/A In-house: ~$100 one time, up front for equipment (pH meter, calibration set, specimen cups)	In-house

[a] *In-house analysis costs do not include cost of field materials to collect samples. When labor and cost are presented as ranges for a given method, this is to account for differences in sampling depth and soil conditions and lab fees. Project costs can be estimated using the Crop-C Project Cost Calculator.*

[b] *Soil organic matter (via loss-on-ignition) is not a recommended method for the Crop-C Program (explanation on pg. 52).*

[c] *We recommend calculating soil carbon stocks using equivalent soil mass, which is a technical way to say that calculated 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 the soil that is used is a subset from the SOC sample and the soil used for soil pH is a subset from the texture sample. 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: Select Indicators to Measure

What methods will you use to monitor your indicators? For those indicators where more than one method is provided, choosing Tier 1 methods will strengthen your Inference Score.

Identifying the Study Area

Management practices on croplands can occur farm-wide or on a field or subfield basis. **The study boundary should encompass, but not extend beyond, the entire area that received the management practice of interest** (hereafter the "treated site"). When initially setting up the field boundaries remove roads, waterways, sheds, exposed rock or similar unproductive areas, or otherwise you must later reject sampling points that fall on these areas.

For particularly large areas, it may be tempting to monitor only a subset of the total area for practical purposes. However, under this approach, conclusions from the data should only be applied to this smaller area, rather than the full field or operation.

Areas that received the same management practice at different times (e.g. winter vs. summer cover crops) or areas that use meaningfully different approaches (e.g. broadcast vs. drilled seed) should be considered as distinct management units and monitored as separate strata (p. 32) or as separate monitoring projects.

Marking the Boundary

It is best practice to mark the boundary of the treated site (and, if applicable, control site) at the beginning of a project. Doing so helps to facilitate accurate monitoring of the landscape over time. The following are suggested options for marking your study area boundary:

- **Walk the perimeter.** This is the most accurate method. Do this for the treated site and, if applicable, the control site. You can use a GPS unit or smartphone and free applications (e.g. *GPS Fields Area Measure* or *Avenza Maps*) to 'drop' GPS points. Use these points to draw a boundary with mapping tools like QGIS (see Appendix E) or Google Earth. If stratifying the area based on existing field knowledge (rather than using a mapping software), follow these instructions for each strata boundary.

- **Use Maps.** For larger areas, spatial boundaries can also be identified and marked using aerial photographs, farm 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. If stratifying the area based on geospatial data, follow the instructions in Appendix G.

Control Sites

All projects are encouraged to include a control site with very similar field conditions and management history, but where the specific practices you're monitoring are not taking place. Including a control site enhances your ability to interpret the impacts of a management practice by distinguishing them from the effects of weather variability or other management interventions that simultaneously impact the study site. A control becomes even more important when measuring indicators that are highly responsive to year-to-year changes, such as plant productivity.

With that said, control sites will double the cost of a project and, for proper comparison, must be carefully matched with the conditions of the main study area. 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 management history, soil type, topography / landscape position, and size of the study area.

Control Site Checklist:

- Dominated by the same soil series and soil texture (see Appendix C & Appendix D)?
- Similar topography (slope grade, aspect, hill position [Figure 5])?
- Similar management history (e.g. cropping systems) at start of the project?
- Is the control site approximately the same acreage?
- As close to the treated site as possible while retaining a 'buffer zone' to prevent any effect from one area to the other?

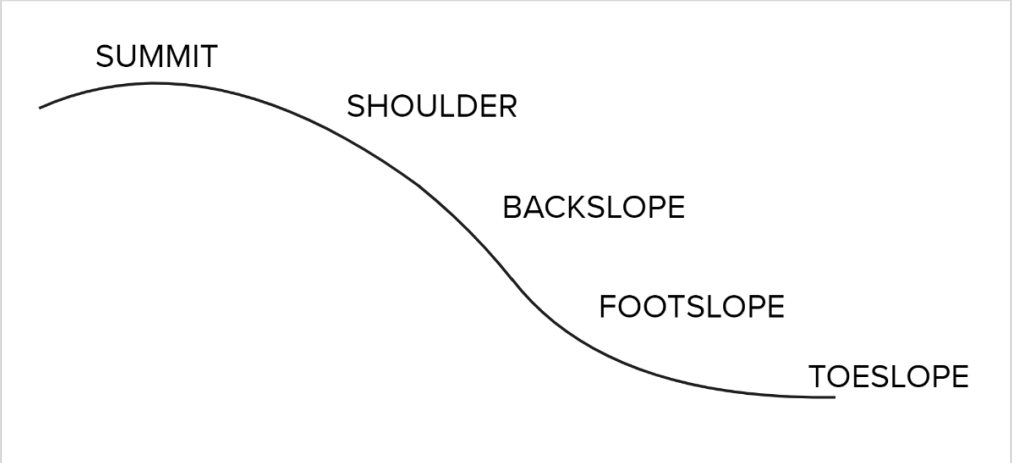


Figure 5. Catenal positions along a hillslope.

If you are including a control site, it should be monitored in the exact same fashion as the treated site: the same process for identifying sampling points, the same sampling density and the same methods for measuring the selected indicators. For farm-wide projects with variable field conditions, consider having more than one control area to better match the range of areas you are monitoring for your project. Budget permitting, it is also best practice to add additional sampling points to both the control and treatment zone since adding a new area introduces another layer of spatial variability.

Examples for Selection of a Control

Control Example 1: Compost was applied to a 10-acre orchard block with a <5% slope and Lowell silt loam soil. An ideal control would be another 10 acre area, on the same or neighboring farm, with the same cropping system type and a Lowell silt loam sloped at <5%.

Control Example 2: A restoration team planted a native tree and shrub hedgerow on 0.5 acres that is adjacent to the east-facing bank of a creek. This area had been devoid of woody vegetation for over 30 years, with herbicide applications occurring every few years. An ideal control would also be 0.5 acres 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 due to herbicide use, and preferably located nearby and upstream.

Decision Point: Baseline and Control Site

Eligible Inference Score points: 8, 13, 16, or 21 pts. of 100

Will you take baseline samples before implementing a new management practice (recommended), or is the practice you're monitoring already underway? Further, will you include a control site to compare against? Adding a control and taking baseline samples results in the highest possible Inference Score.

Reference Sites:

Nearby reference sites can be used to reveal the potential for increasing carbon levels. Soil samples can be taken from under a fence line where the soil has never experienced tillage, or from a remnant meadow that has never been farmed and otherwise has the same soil series, slopes, etc (see control site checklist on pg. 23, for guidance). Collecting these samples will not contribute to the Inference Score of your project, as they do not reflect the change in carbon levels due to management. That said, reference sites can offer valuable insights about historic degradation and viable targets for long-term carbon gains.

Selecting Sampling Points

Sampling point selection is critical to successful monitoring. The goal is to produce unbiased data that accurately represents the area you are monitoring, using an efficient number of samples (Potash et al. 2023). Select samples prior to entering the field to avoid bias.

Methods for Selecting Sampling Points

The following sampling designs offer varying tradeoffs, with respect to their potential to efficiently and accurately represent the field, as described below:

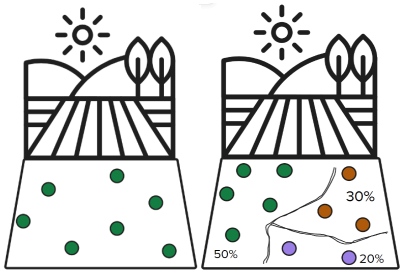
Simple Random Sampling (most basic):

Randomized points are created and placed on a map. This is a simple and effective method for creating unbiased sampling points. The data analysis for this approach is also the most straightforward. Simple random sampling can be performed using a variety of methods, including geographic information system (GIS)-based software as well as a low-tech, in-field approach (instructions provided in Appendix E).

Stratified Random Sampling:

When a field has distinct zones (e.g. soil, topography, mgmt. history), it can be advantageous to divide them into separate groupings or "strata". This ensures greater representation across a field while retaining relatively simple data analyses. Stratification can be performed using digital tools that create grouped or "stratified" sampling plans and points (See "Stratification - Subdividing the Study Area" section on pg. 31, and / or Appendix G). Note that strata should be very distinct, as incorrect groupings can reduce the statistical power of your monitoring design.

Spatially Balanced Sampling:



Spatially balanced sampling can be combined with both of the options above. Using mapping software, points are more evenly distributed across a study area, spaced at least a certain distance from field edges and each other. In the case of stratified sampling plans, the points can be distributed proportionately with the relative area of each zone. While data analyses for this method are more sophisticated.

Note: **Grid-sampling** is not recommended as it tends to be less efficient and can introduce error. If you are committed to this approach, be sure to create a grid / matrix that is sized and oriented differently than the spacing between plants, rows and infrastructure in the field.

Mapping Software: While many software platforms exist to support the selection of sampling points, we prefer to use free, open source and well established tools. We provide detailed instructions on how to pick points using easily available tools in Appendix F. These approaches often require you to either import files with your field boundaries (e.g. kml, kmz or shapefiles) or create them within mapping software. Once sampling points are created, you will have a list of coordinates that can be uploaded to a GPS device 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 either (1) the use of high-accuracy GPS receivers such as the Bad Elf, or (2) using the lower-tech option below.

Random Point Selector Workbook (lower-tech): To select random samples in the field using limited technology, participants of the monitoring project should use The Random Point Selector Workbook (Appendix F). 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 in advance and used on-site to locate each random point in the field. For farm-wide practices over many acres, the worksheet can also 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 F.

Decision Point: Sampling Point Selection

Eligible Inference Score points: 2 vs. 3 pts. of 100

Will you use mapping software (Tier 1) or the *Crop-C Point Selector Worksheet* (Tier 2) to identify sampling locations?

Point Selection Considerations - By Cropping System

Field crops (e.g. wheat, lentils, corn) and irrigated pasture: Where management is consistent across a field, choose a sampling design from the previous section "Methods for Picking Sampling Points" without modification.

Vegetable crops, **where soils are seasonally mixed and shaped into rows**: Choose a sampling design from the previous section "Methods for Picking Sampling Points". Once in the field, reduce bias by tossing an object randomly over your head and take the sample where it lands. Some soil sampling points may end up in the furrows / paths between rows. This is common practice for carbon monitoring as it helps to represent the entire field accurately (remember, the topsoil is mixed annually). Record whether the sample was collected from a row, shoulder, or furrow, and then gather samples from this same field position when collecting samples at this point, in future years.

Perennials (e.g. vineyards, orchards, berries) and annual systems with permanent beds: Choose a sampling design from the previous section "Methods for Picking Sampling Points". Collect samples from across the entire study area. Even if a management practice occurs only within the treerows, we still recommend monitoring in the alleys as well (or vice versa) to accurately represent changes over time in the entire field. One reason for this is that the boundary of a tree- or vine-row expands as the crops grow, so defining the exact dimensions of the rows and alleys is nearly impossible. Depending on where one draws 'the line' the rate of carbon accrual or loss will change and this can introduce error to final calculations. In addition, the influence of a practice can extend beyond the zone where it was applied. For example, compost application between rows can benefit tree growth in the rows. As a result, sampling across the full field is necessary to understand how management affects carbon on a per acre basis.

When you locate the sampling location in the field, determine the exact sampling point by closing your eyes, carefully spinning (to lose your sense of cardinal direction) and tossing an object to mark the point. Take the sample where it lands and note the field position (row, alley, or shoulder) or, even better, how many feet from the tree row the sample was taken. Repeat this field position at this site in future years.

Raised beds in large gardens or smaller scale farms: Either (1) add all eligible raised beds into a single layer of a digital map file and generate any random sampling design, as described above, or (2) number each bed and use a random number generator to determine which to sample from. Within each bed, randomly select where to take samples, which could be as simple as closing your eyes and tossing an objective over your shoulder.

Stratification - Subdividing the Study Area (Optional)

If portions of your study area are distinct from one another (e.g. soil texture, slope, management, etc.) then it may make sense to divide your site into sub-units ("strata"). This process, known as "stratification", helps to ensure that each portion of your field is sufficiently sampled, and can lower the number of total samples needed to detect changes over time (Potash et al. 2023). Stratification is even required to meet the soil monitoring protocols of some carbon market platforms.

Stratifying incorrectly can reduce data quality, however. It may not be appropriate when the study area is small or relatively uniform in topography, hydrology and/or soil type.

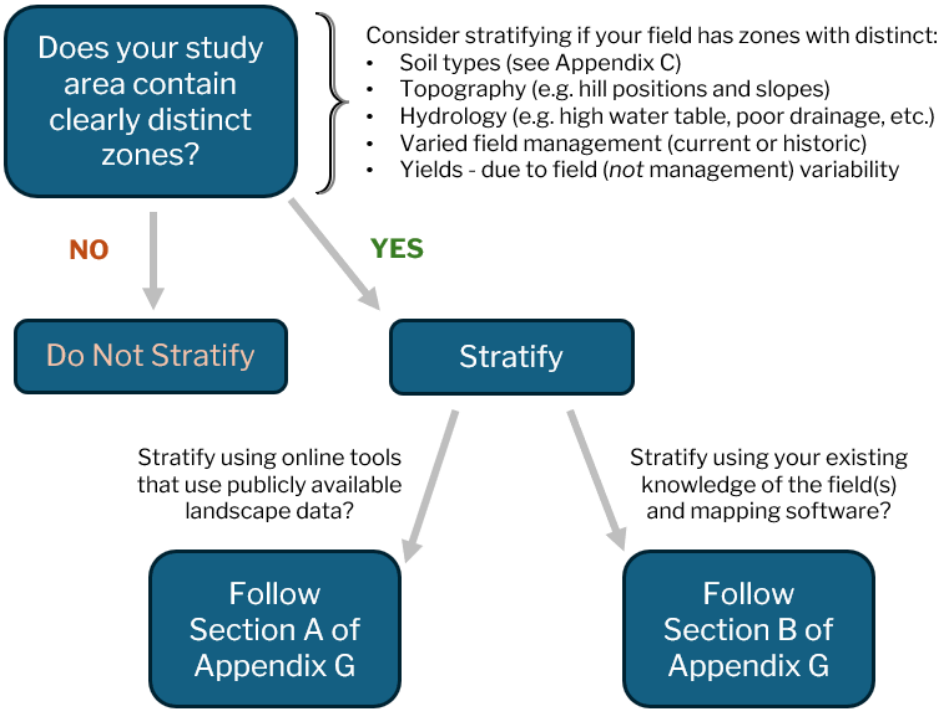


Figure 6: Simple flow chart to inform whether to stratify a sampling area, and how to go about it.

If you're unsure whether to stratify, consider the following: the primary landscape characteristics for stratification are those that are stable over time and are likely to influence how carbon levels change due to management, like soil series and texture. These characteristics form over hundreds of years to millennia, and are influenced by factors like hydrology and topography. If you are not intimately familiar with the area in question, check digital topographic and soil maps (Appendix B), ask other knowledgeable stewards of the land, and/or visit the study area to make in-field observations. Appendix G also provides additional stratification resources, including web tools that help to automate this process.

Stratification Process:
Resources for stratification include full service online tools like Stratifi and SoilStack (Appendix G, Section A), and mapping software (Appendix G, Section B).

Each strata must contain at least three sampling points within it, for data analysis. If your project requires fewer samples (than three times the number of strata), we recommend either (a) adding more sampling points to your project, (b) strategically reducing the number of strata (merging those that are similar, only), or (c) reverting to simple random sampling (i.e. not stratifying).

Stratification Example: Figure 7 shows a crop field on a hill, the entirety of which transitioned from tillage with a disc harrow to shallower, vertical tillage. In this example, the study area could be stratified into four distinct sections based on the orientation of the hill (north vs. south-facing), topography (slope steepness / hill position), distinct soil types or hydrology and/or areas that express legacy effects from prior management (e.g. Zone 1 was historically an orchard).

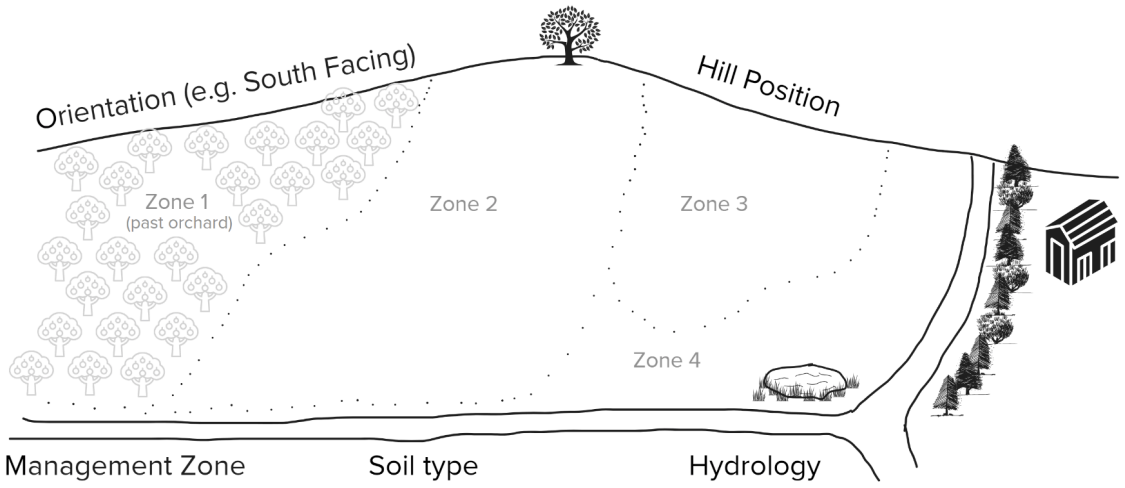


Figure 7. Landscape view of a farm field and potential subdivisions ("strata"), based on features like soil type, landscape position (upslope vs. downslope), and/or varied management history.

Once the strata have been identified, you can calculate the number of samples to collect from within each zone. We recommend allocating points to each strata proportionally, based on its relative area. GIS-based software can be used to pick sampling points (see Appendix G, page 5, pt. 2). If using The Random Sampling Point Selector Workbook to select locations in the field, use the stratification table in Appendix H to allocate the appropriate number of points to each stratum and Appendix F to identify their spacing for each subgroup (Figure 8).

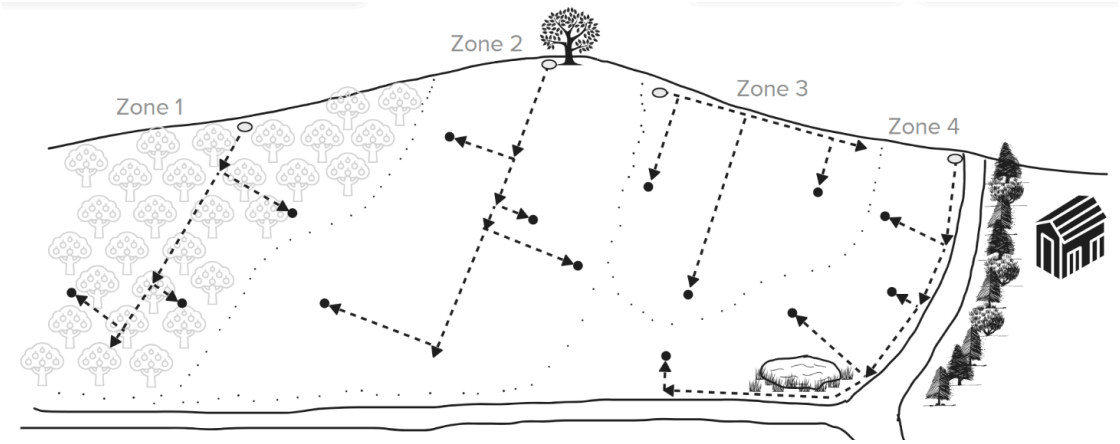


Figure 8. Example of using the Crop-C Random Point Selector Workbook (Appendix F) to select points within each subdivision (Zones 1 to 4). As shown in Zone 3, it is possible to use the straight border of a zone as the primary line and for all secondary lines to point in the same perpendicular direction. This is useful in long, narrow strata with at least one straight edge.

Permanent Sampling Points (Required)

The Crop-C Program requires sampling from permanent locations over time. This approach increases the ability to detect smaller changes in carbon 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 and, when possible, physical markers, such as t-posts, large tent stakes, or very durable flags. The physical markers are important given that GPS accuracy for most handheld units is between 8-10 ft.

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

Sampling points should not be moved unless absolutely necessary. This can happen when:

- a point falls in an area that is prohibitively rocky or ponded,
- a point intersects infrastructure that inhibits the ability or safety to take a sample, or
- a point is on a slope that exceeds a 40% grade or is otherwise unsafe to sample.

If using GIS software to choose points before visiting the field, create up to 10 extra points that can substitute for rejected sites. If sampling from one of these extra locations, make sure to use the first one listed in the table (this ensures the points remain spatially balanced).

When using the Random Point Selector Workbook to choose points, replace rejected sites by returning to the primary line (per Figure 8) and navigating to the next point on the list. When choosing new sampling points, record the reason on pg. 3 of the protocol questionnaire (Appendix Q).

Large zones that cannot be sampled should be removed from the project area.

Determine the Number of Samples

As each monitoring project is unique in its scope, the number of samples required depends on three factors:

1. The amount of change in carbon that is expected (effect size).
2. The expected spatial variability of the field / study area;
3. The desired certainty (i.e. the level of uncertainty one is willing to tolerate); and

If you have previous carbon data from the study area, you might be able to directly calculate the number of samples needed to reach a desired level of statistical certainty (see "1. Certainty" section below). This can be done using an online sample size calculator like GigaCalculator.com. For instructions on how to use this calculator, see Appendix G Section 6.

In *most* cases you will *not* have previous data and should use the *Sample Size Lookup Tables* to determine the number of samples to monitor for a given practice (see pg.42-50).

Decision Point: Point Selection Method

Eligible Inference Score points: 2.5 vs. 3 pts of 100

Will you determine how many samples to take using previous data and a custom sample density calculator, (Tier 1) or the Crop-C *Sample Size Lookup Tables* (Tier 2)? Using the density calculator typically provides a more accurate estimate when prior field data are available.

1. Expected Amount of Change in Carbon

When monitoring carbon, it is necessary to plan for the "noise" in the data that is created by field spatial variability, as well as expected sample processing and lab measurement errors. If the impact of a farming practice is large, fewer samples will be needed to overcome this noise and detect a change. Farming practices with smaller impact require more samples.

Additionally, for each management practice we recommend a different number of years between resampling events; smaller expected effect sizes require more time to accumulate carbon at detectable levels. For any given practice, monitoring "too soon" or "early" would result in a limited ability to detect an impact. Conversely, longer periods between monitoring events can result in greater change in carbon and may require fewer samples, all else equal.

2. Study Area Spatial Variability

We assume here that agricultural fields that contain more spatial variability are going to have a wider range of changes in carbon levels in response to management practices. As a result, these fields will require more samples to be accurately characterized (AbdelRaman et al. 2020). To determine whether the study area is expected to have high, moderate, or low variability in carbon changes, walk through the *The Crop-C Landscape Variability Assessment* (Figure 9). As shown, put a check mark next to each bullet that describes your study area. Select the category that has the most check marks to represent your study area.

Expected Variation in Carbon	Landscape Characteristics
High	☐ Steep slope, and/or contains full top to bottom of a hill ☐ Slopes face ≥ 3 cardinal directions (N, W, S, E) ☐ Greater than 3 soil types ☐ Large area (> 25 acres) ☑ Very uneven drainage, sections can stay saturated for weeks/yr ☐ Mixed land use history within field and/or major past intervention (e.g. deep ripping)
Medium	☑ Moderate slope, without full top to bottom of a hill ☐ Slopes face 2 cardinal directions (N, W, S, E) ☑ 2 - 3 soil types ☑ Medium sized area (5 - 25 acres) ☐ Uneven drainage, sections may stay saturated for days ☐ Meaningful interventions (e.g. tile drainage, laser leveling)
Low	☐ Relatively flat (≤ 2% slopes) ☑ Slopes face only 1 cardinal direction (N, W, S, E) ☐ 1 soil type ☐ Small area (< 5 acres) ☐ Even drainage across field ☑ Same land use history and no major interventions (per above)

Figure 9. Landscape variability assessment, marked up as an example of how to grade a field (check boxes) and select a category (green circle). In this case, the "Medium" category received the most check-marks for landscape characteristics, so it is the best choice. If two categories receive the same number of check marks, use your knowledge of the field to choose the best category and err on the side of higher expected variation. Adapted with permission from Regen Network.

Each level of variability reflects how much carbon sequestration is expected to vary across the study area, informed by the literature and existing monitoring data (Appendix R).

3. Certainty

The number of samples you need depends on how confident you want to be that carbon changed due to management. This is often influenced by your project goals and budget.

The amount of uncertainty a person is willing to tolerate can be defined using statistics. "Significance" (α) 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). This is the same as a "p-value", which is often referred to in research studies. In contrast, "power" (β) is a term used to describe the chance of getting a false negative (i.e., failing to detect an effect that actually exists).

The Crop-C Program *Sample Size Lookup Tables* are grounded in certainty levels that vary in both significance and power (Table 4; Appendix R), as described below:

Standard: (cost efficient)	Adequate for informal uses (see Figure 3). Significance (α) of 0.20, and power (1-β) of 0.30
Advanced:	Often appropriate for incentive programs, certifications, for example. Significance (α) of 0.10, and power (1-β) of 0.25
Academic: (high confidence)	Typical for academia, carbon markets and other high-scrutiny uses. Significance (α) of 0.05, and power (1-β) of 0.20

Decision Point: Monitoring Certainty

Eligible Inference Score points: 5 vs. 13 vs. 21 pts of 100

How certain do you want to be that your management changed carbon levels (or not)? Aiming for higher certainty will increase your Inference Score.

Calculating Final Sample Sizes

At this point, you can determine the number of samples required for each management practice using the *Crop-C Sample Size Lookup Tables* (pgs. 42-50). If multiple conservation practices are simultaneously being applied to this field, use the *Lookup Table* for the practice that has the largest expected impact (see list on pg. 40).

Combining Samples: At a Point, Not Across a Field

Typically, fertility-based soil or plant samples are collected from across a field and combined into a single bag for lab analysis. The result is a "field average" that minimizes costs. However, **combining samples across a plot, field or farm does not meet the requirements for detecting management impacts on carbon.** For one, if these combined samples are not meticulously mixed they will skew the data toward whatever portions of the field are most heavily represented. This could falsely indicate that changes are occurring which do not reflect the reality of the whole field.

Combining samples also obscures information about in-field variability, essentially hiding the range of values that exist across the study area. To illustrate this point, let's consider an example: A farmer begins growing high biomass cover crops in a field. Monitoring efforts show that soil organic carbon went up by 10 tons per acre (t/a) over 5 years. Good news! In one scenario, one of their 5 sampling sites is an outlier, increasing 50 t/a and the rest of the samples show no change over time. In this case, the increased field average of 10 t/a may not be an accurate representation of that field. Under a different scenario, all sampling sites showed organic carbon increased between 8 to 13 t/a. In this case there is more certainty that the results accurately represent the whole field. Combining all samples before sending them to a lab makes it impossible to know which scenario is truly taking place.

As a result, the Crop-C program does NOT permit combining samples across a study area. Instead, samples from each sampling point must **be gathered, stored and analyzed distinct from one another to meet the goals of the Crop-C Program** to track changes in carbon due to management impacts.

In contrast, we recommend combining *sub*-samples around a single monitoring point, when time allows. In this scenario, multiple cores are taken within a short distance (< 5 ft) of each sampling point and thoroughly combined (Figure 10). This can be important in areas with inconsistent conditions (e.g. patchy vegetation), and ensures there is enough weight or volume of a sample for the desired analysis. This is not required.

Rules for subsampling:

- Only combine subsamples taken near a single point in a field. This counts as one sample toward your total number of points.
- Keep the number of subsamples per point the same across your monitoring project.
- Subsamples must be similar to each other. For example, subsamples must be collected close to each other (< 5 ft) and using the same depth increments.
- Each subsample 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).
- Ensure that each subsample contributes an equal amount to the sample (i.e., the same mass or volume).

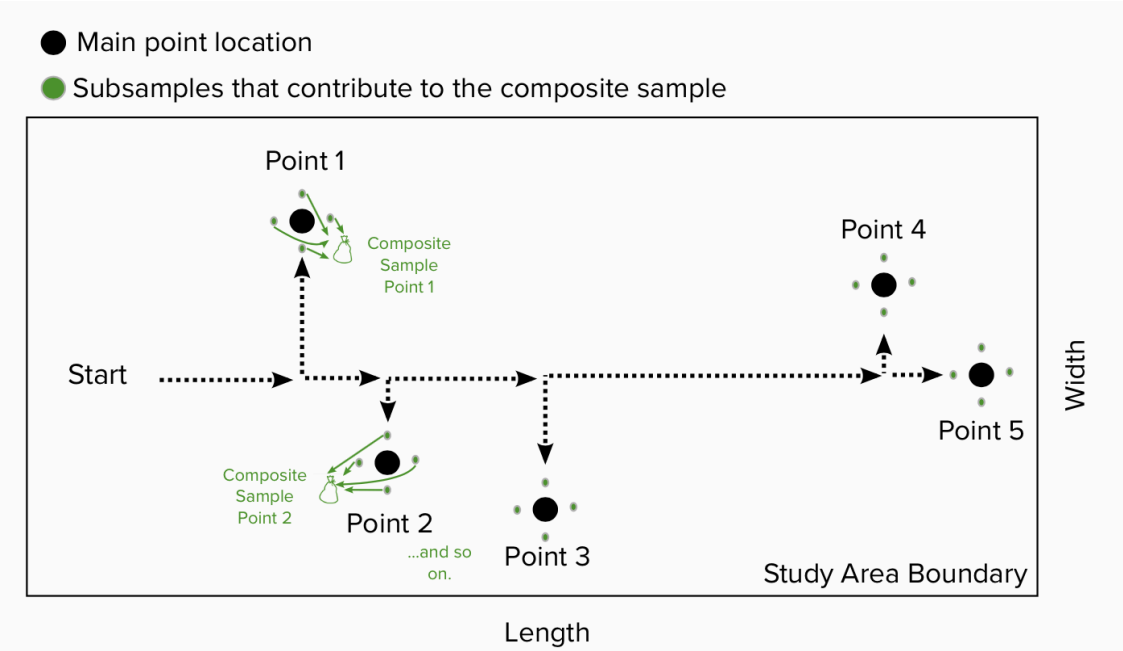


Figure 10. An example of subsampling (green dots) at each main point (black dots) and mixing the subsamples into a sample bag (green bag).

Even in cases where management practices are consistent across multiple fields, the Crop-C Program still requires that all samples from a single field are analyzed separately. Maintaining distinct samples captures spatial variability at the field level to allow for cross-project comparisons. Additionally, when samples are collected with adequately georeferencing, it reduces uncertainty when resampling in future years.

When to Sample

Field collections should occur when it is possible to take the highest-quality samples. Soil sampling, for example, can be difficult when a field is frozen, sopping wet, or teeming with plant roots. Instead, soil samples are often collected before planting in the spring or after harvest in the fall. Herbaceous biomass samples should be collected during peak biomass to capture the full effects of management on plant growth. As such, it may make sense to take different types of samples at different times of the year. The Indicator Methodology section (pg. 50) provides recommendations for each carbon pool.

Future resampling at a site should always match the original sampling conditions, with respect to the season, stage of plant growth and, when possible, phase of a crop rotation.

Field management should also be taken into consideration, requiring basic coordination with the farm manager. Avoid collecting soil samples soon after a field has been tilled, or had compost, manure or other carbon-rich materials applied to it. As a rule of thumb, sample at least three months after these interventions occur (Soil Carbon Project, 2021).

RETURN INTERVALS BY PRACTICE

Sampling return intervals are defined by each management practice (as explained in Appendix R). We note that due to the variable and slow changes to soil organic carbon, detecting field-level differences can require taking a lot of samples (high sampling density) and/or long durations (return intervals) between sampling events. Return intervals for low-impact practices such as reduced tillage, are quite long in order to keep the number of samples within a feasible range. If you wish to resample earlier than the recommended return interval, we will not be as sure that the change in SOC stock on your individual field is due to practice adoption. However, it can still support Point Blue's ability to build regional baselines and standards when analyzed with other cropland data. If you need assistance, please reach out to CropC@pointblue.org.

Here is a summary of practice-specific return intervals for resampling, based on expected changes to soil organic carbon levels:

2 Years	-	Soil organic amendments (e.g. compost)		
3 Years	-	Windbreak & hedgerow establishment		
5 Years	-	Livestock integration	-	No-till
	-	Living groundcover	-	Mulching
7 Years	-	Cover crops	-	Reduced-tillage
8 Years	-	Crop rotations (after ≤ 2 full rotations)	-	Tree / shrub establishment

Practice-Specific Considerations

This section defines specific monitoring instructions for the management practices featured by the Crop-C Program[8]. This includes how many samples to collect and the recommended number of years between sampling events.

If your desired management practice(s) are not included, consider if any are sufficiently similar to use as a proxy. For example, alley cropping between orchard rows is similar to cover cropping between orchard rows - especially if only the fruit/grain is harvested, not the whole plant. If you are unsure how to proceed for your project, follow recommendations for Livestock Integration (for high sampling density)) or contact CropC@pointblue.org.

If your project includes simultaneous implementation of multiple conservation practices, we recommend following the guidance of the practice with the highest expected impact. The below list is ranked from highest to lowest impact on *soil organic carbon* (per acre, per year):

- Soil organic amendments (e.g. compost)
- Windbreak / hedgerow establishment
- Living Groundcover
- Mulching
- Livestock integration
- No-tillage
- Reduced-tillage
- Cover crops
- Crop rotations
- Tree / shrub / vine establishment

Our assumption is that stacking conservation practices will have a positive or neutral effect on carbon levels, relative to implementing just one of those practices. As more data becomes available, we intend to refine our recommendations.

A full explanation of the calculations for the *Sample Size Lookup Tables is in* *Appendix R.*

If you are adding a control site to your study, consider oversampling (adding more points to the lookup tables below). Having a control has many benefits but can compound the influences of spatial variability. Adding more sampling points is recommended to overcome this, yet is optional given potential budgetary constraints.

[8] *The Crop-C Working Groups selected the featured management practices based on their adoption rates, their documented impact on carbon levels, and their integration into NRCS practice standards.*

Management Data to Collect for All Practices:

All Crop-C users will be asked to provide historical management data via Appendix P. The survey includes questions regarding:

- Irrigation management
- Pesticide and herbicide application
- Tillage history
- Fertilizer use
- Livestock integration (if applicable)
- Prior crop rotations

Depending on available management records and the user's understanding of prior management in the study area, the user may choose to include more or less detail in the survey. Providing more detail will increase the interpretability of Crop-C monitoring data.

Cover Crops

Grasses, legumes and forbs planted for seasonal vegetative cover.
(NRCS Conservation Practice Standard: 340)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Carbon Samples for **COVER CROPS**			
	Study Area Variability		
Certainty	**Low**	**Med**	**High**
Standard	6	12	20
Advanced	10	20	33
Academic	15	29	49

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take this measurement from *at least* half of the sites used for soil organic carbon. When possible, take bulk density samples at all soil organic carbon sites for the most accurate soil carbon stock calculations.

Sampling Interval:
Allow ≥ 7 years between each sampling event. Ideally, at the same part of the crop rotation.

Practice-Specific Management Details (Collect and Add to Appendix P):
Species planted each year; planting method and approximate date; planting density (e.g. seed/acre per plant species); termination method and approximate date.

Crop Rotations

Adding functional diversity to a sequence of crops grown on the same ground over time.
(NRCS Conservation Practice Standard: 328)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Carbon Samples for **CROP ROTATIONS**			
	Study Area Variability		
Certainty	**Low**	**Med**	**High**
Standard	6	11	18
Advanced	9	18	29
Academic	13	26	43

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take this measurement from *at least* half of the sites used for soil organic carbon. When possible, take bulk density samples at all soil organic carbon sites for the most accurate soil carbon stock calculations.

Sampling Interval:
Allow ≥ 8 years between each sampling event. Ideally, at the same part of the crop rotation.

Practice-Specific Management Details (Collect and add to Appendix P):
Crop types in rotation; planting density (seed per acre); planting method; termination method (if applicable); replanting details; planting and harvest dates.

Livestock Integration

Grazing in croplands for ecological and/or agricultural gains.
(NRCS Conservation Practice Standard: n/a)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Carbon Samples for **LIVESTOCK INTEGRATION**			
	Study Area Variability		
Certainty	**Low**	**Med**	**High**
Standard	7	13	16
Advanced	11	21	35
Academic	16	31	51

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take this measurement from *at least* half of the sites used for soil organic carbon. When possible, take bulk density samples at all soil organic carbon sites for the most accurate soil carbon stock calculations.

Sampling Interval:
Allow ≥ 5 years between each sampling event. Ideally, at the same part of the crop rotation.

Practice-Specific Management Details (Collect and add to Appendix P):
Species of livestock; stocking density (e.g. animal units per acre); paddocks / subdivisions in field; target number of rest days between grazing events; target residue grazed vs. left behind (%).

Living Groundcover

This category includes multiple practices aimed at maintaining living ground cover, many of which focus on reducing erosion and can be planted in strips or across a field.

(NRCS Conservation Practice Standards: Contour buffer strips (332), filter strips (393), grassed waterways (412), veg. barriers/buffers (601), conservation cover (327), and herbaceous wind barriers (603)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Carbon Samples for **LIVING GROUNDCOVER**			
	Study Area Variability		
Certainty	**Low**	**Med**	**High**
Standard	5	10	16
Advanced	8	16	27
Academic	12	24	39

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take this measurement from *at least* half of the sites used for soil organic carbon, or at least 3, whichever is higher. When possible, take bulk density samples at all soil organic carbon sites for the most accurate soil carbon stock calculations.

Sampling Interval:
Allow ≥ 5 years between each sampling event. Ideally, at the same part of the crop rotation.

Practice-Specific Management Details (Collect and add to Appendix P):
Species planted; planting method; planting date; planting density.

Special Consideration(s):
It is best practice to take samples away from the edge of a plot or field due to potential for neighboring conditions to influence results. For practices that occur along a line, most of the sampling area is near an edge. Where possible, try to take samples toward the middle of these strips to reduce edge effects, while maintaining random placements.

Mulching

Applying plant residues or other suitable materials to the land surface.
(NRCS Conservation Practice Standard: 484)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Carbon Samples for **MULCHING**			
	Study Area Variability		
Certainty	**Low**	**Med**	**High**
Standard	6	12	19
Advanced	10	19	31
Academic	14	28	46

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take this measurement from *at least* half of the sites used for soil organic carbon. When possible, take bulk density samples at all soil organic carbon sites for the most accurate soil carbon stock calculations.

Sampling Interval:
Allow ≥ 5 years between each sampling event. Ideally, at the same part of the crop rotation.

Practice-Specific Management Details (Collect and add to Appendix P):
Application rates; type of material (e.g. rice straw); composition of material (carbon and nitrogen content)*[9]; practice frequency (e.g. yearly or every 3 years).

[9] **Knowing the carbon content of the mulch is critical for calculating how much of the change in soil carbon is derived from the mulch itself.*

Reduced Tillage / No-Till

Limited or no soil disturbance from tools like discs, chisels, cultivators, etc. Typically this pairs with strategic retention of plant residue on the soil surface year-round.
(NRCS Conservation Practice Standards: 329, 345)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Carbon Samples for **REDUCED TILLAGE**				Number of Soil Carbon Samples for **NO-TILL**			
	Study Area Variability				**Study Area Variability**		
Certainty	**Low**	**Med**	**High**	**Certainty**	**Low**	**Med**	**High**
Standard	6	12	20	**Standard**	7	13	22
Advanced	10	20	32	**Advanced**	11	21	35
Academic	15	28	47	**Academic**	16	31	52

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take this measurement from *at least* half of the sites used for soil organic carbon. When possible, take bulk density samples at all soil organic carbon sites for the most accurate soil carbon stock calculations.

Sampling Interval:

- Reduced Tillage: Allow ≥ 7 years between each sampling event.
- No-Till: Allow ≥ 5 years between each sampling event.
- (Ideally, during the same phase of the crop rotation as the original sampling event)

Practice-Specific Management Details (Collect and add to Appendix P):
Yearly tillage type; tillage depth; number of tillage / cultivation passes per crop; target residue cover after final tillage pass.

Special Consideration:
If converting to no-till, soil samples must be taken at least 4 in. below the deepest tillage level (Climate Action Reserve. 2022). Soil organic carbon can migrate across depths of the soil profile, materially influencing carbon levels. No-till research often finds that topsoils gain carbon while subsoils lose carbon, so both areas should be included in your sample.

Soil Carbon Amendments (e.g. Compost)

Applying amendments derived from plant materials or treated animal byproducts.
(NRCS Conservation Practice Standard: 336)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Samples for **SOIL CARBON AMENDMENTS**			
	Study Area Variability		
Certainty	**Low**	**Med**	**High**
Standard	7	13	22
Advanced	11	22	36
Academic	16	32	52

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take this measurement from *at least* half of the sites used for soil organic carbon. When possible, take bulk density samples at all soil organic carbon sites for the most accurate soil carbon stock calculations.

Sampling Interval:
Allow ≥ 2 years between each sampling event. Ideally, at the same part of the crop rotation.

Practice-Specific Management Details (Collect and add to Appendix P):
Application rates; type of material (e.g. compost vs. biochar); application method; timing; carbon and nitrogen content of amendments[10]; practice frequency (e.g. yearly or every 3 years).

[10] **Knowing the carbon content of the mulch is critical for calculating how much of the change in soil carbon is derived from the mulch itself.*

Tree / Shrub / Vine Establishment

Establishing woody plants for production of timber, crops, or habitat. This should NOT replace native habitat or wildlands.
(NRCS Conservation Practice Standard: 612)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Carbon Samples for **TREE / SHRUB / VINE ESTABLISHMENT**			
	Study Area Variability		
Certainty	**Low**	**Med**	**High**
Standard	6	12	20
Advanced	10	19	32
Academic	14	28	47

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take these measurements from *at least* half of the sites used for soil organic carbon. When possible, take bulk density samples at all soil organic carbon sites for the most accurate soil carbon stock calculations.

Sampling Interval:
Allow ≥ 8 years between each sampling event.* Ideally, at the same part of the crop rotation.

Practice-Specific Management Details (Collect and add to Appendix P):
Species planted; planting date; planting method; plant spacing (between trees and rows); replanting details; pruning notes.

Special Consideration(s):
If you intend to claim that practices (e.g. mulch) are influencing carbon levels through woody biomass accumulation, we highly recommend a control area to clearly illustrate the effect of implementing the practice relative to normal growth rates.

*Tree/shrub/vine establishment is rated as having low impact on *soil organic carbon* levels because young woody plants grow slowly when first established, and measurements are averaged out across a field, including open areas away from the plantings.

Windbreak and Hedgerow Establishment

Windbreaks are trees planted on field edges to reduce wind erosion and evapotranspiration. Hedgerows are shrub or tree plantings also on field edges that serve multiple co-benefits, like promoting wildlife habitat. Hedgerows can also be used as a windbreak.
(NRCS Conservation Practice Standards: 380, 422)

Number of Sampling Points (per sampling interval):
Use the table below (or calculate using existing soil carbon data from the same farm, instructions in Appendix R, Section 6).

Number of Soil Carbon Samples for **WINDBREAK + HEDGEROW ESTABLISHMENT**			
	Study Area Variability		
Certainty	**Low**	**Med**	**High**
Standard	5	10	16
Advanced	8	16	27
Academic	12	23	39

If stratifying your field (pg. 31), include at least 3 samples per strata. If this exceeds the value you identified for your project in the table above, either (a) add more samples as needed, (b) reduce the # of strata, or (c) do not stratify the field.

Above- and Belowground Biomass: collect samples at all of the soil carbon sites.

Bulk density, soil texture or pH samples: take this measurement from *at least* half of the sites used for soil organic carbon, or ≥ 3, whichever is higher. If half, sample from every odd numbered site. When possible, take bulk density samples at all soil organic carbon sites.

Sampling Interval:
Allow ≥ 3 years between each sampling event. Ideally, at the same part of the crop rotation.

Practice-Specific Management Details (Collect and add to Appendix P):
Species planted; planting date; planting method; plant spacing (between trees and rows); pruning notes.

Indicator Methodology Overview

This section outlines the key materials and basic methods for measuring carbon indicators in your monitoring plan. There are multiple methods for measuring every carbon indicator; therefore, tiers are assigned to each method based on accuracy and precision.

Follow all protocols and instructions as closely as possible to ensure data standardization. Use Tier 1 methods as much as possible, as budget allows and based on your project needs.

Soil Carbon (Organic and Inorganic)

Printable, detailed protocols: Appendix K
Materials lists: Appendix S

Why Measure: Soil organic carbon measurement is not only necessary for tracking carbon sequestration but it reflects how much organic matter is in the soil. Soil organic matter directly influences functional qualities of a farming landscape via changes to soil structure, water holding capacity, nutrient availability, and decomposition, for example.

Especially in arid environments with pH levels >7, soil inorganic carbon also constitutes an important pool locking carbon dioxide out of the atmosphere and therefore is critical to measure for sequestration purposes.

When to Sample: When possible collect baseline samples prior to practice implementation. Sampling when soils are moist but not saturated will ease collection. Be consistent over time. For example, if baseline samples collected in April dictates that samples will be collected in April of future years. Sample prior to annual tillage when possible, especially when collecting bulk density to calculate carbon stocks.

Key Materials & Supplies:

Field
- Bucket auger, step probe, or sharp shooter shovel
- Ruler or similar
- Long screwdriver or similar
- Clippers/shears or similar

Sample Collection Overview: Tier 1 recommendation uses the soil carbon sample to also measure bulk density, going to a specified depth (at last 12 in.) and then uses equivalent soil mass, taking an additional sample to 4 in. below the last sample (e.g. from 12-16 in). Briefly, clip and clean the soil surface of debris. Use an auger, push probe or shovel to sample the soil as vertically as possible. 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. If subsamples

at a single point are being used to make a composite sample, mix thoroughly and combine them in a single bag. Keep depth increments separate when sampling more than one depth.

Depth increments: Crop-C requires sampling to at least a 12 in. (30 cm) to capture the bulk of the root zone in annual cropping systems and to aid comparisons across sites. If you sample deeper than 12 in., you must analyze soil from the 0-12 in. depth separately. Deeper samples may be desired when considering the expected depth of management impact and/or local knowledge of soil layers. Users can also assess the soil profile using online platforms: SoilWeb or Web Soil Survey ("Depth to Any Soil Restrictive Layer" section in the "Soil Properties and Qualities" tab).

Additionally, if you want to detect cropland changes on a shorter timescale, then consider dividing your soil samples into multiple depth increments (e.g. 0-4 in., 4-8 in., and 8-12 in.). Often changes in cropland soils occur fastest at the surface.

Sample Handling and Storage: Keep soil samples out of the sun while in the field (or in a cooler), and bring them back to a cool, dry location as soon as possible. Samples in plastic bags can be refrigerated for up to 2 weeks.

Sending to a lab: Air dry samples as soon as possible to stabilize soil processes. Open up each resealable bag, break up the soil slightly, and allow them to air-dry. Best practice includes laying the soil out on butcher paper (paper bag, or equivalent) and turning/mixing every day. 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.

Or in-house bulk density: Again there is a 2 week window to process the sample for bulk density and maintain accurate soil carbon measurement and bulk density via a sieving and drying process (see Appendix K).

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. Fractionation provides insight into rates of carbon cycling, carbon storage, and can act as an early indicator of change. For Tier 2 methodology, request analysis via dry combustion and for soils with pH > 6.5 with acid pre-treatment. We recommend calculating carbon stocks (e.g., tons of carbon per acre), which requires soil bulk density measurements. We highly recommend taking two bulk density depth increments (to 4 in. below SOC depth) to report values on an equivalent soil mass basis (calculations available in the far-right tab of Appendix M).

> *A note on Soil Organic Matter:* The loss-on-ignition method for measuring soil organic matter (SOM) is not included as an option for the Crop-C Program. This was decided after much deliberation. One reason is that soil organic matter can range from 45% to over 70% carbon content (Pribyl, 2010; Lal, 2016), so generalized conversions can introduce significant error. In addition, this laboratory procedure entails burning off

organic material in a muffle furnace, but other inorganic substances can also be lost at the high temperatures, skewing the data. Finally, between labs high variance exists between protocols and ovens; we require using the Tier 1 or Tier 2 methods listed above.

Soil Inorganic Carbon: If measuring soil inorganic carbon, request analysis via the modified pressure calcimeter method or similar direct quantification of CO_2 released after sample acidification. 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 soil 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 (i.e. same quantity of soil across all depths). If the targeted depth cannot be reached (e.g. due to rocks or shallow soils), or if an appreciable amount of soil is lost during transfer out of the ground into the resealable bag, then set aside the sample and try again 6 in. to the north and/or south. If there are still issues reaching the desired depth after three attempts, then keep the best sample and make note of the final depth achieved on the data collection sheet (Appendix M) .

Decision Point: Soil Depth

Eligible Inference Score points: 2.5 or 5 pts. of 100

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

References:

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Robertson G.P., et al. (eds.), 1999. Standard soil methods for long-term ecological research (Vol. 2). Oxford University Press.

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Soil Bulk Density

Printable, detailed protocols: Appendix K
Full materials lists: Appendix S

Why Measure: Soil bulk density reflects how much pore space a soil contains and can be an indicator of water holding capacity, infiltration rates, and compaction. Bulk density measurements are required to calculate soil carbon stocks in weight per area (tons/acre).

When to Sample: Before seasonal tillage, or at least three months after. Take samples at the same time as soil organic carbon. Best when soils are moist. Be consistent over time.

Key Materials & Supplies:

Tier 1 - Equivalent Soil Mass Method: Use a "tier 2" method below, add another 4" depth.

Tier 2 - Millet Method (Recommended if sampling to 12 in depth) (Tier 2):

- Auger or coring device with diameter > 1 in.; ≥ 2 in. is better
- Size small, medium weight nylon stocking (e.g. 50 denier) cut to hole depth +/~ 5 inch)
- 1 kg millet in a resealable bag; ensure seeds are not viable.
- 1000 mL (4.25 cups) measuring cup
- (Optional) For in-house bulk density: sieve, oven, other lab supplies

Tier 2 -Slide-hammer Method (Recommended if sampling below 12 inch depth):

- Slide-hammer core sampler with thin-walled metal sleeves (AMS Inc., diameter selected based on amount of soil needed for analyses)
- (Optional) For in-house bulk density: sieve, oven, other lab supplies

Tier 3 - Ruler Method (For any depth)

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

Sample Collection Overview: *With all of the approaches below:* Clear the soil surface of debris, then lift the sample out of the ground. 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 a single depth) to make a composite sample, combine them in the same bag. Keep depth increments separate when sampling more than one depth.

Tier 1: Equivalent Soil Mass (ESM) calculation: This method requires taking an additional sample at least 4 in. below your deepest soil organic carbon depth increment, using one of the other methods to extract the soil. Use the instructions in Appendix M to convert the regular bulk densities to ESM. This ESM method is the gold standard and especially recommended where soil volume might change (e.g. due to tillage or vehicle compaction),.

Tier 2: Millet method: Bulk density will be calculated by measuring the volume of the sample 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). Fill the hole with millet inside of a stocking and measure the millet volume in a measuring cup, twice per hole.

Tier 2: Slide-hammer method: For best practice, collect one sample for bulk density and carbon. If collecting a separate bulk density sample, go within 3 feet of the carbon sample Drive the slide-hammer core to the desired depth, keeping a firm downward pressure. Lift out the slide hammer, and remove the cylinder from the sleeve, cutting the soil flush with the bottom of the cylinder for each depth increment.

Tier 3: Ruler method: Bulk density will be calculated by using the diameter of the auger or probe and also measuring the depth of the hole excavated for the soil carbon. The method uses a ruler or stick, separately for each depth increment (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. Combine this with ESM (Tier 1) calculations to achieve a Tier 2 inference score.

Sample Handling and Storage: Keep the samples out of the sun while in the field, and bring them back to a cool dry location as soon as possible. If using for soil carbon also, samples must beSamples may be refrigerated, stable for up to two weeks. Best practice is to air dry samples immediately by opening each bag, breaking up the soil slightly (ensuring none is lost). To speed up this process lay soils on butcher paper and stir samples every day or so.

Analysis: Samples can be sent to a lab for bulk density analysis along with the sample volumes or sieved and dried in-house with the correct equipment, calculating bulk density using Appendix M in grams/cm^3.

Quality Assurance: If you cannot sample to the correct depth, discard the sample and collect a new one 6 in. north and/or south. If it continues to happen, consider coming back when conditions are improved. As 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.

Decision Point: Bulk Density

Eligible Inference Score points: 4 to 12 pts. of 100

If you are assessing bulk density, what method will you use and how deep will you sample? Using the ESM plus millet or slide hammer method will increase your overall Inference Score.

References:

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.

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Aboveground Herbaceous Biomass

Printable, detailed protocols: Appendix K
Full materials lists: Appendix S

Why Measure: As the vast majority of herbaceous biomass decomposes annually, turning back into CO_2, it is not a trusted measure of long-term carbon sequestration.. However, biomass carbon is an early indicator of increased landscape productivity and an area's capacity to drawdown carbon at a new threshold. This metric can also help to evaluate annual productivity

When to Sample: During peak plant biomass is ideal. If this is not viable because it would damage crops, sample at the latest plant growth stage possible. Most importantly, be consistent across years (e.g. at same phenological stage, or within a week of harvest).

Key Materials & Supplies:

- 0.5 m^2 quadrat (28 in. per side), and/or tape measure and marking flags
- Paper grocery bags, lunch bags, or potato / coffee sacks
- Clippers, shears or similar
- Lab supplies: Drying oven, scale

Sample Collection Overview:
Field Crops – Collect herbaceous biomass samples within 10 feet of the soil organic carbon sampling point using a randomly placed quadrat. For all plants rooted within the quadrat, cut the plant flush with the ground, and place the clipped material into a pre-labelled paper bag.

Vegetable Crops (shaped beds) – For fields with distinct paths or furrows, collect biomass samples from 2 linear feet of adjacent rows (4 linear feet, total). Start from the points in each row that are nearest to the soil sample point, then sample down the row in a consistent direction across all points. For all plants in this zone, cut the plant flush with the ground and place the clipped material into a pre-labelled paper bag.

Sample Handling and Storage: Keep refrigerated (not frozen) for up to 24 hours. 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: Record the weight of the bag and dried plant samples in Appendix N.

Quality Assurance: When harvesting biomass, the weight of the samples will be affected by where the samples are cut in relation to the ground; keep the harvest height consistent.

Reference:

Abbot, L. The Landscape Toolbox Learning Center: Vegetation Measurement and Monitoring, Harvest and Estimation Methods. Accessed: December 2020.

Herbaceous Root Biomass

Printable, detailed protocols: Appendix K
Full materials lists: Appendix S

Why Measure: Direct measurement of fine root production provides additional resolution on conservation management impacts. Up to 50% of plant productivity can occur belowground, yet rarely is time taken to monitor roots (Byrne 2021). Belowground root production connects aboveground changes in plant biomass to soil health and carbon sequestration.

When to Sample: During peak plant biomass is ideal. If this is not viable because it would damage crops, sample the latest plant growth stage that is possible. Consider if the soil will be too hard to sample early or late in the season, depending on your location. Most importantly, be consistent across years (e.g. in the same phenological stage, or within two weeks of harvest).

Key Materials & Supplies:

Field
- Battery-operated cordless drill
- Hole saw with pilot drill bit (~ 3")
- Clippers/shears or similar

Lab
- 2 x No. 40 sieve
- 5 quart plastic bucket with pour spout
- Flexible plastic cutting board
- Baking sheet (8 x 13 inch)
- Aluminum baking tins
- Compressed air
- Drying oven (preferably forced-air convection)
- Scale (0.01 g precision)

Sample Collection Overview: Take the sample 3ft from soil carbon point. Cut away any plants at the soil surface, leaving roots intact. Use the hole saw to collect samples to at least 6-in depth. Keep the saw as vertical as possible during the collection process. If applicable, combine any subsamples at a location to make a single composite sample per point.

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.

Analysis: To analyze a sample for root biomass, we use a multiple step wet sieving process, using water to flush excess soil and clean roots on top of a No. 40 sieve. Once all organic

material has been transferred off of the sieve, spend a fixed amount of time (at least 3 minutes) removing any non-root debris from the samples, such as plant leaves and sticks.

After the final steps, move the roots from the baking sheet to a pre-weighed aluminum baking tin. Place the sample and tin in an oven at 150 ℉ for at least 48 hours, or until constant weight. Weigh to the nearest 0.01 gram. Use Appendix O to calculate root biomass.

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. 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, discard the sample and collect a new one 6 in. north of the previous hole.

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

Reference:

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

Woody Biomass (Aboveground and Roots)

Printable, detailed protocols: Appendix K
Full materials lists: Appendix S

Why Measure: Woody biomass can store large amounts of carbon in croplands, whether in the form of the crops themselves, or as hedgerows, windbreaks, or naturalized trees/shrubs. Woody roots not only store carbon but also emit carbon-rich compounds into the soil.

When to Sample: Consider sampling when woody species are dormant or in stages of slow growth (e.g. late-fall to early-spring) to reduce fluctuations in annual variability. Always be consistent over time. For example, if baseline measurements are taken in April, collect all future measurements in April as well

.**Key Materials & Supplies:**

- Long rope or field measuring tape
- Compass
- Diameter tape or pliable measuring tape
- (optional): clinometer or similar app for measuring height

Sample Collection Overview:
Orchard / Vineyard / Berries: Randomly select a subset of the points originally identified for soil organic carbon (SOC). With the SOC sampling point as the center, measure the closest two woody plants in each of the adjacent crop rows (4 plants total). Measure the diameter at breast height (DBH in inches.; 4.5 feet from the tree base). Note that existing woody biomass calculations for tree crops do not require taking height measurements, but this information may still be useful to collect for reference.

For trees, shrubs or vines with a single trunk, only include plants with > 2 in. DBH. It is possible that the trunk will fork or "split" below 4.5 feet, resulting in two or more stems. If this happens, measure each stem that is at least 0.5 inches in diameter and add them together when inputting into Appendix L. Only include plants where the *total* biomass of all measurable stems would be equal to or greater than a single-stemmed plant that has a 2 in. DBH. In that appendix, include information on plant spacing (in row and between rows).This data will enable calculations of carbon stocks (in tons C/acre) for above and belowground woody biomass.

Measuring at an angle: In some cases, a tree may grow at an angle out of the ground, or be located on a slope, so we list special rules in the detailed protocol (Appendix K)

Hedgerow and Windbreak 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. We therefore recommend using a volume-based approach. Measure total length, width and height of the hedgerow and record the values in Appendix L ("Hedgerow Biomass" tab). Then, estimate the density of the hedgerow by calculating percent canopy cover by laying a tape measure or rope with regularly marked

intervals (distance depends on how long the hedgerow is) along the length of the hedgerow (Fig. 11). Record whether the hedgerow canopy covers each marked interval, and record the number of points covered (i.e., the number of "hits") in Appendix L ("Hedgerow Biomass" tab). This information will be used to estimate total aboveground and belowground biomass using this approach.

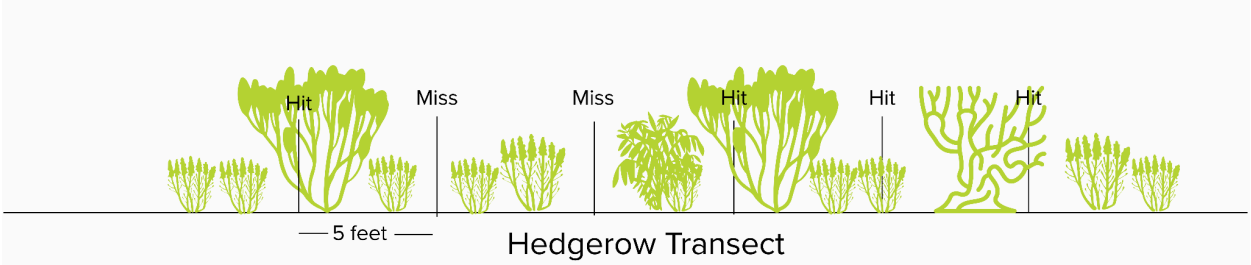

Figure 11. Measure the length, width, and average height of the hedgerow. Then, use a tape measure or rope to determine cover of the hedgerow. This information will be used to estimate above and belowground biomass.

Sample Handling and Storage: N/A

Analysis: Use the in-field measurements to run calculations in Appendix L 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. When taking measurements, ensure the diameter tape and calipers are squarely perpendicular to the tree.

References:

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.

Black et al. 2022. Biomass pools in intensively managed hedgerows can be a net emission of carbon dioxide. Research Square.

Soil Texture

Printable, detailed protocols: Appendix K
Full materials lists: Appendix S

Why Measure: Soil texture quantifies the percent sand, silt and clay within the soil, which relate to multiple soil properties, such as pore space, water holding capacity, nutrient availability and organic carbon stability. Soils with higher clay contents generally can store more stable forms of carbon in many agroecosystems.

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

Field Texture by Feel (Tier 2)

- 25 g soil per each sample location
- Water
- Ruler or similar (if conducting in house)

Sample Collection Overview: Either use a subsample of the soil carbon sample or sample within 1 foot of that point, to the same depth(s).

Sample Handling and Storage: Textural analysis using the feel or hydrometer method can be completed on field moist or air dried soils.

Analysis: Labs can use either a hydrometer (Tier 1) or feel method (Tier 2) to measure texture. If sending the sample to a lab simply ensure you have enough sample (40-100g) just for texture. If testing in the field, follow the flow chart to test separately for sand, clay and silt as in Appendix D.

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

Decision Point: Soil Texture

Eligible Inference Score points: 0.5 or 2.5 pts. of 100

If you are assessing soil texture, which method will you use? Using the hydrometer method (Tier 1) will strengthen your Inference Score.

References:

Soil Survey Staff. 2014. Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations Report No. 51, Version 2.0. R. Burt and Soil Survey Staff (ed.). USDA, NRCS, pp 54-61.

Small Shareholder Soil Health Assessment. Accessed Jan 07, 2022. https://smallholder-sha.org/protocol-1/texture-by-feel/.

Soil pH

Printable, detailed protocols: Appendix K
Full materials lists: Appendix S

Why Measure: Soil pH offers context for interpreting changes in soil carbon, both due to its influence on plant productivity and organic inputs, and/or its interaction with soil chemistry and inorganic carbon levels.

When to Sample: Anytime when the soils are not saturated with water, likely paired with soil carbon sampling. Be sure to be consistent over time.

Materials & Supplies:
Tier 1 - Lab pH measurement - Requires ~15g soil per location

Tier 2 - In-field pH measurement - Requires ~15g soil per location

- Distilled or bottled water
- Handheld field pH meter
- pH buffer solution of two levels (pH 7 and pH 4 or pH 10)

Sample Collection Overview: Using existing soil for texture or carbon may be possible, simply mix the sample well before taking a small portion for pH. If a new sample is required, sample within 1 ft of the soil carbon point and follow those sampling guidelines.

Sample Handling and Storage: For in-house analysis soil can be moist as water is added prior to analysis. If shipping to a lab for analysis, air dry the sample as soon as possible after removing it from the field and store in a cool dry place.

Analysis:
Tier 1 - Laboratory pH with $CaCl_2$: Request that the lab uses a 1:2 soil sample to solution of calcium chloride ($CaCl_2$), which helps with measurement consistency.

Tier 2 - In-field with water: Calibrate the pH meter with two pH buffer solutions (either pH 7 and pH 4 or 10). Create a 1:2 soil to water solution, stir, wait 10 minutes and then insert the pH until numbers stabilize. Record the results in Appendix J.

Quality Assurance: Due to lower accuracy of the in-field meter, repeating the text 2-3 times per sample will ensure more reliable results via a calculated average.

Decision Point: Soil pH

Eligible Inference Score points: 1 or 1.5 pts. of 100

If you are assessing soil pH, which method will you use? Using the pH electrode in $CaCl_2$ (Tier 1) will strengthen your Inference Score.

References:

USDA and Soil Quality Institute Staff. 2001. Soil Quality Test Kit: Soil pH Test. Accessed Jan. 7, 2022.
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.

Record Monitoring and Management Information

Field and lab analyses are only useful as far as we can interpret the information. To make the most out of a monitoring project, context is needed to increase our understanding of why the results are occuring at a given project site.

Use the guidance and forms in Appendix P to collect information about management history and the current conservation practices. When submitted to the Crop-C database, clear and complete records support broader understanding about the impacts of common management practices on carbon across regions and cropping system types.

A process is underway for projects that use Crop-C to submit information into a secure, aggregated database containing a data privacy policy that protects users rights and simultaneously extends the use of the data beyond a single site. The Crop-C Monitoring Program administrators can judiciously share data privately with trusted collaborators to advance conservation implementation and science. By sharing data into this aggregated format, you will receive access to Crop-C dashboards and reports comparing your site to regional averages. This process should be available in the second half of 2025.

Data Management and Interpretation

In 2025, Crop-C users will have the opportunity to create an account online to access Crop-C materials, submit their data and receive a report interpreting results.

Crop-C data will be hosted on servers that meet extremely high security standards, managed by Point Blue informatics experts with decades of experience facilitating ecological data protection and privacy. The source code (i.e. architecture) used to store and summarize Crop-C data will be documented following open-source standards. Crop-C users will own their data with the ability to download it, completely delete it from the system and/or move it to their own server at any time. Point Blue will use the data to generate private reports for Crop-C users on a project-by-project basis. Point Blue will utilize the data for regional analysis and interpretations to further our understanding of practice impact for managers, incentive programs, and broadly achieve our collective conservation goals. This may include very judiciously sharing data with scientific collaborators; not for public use.

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

We thank you for participating in the Crop-C program and, for those who submit their data, the opportunity to partner with you in advancing conservation science.

Appendices

Scan this QR code to access these files

Calculators

- Appendix A: Inference Score Calculator (Tiered Scoring System)
- Appendix B: Project Cost Calculator

Informational Guides and Resources

- Appendix C: Determining Soil Type
- Appendix D: Estimating Soil Texture by Feel
- Appendix E: Using Mapping Software to Select Random Sampling Points
- Appendix F: Random Sampling Point Selector Worksheets
- Appendix G: Stratification Resources

Printable Forms - Data Collection

- Appendix H: Stratification Table (For Use After Point Selector Worksheet)
- Appendix J: Printable Forms for In-Field Data Collection
- Appendix K: Printable Field Sampling Instructions

Worksheets for Data Processing & Recordkeeping

- Appendix L: Woody Biomass - Data Worksheets
- Appendix M: Bulk Density & Carbon Stocks - Data Worksheet and Calculator
- Appendix N: Herbaceous Biomass - Data Worksheet
- Appendix O: Root Biomass - Data Worksheet
- Appendix P: Historic Management and Conservation Practice Questionnaire
- Appendix Q: Final Monitoring Design Questionnaire

Supplementary Information

- Appendix R: Sample Size Calculations by Practice - Background Details
- Appendix S: Materials List for All Methodologies
- Appendix T: Decision Brief

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