Harnessing Farms and Forests in the Low-Carbon Economy

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Harnessing Farms and Forests in the Low-Carbon Economy

How to Create, Measure, and Verify Greenhouse Gas Offsets

The Nicholas Institute for
Environmental Policy Solutions

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Preface

In 2003, a kind of economic nightmare seemed to be emerging in the United States. Although the nation had not created a mandatory cap-and-trade system for greenhouse gas (GHG) emissions, voluntary trading of such emissions and *offsets* (efforts to remove carbon dioxide from the atmosphere or prevent GHG emissions in the first place) had already begun. Businesses and individuals seeking to limit or neutralize their carbon footprint, their impact on global warming, began to purchase offsets from other businesses and individuals who had found ways to reduce their own emissions. Local markets and exchanges, brokerages, registries, and trading clubs sprouted up to meet the demand. However, the standards used to define the commodities to be traded varied wildly. In contrast, trade of GHG emissions and offsets among European Union nations was proceeding in a relatively orderly fashion. That is because participation in the Kyoto Protocol's cap-and-trade program had required the EU to create a regulatory framework with consistent and credible definitions of GHG offsets.

In the United States, a federal program regulating GHG emissions does not exist. The result is a piecemeal market for carbon offsets, in which the credibility of the commodities for sale can vary substantially. In the long run, this is an untenable situation for buyers and sellers alike. For buyers, *caveat emptor* ("let the buyer beware") is the watchword. For sellers, the lack of a system for verifying and validating offsets tends to depress the price they command.

Targeted changes in land uses and management practices in both agriculture and forestry can provide a major source of GHG offsets. These benefits result from using forests and soils to remove and store carbon already in the atmosphere and from reducing emissions of GHGs in the first place. The agriculture and forestry sectors have significant potential to help stabilize GHG emissions in the United States, particularly over the next several decades. For that to happen, however, such terrestrial GHG offsets must rest on transparent definitions and standards based on first-rate science. Such standards would give buyers and sellers alike a basis for establishing the value of the offsets and also provide a model for regulations that will surely ensue at the state and (eventually) federal level.

In early 2004, Environmental Defense contacted two groups of independent scientists to help provide these guidelines. The goal was to provide a gold standard for ensuring quality and integrity—a step-by-step guide to quantifying and verifying GHG offsets based on changes in land use and management in agriculture and forestry. Five highly regarded scientists agreed to serve on an advisory and review committee for the project. Dr. William H. Schlesinger, dean of the Nicholas School of the Environment and Earth Sciences at Duke University, chaired the committee. Dr. Schlesinger and his colleagues provided the wisdom and advice needed to steer this daunting, multidisciplinary project through its many technical mazes.

A second group of scientists then applied its unique and varied experience to key aspects of creating terrestrial GHG offsets. These scientists contributed papers that answered the central question: how much will any specific farm or forestry project reduce levels of GHGs? Dr. Gordon R. Smith spearheaded the distillation of those papers into this guide, supported by the advisory and review committee and other consulting scientists. Dr. Dennis O'Shea, and later Sandra Hackman and Dr. Bill Chameides, then undertook two difficult tiers of editing.

All these individuals working in tandem over the past several years have produced the document that follows. We all are grateful to Peter Nicholas for his gracious funding—and infinite patience—in support of this work.

The extensive knowledge and guidance embodied here will provide invaluable direction to farmers, foresters, and other land managers, as well as consultants, brokers, investors, and others interested in creating consistent, credible GHG offsets as a new tradable commodity in the United States. This guide will help make tangible a new economic opportunity for rural America. In addition, it will provide important guidance to the policy community pursuing controls on GHG emissions—in the United States and other parts of the world.

Part I

Overview

Chapter 1

The Role of Landowners and Farmers in the New Low-Carbon Economy

A new economy is coming—a low-carbon economy in which greenhouse gas emission allowances and offsets will be a commodity that is bought and sold on the open market. Landowners and farmers, the people who work the land, will have a competitive advantage in this new economy because land, if properly managed, can be made to store carbon. Industries that emit carbon dioxide will pay landowners and farmers who store carbon to offset industrial emissions.

Why a Low-Carbon Economy?

The low-carbon economy will place a premium on technologies that can produce energy with little or no carbon dioxide (CO_2) emissions, as well as on activities that help remove carbon dioxide from the atmosphere. Why? The answer is simple: global warming. While uncertainties about climate remain, the basic facts of global warming are now well established:

- The globe is warming. The warming is due in large part to emissions into the atmosphere of CO_2 and other heat-trapping or greenhouse gases (GHGs) that result from human activities.[1]
- Unless we slow the rate of these emissions, the consequences could be dangerous, expensive, and irreversible.

In a communiqué issued in June 2005, 11 national academies of science (including the U.S. National Academy of Sciences) held that "the scientific understanding of climate change is now sufficiently clear to justify nations taking prompt action . . . We urge all nations . . . to take prompt action to reduce the causes of climate change."

The only way to curb human-induced climate change is to reduce emissions of CO_2 and other GHGs. And the only way to accomplish that is to move to a low-carbon economy that values technologies that limit GHG emissions and devalues technologies that produce GHG emissions.

Momentum toward a low-carbon economy is building. Thirty-five of the world's developed countries have agreed to reduce their GHG emissions 5 to 8 percent below 1990 levels through the Kyoto Protocol.[2] While the U.S. government has not joined the Kyoto process, many states and local governments have made Kyoto-like commitments. California has committed to a cap on its state-wide greenhouse gas emissions that will lead to substantial cuts in emissions in the coming decades. Four other southwestern states (Arizona, New Mexico, Oregon, and Washington) have joined California in the Western Regional Climate Initiative with the goal of setting a regional greenhouse gas emissions reduction goal. Seven northeastern states (Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York, and Vermont) have joined the Regional Greenhouse Gas Initiative (RGGI) and agreed to cap CO_2 emissions from power plants. Many other states have announced climate initiatives and are considering statewide caps on GHG emissions. In the private sector, major U.S. businesses (including Alcoa, BP America, DuPont, Caterpillar, and General Electric) have formed the United States Climate Action Partnership calling for mandatory caps on the nation's greenhouse gas emissions.[3]

Although the United States has yet to adopt a mandatory program to reduce GHG emissions, many people believe it is only a matter of time before it does. Indicative of this is a resolution passed in 2005: "It is the sense of the Senate that Congress should enact a comprehensive and effective national program of mandatory, market-based limits and incentives on emissions of greenhouse gases (S.AMDT.866)."

The Transition to a Low-Carbon Economy

History has shown that markets, rather than mandatory controls, can be the most cost-effective way to cut pollutant emissions. In a regulatory system, a market approach often takes the form of a "cap-and-trade" mechanism.[4] Such a mechanism caps total emissions from regulated entities—which may include a specific sector, such as power production in the case of RGGI, or the entire economy, as in the case of Kyoto—at a specified level, usually significantly below the current level. Regulators then assign individual emitters allowances, or caps, such that the total allowances equal the overall cap. Emitters have some period of time to comply with their cap.

Emitters can comply in three ways. First, they can use efficiency measures, technological advances, or lower activity levels to reduce their emissions. Second, they can purchase allowances from other emitters who have reduced their emissions below their caps. Third, they can purchase *carbon offsets* from individuals or entities, which remove CO_2 from the atmosphere or prevent GHG emissions.[5] This market approach allows emitters to find the cheapest way to meet their individual caps, as emitters that would incur relatively high costs can acquire allowances and offsets from those that can generate them at lower costs.

In this approach, CO_2 and other GHG emissions become a commodity that is bought and sold, and the marketplace (rather than regulators) determines the price of carbon allowances and offsets. These allowances and offsets can be relatively cheap or costly, depending on supply and demand. Businesses and individuals also have an incentive to develop cost-effective methods of reducing GHG emissions and creating carbon offsets. By allowing the marketplace to control the price, the system guarantees that emitters will choose the most inexpensive and effective methods for reducing or offsetting emissions.

In unregulated systems, corporations and individuals can voluntarily cap their GHG emissions, as some companies have done. Cities and other municipalities have also adopted voluntary caps on the emissions arising from government activities. Voluntary caps usually do not include trading, but emitters may still purchase offsets when internal efforts to boost efficiency and adopt new technology do not produce the desired results. Here again the marketplace sets the price of the carbon offsets. As more companies and individuals take on a cap, demand for offsets rises, as does the price they command.

Despite the absence of a mandatory nationwide cap on GHG emissions, a U.S. market for carbon offsets is already burgeoning. Numerous companies have formed to buy and sell offsets, while other companies have emerged to verify and register those offsets. Many of these companies can be identified through a simple Internet search. However, potential buyers should exercise caution because the system is not yet regulated, and many developers of offsets do not yet follow rigorous procedures for creating them, such as those outlined in this volume.[6]

Farmers' Entrée into the Low-Carbon Economy: Carbon Offsets

Land-management practices can play a significant role in slowing the buildup of GHG. Forests and farmlands act as natural carbon storehouses, or *sinks*, offering major opportunities to reduce global warming. As forests grow, they absorb CO_2 from the atmosphere, storing (or sequestering) vast amounts of carbon in wood, leaves, roots, and soils. Agricultural practices such as no-till or low-till farming, grassland restoration, and the use of cover crops also sequester carbon in soils. By protecting and restoring forests, replanting grasslands, and improving cropland-management practices, landowners can help reduce atmospheric concentrations of GHG.

Besides removing carbon already released into the atmosphere, better land-use practices can also reduce emissions of potent GHG such as methane and nitrous oxide. For example, using fertilizer more precisely can reduce emissions of nitrous oxide from soil. Reducing the saturation of soil with water (particularly during rice cropping) can curb methane emissions, as can the capture and burning of methane emitted from manure.

While environmentalists have pointed to the potential for these activities to slow global warming, farmers and landowners today have little economic incentive to adopt them. However, this will change as the transition to a low-carbon economy puts a market value on land-management practices that store carbon and reduce GHG emissions.

In fact, even where caps on emissions remain mostly voluntary, offset projects targeting carbon dioxide, methane, and nitrous oxide are already under way. In the Northwest, the energy company Entergy has funded Pacific Northwest Direct Seed Association, a nonprofit composed of more than 100 farmers, to create marketable offsets by using low-till farming to sequester carbon in soil and lower CO_2 emissions. In the Midwest, a grain-milling cooperative is creating offsets based on the land-management practices of several hundred farmers in Kansas, Missouri, Nebraska, and Iowa, such as through the use of no-till farming to store more carbon in soil. In the Northeast, a group of dairy farmers is seeking buyers for offsets based on cuts in methane emissions resulting from the use of anaerobic digesters to treat manure. In the South, a consortium of farming operations is creating offsets by shifting to low-till cropping to reduce CO_2 emissions, changing crop rotations to store more carbon, and improving livestock and manure management to reduce methane emissions.

The Potential of Offsets Based on Land Management

Land-management practices have the potential to make a significant dent in GHG emissions. The U.S. Environmental Protection Agency (EPA) estimates that the United States emits some 6,000 million metric tons of CO_2 each year, as well as the equivalent of another 1,000 million metric tons of CO_2 in the form of other greenhouse gases, including methane, nitrous oxide, and chlorofluorocarbons. Overall, annual GHG emissions total the equivalent of some 7,000 million metric tons of CO_2 (see Figure 1.1).

If the United States takes no steps to reduce GHG emissions, how large would they be in, say, 2025? The recent past can provide a clue. In 1990, U.S. greenhouse gas emissions were equivalent to about 6,100 million metric tons of CO_2 per year; in 2004, they were reaching nearly 7,100 million metric tons. GHG emissions are therefore rising at an annual rate of about 1 percent. Without a limit on such emissions, we can assume they will continue to rise an additional 1,600 million metric tons per year by 2025, to the equivalent of about 8,700 million metric tons of CO_2 annually.

Climate models suggest that by the later part of the twenty-first century, humanity must reduce global GHG emissions by about 50 percent from their present rates to avoid dangerous climate change (O'Neill and Oppenheimer 2002; Den Elzen and Meinshausen 2005).[7] This prospect is challenging to say the least. In the United States, this would require cutting annual emissions by some 3,500 million metric tons of CO_2. The good news is that we do not have to attain this 50 percent reduction immediately. We can slowly ramp down our emissions to reach the 50 percent reduction by the end of the century, when new technologies and energy sources will hopefully have replaced the carbon-intensive forms we rely on today.

Over the next 20 years or so, developed nations might reasonably aim to lower their emissions by about 10 percent (Den Elzen and Meinshausen 2006). For the United States, this would require cutting the equivalent of about 700 million metric tons of CO_2 per year. Adding the estimated annual increase in GHG emissions during this period of 1,600 million metric tons, the United States would have to find emissions cuts equivalent to about 2,300 million metric tons of CO_2 per year. Although not as imposing as the 50 percent target, this goal will still significantly test our economic and technological ingenuity.

Could land-management practices help the United States meet the 20-year target cut of 2,300 million metric

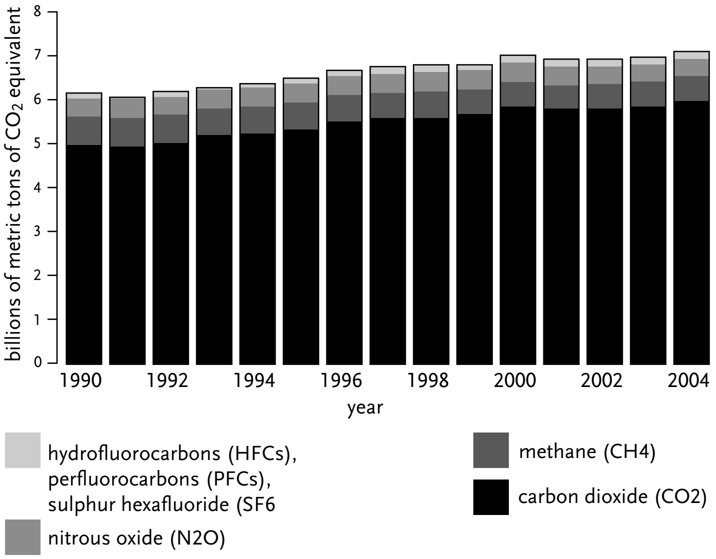
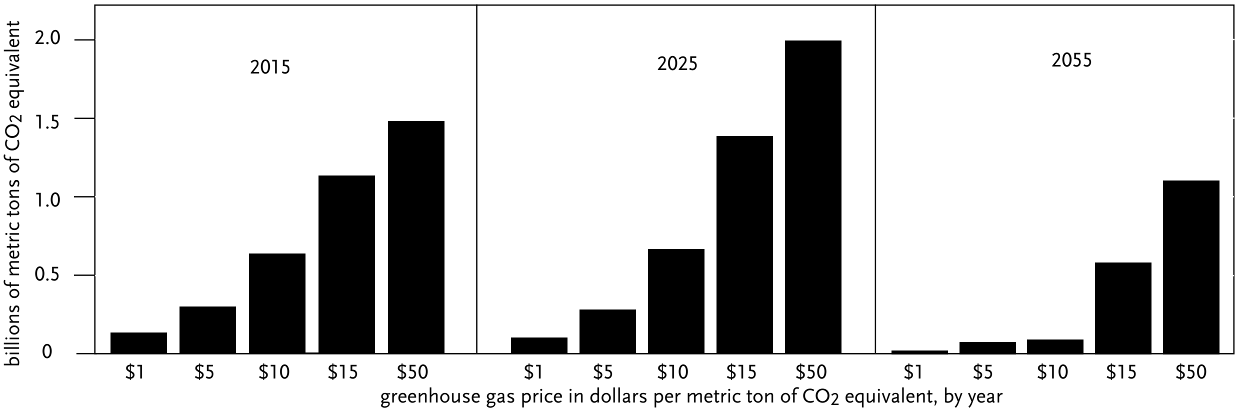


Figure 1.1 U.S. CO_2 and other greenhouse gas emissions, 1990–2004 (in millions of metric tons of CO_2 equivalent). Emissions rose at an average annual rate of about 1% over the period. If that rate persists, U.S. emissions will grow from the present 7,000 million tons a year to about 8,700 million tons in 2025. *Note*: From U.S. EPA 2006.

Figure 1.2 Carbon offsets that U.S. land-management practices could create, as a function of year and price (in millions of metric tons of CO_2 equivalent). With the rising price of offsets the total amount of offsets available should increase, as more farmers and landowners perceive an opportunity to profit and participate in the market.
Note: From U.S. EPA 2005.



tons of CO_2 per year? Consider a recent EPA study (2005), which estimated the potential for carbon offsets from land-management practices (see Figure 1.2).[8] Not surprisingly, as the price of offsets rises, more farmers and landowners opt to participate in the market, and thus the total amount of offsets also increases. The amount of offsets also depends on time. Although the amount of offsets grows as more farmers and landowners participate and soils and forests increase their capacity to store carbon, the amount of offsets could peak in 2025 because soils and forests eventually become saturated with carbon and lose their ability to store more. The amount of offsets could even decline if cutting of forests used to create offsets outstrips reforestation.

The results from the 2005 EPA study suggest that land-management practices can play a major role in enabling the United States to meet the emissions target over the coming decades if the price of carbon offsets is high enough. If offsets command a price of $15 per ton of CO_2, land-management projects could offset almost 1,500 million metric tons of CO_2 per year by 2025—around two-thirds of the needed reduction. At $50 per ton, offsets could total almost 2,000 million metric tons of CO_2 per year—nearly the total required cut in emissions.

Will the price of offsets be high enough to generate the needed amount? That depends on demand. In the United States, where emissions caps are voluntary and the market for offsets is currently relatively weak, offsets are now selling for a few dollars to about $10 per ton of CO_2. However, in the European Union, which has adopted a mandatory cap under the Kyoto Protocol, CO_2 prices rose into the range of $30 to $40 per ton of CO_2 in 2006. This suggests that if the United States adopts a mandatory cap, the price for offsets will be high enough for land-management practices to play a major role in meeting the cap. Because carbon offsets will be critical in the transition to low-carbon technologies, farmers and landowners who enter the offset market early stand to profit the most.

The Need for Offset Quantification Guidelines

While projects based on changes in land-management practices have the potential to offset significant amounts of GHG emissions and to provide a new income stream for farmers and landowners, they present significant challenges to the individuals and entities that undertake them. At the front end of an offset project, developers need to reliably estimate its potential value and thus the amount of GHG mitigation it is likely to produce. As any farmer can attest, projecting crop yields at the beginning of a planting season is difficult. In an offset project based on changes in land management, developers must attempt to project outcomes over many years, in some cases more than a decade. Moreover, to market the GHG mitigation they achieve, project developers must reliably document it. This, in turn, requires developing and implementing a comprehensive plan for monitoring and analyzing the results of the project, as well as contracting for independent verification of the plan and its implementation.

Monitoring itself presents challenges. Instead of simply documenting the yield of wheat or corn, land managers must quantify the amount of carbon they store in soil or forest wood or the amount of methane they capture from processed manure. To ensure that the project does in fact lead to real GHG benefits, land managers must also often track conditions and carbon-sequestration rates on nonproject lands. They must make a long-term commitment to monitoring and tracking. Not only does the amount of carbon a project adds to soil or forest vary from year to year, but the carbon stored in years past can be lost because of fire or annual changes in climatic conditions. Finally, marketing carbon offsets requires careful analysis of monitoring and tracking data to ensure that the offsets claimed are accurate with a known and acceptable level of uncertainty.

An additional complication arises from the fact that the validity of any carbon offset project is ultimately based on our scientific and technical understanding of how carbon and other elements are cycled through agricultural and forest systems and how these systems interact with the climate system. Because science is continuously evolving, the system used to manage, quantify, and verify the value of a carbon offset project must be sufficiently flexible to accommodate scientific advances. See for example, Keppler et al. (2006), Gibbard et al., (2005), and Olander (2006).

Furthermore, for buyers, regulators, and the public to accept offsets stemming from changes in land management, they must have confidence that the mitigation is real. Credible and transparent rules and methods are therefore critical to ensure that offsets are fully tradable. This volume attempts to address this need by providing specific guidelines for developing and implementing land-management projects that produce carbon offsets.

This Manual

This manual aims to provide a comprehensive, user-friendly description of the principles and methods needed to quantify cuts in GHG emissions and removal of CO_2 from the atmosphere stemming from land-management practices. These principles and methods build on years of scientific study of the most accurate ways to measure changes in methane and nitrous oxide emissions from soil and manure and changes in carbon stocks in trees and soil. The approaches presented here aim to strike a balance between reliability and affordability. That is, participants in the system, regulators, and the public must believe that the offsets landowners create are real, but the costs of measuring and verifying the offsets must not rise so high that projects become economically impractical.

Types of Projects

This volume focuses on four basic categories of land-management projects designed to create marketable carbon offsets:

1. Projects designed to sequester carbon in soils, such as through the adoption of no-till farming.
2. Projects designed to sequester carbon in biomass through cultivation of new forests and grasslands or delays in harvesting forests.
3. Projects designed to reduce methane emissions through changes in the practices used to process and dispose of manure.
4. Projects designed to reduce emissions of methane and nitrous oxide through changes in farming practices.

Farmers and landowners also have other options for developing carbon offsets, such as by producing bioenergy crops and constructing wind turbines for generating power. However, because these types of projects do not involve specific land-management practices, this volume does not address them.

The Audience

This book is designed for use by all who might participate in developing, marketing, and purchasing offsets based on changes in land management. These include

- *Landowners*, on whose land a project is executed.
- *Farmers*, who pursue project activities.
- *Project developers,* who plan and implement the project, even though they may or may not be the farmers or owners of the land.
- *Quantifiers,* who perform the monitoring and analysis required to assess the quantity of legitimate offsets the project achieves and who may or may not be the project developers.
- *Verifiers,* independent agents who audit the quantification of the project's offsets, vouching for their accuracy and adherence to specific guidelines established by regulators of a carbon market.
- *Regulators,* who develop and enforce regulations governing carbon offsets in a cap-and-trade system.
- *Retailers or brokers,* who may purchase offsets from multiple projects, aggregate them, and resell them directly to buyers or through a carbon offset market.
- *Buyers,* who purchase offsets directly from project developers or retailers or through a carbon offset market.
- *Offset owners,* who have legal ownership of offsets and who may be the landowner, project developer, retailer, or ultimately the buyer.

Landowners, project developers, quantifiers, regulators, and retailers are obviously interested in the principles and methods needed to produce accurate and credible offsets. However, buyers of offsets would also be well advised to understand the basic principles used to produce offsets because creating them can be challenging, and potential buyers, especially in unregulated markets, need to assure themselves that the offsets they purchase are real. For example, some carbon offsets for sale in the United States have not been independently verified, and others lack evidence that they represent GHG benefits that would not have occurred without the project. Those projects that adopt the principles and methods outlined here should not be subject to these types of shortcomings.

Applications of the Manual

This volume could be valuable in at least three scenarios involving the development of carbon offsets:

1. Voluntary development on the part of landowners without a carbon offset market: This scenario does not involve a mandatory, government-imposed cap-and-trade program. Instead, landowners who want to voluntarily offset their emissions embark on a project.
2. Voluntary development by individuals and companies within a carbon market: Although regulators have not imposed a mandatory cap-and-trade program, individuals and companies who want to voluntarily offset their emissions contract with landowners and developers or retailers to purchase offsets. This situation now applies to most of the United States.

3. Mandatory development for major emitters within a government-imposed cap-and-trade program and carbon market: This situation now applies to power companies participating in the Northeast's (U.S.) Regional Greenhouse Gas Initiative and to countries participating in the Kyoto Protocol.

This manual is primarily targeted to the second and third scenarios. Of course, any regulatory systems that limit GHG emissions and allow trading will require the use of specific procedures to create offsets. Such systems may also accept only certain types of offsets greater than a specified size, and they likely would require authorized entities to quantify them.[9] In these cases, the regulatory system's guidelines will supersede those presented here. However, even in such cases, this manual should prove useful in helping individuals interpret and understand regulatory requirements. This volume also can serve as a guide to legislators and regulators who aim to design, implement, and strengthen a cap-and-trade system that includes land-management options for offsetting GHG emissions.

The Organization of the Manual

This manual provides a comprehensive overview of the principles that underpin carbon offsets based on changes in land management, as well as the methods used to quantify them. It is divided into three sections. The first provides an overview for legislators, landowners, and those who are unfamiliar with offset markets but interested in learning about them. The second provides a more detailed but nontechnical exposition of the offset process for project developers, investors, and purchasers of offsets. The third, contained in the appendices at the end of the volume, provides the technical information that is critical to the individuals responsible for quantifying, verifying, and/or regulating offset projects.

Chapter 6

Step 3: Quantifying the Carbon Sequestered in Forests

Forests represent significant reservoirs of carbon captured from the atmosphere through photosynthesis. If released from forests, this carbon would largely convert back into atmospheric CO_2. Reforestation—the process of shifting previously forested lands that had been converted to other uses to stands of growing trees through natural regeneration or planting[1]—sequesters carbon from the atmosphere and thus produces GHG benefits.

The amount of carbon stored in forests depends on their type, as well as the climatic conditions and management practices to which they are subjected. However, patterns of sequestration are similar among different types of forests. Shortly after a clear cut or fire, when new trees are relatively young and small, sequestration rates are low. After trees grow to the point where they fully occupy the canopy, the rate of sequestration rises and continues at a high rate for several years. In many forests, this period of rapid accumulation of carbon persists for several decades. As the trees mature, annual growth and sequestration slow, but the cumulative amount of stored carbon is substantial. In very old forests, the amount of carbon in the stand may continue to increase slowly or may decline. In very old forests, tree death can cause large trees to become widely spaced, reducing the total carbon stock of the forest. The carbon stock in mineral soil and the forest floor can continue to increase as a result of annual litter inputs and the decomposition of woody debris. Overall carbon stocks can decline, however, if succession produces a shift to species in which individual trees do not grow as large.

Because of these complex changes in carbon accumulation, a well-designed system for sampling forest biomass is critical to an offset project.[2] Developers must be able to accurately measure carbon sequestration without incurring prohibitively high costs. This is especially important because forest projects usually last for decades.

Sampling designs for forest projects must therefore be

- Accurate and repeatable over long periods of time.
- Adaptable to unforeseen circumstances, such as wildfires, forest management changes, and the addition or removal of lands from a project.
- As simple as possible to allow outsiders to audit results.

This chapter describes an approach for quantifying sequestration that is designed to reduce variability, control costs, and detect much of the sequestration a project achieves. This approach is based on extensive experience in measuring changes in forest carbon and entails the following steps:

- Designing a forest sampling system that is robust with respect to the different locations of carbon accumulation.

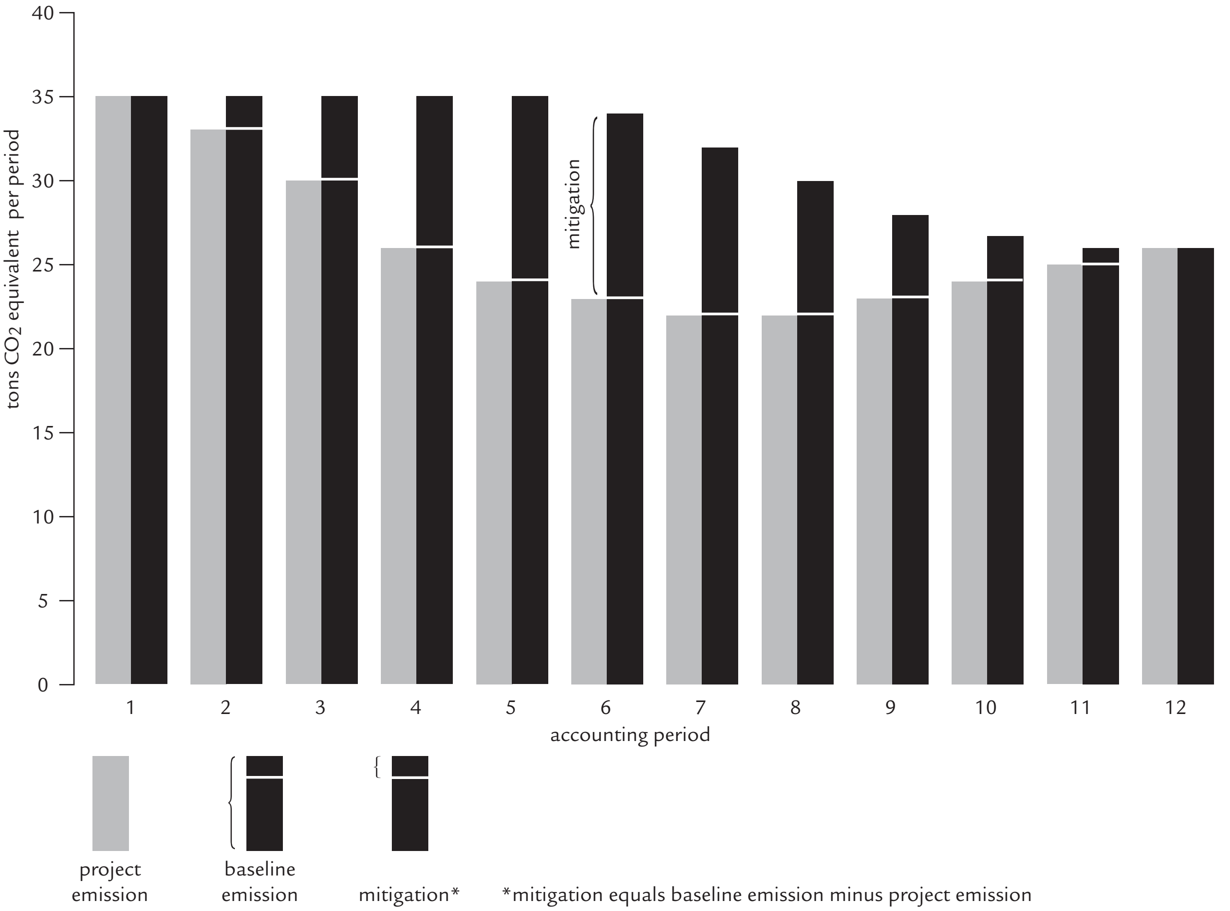


Figure 6.1 How changes in baseline and project emissions affect the tons of CO_2e that a project creates. The mitigation or net greenhouse benefit from a project is the difference between the baseline and project emissions. Because both types of emissions can change over time, both must be tracked over each accounting period. In this figure we show how emissions might change for an afforestation project that is divided into 12 accounting periods.

- Conducting initial field measurements of the different sites of carbon stocks in a forest.
- Selecting allometric equations for converting field measurements into carbon mass, or developing new ones.
- Taking subsequent field measurements to determine changes in carbon stocks over time.

Crucial aspects of this approach include performing unbiased sampling, choosing an adequate number of sampling sites, and deciding whether and how to stratify sampling across a site. (See Appendix 2 for more on sampling, and see Appendices 7–15 for more details on the steps described in this chapter.)

Quantifiers must perform the steps listed correctly when the project is established, the first time, as they cannot go back in time and redo them. They should repeat quantitative field measurements every five or 10 years, relying on annual qualitative or quantitative observations in intervening years to determine whether a project is proceeding according to plan and to take remedial action, if needed. As with other projects, developers should aim to detect net carbon sequestration with an uncertainty of 10 percent at a 90 percent confidence level, as the potential benefits of greater accuracy are generally not worth the added cost (see Appendix 3).[3]

To ensure that its system for quantifying carbon is accurate but not overly costly, a forest project should encompass at least several hundred hectares and generate at least 100,000 tons of CO_2 equivalent in offsets. Project developers with smaller areas, or who seek to generate fewer offsets, should consider combining their lands with other parcels.

Dividing a Forest into Carbon Pools and Using Subplots

A forest project's plan for sampling carbon stocks in the field must evaluate all types of biomass,[4] including live trees, shrubs and seedlings, standing dead trees, downed woody debris, the forest floor, and possibly mineral soil. Quantifiers will track these *carbon pools* separately throughout the project. Remotely sensed imagery can provide a helpful guide in locating the various types of pools present on a project's lands (see sidebar). If quantifiers conclude, based on existing scientific knowledge, that a particular pool will not lose or gain a significant amount of carbon, they may remove it from the sampling plan, but comprehensive field measurements will be far more persuasive to independent verifiers and potential buyers. Quantifiers should certainly measure pools that are likely to lose carbon, to avoid accusations that their analysis is biased. (See Appendix 7 for more on carbon pools.) Attention should also be paid to deciding whether mineral soil carbon stocks should be measured. Scientific knowledge should be used to predict whether project activities have a significant chance of causing a decrease in mineral soil carbon. If so, mineral soil carbon should be measured (see Chapter 7 for methods for measuring change in mineral soil carbon stocks),

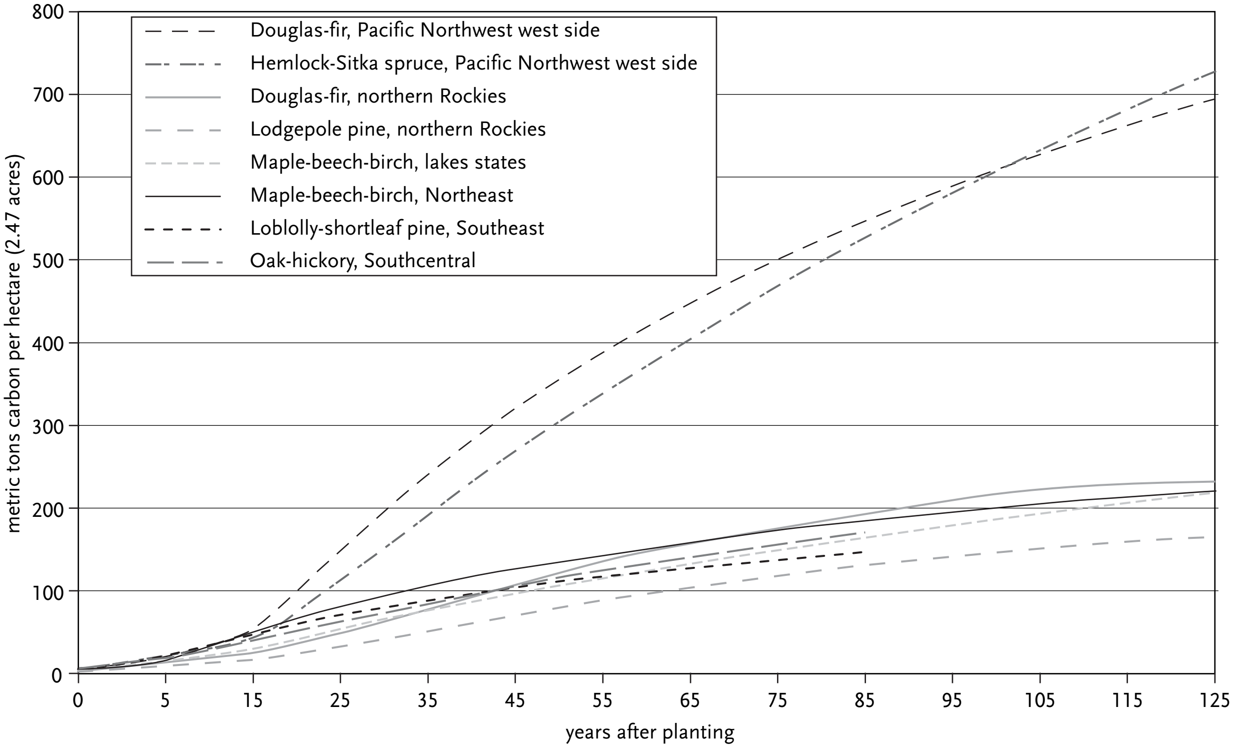


Figure 6.2 Growth in total above- and below-ground forest carbon stock, after planting land previously in non-forest cover. This includes carbon associated with live and dead woody material but excludes carbon in the mineral soil. The total amount of carbon stored in forests depends on their type, as well as the climatic conditions and management practices to which they are subjected. However, the basic patterns of sequestration tend to be similar.
Note: Calculated from amounts reported in U.S. Department of Energy 2006. 1 hectare = 2.47 acres.

To measure biomass carbon, field crews first create an adequate number of unbiased located sampling sites, or plots.[5] Then, within each plot, field crews locate several circular subplots—one for each type of biomass, or carbon pool—around a single point known as the plot center (see Figure 6.2).[6] Crews then make measurements specified in the field protocol of the monitoring plan. They then measure woody debris along perpendicular lines that extend in each cardinal direction from the plot center because such debris can be affected by trampling. (If the project expects to store a large proportion of carbon in woody debris, quantifiers may want to extend the length of those transects.) Calculating carbon stocks accurately requires determining whether plants (or other materials being measured) near plot boundaries are in or out of the plot, which necessitates establishing plot boundaries precisely and accurately.

Quantifiers should size plots to measure larger trees precisely (larger trees generally being greater than 15 cm dbh in most forests or greater than 10 cm dbh in forests with smaller trees), as they will sequester the most carbon in most projects. Experience has shown that plots with as few as four trees can provide an accurate and precise sample of the amount of carbon a project is sequestering, even if tree size varies. However, large

Using Imagery to Design a Carbon-Sampling Program

In all but the simplest projects that aim to sequester carbon in forests or soil, detailed remotely sensed imagery provides key information for designing and executing an efficient system for measuring changes in carbon stocks. Images can help delineate the project area, define the extent of project activities, and group similar areas together, thereby increasing the precision of measurements of carbon sequestration.

Several types of remotely sensed images are available:

- *Orthophotos* (in either hard copy or digital format). Orthophotos provide the best tradeoff between high resolution, timeliness, and limited cost. Orthophotos have a uniform scale because they correct for parallax, enabling quantifiers to calculate the size of areas subject to specific activities. Orthophotos also typically show latitude and longitude coordinates or state plane coordinates. Such *geo-referencing* allows quantifiers to calculate the coordinates of specific locations and then use a handheld GPS receiver to travel to those locations on the ground, or vice versa.
- *Aerial photographs.* Standard aerial photographs taken on 9-inch-square negatives have high resolution and can help reveal which areas are alike and which are different. Such photos are available for most of the United States, starting in the late 1930s.
- *High-resolution satellite images.* Satellite imagery comes in very different levels of resolution, many of which are too coarse for use in quantifying carbon sequestration, and it is often very costly. Analyzing such images require more skill and software than do aerial photos. The ability to automate analysis makes satellite images a very useful tool for use in larger projects. However, because they are taken on a weekly to monthly basis, satellite images are much more likely to capture a project closer to its start date than aerial photos. Such images are useful in tracking land-use changes (such as distinguishing annual cropping from pasture, forest, and development) or in recording wind or fire disturbance.

Maps are an alternative source of spatial data that can help users document the general location and, sometimes, the sizes of land parcels enrolled in a carbon sequestration project. Seldom can administrative/ownership boundaries be inferred from maps, unless they were created for this purpose. Maps must be detailed enough to show land attributes such as elevations, streams, roads, and administrative boundaries; scales coarser than 1:25,000 are of limited use.

trees are more widely spaced than small trees, so quantifiers will need larger plots to precisely sample them. If a project is designed to grow a mature forest, and such a forest includes at least 40 large trees per hectare, a 0.1-hectare plot would probably be efficient. Trees in a natural forest are often located in clumps and at a density of 40 trees/ha. This clumpiness means that a 0.1-hectare plot would have a probability of less than 0.5 of actually encompassing four trees. However, in most forests (not woodlands savannahs), the density of moderate and large trees is usually greater than 100 trees/ha, and even with a clumpy distribution of trees, a 0.1-hectare plot would usually encompass at least four moderate- or large-size trees. If a project encompasses more than 1,000 small trees per hectare, 0.02-hectare plots might work, as they would average five evenly spaced trees. If few trees will ever get larger than the small-size category, it may require only a little more effort to make the plots a bit bigger. Having more trees per plot would substantially increase precision. However, if the project is expected to grow larger trees, it may not be worth any additional effort to get a more precise measurement of the carbon stocks in small trees. Somewhat larger plots might be efficient for sparsely vegetated woodlands or natural, spatially heterogeneous forests.

Statisticians often maintain that many small plots provide greater statistical power than fewer large plots, given a homogeneous population of objects being measured. However, in practice, maximizing statistical power for a given cost usually means establishing fewer large plots. This is because the cost of traveling from one plot to the next can be substantial. Spending that effort on measuring larger plots instead of a greater number of plots can yield greater precision. For example, in Table 6.1, travel time between plot centers would have to be just less than four minutes to drop the cost of establishing and measuring 0.01-hectare plots below the cost of measuring 0.1-hectare plots. This short travel time is not feasible for widely spaced plots or for those located on noncontiguous parcels. Note also that the time to travel between plots would have to fall to just over one minute for 0.001-hectare plots to become more cost-effective than 0.01-hectare plots.

The effort and expense of measuring each carbon pool should be commensurate with the amount of carbon it is expected to sequester over the course of the project. Relatively imprecise measurements of pools with small changes in carbon stocks will have little impact on the precision of the overall measurement.

Consider a hypothetical project that expects to sequester 100,000 tons of carbon. Suppose this forest stores carbon in large and small trees only; the large trees are expected to store 90,000 tons of CO_2e, and the small trees are expected to store 10,000 tons of CO_2e. Because quantifiers expect the large-tree pool to contain roughly 90 percent of the sequestration, they should devote roughly 90 percent of the sampling effort to that pool.

Similarly, because the forest floor usually does not gain much carbon in most forest ecosystems, quantifiers may choose inexpensive methods to measure it, even if they are not very precise. For example, crews could measure the combined thickness of duff and litter[7] at one specified point on each plot. Then the density of the litter and duff could be used to estimate the forest floor mass on each plot.[8] However, the litter and duff density should be measured for each project, taking into account that it can vary significantly from season to season. If a project may have change in the forest floor carbon stock that is a substantial fraction of the total carbon stock change within the project area, it is strongly recommended that forest-floor mass be directly measured by weighing material collected on subplots of fixed size, not inferred from thickness.

Quantifiers may decide to stratify a carbon pool across a project area or across physical characteristics to decrease variability. If there is a known difference in the physiographic characteristics (e.g. soil drainage, soil parent material, and forest composition) it is useful to stratify the project area by these variables and calculate the carbon stocks independently for each stratum. This approach reduces the total uncertainty in the final stock estimates with no additional sampling. However, stratifying requires establishing more boundaries and analyzing separate sets of data. Stratum boundary choices depend on the frequency of the occurrence of trees or other objects being measured, the size of subplots, the time needed to measure and analyze each subplot, and the sequestration likely to occur within each class of biomass. It is generally efficient to divide

Table 6.1 The Cost of Estimating Carbon Stocks on Plots of Different Sizes

Plot size	Number of plots	Time to measure one plot	Total field cost
0.1 hectare	10	1.5 hours	$700
0.01 hectare	95	0.1 hours	$1,330
0.001 hectare	288	0.02 hours	$3,110

Notes: These estimates represent typical costs in lightly roaded areas of the United States. Assuming They assume the total bundled cost of a field technician is $40 per hour, the time to get from one plot to the next and establish or re-locate the plot center is 0.25 hours per plot, and the amounts of time to measure a plot of each size areis as given in the tTable. The number of plots of each size is based on observed variability in an unmanaged, second- growth stand of mature natural regeneration in the Pacific Northwest, with the numbers of smaller plots set to yield the same statistical confidence interval as observed for 10 plots of 0.1 ha in size.

Source: Gordon Smith, EcoForEcofor.

woody debris into two or three classes based on size, and to divide standing vegetation into at least three classes.

Another approach to measuring biomass is to sample a given proportion of the project area. Experience shows that sampling 1.5 percent of the project area can provide reliable measurements of forest carbon if the plan calls for several dozen sites. This approach is best for moderately sized projects of 300 to 1,000 hectares. Quantifiers can base the percentage of the project area to sample on the size of the subplot for the carbon pool expected to record the largest change.

For a plot size of 0.1 hectares, sampling 1.5 percent of the project area would mean installing one plot for every 6.6 hectares. If large changes in carbon stock are expected to occur in a pool other than large trees, obtaining the needed precision may require more intensive sampling. Quantifiers may find it more efficient to expand the size of the subplot used to sample that pool rather than increase the total number of plots because the latter approach would require more overall effort. For projects larger than 1,000 hectares, installing one plot every 6.6 hectares would require more than 150 plots. If several strata are sampled separately, it may be feasible to measure no more than 15 plots in each stratum, if the total number of plots is sufficient to achieve the desired level of precision (see Appendix 1).

After determining the number of plots, project developers should evaluate whether the measurement system will generate precise enough data to yield enough sequestration (once uncertainty is considered) to make the project economically worthwhile. If the answer is no, they can investigate whether a different level of precision would make the project financially viable. Independent verifiers should check the project's sampling approach and financial structure to determine whether the project is likely to fulfill its commitments.

Installing the Sampling Plots

Field crews must establish permanent sampling plots so crews can return decades later to remeasure the amount of carbon on each plot. Using a GPS receiver to record the coordinates of plot centers and place permanent markers is essential. A mapping-quality GPS receiver (which should be accurate to 1 to 10 meters) should enable field technicians to find the monument that marks a plot center later, although GPS measurements will be less accurate under heavy forest canopy and in narrow valleys.

To mark the plot center on sites where significant soil disturbance is unlikely, crews can drive a piece of rebar 1 to 2 feet into the ground. Fire, tree fall, and vehicle traffic will usually not disturb the rebar if it is flush with the ground, and later crews can use a metal detector to find it. For sites where significant soil disturbance is likely, crews can bury a magnetic ball marker 0.5 meters deep to mark the plot center. If major ground disturbance is likely, crews should establish two additional monuments, using a GPS receiver to record their distance and direction from the plot center. (For specific steps in installing field plots, see Appendix 8.)

Plot centers should also be recorded in a geographic information system (with a scale of 1:12,000 or larger) to help crews reach the vicinity of plot centers later. Narrative descriptions of how to find plot centers from a landmark can be useful, although things often change, making descriptions hard to follow decades later.

Choosing Resampling Intervals

Field measurements of forest biomass inevitably entail error. For example, measurements of tree diameter by two different field technicians (even if they are skilled) are likely to vary by up to 1 cm dbh in larger trees. Quantifiers can minimize this problem by lengthening the interval between field measurements, as changes in carbon stock will vastly exceed the uncertainty attributable to measurement errors. Measuring carbon stocks every five to 10 years also averages out annual variations in sequestration and allows quantifiers to detect a greater proportion of sequestration while reducing cost.

However, more frequent measurements can help project developers remedy any shortfall in sequestration that field data indicates, for example as a result of the invasion of low-carbon-sequestering species. In addition, as the time between measurements grows, so does the cost of waiting to quantify the increase in carbon sequestrated. Thus, at some point, expanding the time between field measurements becomes counterproductive.

The optimal period between measurements will vary with their precision, the speed of change in carbon stocks, the costs of measurements, and the value of the resulting offsets. Larger projects may want to measure carbon stocks every five years for the first few decades and then less often as quantifiers gain information on how much carbon a project is likely sequester moving forward, especially if sequestration rates are declining. Projects usually schedule a field measurement shortly before they end to determine total project carbon.

Quantifiers should make annual observations, either visually or using remote sensing, between more detailed field measurements, to detect major deviations from expected conditions. For example, scanning a landscape from a high point can reveal whether it is substantially covered with healthy trees. Observations of the "leader" stems of young trees can also reveal whether they are growing vigorously. If large areas show discolored foliage or if many trees are dead or missing, quantifiers can conduct detailed measurements of biomass. If projections of how much carbon a project will sequester are conservative, an observation that 25 percent of the project area is not in a healthy, growing condition might trigger remedial action. If projections are less conservative, the threshold for remedial action may be as low as 5 to 10 percent of the project area. These annual checks may be qualitative assessments or quantitative stocking surveys, such as those performed to measure the survival of planted seedlings (see Appendix 9).

Satellite imagery can be used to measure leaf area and estimate growth. However, this kind of analysis requires multiple, fine-scale images through the growing season and a skilled analyst. The costs of data and analysis necessary to estimate growth rates from satellite imagery may be more than the cost of ground-based assessments. These costs and the capacities of the quantifier will determine whether it is most cost-effective to assess vegetative condition using satellite imagery, aerial photographs, or ground based surveys.

Some offset contracts require developers to model future tree growth partway through a project to determine whether it will achieve its goals. Quantifiers should use such a model only if it has been validated for the project's location and forest type. Validation requires running the model for locations not used to build the model and for which independent data exist. Because each model has its own idiosyncrasies, modelers should have experience running the model they will use.

Modeling usually requires collecting more information than quantifying biomass. If a model requires extra information, crews should collect it from a subset of the trees used to calculate biomass. A model may also require historic information on tree growth and management activities, which can be gleaned from land records and interviews with previous managers. If historical information is unavailable, the modeler must start from current stand conditions and be aware of how this lack of knowledge could affect model accuracy. To accurately estimate future carbon stocks, the model's input should require knowing trees by species, height, and diameter, not just the volume of growing stock.

Measuring Carbon Stocks on Subplots

Determining the amount of carbon stored in the project area entails documenting the physical characteristics of objects or materials measured on the subplots, including the heights and diameters of trees and shrubs, and the mass of organic material on the forest floor. Fieldwork may include collecting samples from subplots and measuring the weight of the material. This material is then analyzed further in a laboratory. Laboratory analysis may be limited to drying the samples and finding their weight, or it may involve determining the carbon content of each sample.

Quantifiers use biomass equations to convert the gathered information into the amount of carbon in each pool per hectare. Different biomass equations use different characteristics of the trees and pieces of woody debris on the subplots (and the carbon contents of different parts of these objects) to derive total carbon content. Quantifiers must therefore identify the specific biomass equations they will use before the project starts so field crews will know what kinds of measurements to make. The next section suggests a protocol for each of these steps. A different sampling strategy would use different protocols, and could be equally valid.

Making Field Measurements and Gathering Samples

Because of the sheer variety of objects, materials, and carbon pools that a forestry project must monitor, as well as the size of some of the objects, making field measurements is challenging. Crews should measure the carbon pools in each subplot in a standard sequence, concentrating on subplots for forest floor and fine debris first, as those are sensitive to disturbance from trampling. Adhering to a standard sequence reduces the chance that the crew will forget to measure a subplot or to measure a tree on a large subplot. A standard pattern for taking measurements also helps quantifiers check them for quality control.

In making all these measurements, each crew will adapt its division of labor to its skills and the types of biomass on a plot, although one person usually records all the data. In a two-person crew, one person can measure woody debris and litter while the other person measures trees. If two people examine trees, one person can determine which trees to measure and measure diameters while the other person measures heights, determines vigor, and records data. In a three-person crew, one person can measure litter, woody debris, and small live material while the other two people measure larger trees and snags.

Fieldwork to remeasure carbon stocks later in the project resembles initial measurements, except that crews re-locate plots instead of installing them. If a layer of decomposed organic material was present above mineral soil during the first measurement, crews should remeasure this material at different locations to avoid the disturbed areas. If a crew cannot re-locate a plot, it should make its best guess as to where the plot should be and establish a new one at that location, noting the change in field records. Quantifiers can judge whether to use the new measurements when analyzing the data.

Most projects will focus most intensely on the amount of carbon in living trees. To accurately determine tree growth, and thus changes in carbon stocks, crews should follow U.S. Forest Service procedures for measuring the diameter and height of trees over 5 cm dbh. Crews measure smaller trees, saplings, and shrubs at the base.

Because small pieces of woody material and decomposed organic material will never provide a significant source of carbon, crews can count the number of pieces of a particular size rather than measuring their exact diameter or length. Quantifiers can then calculate the biomass within each class based on the median size.

To measure the amount of biomass in litter, crews gather loose leaves, twigs, bark, seeds, and other identifiable plant parts that accumulate on the ground above mineral soil up to a threshold size, and they weigh a representative subsample from each subplot. These subsamples are then dried and weighed to find the ratio of dry weight to wet weight. Quantifiers use this information along with biomass equations to quantify the amount of carbon (see below).

If a soil O horizon is present or is expected to become present during the course of the project, the O horizon should be measured separately. In locations where O horizons form, the O horizon carbon stock can become very large over time and can be lost quickly though disturbances such as fire or logging. If an O horizon will be measured, it is recommended to measure duff with the O horizon, not with litter. One method for measuring mass of organic matter above mineral soil is to obtain a round template of known area (225 cm^2 is a favored size), place it on the ground at the point to be sampled, cut around the template, lift the organic material, place it on a plastic sheet, and carefully remove any mineral soil from the sample of organic material. The entire sample may be bagged and removed for drying and weighing, or the sample may be weighed in the field and a subsample removed and weighed in the field, and the subsample taken to a laboratory for drying and re-weighing to establish the dry to wet weight ratio to be used to calculate the dry weight of the whole sample.

Forest soils may also comprise a significant carbon pool and thus should be measured (see Chapter 7). Calculation of the mass of woody debris requires information on the density of material of various degrees of decomposition (see Appendix 10).[9] When forested lands are hilly or mountainous, quantifiers must correct for these sloping land features in their area calculations or instruct crews to install sampling plots in the horizontal plane (see Appendix 11).

Analyzing Biomass Samples in the Laboratory

For most species, the concentration of carbon in whole trees is very close to 50%. As a result, it is acceptable to assume that the concentration of carbon in live tree biomass is 50% and not measure the concentration. In nontree biomass (such as leafy annual vegetation) and decomposed material, the concentration of carbon is often significantly different from 50%, and the concentration should be obtained from a published source or by laboratory measurement of samples from the project area.

To determine the concentration of carbon in the samples collected, each sample must be analyzed for its dry weight and carbon content. Quantifiers with technical expertise and access to laboratory facilities can perform this analysis themselves. However, engaging a qualified laboratory will often prove less costly. In the United States, many university labs provide analytic services for a fee, as do some commercial labs. (Projects in less industrialized countries may not have access to analytical equipment.) The cost of analysis is generally a few dollars per sample—higher if more sample preparation is needed, and lower if more samples are run. Forestry and agricultural extension professionals should be able to point quantifiers to nearby labs that can analyze the chemical content of organic materials or soil. Some commercial laboratories that focus on soil nutrient testing, and many laboratories in developing countries, still use the Walkley-Black method to analyze samples. This method should be avoided. Quantifiers should confirm the process and equipment the labs will use before engaging them. The lab should use standard materials of known composition to calibrate instruments and should participate in interlaboratory comparison of results of analysis of reference materials.

Obtaining the dry weight of biomass samples requires drying them as soon as possible to avoid mold or loss of organic carbon from decomposition. If analysts cannot immediately dry field samples, they should be air-dried or, if that is not possible, refrigerated. Ideally, samples should be dried by cutting them into small pieces and desiccating. However, heat is often used instead of desiccation. Heat does not remove quite as much water from wood as can be removed by desiccating ground samples. For samples from live plants, drying should occur at 60°C to 80°C, as higher temperatures can volatilize modest amounts of the organic carbon. Drying should continue until the weight of the sample becomes constant, indicating that all the water has been driven out. This usually takes several days, and more time for segments of branches longer than a couple centimeters. Quantifiers should weigh the dried samples immediately before they reabsorb moisture, especially in humid climates.

Quantifiers must then analyze the proportion of the dried biomass that is carbon using the modified Dumas combustion method. This entails oxidizing a small sample at very high temperatures, typically about

1,000°C, and then using infrared gas absorption or gas chromatography to measure the amount of CO_2 emitted. This technique is extremely accurate and precise if samples are homogenized well (since only 10–20 mg is used for the analysis, obtaining a representative subsample is critical) and equipment is well calibrated.[10] Other methods such as near-infrared reflectance (NIR) and nuclear magnetic resonance (NMR) provide accurate results, but the equipment and training needed to use them are not widely available.

Finding the Total Carbon Content of a Plot

To determine sequestration, quantifiers must convert plot measurements to carbon stock on each plot at each time, find the change on each plot over time, and scale up to the project area. The carbon stock on each plot is the sum of the stocks of all the carbon pools within the plot, such as live trees, other live plants, woody debris, and the forest floor. When field measurements are weights, such as the weight of litter collected from a subplot of a specified area, field measurements can be converted to carbon by multiplying them by the proportion of weight that is carbon, then scaling up.

When field work measures the sizes of things, these sizes must be converted to weight to calculate carbon stocks. A large part of calculating forest carbon sequestration is conversion of data about the sizes of trees and the frequency with which they occur into carbon mass. A key step in this process is calculating the mass of carbon in each measured tree.

The species, height, and diameter of a tree reliably relate to the mass of that tree. Individual trees of a given species and shape have similar sizes and shapes of trunks and branches and similar wood densities. There is some variation in the relationship of mass to height and diameter, however, depending on the variations within some species, climate, and (to a lesser degree) the conditions under which an individual tree grows. As a result, equations used to predict tree biomass as a function of height and diameter should, ideally, be created from trees in the region in which the equation will be used. Otherwise, they should at least be created from trees that grew under climatic conditions similar to the conditions where the equation will be used. Equations that predict tree weight or volume as a function of tree sizes are also called allometric equations. Quantifiers may use existing biomass equations or develop new ones if appropriate equations are not available.

Equations that predict carbon content of trees from height and diameter are available from a variety of sources. U.S. Forest Service publications contain a wealth of information, including biomass and volume equations for a wide range of species. Quantifiers may need to search the website of individual Forest Service research stations because system-wide searches do not seem to find all applicable materials. Many Forest Service research publications are available for free download.

BIOPAK, software the U.S. Forest Service offers at no charge, includes biomass equations for a variety of North American plants (see http://www.fs.fed.us/pnw/). BIOPAK provides references for the original sources of the equations, which can help users determine their applicability. However, although an extraordinary resource, BIOPAK is not easy to use, and most quantifiers will search for other equations to use in electronic spreadsheets or other programs. Clark et al. (1986) provide equations for eastern North American hardwood species, and Clark (1987) gives sources for equations that predict total aboveground biomass, or the mass of specific components, for southern U.S. tree species. Aldred and Alemdag (1988) provide sources for predicting total aboveground biomass of specific tree components of Canadian trees.[11]

The Internet or a forestry library can also be a source of biomass equations. A search that includes the name of the species, the word “biomass,” and the words “equation or estimat*” will likely turn up references. (The * serves as a wildcard in most search programs, and it will return any word that starts with the letters preceding the wildcard, such as either “estimate” or “estimation.”) If such a search does not yield results, the word “biomass” can be replaced with “volume” and the search repeated.

Stem-volume equations are available for many species because the volume of tree trunks is commercially important for the production of lumber and wood fiber products such as paper. Such equations use information on the density of carbon in different species to convert the volume of wood, as indicated by field measurements, to carbon mass. Some volume equations are for wood only; others include both wood and bark. Because the wood-products industry developed many of these equations, they often exclude branches, foliage, tops, and stumps, but quantifiers can estimate crown mass as a function of stem size or mass.

An equation may apply to a single species or group of species, or it may be limited to a single species grown under a specific management regime. Experts develop the equations by cutting and weighing trees and then using regression analysis to develop an equation that relates the measured weights to the physical characteristics of the trees. The resulting equations apply only to the range of tree sizes from which they were developed. Quantifiers are often tempted to use equations intended to estimate the biomass in smaller trees to estimate biomass in large trees if the equations match the species and location. However, that approach may cause significant errors, and there will be no way to detect them. If an equation for large trees is needed, it is better to adapt an equation for large trees of a similar species that have a similar growth form than to apply an equation for smaller trees. A biomass equation can be adapted for application to a different species having a similar growth form by adjusting for any difference in the specific gravities of the woods of the two species in question.

Equations for shrubs and very small trees often use the diameter measured at the base, just above the root crown, rather than the diameter at breast height. Some shrub equations use canopy diameter rather than stem diameter. Some equations provide volume rather than biomass. (Quantifiers can convert volume to biomass by multiplying by the density or specific gravity; see Appendix 10.) Some equations calculate the dry-weight biomass or carbon mass of a single tree, typically as a function of diameter or both diameter and height. Most such equations are made from measurements of the aboveground parts of trees. Some equations predict biomass of a single component of a tree, such as foliage, branches, bark, or bole wood. Relatively few studies of the root biomass of trees have been published, although general equations for North America predict root biomass as a function of aboveground biomass and diameter.

Biomass equations that do not use tree heights give less reliable estimates of biomass than equations that use both height and diameter. This is because tree height—for a given diameter—can vary tremendously as a function of site productivity and the tree density under which the stand developed. However, much of the time, using both height and diameter gives no more than 10% more accurate predictions of biomass than using diameter alone. If forest stands are managed and biomass equations are developed from similar stands and not applied to old-growth trees, equations that use only diameter and species to predict biomass should be adequate.

Quantifiers must specify the equations they will use to calculate biomass, and the properties of the trees that will be used to drive them, before designing the sampling system and specifying the field protocols. If quantifiers do not select equations until later, field crews may not collect all the information needed for the calculations, and the money spent on sampling may be wasted.[12]

If more accurate equations become available during the project, or if the factors used to drive the equations change, quantifiers may be able to adopt the new equations. However, this may not work if measurements from earlier fieldwork cannot drive the new equations. A project's monitoring plan may also call for developing new factors, such as site-specific densities of woody debris not present on the site earlier. Waiting until the second measurement of biomass stocks to develop new density factors or equations is often efficient, as other analysts may have created usable factors or the project's needs may have changed. All the needed data must be collected at the appropriate time, though, and quantifiers should use extreme caution in changing methods for collecting information because such changes may rule out comparisons of earlier and later biomass measurements.

If quantifiers do not have enough information to use a specific biomass equation for a given species, or if they cannot find an appropriate equation, they have several options. They can use equations developed for other species, they can create new equations, or they can use an equation for a group of species instead of an equation for a specific species (see Appendices 13–15).

Calculating Changes in Carbon Stocks

After calculating the mass of each carbon pool on a plot and scaling the results into common units (such as tons of carbon per hectare), quantifiers sum them to determine the total carbon mass for each plot. They then subtract the amount of carbon present on that plot at the start of the project from the new amount to find the change in carbon stocks. Of course, quantifiers must use the same biomass equations to estimate both amounts.

Using permanent plots allows finding the change in carbon stock on each plot before expanding to the change in carbon stock on the project area as a whole. This approach of finding the change on each plot is called paired plot analysis; the carbon density of each plot measured at a later time is paired with the carbon density on each of those plots measured at the start of the project. Paired plot analysis is different from the typical analysis of difference of means. The difference of means would be found by calculating the mean estimated carbon stock of the entire project area at the start of the project, calculating the mean estimated carbon stock of the entire project are at a later time, and then finding the difference between these two estimated mean carbon stocks. Paired plots are used because pairing plots through time reduces variability, thus giving a more precise estimate of the change in carbon stock.

After calculating the change in carbon stock on each plot, quantifiers then calculate the change in carbon stock for the entire project area, along with its uncertainty. If the project has only one stratum[13] and has installed plots randomly, then the overall change in carbon stock is the average of the changes in all the individual plots, in metric tons of carbon per acre. The average change per plot is

$$\Delta C_{avg} = \left[\sum_{1}^{i} \left(C2_i - C1_i\right)\right] / n \qquad \text{Equation 6.1}$$

where ΔC_{avg} is the average amount of carbon gained throughout the project area, $C1_i$ is the amount of carbon observed on subplot i in sampling site s at time 1, $C2_i$ is the amount of carbon observed on subplot i on plot s at time 2, and n is the number of subplots in the area sampled. If the project has multiple strata, this calculation is performed for each stratum.

Before applying Equation 6.1, quantifiers should convert $C2_i$ and $C1_i$ to tons of carbon per hectare so that ΔC_{avg} will also be in tons per hectare.

The next step is to calculate the mean estimated change in carbon stocks for the entire project area. If all plots have the same area, quantifiers can do this by calculating the average change per plot (in units of tons per hectare) and then multiplying by the total hectares in the project:

$$C_{seq} = \Delta C_{avg} \times A \qquad \text{Equation 6.2}$$

where C_{seq} is the total amount of carbon sequestered by the project (in tons), ΔC_{avg} is the average change in carbon stock observed on plots (in units of tons per hectare), and A is the total area of the project lands. If the project is stratified (see Appendix 1), C_{seq} is the sum of the amounts of sequestration calculated for each stratum.

As described in Chapter 2, the project's net GHG benefit is the overall gain in sequestration minus the baseline (C_{seq}—B) and inadvertent emissions from project activities (see Appendix 2). The project's offsets equal the net GHG benefit minus leakage and the statistical uncertainty in the calculations (see Appendix 3).

Of all biotic offset projects, forestry projects have the potential to provide some of the greatest GHG benefits—both per hectare and per dollar invested. Thus they can provide an important contribution to a carbon market. However, forestry projects are complex, and their benefits are difficult to measure precisely. Careful planning and strict adherence to the procedures outlined here is essential to the success of these projects.

Chapter 7

Step 4: Quantifying the Carbon Sequestered in Soil

Although soil and plant detritus contains 1.5 to 2 trillion metric tons of carbon worldwide, carbon accounts for only 1 to 5 percent of the soil on the surface and less than 1 percent of soil below the surface. Moreover, the amount of carbon a land-use project sequesters is usually small compared with the amount of carbon already stored in the soil. The gain is almost always less than 10 percent and often less than 5 percent, and if carbon is measured to a depth of only 1 meter, the gain is usually less than 3 percent.

These attributes make quantifying the offsets a soil project produces challenging. Measurements must be precise and designed to account for variations in soil carbon from one from location to another. This chapter provides an overview of how to design a quantification system to achieve those goals (see Appendix 16 for more information).

Because a system for quantifying soil carbon is complex, most developers will want to consider projects that encompass at least 25,000 acres and sequester at least 25,000 tons of carbon,[1] to make the costs of measuring changes in soil carbon cost-effective. Project developers with smaller land areas, or who are seeking to generate fewer tons of offsets, should consider aggregating their lands to reduce the cost per ton of measuring and verifying offsets. As a last resort, smaller projects may be able to rely on modeling to estimate how much carbon they sequester. However, some carbon markets or regulatory systems may not accept less rigorous quantification, or the resulting offsets may sell at a lower price.

In most cases, developers must quantify the carbon sequestered in soils on project lands by

- Designing a system for measuring changes in the amount of carbon in the soil.
- Taking field measurements of carbon stocks at the start of the project.
- Monitoring project conditions over time to assess whether managers have implemented changes in land-use practices and to gauge the amount of carbon stored.
- Remeasuring carbon stocks in soil and calculating changes in those stocks.

Designing the Measurement System

Quantifiers must be able to document and accurately quantify the sequestration that occurs on project soils. Without an acceptable method for estimating benefits, project developers cannot say with confidence that sequestration has occurred, and thus they will likely be unable to market their offsets.

A sampling design and protocol for analytic measurements must be designed at the outset to accurately quantify the changes in soil carbon over the project period. Sampling and analyzing soil samples can be costly, so the design of the sampling program can strongly affect the cost of the project and its profitability. The goal is to select a sampling program that achieves a level of precision high enough to detect tons of sequestered carbon without incurring untenable costs. An appropriate sampling design and analytical framework, careful fieldwork, and high-quality laboratory testing can provide a high level of precision for acceptable cost. For some types of projects, establishing an adequate sampling strategy may prove prohibitively difficult (see the sidebar on erosion).

Quantifying carbon sequestration is made especially difficult by the fact that the increase in soil carbon stocks in most projects will be less than 10 percent of the total soil carbon content—and much less if deeper soil is sampled. This means that if quantifiers need to measure the net sequestration (or change in the soil carbon content) to an accuracy of 10 percent (as recommended in Appendix 3), they will have to measure the total soil carbon content to an accuracy of at least 1 percent.

For example, consider a project that switches from plowing to no-till farming. Such projects will typically store on the order of 2 to 4 tons of carbon per acre. Suppose that the project actually stores an extra 0.75 ton of carbon per acre. Further suppose that the project developer hopes to get credit for sequestering at least 3.5 tons of carbon per acre. That means that the uncertainty in the measured change in carbon stock must be no more than 0.5 tons of carbon per acre (see Chapter 3).

Achieving that level of accuracy can be challenging. Project developers can increase their odds of meeting it by adopting a strategy that involves choosing sampling sites randomly to avoid bias, using paired sampling,[2] selecting enough sampling sites to ensure statistical accuracy, and adopting stratified sampling to further increase statistical power (see Appendix 1). A typical project would probably require about 50 to 100 sampling sites to achieve that level of statistical precision, with one site located every 100 hectares.[3] That means each field would probably include only one plot, and some fields would have none. With this wide a distribution of plots, projects need a system to ensure that the locations of sampling sites are in fact random. If developers are using a GIS program to map the project area, the software can randomly assign plot centers.[4] If developers are not using a GIS program, quantifiers can use a random-sampling technique to assign plot locations manually.

A sampling strategy should include a detailed protocol for collecting samples of a specified volume from numerous sites. Field crews will have to remove rocks and roots from each sample. The soil is then ground and mixed, and a subsample is analyzed in a lab to determine its carbon content. The sampling protocol should specify

- The number and spatial arrangement of soil samples to be taken at each site.
- The steps field crews should take if they cannot extract a sample at the specified location.
- The diameter of the soil cores and the depth to which field crews will collect each core.
- The guidelines for how crews should deal with materials on the surface of the soil and for how they should label, package, and handle samples.

Coring is the most efficient soil-sampling technique that uses commercially available tools. In this approach, field crews collect soil cores from specified sites by hand or by using hydraulically powered coring

The Challenges of Erosion-Abatement Projects

Conservation practices such as contour plowing, planting of grass strips, and reduced tillage can greatly reduce erosion and thus increase the amount of carbon in soils. However, reducing erosion may merely prevent the transport of stored carbon off project lands, rather than increase the total amount of carbon stored inside and outside the project. Moreover, carbon stocks under a given type of vegetation for a particular soil and climate tend to approach equilibrium. Thus when erosion removes carbon from a site, the vegetation will usually store more carbon for a period of time to make up the deficit. If soils outside project boundaries trap the eroded carbon, and vegetation begins sequestering more carbon at the eroded site, erosion may actually increase rather than decrease overall carbon stocks (Smith 2005).

machines. (The latter can take larger and deeper cores, but the cores must be transported by a truck or tractor.) Obtaining the desired level of precision requires mixing multiple cores from each site to account for variability and reduce measurement error.

Corers employed to sample soil are usually tubular and range in diameter from about 2 to 8 centimeters. Although using the smallest-diameter corer that will gather intact samples is most cost-effective, a larger corer may work best in soils with some buried gravel. If crews are uncertain about whether a particular corer will collect samples to the desired depth, it is cheaper to field-test the corer than to choose a large-diameter corer, transport hundreds of kilograms of soil, and spend days processing the larger samples.[5]

Coring may not work if crews are taking measurements at multiple depths in soils that compact a great deal when cored, that contain large numbers of rocks or buried wood such as roots, or that are very noncohesive (such as dry sand). If the amounts of rock or buried wood are so great that crews cannot extract cores after a few attempts, crews may need an instrument designed for sampling noncohesive materials, such as a bucket auger for sampling sand. A drawback of bucket augers is that they extract disturbed material, not an intact core, thus mixing soil from a range of depths.

Quantifiers may soon be able to use new portable technologies such as laser-induced breakdown spectroscopy, inelastic neutron scattering, and near-infrared spectroscopy to measure carbon content in the field. However, these emerging technologies require further testing and refinement before they become accepted approaches to measuring changes in soil carbon.

Deciding on Sampling Depth

The decision of how deeply to sample soil is perhaps the most important decision in designing a system for measuring soil carbon. Most of the increase in carbon in soil projects will usually occur in the top few centimeters of soil. However, these increases may simply represent carbon redistributed from deeper depths, with the project having produced little or no net sequestration, especially in the first few years after a change in land management or vegetation. This may be the case, for example, during the first decade after a switch from plowing to no-till farming because the lack of plowing slows the transport of plant material (and its attendant carbon) to lower depths. Such projects may even see an overall loss of soil carbon during the first few years, especially in dry climates. For this reason, no-till sequestration projects should usually sample at least the entire plow layer of soil, which typically extends about 20 centimeters below the surface.

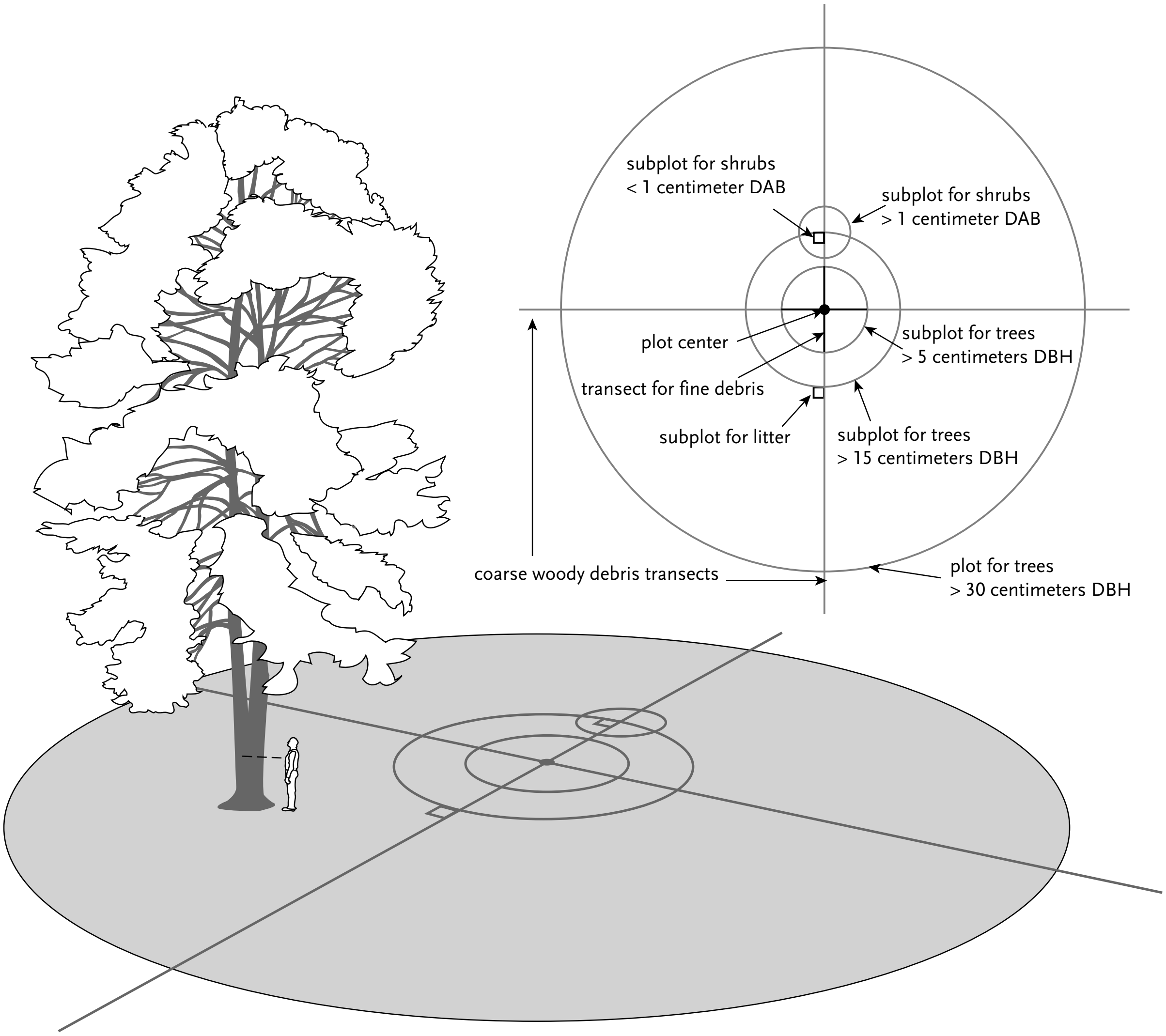
On the other hand, sampling deeper than 20 to 30 centimeters may not be worthwhile unless species and soils have unusually large amounts of root mass or carbon deposition at greater depths. Projects should conduct deeper sampling if amounts of soil carbon may decline at those depths, or if the project will establish deep-rooting grasses, which can add significant amounts of carbon to soil to 2 meters, and small amounts to 4 meters. Sampling to deeper depths makes discerning sequestration against a larger volume of soil more difficult. Developers may choose to forego measuring some of the carbon gain at those depths if the cost of doing so is greater than the value of the carbon or if attempting to measure some of the carbon stock would dilute the precision of the overall measurement. However, if there is serious concern that the change in land management will cause loss of carbon deeper in the soil, sampling must encompass the depth where loss may occur.

Determining the Number of Cores

A detailed measurement plan must specify techniques for establishing permanent sampling sites where crews collect a set number of cores with a specific spatial distribution, which are then mixed into a single sample and sent to a laboratory for analysis. Establishing permanent plots allows crews to return years later to remeasure soil carbon and calculate the change on each plot, which gives the overall results for the project statistical power. To help field technicians find each plot during later sampling periods, crews should mark each plot center, such as by placing an electronic marker in the soil. (An electronic marker is an antenna that is encased in plastic [to keep it from rusting] that is buried deep enough so any likely disturbance, such as plowing, will not move it.) Field crews collecting later samples use a electronic locator, which is similar to a metal detector, to find the marker.

Plots are typically at least 2 by 5 meters (10 square meters), but not larger than 9 by 9 meters. Field crews collect a predetermined number of cores around the plot center, even though the center may be on the corner of the grid (see Figure 7.1). The spacing between cores, usually 2 meters, should not be so great that plots cross soil types or landforms or that plots vary significantly in some other way.

The number of cores to collect and mix on each



DBH: Diameter at Breast Height is calculated 1.3 or 1.37 meters above ground
DAB: Diameter At Base

Figure 7.1 Recommended design of a forest plot. Measuring carbon stocks in the field requires evaluating all types of biomass, including live trees, shrubs and seedlings, standing dead trees, downed woody debris, the forest floor, and possibly mineral soil. Here we illustrate the design of a forest plot to do this. If the project encompasses areas where a soil O horizon exists or can accumulate, this horizon should also be measured. A project may also choose to measure carbon in mineral soil. See the chapter on measuring soil carbon for methods of quantifying changes in amounts of carbon in these pools.
Note: DBH = diameter at breast height, typically defined as the point 1.3 or 1.37 m above the ground.

sampling site is a key determinant of whether the sample accurately represents the amount of carbon in soil. Collecting and mixing as few as six cores per plot may work for soil that has been tilled many times, as tilling makes soil more homogeneous. Mixing 10 to 16 cores per site is best for soil that has not been tilled or for soil where woody plants have been growing.

If early measurements show that collecting fewer cores per site or using a smaller-diameter corer will yield measurements of acceptable variability, quantifiers can make those changes to reduce costs. Quantifiers may also decide to analyze different depth increments separately and to collect fewer cores to the full depth. For example, if the plow layer is 20 centimeters deep and crews sample to a 50-centimeter depth, quantifiers might analyze the 0–20-centimeter layer separately from the 20–50-centimeter layer. This approach can reveal where sequestration is or is not rising. However, it does not give more statistical power because it does not increase the number of plots. Measuring depth increments separately also increases the costs of transporting and processing soil samples. Collecting fewer deep cores at each site and processing an additional sample at the added depth is usually more cost-effective.

Although most aspects of sampling should remain constant from one measurement round to the next, two aspects *should* change. Crews should extract soil cores at points displaced from those used during prior sampling to ensure that the results are not influenced by disturbances incurred by the sampling itself (see Figure 7.2). Consider a sampling design that removes nine cores from each sampling site in a 4-by-4-meter grid, with 2 meters between intersections. During initial sampling, the northwesternmost sampling point is the reference point. For the next round of sampling, crews could displace each sampling point 1 meter south. During a third round, they could displace each sampling point 1 meter east of the initial points, and during a fourth round they could displace each point 1 meter south and 1 meter east.

The second aspect of measurement that should change is the location of points for sampling decomposed organic material. If a layer of such material sits above mineral soil, sampling will reduce the carbon stock in this layer for at least several years, and possibly for more than a century. To keep this local disturbance from biasing the estimate for the project, field crews should displace locations for sampling decomposed organic materials from earlier locations. However, crews can sample such litter at the same locations if they do so only every five years or more, as most litter will have accumulated during that time.

A project's sampling protocol should specify how to deal with obstacles such as large rocks and trees that prevent crews from collecting cores at designated points. If they cannot extract a core from a specified point, moving a fixed distance such as 10 centimeters north may introduce less bias than moving only as far as needed. If crews still cannot extract a core, they can move another 10 centimeters north and try again. If they hit bedrock, they should collect a sample to that depth and record it. If no soil is present, they can also record that fact.

Quantifiers should remove plots from the measurement system only if the land on which they sit has been dropped from the project. Plots should not be removed because they have been bulldozed or otherwise disturbed, a road has been built through them, or a river has shifted its channel. If field crews fail to find a plot marker after a diligent search, they can consider the plot lost and establish a new one at the prescribed location.

Determining Frequency of Measurement

The optimal interval for measuring changes in soil carbon depends on the rate of change, the cost of conducting measurements, and the value of any offsets. More frequent measurements reveal any shortfall in carbon sequestration quickly, giving developers a chance to address problems. Project developers also wish to deliver offsets and get paid for them as soon as possible. In addition, uncertainty rises as time passes since the last measurement, eroding the amount of offsets verifiers will accept and lowering the price these offsets might command. On the other hand, lengthening the time between remeasurements spreads quantification costs over a larger amount of offsets, which tends to increase the profitability of the project. The challenge is to balance the tension between delaying remeasure-

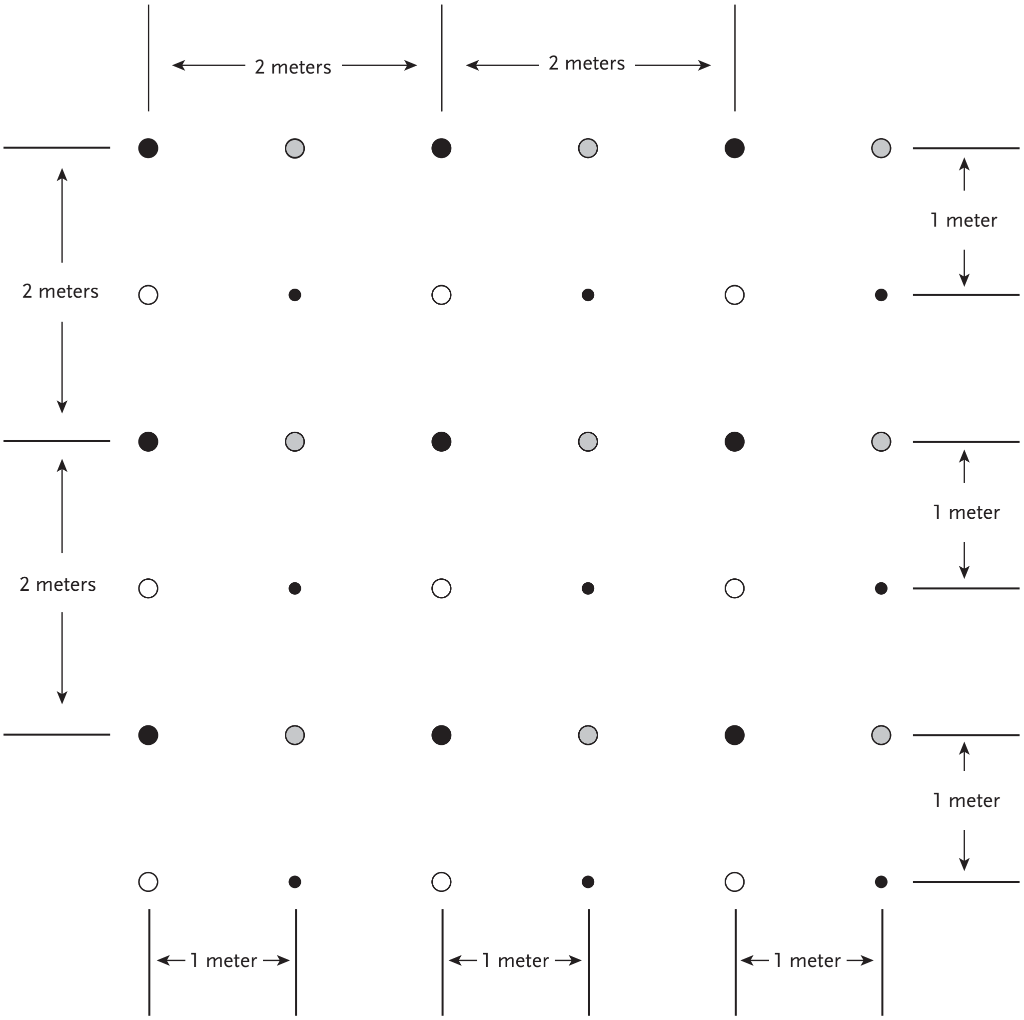


Figure 7.2 Layout of cores at a sampling site. Establishing permanent plots allows crews to return years later to re-measure soil carbon and calculate the change on each plot, which gives statistical power to the the overall results for the project. Although most aspects of sampling should remain constant from one measurement round to the next, crews should extract soil cores at points displaced from those used during prior sampling to ensure that the results are not influenced by disturbances incurred by the sampling itself.

ment to reduce costs and hurrying it to verify sequestration as it occurs.

Changes in soil carbon are typically not measurable from one year to the next because the change is too small relative to the total carbon stock. Moreover, such frequent measurements may prove unreliable because sequestration varies from year to year depending on the weather. The dynamics of soil carbon during the first one to three years after a switch from plowing to no-till farming are also poorly understood, and it is unclear how quickly net sequestration begins. Given current technology, costs, and annual variability in sequestration, most project developers should probably choose to measure soil carbon every five to 10 years for the first 10 to 15 years. Developers may plan further measurements in later years, or they may simply monitor a project to ensure that conditions are conducive to maintaining sequestration, if they expect the soil to store little additional carbon. Projects usually measure soil carbon shortly before they end, to determine whether they have met their overall target.

A project's measurement plan may call for a hybrid approach wherein quantifiers measure carbon stocks for several years and then use the resulting data in models to calculate changes in later years. Before choosing a hybrid approach, project developers should assure themselves that the needed modeling capacity is available at an acceptable cost. Although leading soil carbon models are available free of charge, paying people with the expertise to run them may prove costly.

Designing a sampling system; conducting an initial measurement of soil carbon within the project area; measuring changes in soil carbon later; and paying for laboratory costs, data analysis, and verification can easily cost several tens of thousands of dollars. After calculating the number of plots needed and setting a schedule for remeasurement, developers may wish to estimate the cost of all the quantification work over the lifetime of the project to see if it is likely to detect enough sequestration to be financially viable.

Developers may choose to monitor at more frequent intervals to determine whether land managers have implemented the promised activities and those activities are yielding the anticipated sequestration rates. These extra monitoring activities should specify performance thresholds, such that if the thresholds are met, the project is likely to be sequestering carbon according to plan. A near miss might trigger further measurements to better understand project conditions, whereas a complete miss could trigger remedial action.

Thresholds may be quantitative rather than categorical. Suppose a project plans to boost soil carbon by increasing crop residue left on fields to 5 tons per acre. Field crews weigh the residue on small, randomly located plots. If the average mass is less than 5 tons per acre, or if more than 10 percent of the plots have less than 4 tons per acre, such a finding would trigger more intensive measurements of residue and modeling of the sequestration likely to result.

Quantifying Carbon in Samples

The most common techniques for analyzing the proportion of soil that is carbon are based on measurements of the emissions from the dry combustion of soil samples. (This approach is quite similar to that described in Chapter 6 for analyzing samples collected in a forestry project.) Cores of a known volume are collected, dried, and weighed. The weight is then divided by the volume to yield soil bulk density.

To find the amount of carbon in the sample, laboratory analysts first take a small subsample from each core and measure its mass. They then oxidize (or burn) the subsample at a very high temperature, using infra-

Modeling Future Changes in Carbon Stocks

Developers typically use modeling or extrapolation from benchmark sites to estimate how much sequestration a project will produce before they embark on it. However, developers may also use data collected during the initial measurement of carbon stocks to model potential sequestration and to check progress during the project.

Developers need at least one modeling run for each combination of conditions. For example, if the project encompasses two different soil textures and cropping regimes, they need to run the model for each combination of soil type and cropping regime. Modeling is typically done on a per-hectare or per-acre basis and scaled up. Two user-friendly computer programs, the soil carbon tool of the Intergovernmental Panel on Climate Change (IPCC) and the COMET model (both available free online), quickly give a scientifically based estimate of changes in soil carbon resulting from changes in land management. A third soil carbon model, CENTURY, can make site-specific predictions based on data from land managers, an initial measurement of soil carbon, and other sources. CENTURY has been widely validated and is also available online at no cost. However, formatting data for use in this model, selecting factors for the calculations, and assessing outputs requires substantial expertise. The information needed to operate the IPCC and COMET models includes soil texture, cropping regime, tillage practices, productivity, and nutrient inputs, whereas the CENTURY model also requires historic weather data from a nearby location.

Assessing Uncertainty

Regardless of whether quantifiers use measurements or models to determine changes in soil carbon, they must assess the uncertainty in the calculated offsets. Using site-specific information to better represent actual carbon dynamics may yield more precise estimates, reducing uncertainty. Smaller uncertainty ranges, in turn, may allow quantifiers to detect more of the sequestered carbon with a high level of confidence, thus producing more credited offsets and gaining a higher price for the offsets.

Empirical measures of uncertainty are far better than expert opinion. Studies have shown that people often think their predictions are much more accurate than they turn out to be.[6] Whereas an evaluation of uncertainty based on actual measurements of soil carbon stocks is fairly straightforward (see Appendix 3 on statistics), such an evaluation based on models is more problematic. One approach to quantifying the uncertainty of estimates by a model involves finding the difference between modeled and observed outcomes in a number of cases and using that difference to calculate the standard deviation of the model's errors.

Some analysts use Monte Carlo analysis to estimate uncertainty. Properly done, Monte Carlo analysis examines variation in predicted outputs from thousands of model runs, where the inputs for each run are randomly selected from the possible range for each input.[7] For example, suppose that a model uses the amount of rainfall occurring each month as an input, and the model is run with rainfall records for a 25-year period. For each month, there are 25 possible values for the amount of rainfall for that month. During each run of the model, for each month, the Monte Carlo analysis would randomly select a year and use that amount in the model run.

Using Monte Carlo modeling to estimate uncertainty assumes that the model correctly represents dynamics in the physical world. This assumption is never totally correct; all models, by definition, are simplifications. If the model represents the world reasonably accurately, the modeled uncertainty will be close to the observed uncertainty in the world. If the model does not reliably depict the world, the modeled uncertainty may be much smaller or larger than the true uncertainty. Monte Carlo simulation is appropriate for a complex model such as CENTURY. The IPCC's soil carbon tool and COMET do not allow enough variation in inputs for users to perform Monte Carlo simulations. However, the COMET tool does provide estimates of uncertainty by comparing differences between modeled outputs and measurements at benchmark sites.

Validating Model Estimates

If a project will run for a long time and quantifiers will calculate soil carbon stocks more than twice, modeling can be very useful in determining whether initial projections match what is occurring. Initial measurements can be used as inputs to model runs, and predicted soil carbon values can be compared with those observed during the second field measurement. If the modeled and measured values match, users can have much higher confidence in model projections of later sequestration. If modeled and measured sequestration amounts do not match, project developers can adjust projections of future sequestration. Only a few sampling points, spanning the range of conditions across the project area, need to be measured during the second field measurement. Quantifiers can run the model using information from these sites as a check on the reliability of predictions for all sites.

Sensitivity analysis can be used to determine which inputs have the greatest impact on outputs. Quantifiers can then focus on obtaining more reliable data for those input variables.

red gas absorption or gas chromatography to measure the amount of CO_2 emitted. Analysts can convert this amount to grams of carbon by dividing it by 3.667 (the ratio of the mass of CO_2 to carbon). They can then find the amount of carbon in soil per unit of area by dividing this quantity by the mass of the subsample and multiplying it by the bulk density of the sample and depth of the core (see Appendix 16). The amount of carbon sequestered in soil is best expressed in tons per hectare.

This technique is extremely accurate if samples are prepared properly and equipment is calibrated and used correctly.[8] Crews must be careful to collect all soil from sample cores and to exclude soil that is not from the cores. If samples will not be processed for several days, they should be refrigerated or frozen to slow decomposition and loss of carbon.

To obtain an accurate reading of soil carbon, laboratory staff should thoroughly mix the entire soil sample or preferably mill the entire sample except for roots or other materials that are not classified as soil. At minimum, it is essential to mill a subsample of soil to a very fine texture and homogenize it. If such preparation is insufficient, carbon numbers will be highly variable, and quantifiers will not detect the modest amounts of carbon that projects are likely to sequester. (Subsamples typically weigh only a fraction of a gram, although their weight may vary with their carbon content.)

If a significant proportion of the particles in the soil are larger than 2 millimeters, analysts should grind a sample of this material and test it for the presence of carbon. If they find carbon, they should process 10 to 30 samples to see if such material contains a uniform percentage. If it does, they can use that percentage in evaluating the overall amount of carbon that such material contributes to soil samples. If the carbon content in this material varies significantly, analysts should measure more samples until they find an acceptably small standard of deviation. Porous rocks such as sandstone and some volcanic rocks are particularly likely to include carbon. Rocks with carbonates, such as limestone, include inorganic carbon that will produce CO_2 when combusted, so their presence would require further analysis to distinguish organic from inorganic carbon.

A number of universities operate high-quality analytical facilities and will analyze the amount of carbon in soil subsamples for a modest fee. A useful approach is to rely on a lab that analyzes samples jointly with other labs and compares results. After chemical analysis of soil subsamples, quantifiers should archive remaining samples for reanalysis later, if necessary.

Determining the Change in Carbon Stocks

One might assume that the change in carbon stocks at any specific site is simply the difference between the mass of carbon per unit of area at the beginning of the measurement period and the mass at the end. However, if the bulk density of the soil changes over time, the calculation process must account for this change. Failure to do so can lead to errors that range from doubling actual sequestration to falsely concluding that the soil has lost carbon when it has gained carbon (Gifford 2003).

Changes in bulk soil density usually reflect the fact that soil has become more or less compacted. For example, soil density usually rises for several years after land managers switch from plowing to no-till farming. That is because the soil collapses until soil aggregates form and re-create the porous structure found in productive soils with little disturbance. The height of the soil surface usually changes along with bulk soil density: when soil compacts, the surface drops; when soil becomes less compact, the surface rises.

When soil density increases, resampling to a given depth captures more soil. The inverse is also true: if soil density decreases, resampling to a given depth captures less soil. For example, suppose that in project year 1, crews sample soil to a depth of 20 centimeters. Further suppose that over the next few years, the soil increases in density (or compacts) by 10 percent, and the surface drops. If resampling in year 10 also occurs to a depth of 20 centimeters, it will capture about as much soil as sampling to 22 centimeters would have captured in year 1 (see Figure 7.3).

To account for this effect, quantifiers must calculate bulk soil density for each sampling site each time they measure carbon stocks. They can do so by separating any rocks, roots, and other material larger than a specified size (such as 2 millimeters) from fine soil and then consulting soil-sampling manuals on how to measure the density of this material. This approach accounts for the fact that samples taken at different times may in-

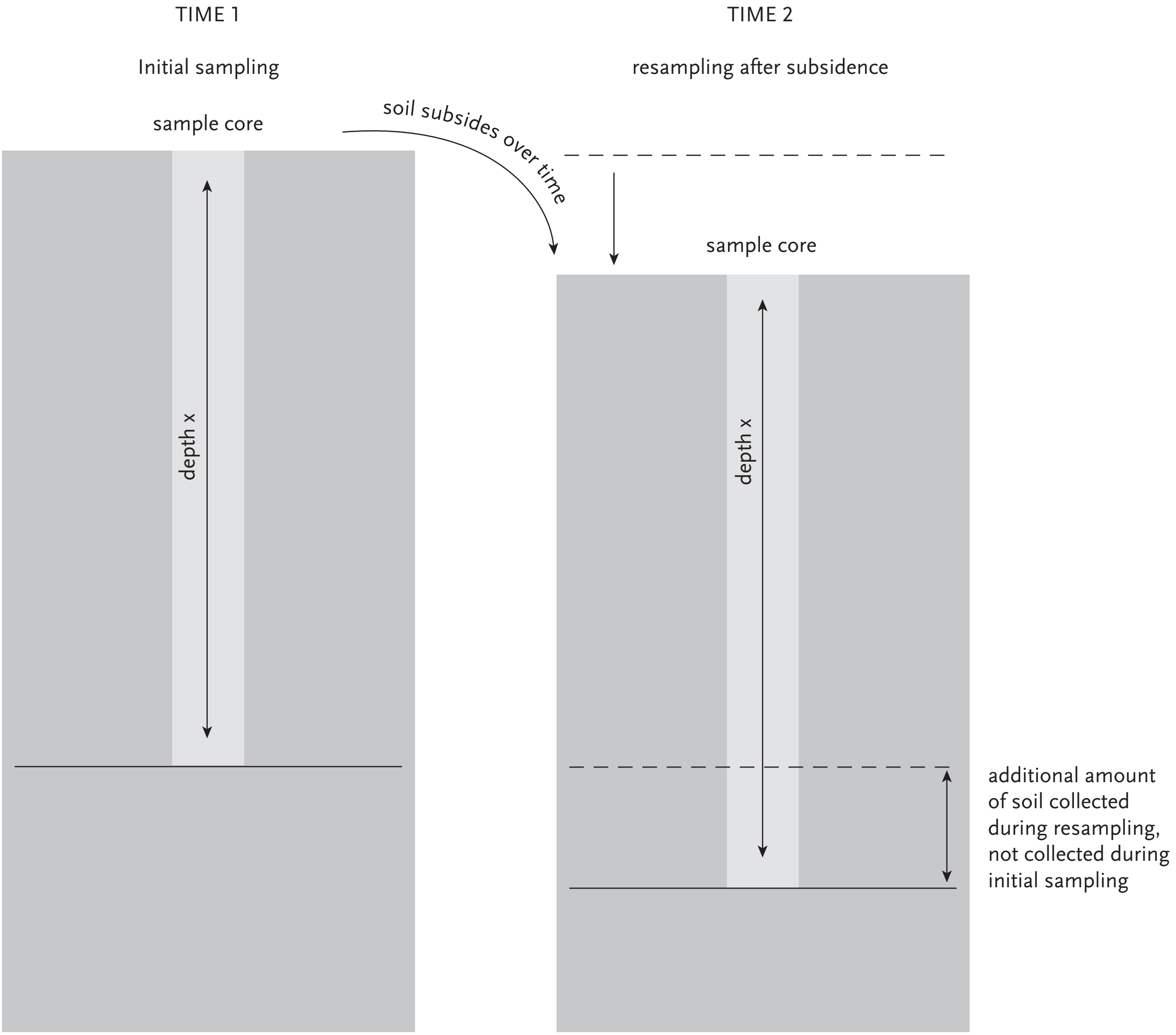


Figure 7.3 The effect of changes in bulk soil density on the amount of soil sampled. Soil density can change over time (for example because of compaction and subsidence) and often changes in density are accompanied by changes in soil height. When soil density increases (as illustrated here), resampling to a given depth captures more soil. The inverse is also true: if soil density decreases, resampling to a given depth captures less soil. To account for this effect, quantifiers must calculate bulk soil density each time they measure carbon stocks.

clude more or fewer rock fragments and roots. (Unbiased measurement of the density of rocky soils requires the use of more laborious pit sampling, as corers cannot encompass large rocks and usually do not yield intact cores when encountering them.)

To determine whether soil density has changed during out-year sampling, field crews should extract an extra 5-centimeter portion of soil from the first few sites (see Figure 7.4). For example, if the initial sampling included soil to a depth of 20 centimeters, crews should remove soil from a depth of 20 to 25 centimeters as a separate sample.

Quantifiers then measure the density of several soil samples taken at the original depth. If densities are within 1 to 2 percent of remaining constant over time, field crews may stop collecting the extra depth increments. However, they should not discard the samples collected until the overall analysis is complete. If bulk density has changed, the change might be a fairly constant percentage across sites, or it might occur only under some conditions. Quantifiers may need to analyze 20 to 30 sites to discern a pattern. If they cannot detect a pattern, crews should collect the extra depth increment at all sites. Quantifiers then use those depth increments to correct for changes in bulk soil density (see Appendix 16).

After calculating the change in carbon stock at each sampling site and correcting for changes in bulk density, quantifiers then calculate the change in carbon stock for each plot. Next, they calculate the mean change in carbon per plot for all the plots analyzed. If the project has only one stratum[9] and has installed sampling sites randomly, then the average change in carbon per plot is

$$\Delta C_{avg} = (\Sigma(C2_i — C1_i) / n \qquad \text{Equation 7.3}$$

where ΔC_{avg} is the average amount of carbon gained, $C1_1$ is the amount of carbon observed on plot i at time 1, $C2_i$ is the amount of carbon observed on plot i at time 2, and n is the number of plots. ΔC_{avg} will be in the same units as $C2_i$ and $C1_i$. As noted, quantifiers should convert plot measurements to tons of carbon per hectare before performing this calculation.

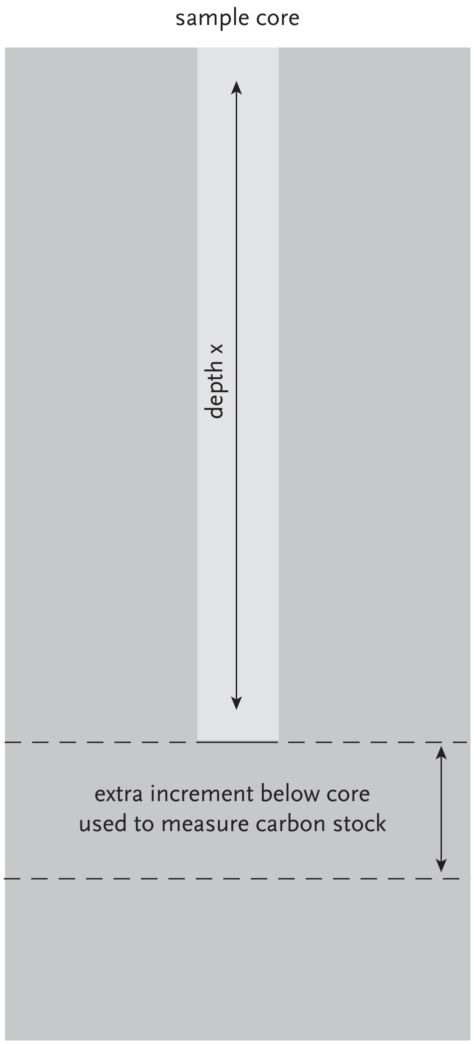


Figure 7.4 Extra sampling to calculate soil bulk density, Soil density can be obtained from the same cores used to measure carbon content by extracting an extra 5-centimeter portion of soil from the first few sites.

The mean estimated change in carbon stock is the average of the changes measured at each sampling plot (in metric tons of carbon per hectare) times the number of hectares in the project:

$$C_{seq} = \Delta C_{avg} \text{ x } A \qquad \text{Equation 7. 4}$$

where C_{seq} is the calculated amount of carbon sequestered over the project lands in metric tons of carbon, ΔC_{avg} is the average of the changes per unit of area measured at all plots (as metric tons per hectare), and A is the number of hectares encompassed by the project. Note that the mean estimated change is not the amount of offsets credited to the project. The credited offsets are equal to C_{seq} minus inadvertent emissions, the baseline, the uncertainty or confidence interval, and the leakage.[10]

Calculations of total project sequestration are somewhat more complex if the project is stratified. In that case, project sequestration is the sum of the amounts of sequestration calculated for each stratum. Quantifiers calculate sequestration for each stratum using the method for a project without stratification.

Soil projects offer an opportunity for farmers and land managers to participate in burgeoning carbon markets by making only minor adjustments to their normal practices, such as by switching to no-till farming. With a moderate investment in labor and monitoring equipment, landowners can realize extra profits while taking steps to absorb greenhouse pollutants from the atmosphere.