Design and Costs of a Measurement Protocol for Trades in Soil Carbon Credits

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Previous work has demonstrated that in the absence of transaction costs, contracts that pay producers per carbon (C) credit are more efficient than those that tie payments to changes in management practices. In this paper we develop a measurement protocol to support contracts for C credits and estimate its implementation costs using an empirical example. We find that the costs of implementing a measurement protocol for soil C credits depend on: the price of credits; the regional heterogeneity in C values as well as assumed error and confidence intervals. We find that the upper estimate of measurement costs associated with a contract that pays producers per C credit can be as little as 3% of the value of a credit. These contract measurement costs are less than the efficiency gains from implementing a per-credit contract.

Des travaux antérieurs montrent que si la transaction ne coûte rien, les ententes prévoyant la rémunération des agriculteurs par crédit carbone (C) sont plus efficaces que celles où les paiements sont liés à l'adaptation des pratiques culturales. Dans leur article, les auteurs proposent une méthode de calcul pour de telles ententes et estiment ce que coûterait son implantation au moyen d'un exemple empirique. On constate que, pour les crédits C du sol, le coût de mise en œuvre dépend du prix des crédits, de l'hétérogénéité régionale de la valeur des crédits ainsi que de l'erreur présumée et des intervalles de confiance. On se rend compte que la plus haute estimation du coût des ententes rémunérant les agriculteurs en fonction des crédits C ne dépasse pas trois pour cent de la valeur du crédit. De tels coûts sont inférieurs aux gains de productivité résultant de l'adoption d'une entente articulée sur les crédits C.

INTRODUCTION

Many industrialized countries are taking measures to reduce their net emissions of greenhouse gases (GHG), such as carbon dioxide, that potentially contribute to global warming (Watson et al 1996). The Kyoto protocol of the United Nations Framework Convention on Climate Change is part of an ongoing international discussion that aims to identify ways to reduce global concentrations of GHG (UNFCCC 1998). One proposal under the protocol is a carbon (C) credit-trading scheme that would allow participating countries to receive credits for domestic or international projects that reduce net GHG emissions beyond a "business as usual" case either by reducing emissions or storing (sequestering) C in natural ecosystems (UNFCCC 2002). Canada ratified the protocol in 2002, but the U.S. has not followed suit. However, in 2002 the U.S. administration announced an initiative to include forest and agricultural soil C sequestration in U.S. conservation programs and develop accounting rules for sequestration projects (White House 2002). While this initiative is voluntary, limits on net GHG emissions are an option in the future. Many firms anticipate that a cap on GHGs will be imposed, either through an international agreement like the Kyoto protocol or through domestic policy, and have started to take voluntary actions to reduce their net emissions (Rosenzweig et al 2002; Pew Center 2002).

Since 1996, more than 65 credit trades have occurred worldwide and since 1995 over 150 projects have been implemented to reduce C emissions or increase C sequestration (Rosenzweig et al 2002). Approximately 10% of these projects increase C sequestration using forestry activities (Watson et al 2000; Rosenzweig et al 2002). Recent research suggests that agricultural soils have the technical potential to reduce up to 9% of Canadian and U.S. emissions by increasing the amount of C sequestered (Lal et al 1998; GCSI 1999). Although it may not be economically feasible to achieve this entire technical potential, Antle et al (2002) have shown that some credits could be purchased at prices competitive with those produced by forests. However, scientists and policy makers have questioned whether it will be feasible to sell agricultural soil C within a market based credit-trading program. A major issue with soil C is that it cannot be observed or measured directly in the same way as point-source industrial emissions or creation of above-ground biomass in forests. It must be possible to verify that C in soils has increased and can be maintained over a specified period before agricultural producers can participate in the emerging market for tradable credits. Thus the design and associated implementation costs of a measurement protocol that could support trades in soil C is an important issue remaining to be resolved.

In this paper, we address this issue by reviewing trades to date and using this information to develop a measurement protocol that could be used to implement contracts for credits sequestered in agricultural soils. In addition, we estimate the costs of implementing the measurement protocol using an empirical example. Three key results emerge from the prototype framework and application. First, the efficiency of adopting a measurement protocol for agricultural soil C sequestration depends on the price of credits. This result follows from the fact that producer participation in contracts to sequester soil C is dependent on the economic incentives provided. The average measurement cost per credit is influenced by the number of producers that enter into contracts at different price levels and the total credits produced. Second, we find that over the range of credit prices considered in this paper, measurement costs are largest in areas that exhibit the greatest heterogeneity in C values. Third, in a case study application of our prototype measurement protocol, we find that if we assume error and confidence levels similar to existing forestry contracts, the upper estimate of measurement costs associated with a contract that pays producers for each credit sequestered does not exceed 3% of the credit price at low carbon prices, and is much less at higher carbon prices. These findings indicate that measurement costs would not be large enough to prevent producers from trading soil C credits.

This paper is organized as follows. In the next section, we present the mechanisms by which C is sequestered in agricultural soils and review current credit trades and accounting protocols to identify technical considerations for C sequestration projects that could produce marketable credits. Two contracts that could be used to encourage producers to sequester soil C and their measurement demands are described in the third section. The modeling framework and empirical application used to estimate the measurement costs of a market based contract for credits are presented in the fourth section. We finish with a discussion of the results and conclusions.

SOIL C SEQUESTRATION AND PROJECT DESIGN

Industries can directly lessen GHG emissions by reducing fossil fuel combustion. In many cases, this requires firms to develop and adopt new technologies or change existing production methods prior to planned replacement and could be very costly. Another alternative is to purchase credits from a less expensive source until a time when it is economically efficient to bring new technologies on line. If agriculture and forestry generate credits at lower cost than other sources or technological change, these industries will be strong participants in a market for credits.

Forestry and agriculture sequester C through photosynthesis. During photosynthesis, plants take CO_2 from the atmosphere and convert it to C in their above-ground biomass and below-ground root systems. In forest ecosystems, approximately 80% of C is stored in above-ground woody biomass and 20% in the below-ground root system and soils (Watson et al 2000). In agricultural systems, the annual nature of most crops means that a small amount of C is stored in biomass (later harvested and taken from the field) but over time C can be sequestered in cropland soils. When land is converted from native vegetation to modern agriculture, C stored within the soil is released into the atmosphere through oxidation and, in some cases, above-ground biomass production decreases, reducing inputs of C into the soil (Watson et al 1996; Lal et al 1998). Tiessen, Stewart and Bettany (1982), Mann (1986) and Rasmussen and Parton (1994) estimate that 20–50% of soil C is lost during the initial 20–50 years of cultivation. Because of this past depletion of soil C levels, cultivated soils in many areas have the capacity to store more C than they do at present (Lal et al 1998).

Although credit-trading rules are not finalized, private companies and nonprofit groups are engaging in pilot projects that generate credits. For example, PacifiCorp has invested in forest preservation in Bolivia as well as tree-planting projects in Oregon (PacifiCorp 1997). GEMCo (The Greenhouse Emissions Management Consortium) has participated in the purchase of soil C credits, as well as credits from methane and other emissions reductions (GEMCo 2003). Entergy Corp. has contracted with farmers in northern Idaho, Oregon and Washington states for soil C credits (Environmental Defense 2002). Many other projects are described by Watson et al (2000) and Pew Center (2002). In addition to these individual trades, Canada is establishing the Canadian Climate Exchange, and the U.S. is establishing the Chicago Climate Exchange to facilitate trades in C credits.

These previous trades and current pilot markets are exploring a range of contracts and market structures. In the event a fully functioning formal market is established, the contracts and trading structures could differ from those seen at this time. However, present experiences are being used to inform future designs. Buyers have an incentive to purchase credits voluntarily in the absence of formal domestic markets, to gain early-mover advantage in a developing market, amass experience with early trades or inform the policy debate. These buyers will be well positioned to begin trading if a formal market is established. Credit sellers may also participate for similar reasons as well as the opportunity to market a new commodity.

Currently, the market for credits is thin, and trades rely on simple legal and financial arrangements. Some buyers have purchased properties outright and established projects that generate credits, while others have purchased rights to credits from projects established on the seller's property (see projects described by Watson et al 2000; PacifiCorp 1997). At a minimum, projects that generate credits involve one buyer and one seller in addition to some form of measurement, monitoring and certification.

Transactions to date suggest that credits will trade in contracts larger than 273 tonnes of C[1] (1,000 tonnes of CO_2) (Rosenzweig et al 2002).[2] This amount is likely too large for a single agricultural producer to fill and in practice many trades involve quantities that are significantly larger (Rosenzweig et al 2002). Contracts for forest credits have taken many forms, either a single seller with large C quantities and multiple buyers (for examples, see Watson et al 2000) or multiple sellers with a single buyer (ENN 2001). Contracts for credits generated from agricultural practices are likely to share many common elements with those used in forestry. We expect that individual buyers will contract with many sellers for soil C credits or, more efficiently, an intermediary that pools credits from many sellers. Several companies have formed already to provide credit aggregation services within the current voluntary market, for example, the National Carbon Offset Coalition and Blue Source Inc., among others. Previous studies (for example, Antle et al 2003; Pautsch et al 2001) have shown that agriculture can supply C at a cost that is competitive with other sectors and thus a low-cost, effective measurement protocol for soil C is an important consideration in developing C credit contracts for agriculture.

Several guides have been developed for measuring and monitoring C within forestry and agroforestry projects (Kerz et al 2002; MacDicken 1997; Vine, Sathaye and Makundi 1999; Brown 1999). Although C is sequestered in forest soils, these guides concentrate on measuring and monitoring above-ground C, or below-ground C stored in roots and do not address soil C sequestration. A transparent and reliable measurement protocol is perhaps even more critical for soil C because, unlike above-ground C, soil C is not readily visible. The measurement protocol needs to be flexible enough to accommodate contracts that involve multiple sellers and accommodate the unique characteristics of sequestered soil C.

CONTRACT DESIGN, OPPORTUNITY COSTS AND MEASUREMENT COSTS

A measurement protocol to support trades in soil C credits must complement the way that contracts are structured and designed. Two alternative contract designs have been proposed for agricultural soil C sequestration (Antle and Mooney 2002; Pautsch et al 2001; Parks and Hardie 1995). The first follows the spirit of existing agricultural programs, such as the Conservation Reserve Program, and provides producers with a uniform payment for every hectare on which they adopt management practices that sequesters additional C. These per-hectare contracts do not link payments to the quantity of C that is accumulated as a result of the change in practices and are typical of many existing government programs. In contrast, the per-credit contract pays producers for each credit that they produce regardless of what practices they use. Under per-credit contracts, each hectare of land entering the contract will receive a different payment corresponding the number of credits produced on that hectare. This type of contract is required for a system of tradable credits. Unlike per-hectare contracts, the number of credits produced and stored needs to be measured to determine the size of producer payments and ensure that the terms of the contract have been met.

Profit-maximizing producers will enter into contracts to sequester C in soil when the benefits of the contracts outweigh the opportunity costs. In order to increase soil C, the producer must change from their current land use and/or management systems to an alternative that sequesters more C. They will do this if the expected net returns from the alternative system plus any payment for C credits, exceed the expected net returns from their current operation. Several studies have demonstrated that a per-credit contract can secure a given number of credits at a lower cost than a per-hectare contract (Antle and Mooney 2002; Antle et al 2003; Pautsch et al 2001; Parks and Hardie 1995) because payments are directly linked to the number of credits produced. In addition to opportunity cost (which influences the cost of supplying credits), there are additional contract costs that could influence the relative efficiency of per-hectare and per-credit contracts. These include costs of program administration, contract negotiation and monitoring whether producers have changed to eligible practices as well as the costs of measuring the produced and stored credit quantities. Both the per-hectare and per-credit contracts will require negotiations with multiple producers of credits and thus we assume that these costs are likely to be similar across both contracts (Mooney et al 2004). However, Stavins (1998, 1999) suggests that the costs of measurement and monitoring required to implement per-credit contracts for forestry could be prohibitively expensive, potentially exceeding the efficiency difference[3] between each contract type.

The difference between the opportunity cost of supplying a given quantity of credits under a per-credit contract versus a per-hectare contract provides an upper bound for any additional contracting costs that are specific to per-credit contracts (Pautsch et al 2001; Antle et al 2003). The magnitude of the efficiency difference plus the costs of measurement and monitoring is an empirical issue. Very little work has examined these costs to date, and it is unclear whether the additional costs associated with measuring and monitoring credits will offset the efficiency difference.

DESIGN OF A MEASUREMENT PROTOCOL FOR AGRICULTURAL CREDITS

Measurement and monitoring costs (MM) associated with contracts for credits can be decomposed into two parts: first, monitoring whether participants are engaged in practices eligible for payments and second, measuring the number of credits that have been sequestered. Ideally, under a per-credit contract, producers would receive payments for credits sequestered using an unlimited range of practices. However, this arrangement could be more costly and more complex to monitor because it is difficult to identify whether producers have changed practices to those that sequester additional soil C. Monitoring is simplified under a per-credit contract if a well-defined subset of practices are eligible for credit payments. If this constraint is implemented, monitoring resources can be focused on and developed for this subset of practices.

Monitoring activities for both contract types could be accomplished through remote sensing, aerial photography, drive-by inspection or other means. The quantity of credits sequestered in agricultural soils could be estimated using statistical sampling similar to forest contracts; that is, a sample will be drawn from the population supplying credits under the contract and C measured on these areas (credits are not measured on areas that are not selected for sampling). Sample results are statistically representative of the entire population. Under this scenario, measurement and monitoring costs (MM) can be expressed in dollars as:

$$MM_z = AV_z + S_z\,(n_{sc}, CN, F) \tag{1}$$

where:
z = type of contract (per-credit contract, per-hectare contract)
sc = sample design (random sampling, stratified random sampling, systematic sampling, or other sampling scheme)
AV_z = cost of monitoring whether producers are complying with practices specified in contract type z (\$)
S_z = cost of implementing a sampling protocol for the contract type z (\$)
n_{sc} = number of samples for a given sample scheme, sc..
CN = cost per sample (\$)
F = frequency of sampling over the contract duration, where it is assumed that $\frac{\partial S_z}{\partial n_{sc}} > 0$, $\frac{\partial S_z}{\partial CN} > 0$, and $\frac{\partial S_z}{\partial F} > 0$.

We expect that under both contract types, $AV_z > 0$, reflecting the need to monitor whether producers have switched to practices that sequester additional soil C. However, monitoring costs, AV_z, may not be substantially different for the per-credit and per-hectare contracts, especially when this can be done using remote sensing or similar visual inspection techniques,[4] thus we assume that $AV_{per\text{-}credit} \approx AV_{per\text{-}hectare}$.

Under a per-hectare contract, payments are independent of the number of credits generated; thus, there is no need to verify their quantity, hence $S_{per\text{-}hectare}(n_{sc}, CN, F) = 0$, whereas under a per–credit contract, the number of credits created is specified in the contract, hence $S_{per\text{-}credit}(n_{sc}, CN, F) > 0$. Therefore, **the additional costs from measurement and monitoring that are unique to the per-credit contracts arise from the costs of measuring the number of credits produced (*M*) and are attributable to the costs of statistical sampling.** In the remainder of this paper, we focus on the quantity $S_{per\text{-}credit}(\cdot)$.

The current requirement of minimum tradable credit quantities suggests that contracts will be filled by aggregating credits from several producers (potentially covering a large geographic area) into a single contract amount. In this situation, we propose a combination of field measurements and predictive models to estimate the number of credits produced. The measurement protocol we propose for per-credit contracts contains the following elements:

- Use predictive biophysical models to estimate the expected rate and variability of soil C sequestration as a result of management changes within the contract area, taking into account specific climatic and soil conditions. These estimates are needed to select the sample size for estimating changes in soil C over the contract duration.
- Measure baseline levels of C within a contract area using statistical sampling techniques and laboratory testing.
- Measure increases in C over the duration of the contract by periodic field samples and laboratory testing.

- Measure total increase in C at the end of the contract.

Several sampling designs can be used to select a sample from a population; for example, simple random, stratified and cluster sampling (Thompson 1992). Stratified random sampling has been used to measure C sequestration in forest projects (Boscolo et al 2000; Brown et al 2000) and is also suitable for estimating soil C sequestered within cropping systems. An advantage of this design is that stratification reduces the sampling error and can reduce the sample size necessary to estimate population parameters and as a consequence, the costs associated with measuring credits (Thompson 1992; McCall 1982).

Using a stratified sampling approach, the population to be sampled is finite and defined as those producers that enter into a per-credit contract. The population can be divided into heterogeneous groups or strata, j, that are internally homogeneous with respect to a chosen characteristic, and then sampled independently using a random sampling design.

Within a given contract region we define the population as all hectares of cropland that switch from a historical cropping system to a new system that sequesters additional C as a result of a payment offered per credit. Each stratum, j, is homogeneous with respect to a cropping system change. That is, each stratum represents those hectares that have switched between the same pair of cropping systems. The unit of analysis is an individual "field" of one hectare in size.

The total sample size, n, required to estimate the mean number of credits supplied by each hectare within a population can be calculated using Eq. 2 (McCall 1982) and distributed among the strata using one of several different schemes (for examples, see Thompson 1992; McCall 1982; Sarndal, Swensson and Wretman 1992):

$$n = \frac{Z^2\left(\sum_{j=1}^{J} N_j\tilde{\sigma}_j\right)^2}{N^2\psi^2 + Z^2\sum_{j=1}^{J} N_j\tilde{\sigma}_j^2} \tag{2}$$

where:
n = total sample size
Z = value from standard normal table corresponding to desired level of confidence in parameter estimate
N = total number of hectares in the population
j = index identifying strata where $j = 1, \ldots, J$; each stratum represents a change between a pair of crop systems.
N_j = total number of hectares in the jth stratum
$\tilde{\sigma}_j$ = initial estimate of the standard deviation of change in C over 20 years resulting from a crop system change in the jth stratum

$$\psi = \left(\frac{\sum_{j=1}^{J} N_j\varepsilon_j}{N}\right)$$, absolute error, and $\varepsilon_j = \varepsilon\bar{X}_j$

ε = chosen percentage measurement error
$\bar{X}_j$ = mean change in carbon per hectare within the jth stratum.

The total sample size, n, is dependent on the number of hectares that enter into contracts to sequester soil carbon within a region, N; the number of hectares that are within each stratum representing possible crop system changes, N_j; the degree of error, ε; the desired confidence level Z; and the variability of soil carbon changes within each strata, $\tilde{\sigma}_j$. Several of these factors will vary with the price offered per credit, the area sampled and the spatial extent of the sampled region.

The number of hectares that enter into contracts to supply credits, N, is a function of the biophysical, technological, policy and economic parameters facing each producer including the payment level or price offered per credit (Antle and Mooney 2002; Antle et al 2001).[5] When the price, P, offered for credits is low, only those hectares with the lowest opportunity costs of producing credits will enter into contracts. As the price offered per credit increases, it is profitable for a larger number of hectares to enter contracts for credits. Therefore, we expect that **the population to be sampled, N, will increase as the price per credit increases.** In the limit, there is some price high enough for every hectare within an area to switch practices and supply credits; after this point, the population to be sampled cannot increase further and would remain constant for any additional price increases. Therefore we expect that $\frac{\partial N}{\partial P} \geq 0$.

The change in the size of each stratum as the price of credits is changed, $\frac{\partial N_j}{\partial P}$, is more uncertain and could be positive, negative or zero. As producers are offered higher prices for credits, the number of hectares making specific pairs of crop system switches will also change. Whether these changes are positive or negative depends on the relative economic profitability and credit productivity of each crop system. Some strata may experience an increase in the number of hectares making a given pair of crop switches, while others may experience a decrease; thus, the sign on $\frac{\partial N_j}{\partial P}$ is indeterminate for all strata j. Similarly, $\tilde{\sigma}_j$, the standard deviation of soil carbon changes within each stratum, will also vary in response to changes in the number and combinations of hectares within each stratum as P changes; thus, $\frac{\partial \tilde{\sigma}_j}{\partial P}$ is also indeterminate *a priori*. Finally, $\frac{\partial \psi}{\partial P}$ is also indeterminate *a priori* because this measure is also dependent on the size of each N_j.

In this paper, the variability of C sequestered by each crop system is calculated using the estimated potential of each crop system to sequester C on different soil types within each agro-ecozone. Thus, the variance of C sequestration by crop system is constant within a given agro-ecozone. Consequently, a single estimate of the variability of C sequestration is associated with each cropping system change and $\tilde{\sigma}_j$ is held constant at each payment level for soil C. Even holding $\tilde{\sigma}_j$ constant, the expected change in sample size as the payment for credits changes, $\frac{dn}{dP}$, is indeterminate. If the denominator in Eq. 2 increases more than the numerator, n will decrease when the credit payments increase, whereas if the denominator does not increase as fast as the numerator, n will decrease.[6] Thus, it is possible for n, the sample size, to either increase or decrease as the payments offered for credits increase. The actual direction of change will be determined by the empirical economic and biophysical relationships present within a given region (Mooney et al 2004).

Soil samples are taken using specialized probes,[7] then bagged and transported to a laboratory where they are air-dried and ground and C measurements are taken. The cost per sample, *CN*, can be calculated from Eq. 3:

$$CN = ((L + R + FC)/ND) + LC \tag{3}$$

where:
CN = cost per sample ($)
L = total labor costs per day ($)
R = daily rental cost of truck and Giddings probe ($)
FC = fuel consumption per day ($)
ND = number of completed field samples per day
LC = laboratory cost of preparation and analysis of single sample ($).

The frequency of sampling activities, *F*, will be influenced by several factors such as the duration of the project, the rate and expected variability of C accumulation as well as the relative risk preferences of the buyer and group of sellers. Measurements to establish changes in soil C may not be needed annually because C levels do not change dramatically from year to year (assuming no disturbance). At a minimum, to support any contract, $F = 2$, reflecting the need to establish baseline levels of C at the beginning of the project and final C levels at its conclusion. A higher sampling frequency can be implemented to provide information on the interim progress of the project or for other reasons but is an arbitrary decision reflecting the need to satisfy goals other than measuring the change in C over the project lifetime. For example, if either the buyer or group of sellers is concerned about stochastic C accumulation over the contract lifetime (and the effect this will have on contract payments), they may wish to sample with high frequency to create detailed records of C accumulation. In determining the preferred frequency of sampling events, both parties need to consider the tradeoff between the higher costs associated with frequent sampling and the expected payments for accumulated C.

Vine and Sathaye (1997) and Vine, Sathaye and Makundi (1999) suggest visual inspection annually to determine whether soils have been disturbed in forest projects and, if no disturbance has taken place, taking measurements every five years. McConkey and Lindwall (1999) suggest measuring soil C every three years on fields converted to no-till. Brown et al (2000) plan to measure C sequestered within a 30-year forest project in years 3, 5, 10, 15, 20, 25 and 30.

Model Description and Data

A site-specific model of producer decision-making is needed to identify the population that will participate in a per-credit contract at each payment level. Site-specific management and input data from a detailed survey of fields on 425 farms (Antle et al 2001) are used to estimate production models of output supply and input demand. These field level data are statistically representative of three Major Land Resource Areas (MLRAs) in Montana with dryland cropping systems. The parameter estimates obtained from these econometric models are then used to drive a simulation model that represents producers' decision-making processes as a sequence of discrete land use and continuous input use decisions at the field level. The model assumes that producers are price takers in input and output markets. Detailed descriptions of the model and estimation procedures can be found in Antle and Capalbo (2001), Antle et al (2001) and Antle et al (2003).

Seven cropping systems are included in the simulation model. These are spring wheat–fallow, barley–fallow, winter wheat–fallow, grass, continuous spring wheat, continuous barley and continuous winter wheat cropping systems. Site-specific expected net returns from each crop system are calculated by taking random draws from price, yield and input use distributions estimated from the survey data and can vary widely. The production system selected by the model for each field is based on the maximization of expected net returns. It is assumed that if a field is fallowed in the current period, the expected net return from a given crop the following season is discounted to the present. Similarly, the expected net returns for a crop grown on fallow are calculated by compounding previous fallow costs to the current period.

The average rate of C sequestered on a hectare in response to engaging in each production system is estimated by agro-ecozone using CENTURY, a crop ecosystem model designed to study soil C dynamics. These estimates are used within the econometric process simulation model to estimate the size of credit payments for each hectare and the total quantity of C sequestered within a given agro-ecozone.

CENTURY is a generalized biogeochemical ecosystem model that simulates C, nitrogen and other nutrient dynamics (see Parton et al 1994; Paustian et al 1996; Paustian, Elliott and Hahn 1999). The model runs on a monthly time step and is driven by monthly precipitation and temperature, soil physical properties (e.g., texture, soil depth) and atmospheric nitrogen inputs in addition to site-specific management information. Soils and climate data were collected for three MLRAs within Montana. An MLRA reflects an area that has relatively homogeneous climatic and growing conditions. To provide better spatial resolution of biophysical conditions for this study, each MLRA was further subdivided on the basis of historical precipitation into high and low rainfall areas, totaling six sub-MLRAs that represent the agro-ecozones in the econometric process simulation model (Figure 1). The simulations showed that most of the C accumulation occurred over a 20-year period after a change in management. CENTURY results show that increasing the intensity of crop production from crop–fallow to grass and continuous cropping systems can generate credits. Detailed results from CENTURY are found in Antle et al (2001).

The framework developed earlier and the models described above are used to estimate the costs of measuring soil credits under a per-credit contract in the small grain-producing region of Montana. Hectares that switch management practices to supply credits in response to payments under a per-credit contract are the population to be sampled under the measurement scheme.

Empirical Application

There are many ways to set up the specific terms for a per-credit contract between buyers and sellers. In this empirical example we assume that producers enter into 20 year contracts to create C credits. Each year, the producers receive a payment based on one-twentieth of the total number of credits they are expected to produce over the contract lifetime as a result of adopting a specific crop system change on each hectare enrolled within the contract. The price per credit is fixed and remains constant over the contract duration.

Under a sampling scheme, credit quantity is measured subject to some error. To date, both credit purchasers and suppliers have been willing to accept some measurement error and

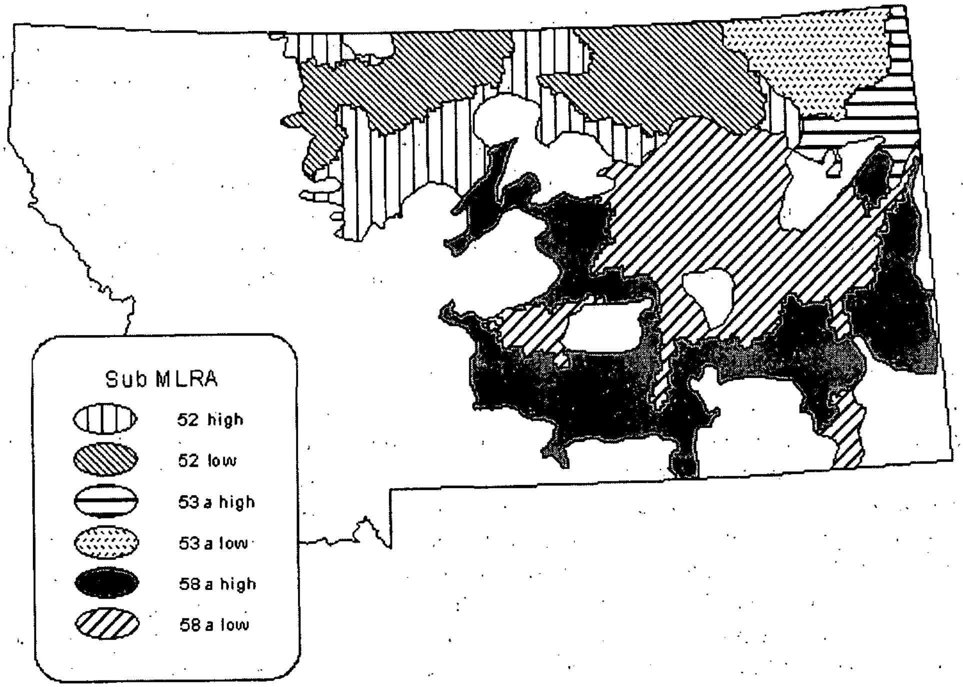

Figure 1. Agro-ecozones as represented by sub-MLRAs[a] in Montana
[a]MLRA = major land resource area. These areas were subdivided into high and low rainfall zones to create sub-MLRAs.

pay the contract price for a project that falls within acceptable error limits. It is possible that if credit numbers fall outside of these bounds, producers may have to assume risks of proving up their project with C purchased from other sources or have produced C that they can sell for additional credit. These scenarios introduce an element of payment risk for which the producer may require an additional positive risk premium. In this paper, we assume a zero-risk premium, but acknowledge that other scenarios are possible that could change the magnitude of costs and payments. An implicit assumption is that once producers have accepted the payment for C they honor the contract for its duration and at the end of the contract soil C measurement will cease. Producers are offered the opportunity to enter into a contract for C with no expectation that additional contracts will be offered in the future; that is, there is no option to wait and enter into a contract in the future. This situation is the same as assuming that producer expectations of future contract prices are constant and thus there is no option value from delaying their decision to participate in the contract for C.

There are many details specific to "real world" enforceable contracts that are not addressed, for example, penalties for nonperformance and options for sellers to buy out of contracts. These details are important for the implementation of contracts but will not affect the design and cost of the measurement protocol that is the focus of this paper.

The econometric production simulation model is run assuming payments are offered to producers for each credit they produce in response to a change in management practice. Ten payment levels were examined, ranging between \$10 and \$100 per credit and increasing in \$10 increments. At each payment level, the simulation model calculates the number of hectares that switch production practices and the number of credits produced within each sub-MLRA.[8, 9]

The number of hectares that switch production practices in response to a payment represent the population to be sampled and the area over which to calculate the cost of measurement. Information generated by the econometric production model and the CENTURY ecosystem model is used to estimate the sample size, n, necessary for measurement activities within each agro-ecozone using Eq. 2. The cost per sample is estimated according to Eq. 3 and specific assumptions are described below.

Determining Sample Size n for Each Agro-ecozone

Within a given agro-ecozone (sub-MLRA), the population can be stratified on the basis of cropping system changes that are relatively homogeneous with respect to their ability to generate credits. For example, hectares that are switched from a spring wheat–fallow system to a continuous-spring wheat system form one stratum, while those fields that switch from a barley–fallow system to continuous-spring wheat are another stratum and so on. In total, the model includes 10 possible cropping system changes that produce credits; thus, each agro-ecozone can have a maximum of 10 strata.[10] The number of hectares participating in a per-credit contract at each payment level (the population of interest) is calculated by the model and is known and finite. As the payment level offered for each credit increases, production practices will change on a larger number of hectares. This means that at higher credit prices, a larger number of hectares within a region will be entered into a contract for C credits. Unlike sampling from an infinite population, changes in the population size will change the size of the sample required to estimate its parameters and the cost of sampling per credit. At different market prices for credits, N and N_j are estimated using the econometric process simulation model described above.

Soil carbon sequestration rates under seven different cropping systems are supplied by the CENTURY model for each sub-MLRA and are used to construct an estimate of the soil C variability for each strata, j. In general, changes from a crop–fallow system to a continuous cropping system result in higher rates of C sequestration and thus generate credits.

The variance within each stratum associated with a change from the original crop system to a subsequent system that sequesters more carbon, $\tilde{\sigma}_j^2$, is calculated as in Eq. 4. We do not have estimates of the covariance between the original and subsequent systems ($COV_{o,s}$) and assume that the events are independent; i.e., $COV_{o,s} = 0$. However, preliminary estimates using sample data suggest that $COV_{o,s}$ is likely to be positive, reflecting the fact that all crop systems on highly productive land areas tend to have high rates of C sequestration while all crop systems on less productive land areas tend to exhibit lower rates of C sequestration. Thus, the assumption that $COV_{o,s} = 0$ could result in an overestimate of $\tilde{\sigma}_j^2$ and the use of higher sampling rates than needed to achieve the desired accuracy:

$$\tilde{\sigma}_j^2 = Var_o + Var_s - 2COV_{o,s} \tag{4}$$

A summary of the data required to estimate sample size is presented in Table 1.

Table 1. Data sources for sample size calculations at a given credit price

Variable	Value	Source
Z	1.96 (95% confidence)	Normal tables.
ψ	Varies by agro-ecozone	Product of relative error (0.1) and the weighted average of estimated strata means. Estimated mean C changes were obtained from CENTURY model runs.
N	Varies by agro-ecozone	Number of hectares that enter into contracts to supply credits at a given price within an agro-ecozone. Obtained from simulation model results.
j	Varies by agro-ecozone	Number of strata within an agro-ecozone. Obtained from simulation model results.
N_j	Varies by agro-ecozone and stratum	Number of hectares within stratum j. Obtained from simulation model results.
$\tilde{\sigma}_j$	Varies by agro-ecozone and stratum	Estimated standard deviation of C changes within each strata and agro-ecozone. Calculated from input data to CENTURY model.

Table 2. Cost estimates for field sampling

Variable	Value	Assumptions and/or sources
L	\$232 per day	Lead technician @ \$17 per hour over 8 hours = \$136 per day. Driver/assistant @ \$12 per hour over 8 hours = \$96 per day.
R	\$70 per day	Lease value calculated from total equipment purchase price of \$40,830, depreciated over seven years with 20% salvage value and 15% before tax return on investment to lessor.
FC	\$16.50 per day	Assuming a driving distance of 150 miles per day, fuel consumption of 15 miles per gallon and price of \$1.65 per gallon.
ND	\$50 per day	Developed from personal communication with Keith Paustian, Natural Resources Ecology Laboratory, Colorado State University; Brian McConkey, Swift Current Research Station, Agriculture Canada; and Bernard Schaff, University Farm Manager, Montana State University.
LC	\$10 per sample	Estimate provided by Keith Paustian, Natural Resources Ecology Laboratory, Colorado State University.

Determining the Cost per Sample CN

Discussions with practitioners in the field resulted in the following assumptions used to determine the cost per sample: soil samples are taken using a Giddings probe mounted on a three-quarter-ton truck; two operators are employed to obtain the samples, and 50 samples are collected per day. Once the field samples are collected, we assume they are taken to a laboratory for further processing. Using Table 2, the cost for a single field sample is estimated at $16.37. This figure is similar in magnitude to those found by Smith (2002), who reports a cost of approximately $25 per sample for a project in eastern Oregon. A detailed breakdown of assumptions, data sources and costs are presented in Table 2.

Frequency of Measurement F

We assume that over the 20 year project lifetime, each area is sampled four times, first to establish baseline C estimates, twice more to ensure that C sequestration is on track in years 5 and 10 and finally at the conclusion of the contract in year 20. Therefore $F = 4$ in the calculation of measurement costs.

Measurement Costs

The total cost of a measurement scheme (M) in any given region can be calculated empirically as $M = n*CN*F$ while the average measurement cost per credit $MPC = M/Q$ where $Q =$ the total number of credits generated within a given area at a specific payment level.

Sensitivity Analysis

Sample size and measurement costs per credit are calculated for three alternative scenarios by varying the percentage measurement error, ε, and confidence level, Z, associated with the sampling scheme. Initially, measurement costs per credit are estimated for each sub-MLRA assuming an error of 10% ($\varepsilon = \pm$ 10%) and 95% confidence ($Z = 1.96$) consistent with previous measurement protocols for forest projects (Boscolo et al 2000; Brown et al 2000). In addition, the sensitivity of the sample size, n, and the measurement cost per credit, MPC, to changes in ε and Z are explored using two additional error and confidence assumptions; an error of 5% and confidence level of 95% ($\varepsilon = \pm$ 5%, $Z = 1.96$) and an error of 10% and a confidence level of 99% ($\varepsilon = \pm$ 10%, $Z = 2.576$). These alternatives will demonstrate how sample size and measurement costs respond to changes in the parameters of the sampling scheme.

RESULTS

Credit Price, Population and Sample Size

As the price offered per C credit increases, the population to be sampled in each area also increases as expected (Table 3). The population in sub-MLRA 52-high increases from 158,524 hectares at a price of $10 per credit to 496,153 hectares at a price of $100 per credit. Each agro-ecozone follows the same pattern, with the proportional increase in population being in the range of 151% to over 300% as the price of credits increase from $10 per credit to $100 per credit, Table 3.

Using a sampling error of 10% and 95% confidence, sample sizes range between a low of 599 in sub-MLRA 52-high with a credit price of $100 to a high of 3,146 in sub-MLRA 58-high at a price of $10 per credit, Table 3. As the price of credits increases from $10 to $100, the sample size required for each agro-ecozone decreases between 10% and 30%. Therefore,

Table 3. Population, total sample size *n* and coefficient of variation in C change by sub-MLRA, with varying price per credit, error and confidence

Price/ credit ($)	Population	CV[a]	Sample size: ε = 10% 95% conf.	Sample size: ε = 5% 95% conf.	Sample size: ε = 10% 99% conf.	Population	CV	Sample size: ε = 10% 95% conf.	Sample size: ε = 5% 95% conf.	Sample size: ε = 10% 99% conf.
		Sub-MLRA 52-high					**Sub-MLRA 52-low**			
10	158,524	1.49	861	3,377	1,476	283,708	2.22	1,884	7,381	3,236
20	225,828	1.38	741	2,923	1,271	334,914	2.12	1,724	6,777	2,961
30	277,276	1.33	683	2,699	1,175	388,611	2.06	1,630	6,426	2,803
40	336,517	1.29	649	2,561	1,112	458,085	2.00	1,548	6,117	2,661
50	372,671	1.27	626	2,477	1,073	494,068	1.98	1,515	5,991	2,605
60	406,601	1.26	616	2,442	1,059	542,506	1.96	1,483	5,876	2,554
70	443,312	1.25	609	2,410	1,043	577,104	1.92	1,429	5,667	2,461
80	465,561	1.25	603	2,389	1,035	600,631	1.90	1,396	5,534	2,403
90	485,585	1.24	600	2,378	1,029	624,158	1.90	1,399	5,542	2,406
100	496,153	1.24	599	2,378	1,029	642,149	1.90	1,399	5,541	2,406
		Sub-MLRA 53-high					**Sub-MLRA 53-low**			
10	108,137	1.43	785	3,067	1,346	154,526	2.89	3,146	11,849	5,351
20	122,276	1.4	760	2,977	1,303	177,471	2.76	2,883	10,987	4,917
30	131,647	1.38	735	2,888	1,264	197,905	2.66	2,703	10,372	4,619
40	139,296	1.37	724	2,840	1,240	212,122	2.61	2,600	10,018	4,445
50	148,722	1.36	714	2,806	1,225	233,194	2.56	2,499	9,671	4,277
60	154,220	1.35	707	2,781	1,213	244,433	2.50	2,399	9,310	4,110
70	158,933	1.35	702	2,763	1,206	258,949	2.49	2,366	9,202	4,057
80	161,813	1.34	698	2,744	1,198	264,100	2.48	2,349	9,135	4,023
90	163,384	1.34	697	2,739	1,195	269,250	2.46	2,322	9,043	3,982
100	163,908	1.34	695	2,737	1,194	272,996	2.45	2,290	8,922	3,925

Table 3. Continued

		Sub-MLRA 58-high					Sub-MLRA 58-low			
10	214,256	1.61	997	3,919	1,711	189,820	1.84	1,307	5,109	2,239
20	237,362	1.55	927	3,646	1,590	209,611	1.80	1,242	4,871	2,133
30	271,843	1.49	864	3,412	1,486	232,890	1.76	1,199	4,711	2,062
40	300,904	1.45	817	3,231	1,403	244,696	1.73	1,156	4,543	1,984
50	312,982	1.43	790	3,122	1,358	254,592	1.73	1,152	4,528	1,977
60	329,261	1.41	771	3,052	1,326	265,388	1.70	1,108	4,368	1,904
70	338,189	1.40	756	2,984	1,295	277,083	1.68	1,086	4,282	1,865
80	341,865	1.38	741	2,934	1,272	286,978	1.66	1,064	4,196	1,827
90	345,016	1.38	736	2,915	1,265	288,778	1.65	1,048	4,134	1,801
100	346,066	1.37	726	2,878	1,248	292,376	1.63	1,032	4,068	1,770

[a]Coefficient of variation of C change, 95% confidence and 10% error.

in this empirical example, if Z and $\tilde{\sigma}_j$ are held constant as the credit payment and population increase, the required sample size decreases. This result may appear counterintuitive but, as discussed above, the relationship between credit payment and sample size is indeterminate. In an alternative location, sample size might exhibit a different relationship with credit price.

Sample Size, Error and Confidence

A smaller error bound or higher degree of confidence increases the sample size required to statistically represent each area at every price level, Table 3. A decrease in the allowable sample error from 10% to 5%, while keeping the confidence level at 95%, increases the total sample size approximately four fold. In contrast, an increase in confidence from 95% to 99%, holding the acceptable error at 10%, increases the sample size in all agro-ecozones at every price approximately 1.7 times. These results suggest that a small error bound and high confidence level will greatly increase the sampling burden and cost of measurement per credit in all areas at every market price for credits. The appropriate error bound and confidence interval will depend in part on the value placed on credits. At higher market prices, the costs of under or over-estimating the number of credits increase for producers and purchasers respectively. Therefore, in this situation there are greater benefits from more accurate measurement.

Measurement Cost per Credit

The average measurement cost of each credit in each agro-ecozone can be estimated by multiplying the number of samples required, Table 3, by the cost per sample and the frequency of sampling over the duration of the project and dividing by the total number of credits produced. Figure 2 plots the measurement cost per credit against the total number of credits produced at payments between $10 to $100 per credit in each agro-ecozone over three error and confidence combinations. Measurement costs range between a low of $0.01 per credit in sub-MLRA 52-high to $0.28 per credit in sub-MLRA 53a-low assuming a 10% error and 95% confidence interval, Figure 2. In each sub-MLRA, the measurement costs per credit exhibit economies of size. As the number of credits produced in a region increases, the average measurement cost per credit decreases. This is driven by two factors. First, as the price per credit increases, the sample size decreases (Table 3) and second as the price per credit increases the number of credits produced also increases. A decrease in acceptable error or an increase in the desired confidence level increases the measurement costs in proportion with the sample size shown in Table 3. This result would change if we relaxed the assumption that the cost of an individual sample remains constant and independent of the total number of samples. In practice we expect that the measurement cost per credit will decline as the sample size, *n*, increases.

Tables 4a, b and c, show that as a percentage of the total credit price, measurement costs per credit range between 0.001% and 10.6%. At 10% error and 95% confidence (parameter values used in several forestry projects) measurement costs do not exceed 3% of the credit purchase price.

Spatial Heterogeneity, Sample Size and Measurement Costs

Both sample size and measurement costs per credit vary between each agro-ecozone at every price level, Table 3 and Figure 2. Regional differences in measurement costs can be explained in part by the different degrees of spatial heterogeneity in soil C changes exhibited by each

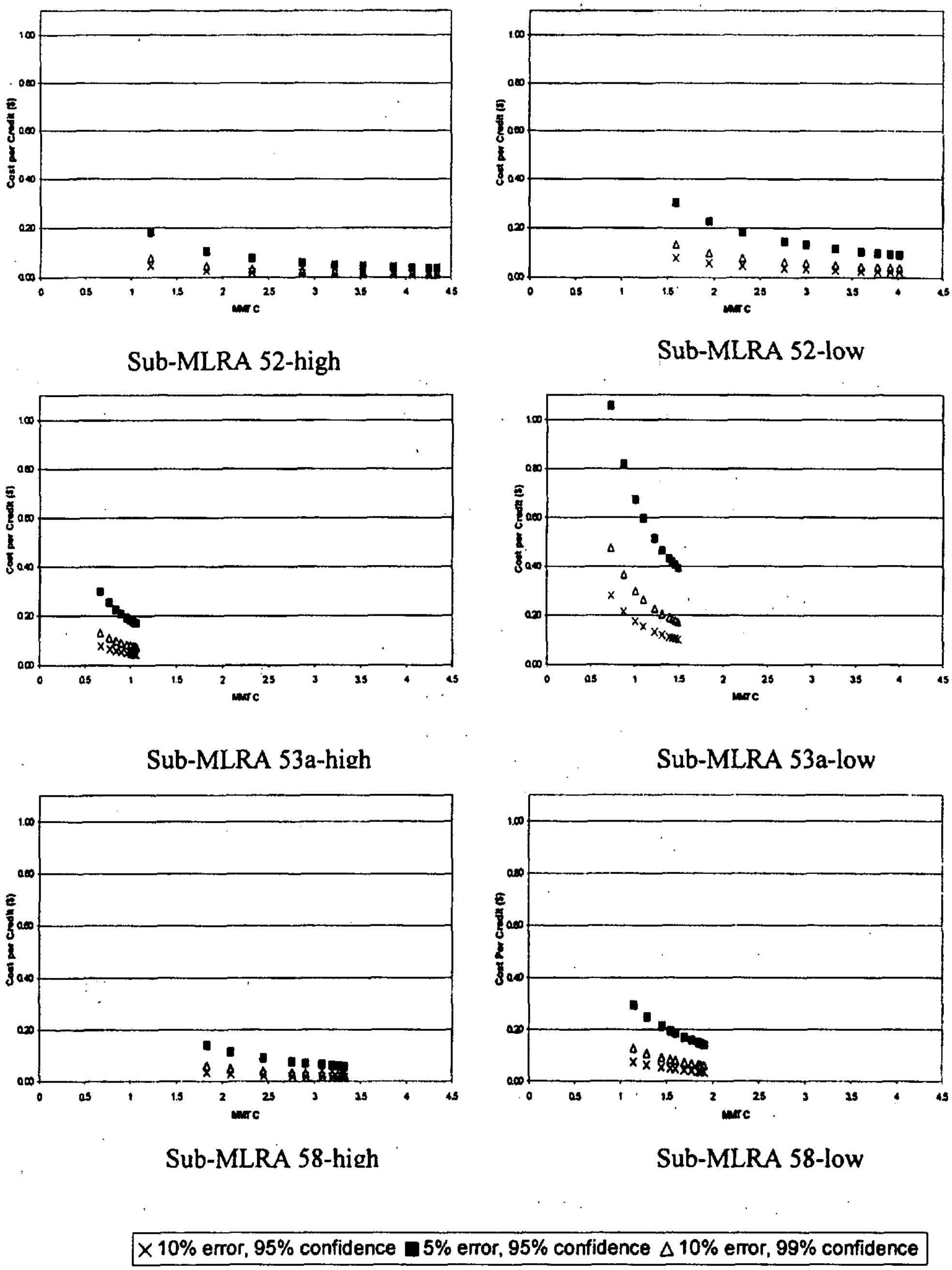

Figure 2. Sub-MLRA sample cost per credit, with varying error and confidence levels

Table 4a. Estimated measurement cost per credit, 10% error, 95% confidence

	Sub-MLRA 52-high		Sub-MLRA 52-low		Sub-MLRA 53-high		Sub-MLRA 53-low		Sub-MLRA 58-high		Sub-MLRA 58-low	
Price/ credit	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost
($)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)
10	0.046	0.463	0.077	0.774	0.077	0.765	0.281	2.808	0.036	0.356	0.075	0.749
20	0.027	0.133	0.058	0.289	0.065	0.323	0.215	1.076	0.029	0.145	0.063	0.316
30	0.019	0.064	0.046	0.154	0.057	0.190	0.175	0.584	0.023	0.077	0.054	0.181
40	0.015	0.037	0.037	0.091	0.053	0.132	0.155	0.386	0.019	0.048	0.049	0.122
50	0.013	0.025	0.033	0.066	0.049	0.097	0.133	0.266	0.018	0.036	0.047	0.094
60	0.011	0.019	0.029	0.049	0.046	0.077	0.119	0.199	0.016	0.027	0.043	0.071
70	0.010	0.015	0.026	0.037	0.045	0.064	0.111	0.158	0.015	0.022	0.040	0.057
80	0.010	0.012	0.024	0.030	0.043	0.054	0.107	0.134	0.015	0.019	0.038	0.047
90	0.009	0.010	0.023	0.026	0.043	0.048	0.104	0.115	0.015	0.016	0.037	0.041
100	0.009	0.009	0.023	0.023	0.043	0.043	0.100	0.100	0.014	0.014	0.035	0.035

[a]MPC = measurement cost per credit.

Table 4b. Estimated measurement cost per credit, 5% error, 95% confidence

	Sub-MLRA 52-high		Sub-MLRA 52-low		Sub-MLRA 53-high		Sub-MLRA 53-low		Sub-MLRA 58-high		Sub-MLRA 58-low	
Price/ credit	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost
($)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)
10	0.181	1.815	0.303	3.031	0.299	2.990	1.057	10.574	0.140	1.399	0.293	2.927
20	0.105	0.523	0.227	1.125	0.253	1.265	0.820	4.102	0.114	0.570	0.248	1.238
30	0.076	0.254	0.182	0.606	0.224	0.748	0.672	2.241	0.091	0.304	0.213	0.709
40	0.058	0.146	0.145	0.362	0.207	0.518	0.596	1.489	0.077	0.192	0.192	0.481
50	0.050	0.101	0.131	0.261	0.192	0.383	0.515	1.030	0.070	0.141	0.185	0.370
60	0.045	0.075	0.116	0.193	0.183	0.304	0.464	0.773	0.065	0.108	0.169	0.281
70	0.041	0.058	0.103	0.147	0.176	0.251	0.431	0.615	0.061	0.087	0.158	0.226
80	0.038	0.048	0.096	0.120	0.171	0.214	0.418	0.522	0.059	0.074	0.148	0.186
90	0.037	0.041	0.096	0.103	0.169	0.188	0.404	0.449	0.058	0.064	0.144	0.161
100	0.036	0.036	0.090	0.090	0.168	0.168	0.391	0.391	0.057	0.057	0.139	0.139

[a]MPC = measurement cost per credit.

Table 4c. Estimated measurement cost per credit, 10% error, 99% confidence

	Sub-MLRA 52-high		Sub-MLRA 52-low		Sub-MLRA 53-high		Sub-MLRA 53-low		Sub-MLRA 58-high		Sub-MLRA 58-low	
Price/ credit	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost	MPC	Measure- ment Cost
($)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)	($)	(% of price)
10	0.079	0.793	0.133	1.329	0.131	1.312	0.478	4.775	0.061	0.611	0.128	1.283
20	0.045	0.227	0.099	0.496	0.111	0.554	0.367	1.836	0.050	0.249	0.108	0.542
30	0.033	0.11	0.079	0.264	0.098	0.327	0.299	0.998	0.040	0.132	0.093	0.311
40	0.025	0.063	0.063	0.157	0.091	0.226	0.264	0.661	0.033	0.083	0.084	0.210
50	0.022	0.044	0.057	0.114	0.084	0.167	0.228	0.455	0.031	0.061	0.081	0.162
60	0.020	0.033	0.05	0.084	0.080	0.133	0.205	0.341	0.028	0.047	0.073	0.122
70	0.018	0.025	0.045	0.064	0.077	0.110	0.190	0.271	0.027	0.038	0.069	0.098
80	0.017	0.021	0.042	0.052	0.075	0.093	0.184	0.230	0.026	0.032	0.065	0.081
90	0.016	0.018	0.04	0.045	0.074	0.082	0.178	0.198	0.025	0.028	0.063	0.070
100	0.015	0.015	0.039	0.039	0.073	0.073	0.172	0.172	0.025	0.025	0.061	0.061

[a]MPC = measurement cost per credit.

area. The relative spatial heterogeneity is represented by the coefficient of variation of soil C changes from potential crop system changes in each agro-ecozone. At each price level modeled for the per-credit contract, we calculate the C changes associated with each crop system change and weight these changes by the number of hectares participating in each crop system change or strata. The coefficient of variation is the standard deviation divided by the weighted mean C change for the agro-ecozone. Table 3 also reports the relationship between sample size and spatial heterogeneity of an area (for 95% confidence and 10% error). The data indicate that these two variables are positively related. Figure 3a demonstrates that the measurement cost per credit is positively related to the degree of spatial heterogeneity within an area. At any given price, **regions with greatest spatial heterogeneity are associated with the largest samples and the highest average measurement costs per credit,** *MPC*, supporting our earlier statement.

Figure 3a demonstrates that there are also other factors that influence the measurement costs per credit. For example, sub-MLRAs 52-high and 53a-low exhibit the same spatial heterogeneity at several points, but the measurement costs per credit are higher in sub-MLRA 52-high over this range. Figure 3b demonstrates that measurement costs per credit decline as the total number of credits produced within an area increase. Figures 3a and 3b suggest that **the measurement cost per credit is in part determined by the spatial heterogeneity of soil C rates within an area and the economic and biophysical resource endowments that govern producer participation and credit generation at each price level.**

Total Contract Measurement Cost

The total cost of purchasing a given number of credits under a per-credit contract is compared with the cost of purchasing the credits under a per-hectare contract to provide an estimate of their relative cost or efficiency difference in the absence of measurement costs (Table 5). The efficiency difference between the two contracts identifies the maximum amount that could be spent on measuring credits under a per-credit program before the program becomes less efficient to implement than the per-hectare scheme. The total measurement costs under three error and confidence interval scenarios are shown in Table 5 and also expressed as a percentage of the efficiency difference between the two policies. At all credit price levels considered in the analysis, measurement costs under a per-credit program are a very small percentage of the efficiency difference between credit purchase costs under the per-hectare and per-credit programs, ranging between less than 1% to just over 12% (Table 5). Based on these estimates, a per-credit contract would remain more efficient than a per-hectare contract for purchasing credits within the study area even if measurement costs increased several-fold.

Table 6 presents the maximum number of samples that could be taken in each area for a cost equal to the efficiency difference between the two programs. These figures show that in the study area considerably more samples could be taken before the per-credit program becomes less efficient than the per-hectare program. The number of samples that could be taken within each agro-ecozone range between less than one to approximately 22 per hectare; that is, it is possible to perform a census of the entire area several times for a cost less than or equal to the efficiency difference between the two contract schemes in many areas. This result suggests that in some areas it would be economically feasible to measure carbon at a smaller spatial scale; e.g., the field scale, if the contracting parties desired this action.

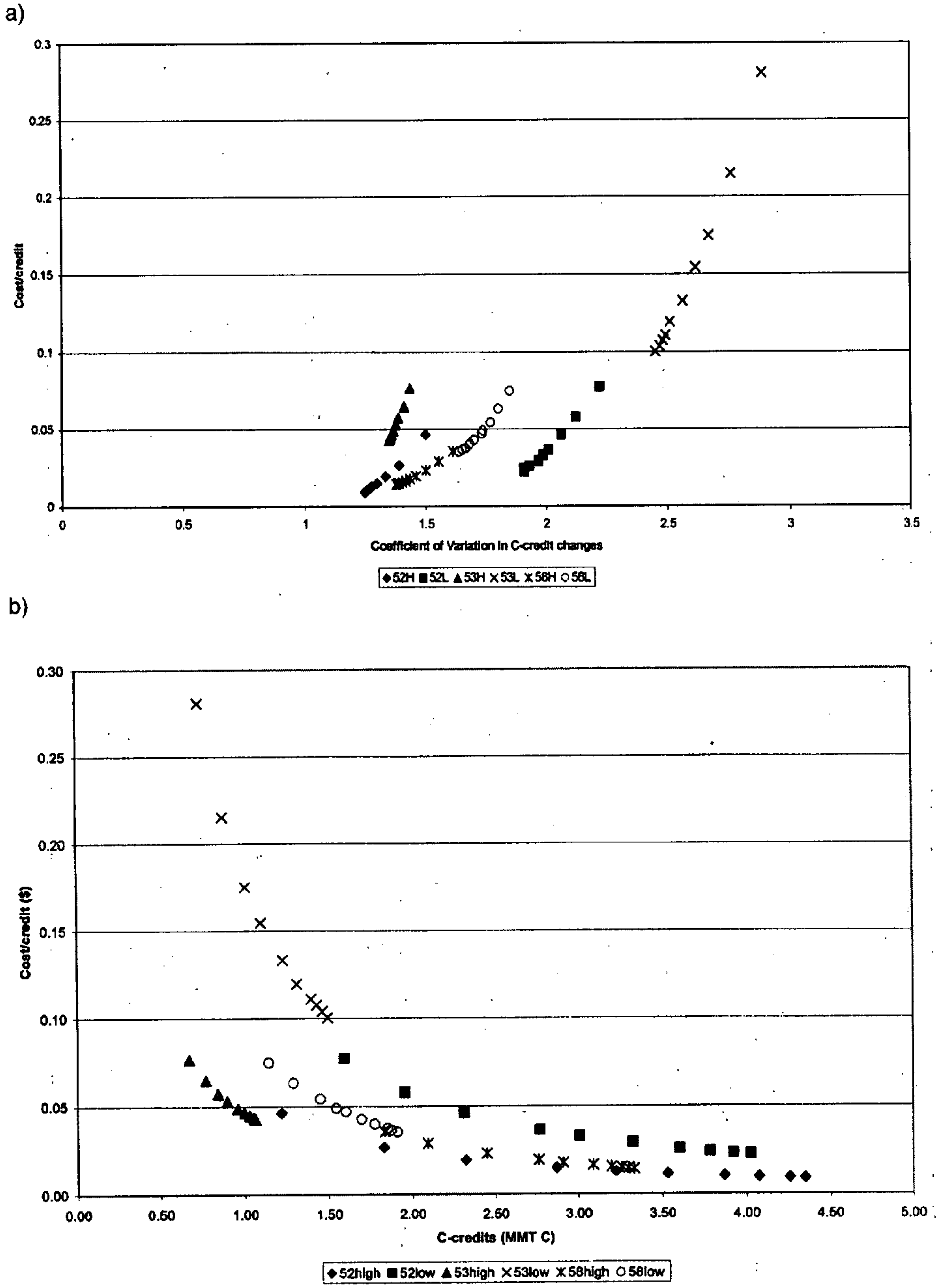

Figure 3 (a) Measurement cost per credit and coefficient of variation in C changes. (b) Measurement cost per credit and total number of credits

Table 5. Relative program efficiency and additional measurement costs under a per-credit program

Price/ credit	C	Ed	Measurement cost			C	ED	Measurement cost		
			ε = 10% 95% conf.	ε = 5% 95% conf.	ε = 10% 99% conf.			ε = 10% 95% conf.	ε = 5% 95% conf.	ε = 10% 99% conf.
($)	(Mt)	($mil.)		($)		(Mt)	($mil.)		($)	
		Sub-MLRA 52-high					**Sub-MLRA 52**			
10	1.06	1.84	56,378	221,126	96,648	1.17	5.44	123,364	483,308	211,893
			(3.06%)	(12.02%)	(5.25%)			(2.27%)	(8.88%)	(3.90%)
30	2.23	7.15	44,723	176,731	76,939	2.58	27.1	3106,732	420,774	183,540
			(0.63%)	(2.47%)	(1.08%)			(0.39%)	(1.55%)	(0.68%)
50	3.14	12.07	40,990	162,194	70,260	3.01	34.32	99,202	392,291	170,575
			(0.34%)	(1.34%)	(0.58%)			(0.29%)	(1.14%)	(0.50%)
70	3.82	14.20	39,877	157,807	68,296	3.48	40.46	93,571	371,075	161,146
			(0.28%)	(1.11%)	(0.48%)			(0.23%)	(0.92%)	(0.40%)
90	4.38	13.11	39,288	155,711	67,379	3.78	39.12	91,607	362,890	157,545
			(0.30%)	(1.19%)	(0.51%)			(0.23%)	(0.93%)	(0.40%)
		Sub-MLRA 53-high					**Sub-MLRA 53-low**			
10	0.54	17.4	51,402	200,827	88,136	0.55	6.37	206,000	775,873	350,383
			(0.30%)	(1.15%)	(0.51%)			(3.23%)	(12.18%)	(5.50%)
30	0.92	49.22	48,128	189,106	82,767	1.00	20.26	176,992	679,159	302,452
			(0.10%)	(0.38%)	(0.17%)			(0.87%)	(3.35%)	(1.49%)
50	0.94	44.10	46,753	183,737	80,213	1.27	28.95	163,635	633,257	280,058
			(0.11%)	(0.42%)	(0.18%)			(0.57%)	(2.19%)	(0.97%)
70	0.98	38.50	45,967	180,921	78,969	1.39	28.20	154,926	602,547	265,652
			(0.12%)	(0.47%)	(0.21%)			(0.55%)	(2.14%)	(0.94%)

Table 5. Continued

90	1.09	40.42	45,640 (0.11%)	179,350 (0.44%)	78,249 (0.19%)	1.44	20.29	152,045 (0.75%)	592,136 (2.92%)	260,741 (1.29%)
		Sub-MLRA 58-high					Sub-MLRA 58-low			
10	1.41	34.26	65,284 (0.19%)	256,616 (0.75%)	112,036 (0.33%)	0.85	24.44	85,582 (0.35%)	334,537 (1.37%)	146,610 (0.60%)
30	2.54	90.28	56,575 (0.06%)	223,418 (0.25%)	97,303 (0.11%)	1.44	61.81	78,511 (0.13%)	308,476 (0.50%)	135,020 (0.22%)
50	2.77	69.57	51,729 (0.07%)	204,429 (0.29%)	88,922 (0.13%)	1.72	73.27	75,433 (0.10%)	296,493 (0.40%)	129,454 (0.18%)
70	3.04	43.84	49,503 (0.11%)	195,392 (0.45%)	84,797 (0.19%)	1.79	55.43	71,111 (0.13%)	280,385 (0.51%)	122,120 (0.22%)
90	3.48	28.02	48,193 (0.17%)	190,874 (0.68%)	82,832 (0.30%)	1.75	23.38	68,623 (0.29%)	270,694 (1.16%)	117,929 (0.50%)

[a]Quantity of C, in millions of tonnes, supplied under payments that range between \$10 per credit to \$90 per credit under a per-credit payment policy. These quantities are estimated using regression analysis of original model results. This was necessary to ensure that the per-hectare and per-credit marginal cost curves overlap at all relevant C levels. These quantities are an approximation of actual model results used to generate figures in earlier tables and reflect the estimated marginal cost curves from Antle et al (2003).

[b]Efficiency difference, ED = Total purchase cost of credits under a per-hectare payment policy minus total purchase cost of credits under a per-credit payment policy. Figures in parentheses are measurement costs as a percentage of the efficiency difference, ED.

Table 6. Maximum number of samples within each agro-ecozone and per hectare

Price/ credit	Population	ED	Total samples	Samples per hectare	Population	ED	Total samples	Samples per hectare
($)	(ha)	($mil.)			(ha)	($mil.)		
	Sub-MLRA 52-high				**Sub-MLRA 52-low**			
10	158,524	1.84	112,401	0.71	283,708	5.44	332,315	1.17
30	277,276	7.15	436,775	1.58	388,611	27.13	1,657,300	4.26
50	372,671	12.07	737,324	1.98	494,068	34.32	2,096,518	4.24
90	443,312	14.2	867,440	1.96	577,104	40.46	2,471,594	4.28
	Sub-MLRA 53-high				**Sub-MLRA 53-low**			
10	108,137	17.4	1,062,920	9.83	154,526	6.37	389,126	2.52
30	131,647	49.22	3,006,720	22.84	197,905	20.26	1,237,630	6.25
50	148,722	44.1	2,693,952	18.11	233,194	28.95	1,768,479	7.58
90	158,933	38.5	2,351,863	14.80	258,949	28.2	1,722,663	6.65
	Sub-MLRA 58-high				**Sub-MLRA 58-low**			
10	214,256	34.26	2,092,853	9.77	189,820	24.44	1,492,975	7.87
30	271,843	90.28	5,514,966	20.29	232,890	61.81	3,775,809	16.21
50	312,982	69.57	4,249,847	13.58	254,592	73.27	4,475,870	17.58
90	338,189	43.84	2,678,070	7.92	277,083	55.43	3,386,072	12.22

[a]Efficiency difference, ED = Total purchase cost of credits under a per-hectare payment policy minus total purchase cost of credits under a per-credit payment policy.

[b]Number of samples that could be purchased for a sum equal to the efficiency difference.

[c]Number of times a soil sample could be taken on **each** hectare within the population over the duration of the contract.

CONCLUSION

This paper develops a conceptual framework designed for measuring soil C credits under a per-credit contract. An empirical example is implemented for the dry-land crop-producing region of Montana and used to examine the factors that influence measurement costs for soil C. We hypothesize that the sample size and measurement costs per credit within a given region are influenced by the market price for credits and the spatial heterogeneity of credit accumulation. Results from the empirical application support these hypotheses and demonstrate that the measurement costs per credit are inversely related to the price offered for each credit. In addition, at every credit price examined, the measurement cost per credit is larger in regions that exhibit higher spatial heterogeneity. A decrease in the acceptable sampling error or, an increase in the confidence level result in higher measurement costs.

The results presented above have several implications for the costs of measuring soil credits and the relative efficiency of a per-credit contract design versus a per-hectare contract design. First and most importantly, the measurement costs per credit could be a very small percentage of the value of the credit as reflected in the payment level. In this analysis the measurement costs ranged between a maximum of 3% to 10.6% of total credit value (depending on the assumed error and confidence level). In addition, we show that total measurement costs at the sub-MLRA scale are a small percentage of the efficiency difference between the two contracts and that measurement at finer scales could be economically feasible in some areas. These results suggest that in most cases the additional costs of a measurement are unlikely to render per-credit contracts less efficient than the per-hectare contract, unless the opportunity costs of supplying credits are very similar under both contract schemes. Previous work by Antle et al (2003) shows that the efficiency gain from a per-credit contract over a per-hectare contract increases with the degree of spatial heterogeneity in each region and, although measurement costs per credit are also positively related to spatial heterogeneity, they do not outweigh the efficiency gains. Regions that exhibit more heterogeneity are able to support higher measurement costs because they have the greatest difference in the opportunity cost of supplying credits under each contract type.

Second, the error and confidence level chosen for the sample design will be, in part, a function of the value of each credit. At high credit prices there are larger costs to over or under estimating the number of credits, thus more resources could be merited to pay for measurement costs. Third, measurement costs are influenced by the size of each contract region. In a recent study, Mooney et al (2004) showed that decreasing the size of the contract and aggregating credits over fewer producers can increase the costs associated with measurement under a per-credit contract. Results from this study suggest that some areas could bear substantially higher measurement costs if greater spatial resolution in the measurement scheme was thought to be beneficial.

Under the measurement scheme proposed in this paper, soil C accumulation rates are fixed over each region and are independent of the actual location and composition of the population supplying credits. When the population supplying credits is small (at low prices) the estimated measurement costs per credit could be larger than necessary because the variability of soil C rates could be overstated. This suggests that the optimal size of each contract area could be related to the price offered for credits. The general results from this study are likely to apply to other agricultural regions that are considering supplying credits and implementing a measurement scheme.

There are several possible extensions to the current work that could provide additional insight into the optimal design of measurement schemes for soil credits. For example, alternative sampling schemes could be considered as well as the implications of accounting for spatial autocorrelation between carbon values. The question of adjusting the estimated C variability to reflect the population at each price level merits further investigation. Another possible extension would be to implement an option value approach to producer decision making that could lead to changes in the number of producers agreeing to participate in a contract in a given period.

There are several other issues that could influence contracting costs that are not considered in this paper. For example, we do not account for any potential cost differences attributable to program administration, tracking participants and negotiating contracts. The relative size of these expenditures will influence the relative efficiency of each contract type. In addition to C sequestration, agricultural practices influence the emissions of other GHGs. Ideally, efforts to mitigate GHGs would require a full accounting framework that accounts for both changes in the net emissions of C (as discussed here) as well as nitrous oxide and other gases. These gases will also require measurement, and could further increase contracting costs.

NOTES

[1]Credits can be expressed either as representing the reduction of one unit of C from the atmosphere or a unit of CO_2. In this paper, a credit represents one tonne (1,000 Kg) of C. Most trades to date are denominated in tonnes of CO_2 (Rosenzweig et al 2002). A tonne of C removed from the atmosphere is equivalent to 3.7 tonnes of CO_2.

[2]In this paper, a credit is equal to one tonne of C.

[3]We define the efficiency difference as the difference in the cost of purchasing a given number of credits under a per-hectare contract minus the cost of those credits under a per-credit contract.

[4]Changes in fertilizer, tillage and other management practices will be more difficult to verify than changes in cropping systems. This creates a potential problem of asymmetric information between producers, who have complete knowledge of their practices, and the buyers of soil C credits, who cannot readily observe producer practices (Wu and Babcock 1996).

[5]The producer opportunity cost of producing each credit can be calculated as:

$$\frac{\textit{opportunity cost of changing a cropping system}}{\textit{change in quantity of carbon sequestered}}$$ and is explained in detail by Antle et al (2001).

[6]The sampling scheme does not assume that changes in C sequestration are spatially autocorrelated. In the event that spatial autocorrelation is present, the sample size could be reduced (or some scheme adopted to ensure samples are further apart) because individual observations will contain information about their neighbors.

[7]For example, a Giddings probe.

[8]In earlier research, we used these models to estimate C supply curves under per-credit and per-hectare contracts (Antle et al 2003).

[9]The number of hectares enrolled within the contract could be the same under an option value approach to producer decision making if producers expect future contracts for C to offer lower long-term prices than the current contract offered (or expect that future contracts for C will offer prices that are the same as those offered by the contract in the current period). In the event an option value approach was used and producers expected contracts for C in future periods to offer higher C prices, it is likely that fewer producers would agree to adopt the carbon contract during the current period.

[10]The possible crop system changes are: spring wheat/barley–fallow to winter wheat–fallow; spring wheat/barley–fallow to grass; spring wheat/barley–fallow to continuous spring wheat; spring wheat/barley–fallow to continuous winter wheat; winter wheat–fallow to grass; winter wheat–fallow to continu-

ous spring wheat; winter wheat–fallow to continuous winter wheat; grass to continuous spring wheat; grass to continuous winter wheat; continuous spring wheat to continuous winter wheat.

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