Contracting for Soil Carbon Credits: Design and Costs of Measurement and Monitoring

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Abstract

Many firms anticipate that a cap on greenhouse gas emissions will eventually 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 emissions. If agricultural producers participate in the emerging market for tradable C-credits, it must be possible to verify that actions farmers take do increase the amount of C in soils and this increase can be maintained over the length of the contract.

In this paper we develop a prototype measurement and monitoring scheme for C-credits sequestered in agricultural soils and estimate its costs for the small grain-producing region of Montana using an econometric-process simulation model. Three key results emerge from the prototype framework. First, the efficiency of measurement and monitoring procedures for agricultural soil C sequestration depends on the price of C credits. Second, we find that at all price levels, costs of measuring and monitoring are largest in areas that exhibit the greatest heterogeneity in carbon values. Third, in a case study application of our prototype measurement and monitoring scheme, we find that if we assume similar error and confidence levels as forestry contracts, the upper estimate of measurement and monitoring costs associated with a contract that pays farmers per tonne of C sequestered is 3% of the value of a C-credit. This cost is small relative to the estimated net value of the contract. Thus we conclude that measurement and monitoring costs are not likely to be large enough to prevent producers from participating in a market for tradable credits.

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Introduction and rationale

Many industrialized counties are considering ways 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 means of reducing GHG (UNFCCC 1998). One proposal is a C (carbon) credit-trading scheme that would allow participating countries to receive credits for domestic or international projects that reduce emissions beyond a "business as usual" case. In 2001, the Bush administration announced that it would not sign the Kyoto protocol but in February 2002 announced a global climate change initiative that proposed to include forest and agricultural soil C sequestration in U.S. conservation programs and to develop accounting rules for sequestration projects (White House 2002). While the Bush climate change initiative is voluntary, the document acknowledged that limits on greenhouse gas emissions are an option to achieve future reductions. Many firms anticipate that a cap on greenhouse gas emissions will eventually 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 emissions (Rosenzweig *et al.* 2002).

Since 1996, approximately 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 agriculture could also contribute to GHG reductions. U.S. emissions could be reduced by up to

8% by increasing C sequestered in agricultural soils (Lal *et al.* 1998) and these credits could be purchased at prices competitive with forest carbon (Antle *et al.* 2002a). Although C-credit trades are occurring, institutions, contracts, enforcement mechanisms and policies have not been standardized. These elements will influence the costs of supplying and purchasing soil C.

If agricultural producers participate in the emerging market for tradable C-credits, it must be possible to verify that actions farmers take do increase the amount of C in soils and this increase can be maintained over the length of the contract. This study is motivated by the fact that C stored in agricultural soils cannot be observed or measured directly in the same way that point-source industrial emissions or creation of above ground biomass in forests. Several scientists and policy makers have questioned whether it will be feasible to include agricultural soil C sequestration in either government programs to sequester C or in a market for tradable C-credits.

In this paper we develop a prototype measurement and monitoring scheme for C-credits sequestered in agricultural soils. Three key results emerge from the prototype framework. First, the efficiency of measurement and monitoring procedures for agricultural soil C sequestration depends on the price of C credits. This result follows from the fact that, farmer participation in contracts to sequester soil C depends on both economic and biophysical conditions. Given typical farm sizes and rates of C sequestration in agricultural soils, a relatively large number of farmers are needed to sequester enough C to create a commercially traded C contract. In this respect, measurement and monitoring for agricultural soil C sequestration differs importantly from procedures that have been developed for contracts between one or a few buyers and single sellers of C sequestered in large forested areas. Second, we find that at all price levels, costs of measuring and monitoring are largest in areas that exhibit the greatest heterogeneity in carbon

values. Third, in a case study application of our prototype measurement and monitoring scheme, we find that if we assume similar error and confidence levels as forestry contracts, the upper estimate of measurement and monitoring costs associated with a contract that pays farmers per tonne of C sequestered is 3% of the value of a C-credit. This cost is small relative to the estimated net value of the contract. Thus we conclude that measurement and monitoring costs are not likely to be large enough to prevent producers from participating in a market for tradable credits.

Generating credits by sequestering carbon

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 C credits from a less expensive source until a time where it is not as costly to bring new technologies on line. At COP 7 – Marrakech, 2001, international discussions indicated that agriculture and forest sinks could be recognized as a source of C credits (UNFCCC 2002). If agriculture and forestry generate credits at lower cost than other sources or technological change, these industries will be strong participants in the market.

Forestry and agriculture generate credits in roughly the same way. 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 woody biomass represented by trees and 20% in the below ground root and soil system (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 *et al.* (1982), Mann (1986), and Rasmussen and Parton (1994), estimate that 20% to 50% of soil C is lost during the initial 20 to 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).

Design of projects to create carbon credits

Although trading rules are not finalized, private companies and non-profit groups are engaging in pilot projects that generate C credits. For example, the energy company, *PacifiCorp* has invested in forest preservation in Bolivia as well as tree planting projects in Oregon that sequester C (PacifiCorp 1997). The Nature Conservancy and Winrock International are also involved in many activities in South and Central America that generate C credits from forest activities. Several projects are described in Watson *et al*. (2000). There are several incentives for buyers to purchase C-credits voluntarily in the absence of a formal US market; for example, gaining early mover advantage in a developing market by amassing experience with early trades, or informing the policy debate. C-credit sellers also participate for similar reasons as well as the opportunity to market a new commodity that previously had no value.

C-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 C-credit represents one tonne (1,000 Kg) of C. Most trades to date are denominated in tonnes CO_2 (Rosenzweig *et al.* 2002). A tonne of C removed from the atmosphere is equivalent to 3.7 tonnes of CO_2. Currently, the market for C-credits is

thin and trades rely on simple legal and financial arrangements. At a minimum, projects that generate certified credits involve one buyer and one seller in addition to some form of measurement, monitoring and certification. Certification is important if credits are intended to be tradable commodities in the marketplace at a future date. Buyers have either purchased property outright and then established a project that generates credits, or purchased rights to C-credits on a property over the project lifetime (see projects described in Watson *et al*. 2000 and PacifiCorp 1997).

To conform to Articles 3.3 and 3.4 of the Kyoto protocol, projects must meet the standards of *additionality*, *permanence*, *duration* and *leakage* (UNFCCC 1998; Watson *et al*. 2000). *Additionality*, means that credits generated must be additional to any changes in C that would have occurred under a "business as usual" scenario. *Permanence* refers to the length of time that C is sequestered and maintained in a sink such as a forest or agricultural soil. *Duration* refers to the length of the contract. *Leakage* concerns the issue of project activities causing economic agents to take actions that would increase GHG emissions elsewhere. An additional concern for soil C sequestration is *saturation*; soil C can be accumulated over time only until some maximum amount of C per volume of soil is reached.

Several guides have been developed for measuring and monitoring carbon within forestry and agroforestry projects (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 stored in woody biomass. Contracts for forest C-credits have involved a single seller with large carbon quantities and multiple buyers (for examples see, Watson *et al*. 2000) or multiple sellers with a single buyer (ENN 2001).

Contracts for C-credits generated from agricultural practices are likely to share many common elements with those used in forestry. However based on sample trades to date, contracts for C-credits are expected to be larger than 273 tonnes C (1,000 tonnes CO_2) an amount too large for a single agricultural producer to fill in most situations (Rosenzweig *et al.* 2002). For example consider a contract for 300 C-credits between a buyer and a group of farmers. Research indicates that under most conditions C can be sequestered in agricultural soils at rates less than 1 tonne/ha/yr over a period of approximately 20 years (Watson *et al.* 2000). Assuming: a rate of 0.5 tonnes/ha/yr for 20 years; and that a typical farm commits 100 hectares, then six farms would be required per contract. In practice many trades have involved quantities significantly larger than 300 tonnes C (Rosenzweig *et al.* 2002) thus we can expect that contracts for agricultural C-credits are likely to be characterized by individual buyers contracting with many sellers or an intermediary that pools credits from many sellers. Measurement and monitoring schemes that are suitable for these arrangements need to be developed for soil C.

Contracting for agricultural soil carbon credits

There are two cost components associated with supplying C-credits. First the opportunity cost of sequestering C and second the costs associated with enforcing contracts and monitoring the quantity of C-credits. The opportunity cost is influenced by the design of incentives provided to producers to sequester soil C. Several studies have demonstrated that per-tonne contracts result in the production of a given number of C-credits at a lower opportunity cost than per-hectare contracts (Antle and Mooney 2002; Antle *et al.* 2002b; Pautsch *et al.* 2001) because payments are directly linked to the number of credits produced. However, very little work has examined the related costs of monitoring and enforcing each contract.

Under a per-hectare contract design, producers are paid for each hectare of land that they convert to a management practice thought to sequester additional carbon. Payments are based on the number of hectares that are converted to a recommended practice, rather than the quantity of carbon accumulated. This design is very similar to existing government programs for agriculture such as the conservation reserve program and is most likely to be used for government programs where the actual amount of carbon stored does not need to be determined, (or at least not to a high degree of accuracy). The measuring and monitoring requirements of such a program are minimal and extend to ensuring that producers are engaged in a recommended production practice. Although government programs have not included detailed measurement and monitoring systems in the past this is no guarantee that they will not in the future.

Under a per-tonne contract design, each hectare of land entering the program receives a different payment corresponding to the number of C-credits created on that hectare. In contrast to per-hectare contracts, the number of C-credits created is an important part of per-tonne contracts and needs to be measured to ensure that suppliers have met the terms of the contract. Per-tonne contracts are suited to a market for C where payments are made for each C-credit created and stored over the duration of the contract. Ideally, producers would receive payments for C sequestered using an unlimited range of practices. However measurement and certification would be simplified if only a subset of the most likely best management practices were considered as eligible for payments related to C-credits. Then monitoring resources can be focused on, and developed for, the most productive practices.

Economic logic suggests that profit-maximizing producers will enter into contracts to sequester C in soil when the benefits of the contracts outweigh the costs. Ignoring for the moment any transactions costs, consider a contract for T periods that pays a producer g dollars

per time period for each hectare that is entered into a contract (a per-hectare contract) intended to increase soil C. In order to increase soil C, the producer must change land use and/or other management practices from the initial system i to some subsequent alternative system s. For the producer to switch management practices, the present value of system s plus the present value of government payments g must be greater than the present value of system i. Letting D be the present value of 1 at interest rate r for T periods, and letting p_i be the annual returns to the ith system, the present value of expected returns for the ith system is $V_i = p_i D(r,T)$ and the present value of expected returns from system s is $V_s = p_s D(r,T)$. The present value of a payment of g dollars per hectare each year is $G = gD(r,T)$. Thus the producer will switch from system i to system s for T years if $V_i < V_s + G$, which implies $p_i < p_s + g$ or $(p_i - p_s) < g$ each period. Thus we can conclude, as expected, that a producer will agree to switch to practice s if the opportunity cost per hectare of changing practices, $(p_i - p_s)$, is less than the payment per hectare g, otherwise the producer will continue to use practice i.

A market for tradable emissions credits would effectively offer producers a payment for each tonne of sequestered soil C (a per-tonne contract). The producer is offered a price, P ($ per tonne of C), if the producer can switch from production system i to system s and produce an additional ΔC_{is} tonnes of C per hectare, the payment per hectare to the producer will be $P \Delta C_{is}$. Following the logic of the previous paragraph, the producer will benefit from the contract if and only if $p_i < p_s + P \Delta C_{is}$ or if $(p_i - p_s)/\Delta C_{is} < P$, that is, if and only if the opportunity cost per tonne is less than or equal to the price per tonne. The greater economic efficiency of the per-tonne contract follows from the fact that it provides the incentive for soil C to be sequestered up to the point where the marginal cost per tonne equals the market price per tonne, whereas the per-

hectare contract provides an incentive to change practices regardless of how much soil C is accumulated.

Figure 1 outlines some transactions costs associated with implementing per hectare and per tonne contracts for soil C. Both contract types are likely to incur costs associated with negotiating contracts and verifying that producers are maintaining practices that generate C-credits and store these credits for a specified duration. Identification and negotiation costs can be thought of as occurring prior to final agreements to enter a contract and are common to both contract designs. Costs associated with measuring and monitoring C-credits occur once the contracts to participate have been finalized. These costs are generated by two main activities: first, ensuring that producers are engaged in practices eligible for a payment and second, measuring and monitoring the number of C-credits.

Under typical per-hectare contracts, such as those used for agricultural conservation programs in the US, practices eligible for payments are specified in the contract but the quantity of environmental benefit such as the amount of soil erosion prevented is not. Thus in a per-hectare contract for soil C sequestration we would expect practices to be specified but not the amount of soil C sequestered and it may not be necessary to monitor the number of credits produced. However as stated earlier, the quantity of C-credits is the key factor under a per-tonne contract. While economists have established that a per-tonne contract results in production of soil C credits more efficiently than a per-hectare contract it is unclear whether the additional costs associated with measuring and monitoring C-credits will offset these efficiency gains. The difference between the opportunity cost of supplying a given quantity of C-credits under a per-tonne contract versus a per-hectare contract provides an upper bound on the additional costs that can be incurred in measurement, monitoring, verification and certification of credits under per-

tonne contracts (Pautsch *et al.* 2001; Antle *et al.* 2002b). The additional costs of measuring and monitoring carbon credits produced by any project need to be considered with the opportunity cost of producing carbon under each contract design to evaluate which is the most efficient for credit trades (Moxey, White and Ozanne 1999). Stavins (1998, 1999) suggests that the costs of measurement and monitoring required to implement per-tonne contracts for forestry could be prohibitively expensive.

Design of a measurement and monitoring scheme for agricultural C credits

Following figure 1 measurement and monitoring costs (M) associated with contracts for C credits can be decomposed into two parts: ensuring that participants are engaged in activities eligible for payments and verifying the quantity of carbon that has been sequestered. Both per-hectare and per-tonne contracts need to verify that producers are engaged in practices that are eligible for a payment under the terms of their contracts. This could be accomplished through remote sensing, aerial photography or drive by inspection. The second cost component comes from measuring and monitoring the number of C-credits produced over a given area. One means of estimating the quantity of C-credits produced by a group of producers is statistical sampling. Measurement and monitoring costs (M) are expressed in dollars as

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

where:

z = per-tonne contract, per-hectare contract

sc= random sampling, stratified random sampling, systematic sampling, or other sampling scheme.

AV = cost of verifying producers are complying with practices specified in the contract ($)

S = Cost of implementing a sampling protocol ($)

n_{sc} = number of samples for a given sample scheme, sc.

CN = cost per sample ($)

F= frequency of sampling

where it is assumed that $\dfrac{\partial S_z}{\partial n_{SC}} > 0,\quad \dfrac{\partial S_z}{\partial CN} > 0\quad$ and $\quad \dfrac{\partial S_z}{\partial F} > 0$.

In the event that both contracts are offered within an area they would attract different sets of participants (Antle and Mooney 2002; Antle *et al.* 2002b). However this may not necessarily result in substantial differences in the costs of large scale monitoring practices (AV)[1] especially when this can be done using remote sensing or similar techniques. Under a per-hectare contract, payments are independent of the number of credits generated, thus there is no need to verify their quantity hence $S_{per-hectare}(N_{sc}, CN, F) = 0$, whereas under a per–tonne contract the number of credits created is specified in the contract hence $S_{per-tonne}(N_{sc}, CN, F) > 0$. Therefore the additional measurement and monitoring costs under a per-tonne contract are attributable to the costs of statistical sampling under this scheme.

Because C-credits for a single contract are likely to be supplied from several producers covering a large area, we propose a combination of field measurements and predictive models to estimate changes in carbon quantities. The prototype measuring and monitoring scheme we propose for per-tonne contracts contains the following elements:

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[1] 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 farmers, who have complete knowledge of their practices, and the buyers of soil C credits, who cannot readily observe farmer practices (Wu and Babcock 1996).

a. Use predictive biophysical models to estimate the expected rate of soil carbon sequestration, resulting from changes in management practices within the contract area, taking into account specific climatic and soil conditions.

b. Measure baseline levels of carbon within a contract area using statistical sampling techniques and laboratory testing.

c. Monitor increases in carbon over the duration of the contract by periodic field samples and laboratory testing.

d. Measure increase in carbon levels at the end of the contract.

Several sampling designs can be used to select a sample from a population including simple random, stratified and cluster sampling (Thompson 1992). Stratified random sampling has been used to measure and monitor carbon sequestration in forest projects (Boscolo *et al*. 2000; Brown *et al*. 2000) and is also suitable for estimating soil carbon 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 thus the costs associated with measuring and monitoring C-credits (Thompson 1992; McCall 1982).

Using a stratified sampling approach, the population is defined as those producers that have agreed to enter into a contract to supply C-credits. The population can be divided into heterogeneous groups or strata that are internally homogeneous with respect to a chosen characteristic, and then sampled independently using a random sampling design. Within a given area covered by a contract, the *population* to be sampled is *all hectares of cropland that switch from a historical cropping system to a new system that sequesters additional carbon as a result of a payment offered per C-credit*. The population within each stratum is homogeneous with

respect to a cropping system change. The *unit of analysis* is an individual "field" of *one hectare* in size.

Population size 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.* 2001a). When the price offered for C-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 C-credits. Therefore we expect that *the population to be sampled will increase as the price offered per credit increases*. There is some price that is high enough for every hectare within an area to switch practices and supply C credits; after this point the population to be sampled would remain constant for any further price increases.

The total sample size, *n*, required to estimate the mean number of C-credits supplied by each hectare within a *population* can be calculated using (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).

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

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,……, J

N_j = total number of hectares in the jth stratum

$\widetilde{\sigma}_j$ = initial estimate of the standard deviation of change in carbon over 20 years

         resulting from a crop system change in the jth stratum

ε = absolute error permitted for the statistic used as an estimate of the population

         parameter

An important implication of (2) is that an increase in the spatial heterogeneity of C-credit production (represented by larger values of $\widetilde{\sigma}_j$), holding Z, ε, N, and N_j constant, will increase the total sample size needed to estimate the change in C credits. Thus, all other things equal, *measuring and monitoring will be more costly in areas that exhibit the greatest spatial heterogeneity, because these areas will require larger sample sizes.*

In general we would expect spatial heterogeneity to increase as the area sampled increases in size. The degree of spatial heterogeneity exhibited by a population electing to supply soil C-credits within a given area will be influenced in part by the relative location of each individual within the area. For example, soil C is likely to exhibit less heterogeneity when the hectares supplying C are clustered together. Conversely if the analysis units are scattered spatially, the degree of heterogeneity in soil C rates could increase. The location of each hectare within the population supplying C-credits at any given price level is unknown before contract agreements are signed and will vary as the price of C-credits change.

Under the measurement and monitoring protocol proposed in this paper an estimate of the expected variability of soil C sequestration resulting from crop system changes is calculated using the C sequestration potential of each major soil type within each agroecozone (described

later). Thus 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. When Z, ε and

$\tilde{\sigma}_j$ remain constant over all payments but $N = \sum_{j=1}^{J} N_j$, increases, the influence on sample size, n,

and the costs of measuring and monitoring, M, is indeterminate. If the denominator in (2)

increases more than the numerator n will decrease as the payments for C-credits increase,

whereas if the denominator does not increase as fast as the numerator, n will decrease.

The sampling scheme described above 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.

In the field soil samples are taken using specialized probes[2], then bagged and transported

to a laboratory to be air-dried, ground and measurements taken of total carbon. The cost per

sample (CN) can be calculated from (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 ($)

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[2] For example a Giddings probe.

The frequency of sampling activities, F, will be influenced by the duration of the project and the rate of C accumulation. Measurements to establish changes in soil carbon may not need to be conducted annually because carbon levels do not change dramatically from year to year (assuming no disturbance). 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 measure/monitor every five years. McConkey and Lindwall (1999) suggest measuring soil carbon every three years on fields converted to no-till. Brown *et al*. (2000) plan to measure carbon sequestered within a 30-year forest project in years 3, 5, 10, 15, 20, 25 and 30. At a minimum, F=2, reflecting the need to establish baseline levels of carbon at the beginning of the project and final carbon levels at its conclusion.

Model description and data

The framework developed above was used to estimate the costs of measuring and monitoring soil C credits under a per-tonne contract for soil C sequestration in the small grain-producing region of Montana. Producers' responses to payments offered for C-credits under a per-tonne contract were simulated using an econometric-process model. Hectares that switch management practices to supply C credits at a given price per tonne of C are the population to be sampled. The amount of C sequestered on a hectare in response to each production system change is estimated by agroecozone using Century, a crop-ecosystem model designed to study soil C dynamics. Antle *et al.* (2001a) present the estimates in detail. These estimates are used within the econometric-process simulation model to estimate the value of C payments for each hectare and the total quantity of C sequestered within a given agroecozone.

Site-specific field scale data are used to estimate production models of output supply and input demand. 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.

Within agroecozone m, let $\delta_k^i = 1$ if system i is used on field k and let $\delta_k^i = 0$ otherwise, define $\delta_k = \Sigma_i \delta_k^i$, and let π_k^n be the returns to a non-crop land use on field k and π_k^i be the returns to cropping system i on field k. The econometric-process simulation model is based on the assumption that producers make land use decisions in the absence of policy according to:

$$\max_{\delta_k^i \ldots \delta_k^I} \sum_{i=1}^{I} \delta_k^i \, \pi_k^i(p_k^i, w_k^i, e_k, z_k^i) + (1-\delta_k)\, \pi_k^n. \tag{4}$$

Under a per tonne contract that pays producers for each C-credit produced, in agroecozone m the returns for a hectare switched from cropping system i to cropping system s are $\pi_k^s + P\Delta c_m^{is}$ where Δc_m^{is} is the increase in carbon accumulation resulting from switching a hectare from system i to system s in the mth agroecozone calculated by the Century ecosystem model. If $\pi_k^s + P\Delta c_m^{is} > \pi_k^i$ then the producer will switch from crop system i to crop system s and sequester Δc_m^{is} tonnes of C. Detailed descriptions of the model and estimation procedures can be found in Antle and Capalbo (2001b), Antle *et al.* (2001a) and Antle *et al.* (2002b). Site-specific management and input data are available from a detailed survey of fields on 425 farms in the dryland-cropping region of Montana (Antle *et al.* 2001a).

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 3 MLRAs within Montana. A MLRA (major land resource area) 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 6 sub-MLRAs (figure 2). Century was used to calculate average C rates for common cropping systems within each sub-MLRA. The simulations showed that most of the C accumulation occurred over a 20-year period after a change in management. Seven cropping systems were considered, spring wheat-fallow, barley-fallow, winter wheat-fallow, grass and spring wheat, barley and winter wheat-continuous cropping systems. Century results show C-credits can be generated by increasing the intensity of crop production and changing from crop-fallow to grass and continuous cropping systems (Antle *et al.* 2001a).

Empirical application

The econometric production simulation model is run assuming payment levels for C-credits that increase in $10 increments between $10 and $100. At each payment level, the model calculates the number of hectares that switch production practices (the *population* to be sampled) and the number of C-credits produced within each sub-MLRA. Information generated from the econometric production simulation model and the Century ecosystem model is used to estimate the sample size necessary for measurement and monitoring activities within each agroecozone. The cost per sample is estimated according to (3) and specific assumptions are described below.

Determining sample size 'n' for each agroecozone

Within a given agroecozone (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 C-credits. For example, fields that switch from a spring wheat-fallow system to a continuous-spring wheat system form one strata while those fields that switch from a barley-fallow system to continuous-spring wheat would be another strata. In total, the model includes ten possible cropping system changes that produce C-credits; thus each agroecozone can have a maximum of ten strata. The number of hectares within any payment scheme (the *population* of interest) is calculated by the model and is known and finite. As the payment level offered for each C credit increases, production practices will change on a larger number of hectares. This means that as the price per C-credit increases a different number of hectares will join the scheme and the size of the population and the cost of sampling per C credit will change. Unlike sampling from an infinite population, changes in the population size will change the size of the sample required to estimate its parameters. At different market prices for C-credits N and N_j are estimated using the econometric process simulation model while $\tilde{\sigma}_j$ is calculated from inputs into the Century model. A summary of the data required to estimate sample size are presented in table 1.

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 ¾ 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 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 for monitoring in years 5 and 10 and finally at the conclusion of the contract in year 20. Therefore F = 4, in the calculation of measurement and monitoring costs.

Measuring and monitoring costs

The total cost of a measuring and monitoring scheme in any given region can be calculated empirically as M=n*CN*F while the average measurement and monitoring cost per C-credit MPC=M/Q where Q equals the total number of credits generated within a given area at a specific price level.

Sensitivity analysis

Sample size and measurement and monitoring costs per credit are calculated for three alternative scenarios by varying the measurement error, ε, and confidence level associated with the sampling scheme. Initially, measurement and monitoring costs per C credit are estimated for each sub-MLRA assuming an error of 10% (ε = +/-10%) and 95% confidence (Z = 1.96) consistent with previous measurement and monitoring protocols (Boscola *et al.* 2000; Brown *et al.* 2000). In addition, the sensitivity of the sample size, n, and the measurement and monitoring

cost per credit, MPQ, to changes in ε, Z are explored using two additional sampling schemes assuming and error of 5% and confidence level of 95% (ε = +/- 5%, Z = 1.96) and an error of 10% and a confidence level of 90% (ε = +/-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

C-credit price, population and sample size

As the price offered per C credit increases, the population to be sampled in each area also increases following the expectations presented earlier, table 3. The population in sub-MLRA 52-high increases from 158,524 hectares at a price of $10/credit to 496,153 hectares at a price of $100/credit. Each agroecozone follows the same pattern, with the proportional increase in population being in the range of 151% to over 300% as the price of C-credits increase from $10/credit to $100/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 corresponding to a C-credit price of $100 to a high of 3,146 in sub-MLRA 58-high at a price of $10/credit, table 3. As the price of C-credits increase from $10 to $100 the sample size required for each agroecozone decreases between 10% and 30%. These results show that in this empirical example, as Z, ε, and $\tilde{\sigma}_j$ are held constant and *the price per C-credit increases, the population to be sampled increases and the size of the sample decreases*. If soil C variability and soil C changes within each agroecosystem were calculated at each price level, population and sample size might exhibit a different relationship.

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 agroecozones 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 and monitoring per credit in all areas at every market price for C-credits. The appropriate error bound and confidence interval will depend in part on the value placed on C-credits. At higher market prices, the costs of under or over estimating the number of C-credits increase for producers and purchasers respectively, therefore in this situation, there are greater benefits from more accurate measurement and monitoring.

Measuring and monitoring cost per credit

The average cost of measuring and monitoring each credit in each agroecozone 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 3 plots the cost/credit of measuring and monitoring against the total number of credits produced at payments between $10 to $100/credit in each agroecozone over three error and confidence combinations. Measuring and monitoring costs range between a low of 1 cent per C-credit in sub-MLRA 52-high to 28 cents per C-credit in sub-MLRA 53a-low assuming a 10% error and 95% confidence interval, figure 3. In each sub-MLRA the measuring and monitoring

costs per credit exhibit economies of scale. As the number of C-credits produced in a region increase the average measuring and monitoring cost per credit decreases. This is driven by two factors. First, as the price per C-credit increases, the sample size decreases (table 3) and second as the price per C-credit increases the number of C-credits produced also increases. A decrease in acceptable error or an increase in the desired confidence level increase the costs of measurement and monitoring in proportion with the sample size shown in table 3, i.e. if sample size increases by 4, the measurement and monitoring cost per credit also increases by 4 at any given payment level within an agroecozone. This result is driven by the fact that we have assumed that the cost of an individual sample remains constant and independent of the sample size.

Tables 4a, b and c, show that as a percentage of the total credit price, measuring and monitoring costs per credit range between 100th of 1% to 10.6%. At 10% error and 95% confidence (consistent with several forestry projects) measurement costs do not exceed 3% of the credit purchase price.

Spatial heterogeneity, sample size and measurement and monitoring costs

Both sample size and measurement and monitoring costs per C-credit vary between each agroecozone at every price level, table 3 and figure 3. Regional differences in measuring and monitoring costs can be explained in part by the different degrees of spatial heterogeneity in rates of C sequestration exhibited by each area. The relative spatial heterogeneity of soil C changes in an agroecozone is represented by the coefficient of variation. Table 5 reports the sample size and spatial heterogeneity of an area. The data indicate that these two variables are positively related. Figure 4a demonstrates that the measuring and monitoring cost per C-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 costs of measuring and monitoring per C-credit, supporting our earlier statement.

Figure 4a demonstrates that there are also other factors that influence the measuring and monitoring costs per C-credit. For example, sub-MLRAs 52-high and 53a-low exhibit the same spatial heterogeneity at several points but the measuring and monitoring costs per credit are higher in sub-MLRA 52-high over this range. Figure 4b demonstrates that measuring and monitoring costs per C-credit decline as the total number of credits produced within an area increase. Figures 4a and 4b suggest that the *measurement and monitoring cost per C-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 C-credit generation at each price level*.

Conclusions

This paper develops a conceptual measurement and monitoring protocol for C-credits generated by increasing agricultural soil C under per-tonne contracts. An empirical example of this framework is implemented for the dry-land crop producing region of Montana and used to examine the factors that influence measuring and monitoring costs for soil C. We hypothesize that the sample size and measuring and monitoring costs per C-credit within a given region are influenced by the market price for C-credits and the spatial heterogeneity of C-credit accumulation. Results from the empirical application support these hypotheses and demonstrate that the measuring and monitoring costs per C-credit are inversely related to the price offered for each credit. In addition, at every price level for C-credits, the measuring and monitoring 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 raise the costs of measuring and monitoring. The proportional increase in costs is larger for a decrease in the acceptable error.

The results presented above have several implications for the costs of measuring and monitoring soil C-credits and the relative efficiency of a per-tonne contract design versus a per-hectare contract design. First, the measuring and monitoring costs per C-credit could be a very small percentage of the value of the credit as reflected in the payment level. In this analysis the measuring and monitoring costs ranged between a maximum of 3% to 10.6% of total credit value (depending on the assumed error and confidence level). This suggests that in most cases the additional costs of a measuring and monitoring protocol for C-credits is unlikely to make a per tonne contract less efficient than the per hectare contract, unless the opportunity costs of supplying C-credits are very similar under both contract schemes. Previous work by Antle *et al.* (2002b) shows that the efficiency gain from a per-tonne contract over a per-hectare contract increases with the degree of spatial heterogeneity, in each region and although measuring and monitoring costs per C-credit are also positively related to spatial heterogeneity, they do not outweigh the efficiency gains. Regions with high heterogeneity are able to support higher measuring and monitoring costs as they have the greatest difference in the opportunity cost of supplying C-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 C-credit. At high credit prices there are larger costs to over or under estimating the number of credits, thus more resources could be merited for measurement and monitoring. Third, the measurement and monitoring costs are influenced by the size of each contract region. Under the measuring and monitoring protocol, soil C accumulation rates are fixed over each region and are independent of the actual location and composition of the

population supplying C-credits. When the population supplying C-credits is small (at low prices) estimated measuring and monitoring costs per C-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 C-credits. The general results from this study are likely to apply to other agricultural regions that are considering supplying C-credits and implementing a measuring and monitoring scheme.

Extensions to the current work could provide additional insight into the optimal design of measuring and monitoring schemes for soil C-credits. For example, alternative sampling schemes could be considered as well as the implications of changing the spatial scale of analysis on measuring and monitoring costs. In addition the question of adjusting estimated C-variability to reflect the population at each price level merits further investigation.

Several other issues that could influence contracting costs are not considered in this paper. In addition to C-sequestration, agricultural practices influence the emissions of other greenhouse gases. Ideally, efforts to mitigate greenhouse gases 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 monitoring, and this could further increase contracting costs. A second important issue not addressed in this paper relates to the transactions costs associated with assembling a large number of producers to jointly fill C-contracts.

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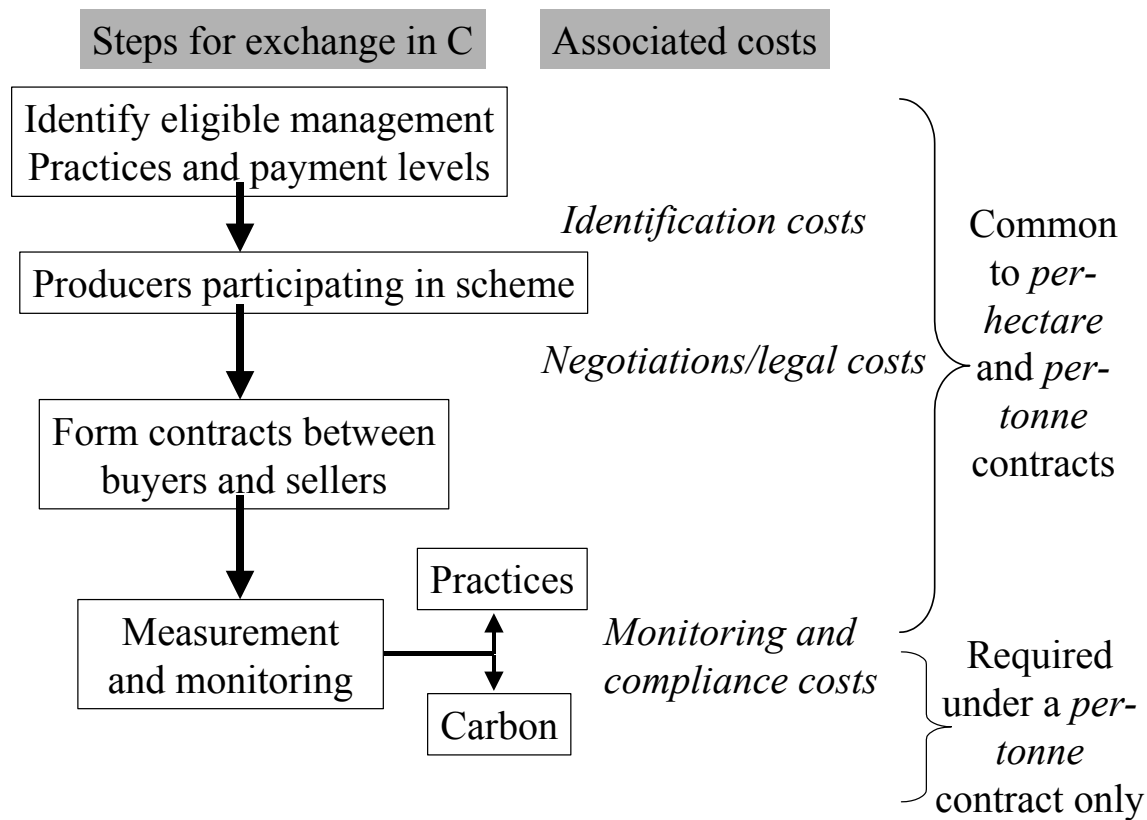
Figure 1. Costs associated with negotiating contracts for soil carbon sequestration
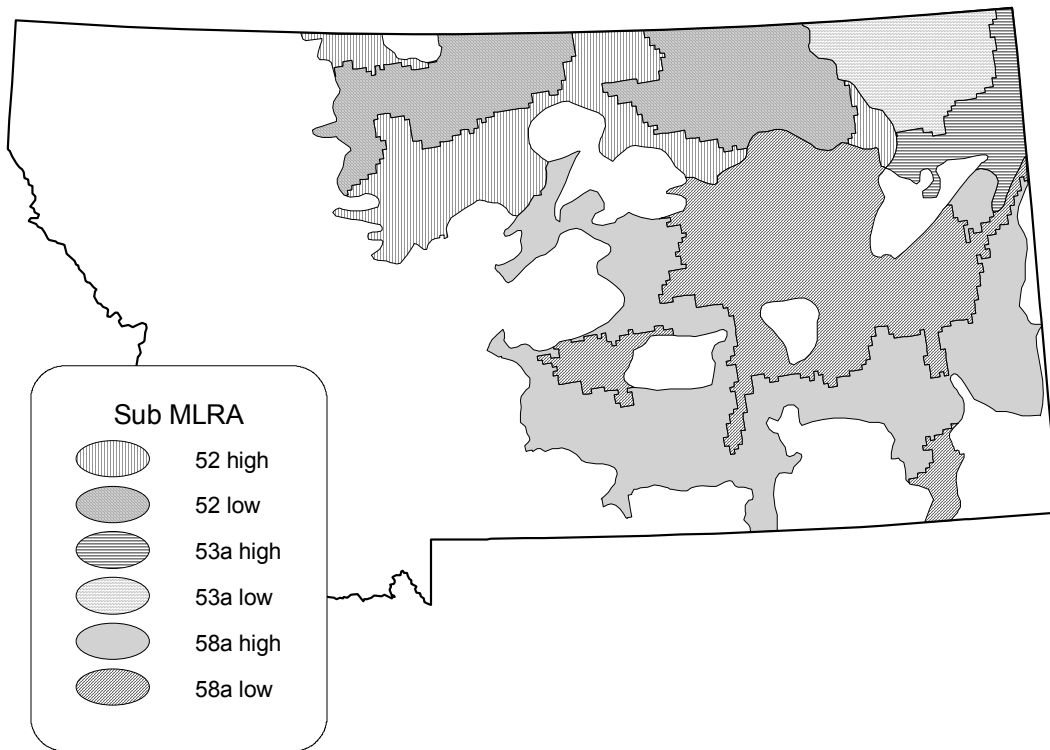
Figure 2. Agroecozones as represented by Sub-MLRAs[1] in Montana
    [1]MLRA= major land resource area. These areas were subdivided into high and low rainfall
    zones to create sub-MLRAs.
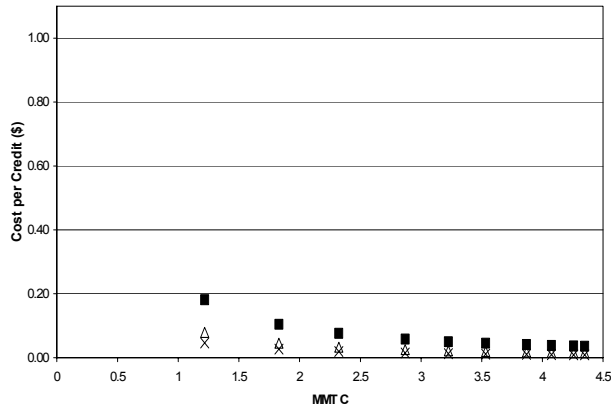
Sub-MLRA 52high
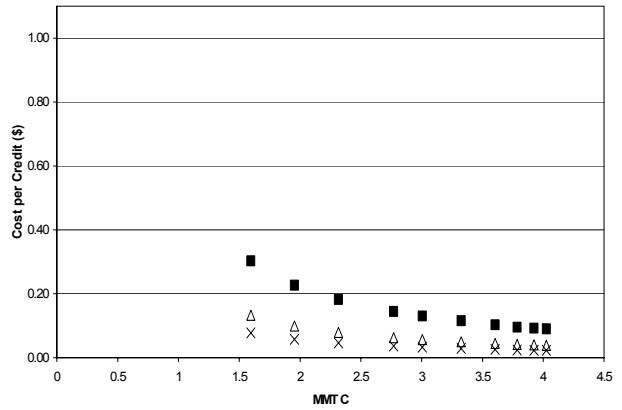
Sub-MLRA 52 low
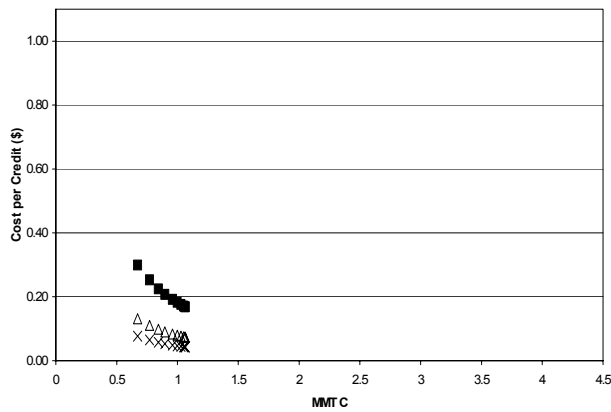
Sub-MLRA 53a high
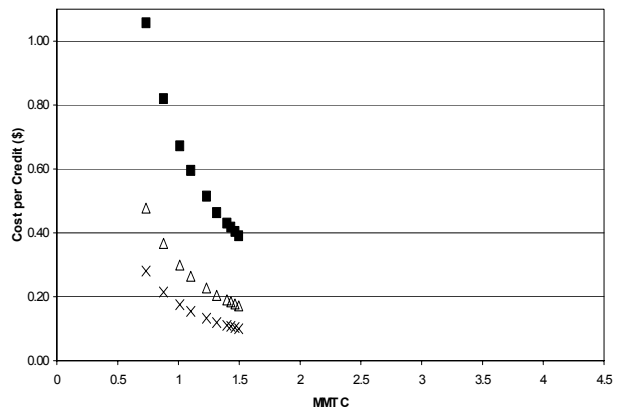
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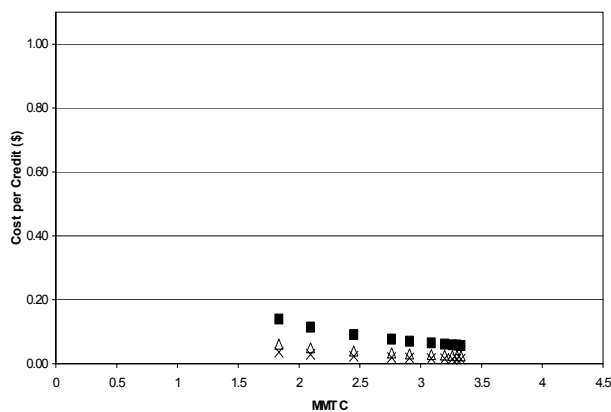
Sub-MLRA 58 high
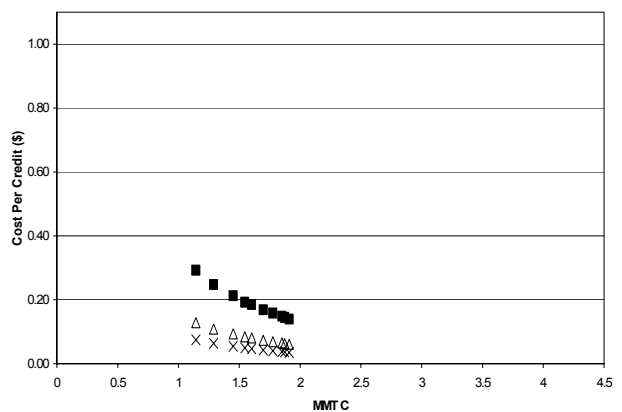
Sub-MLRA 58 low

✕ 10% error, 95% confidence ■ 5% error, 95% confidence △ 10% error, 99% confidence

Figure 3. Sub-MLRA sample cost per C credit – with varying error and confidence levels
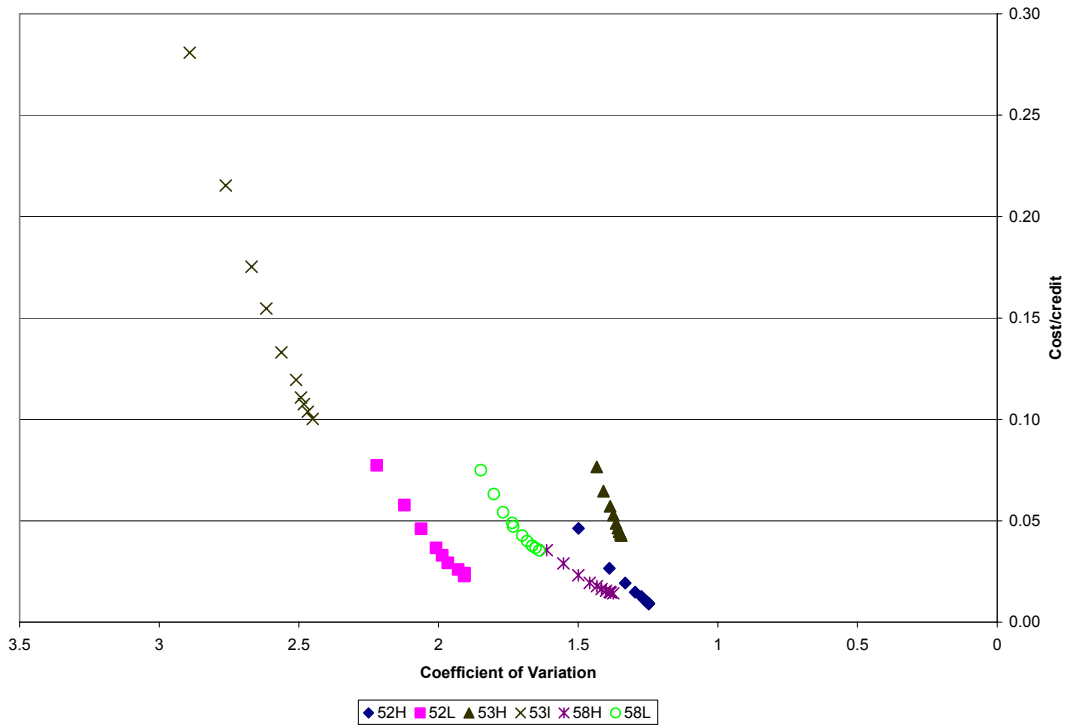
Figure 4a. Measurement and monitoring cost per credit and coefficient of variation in C.
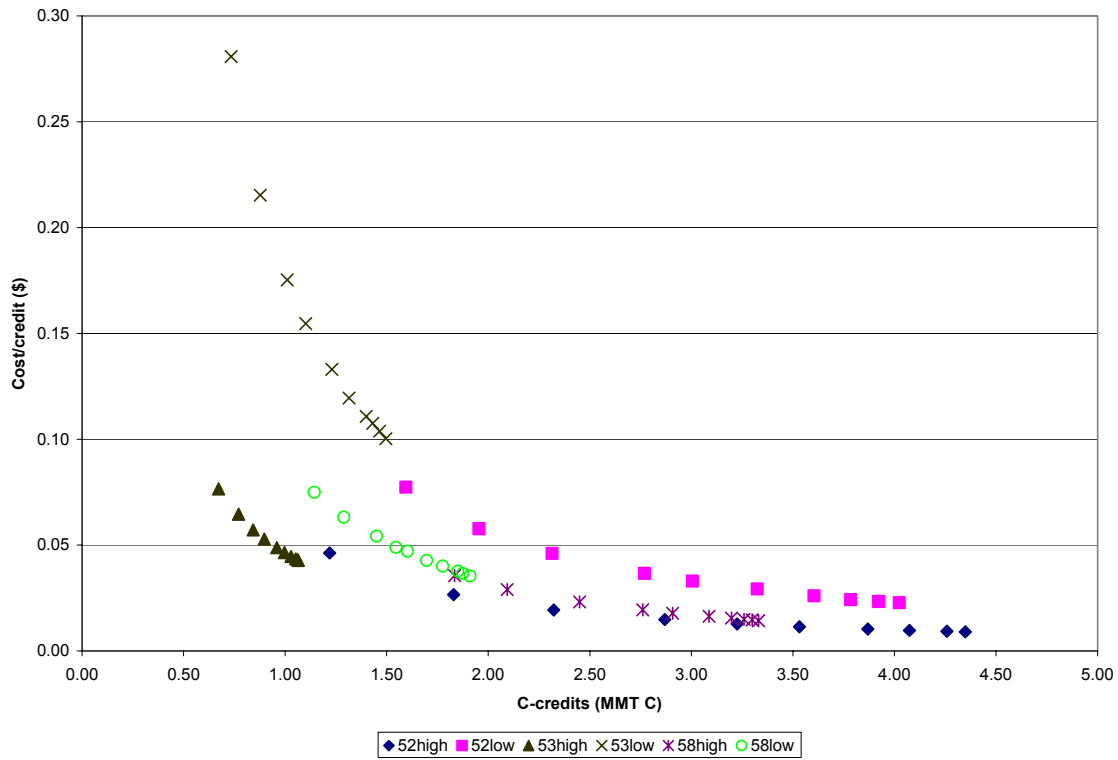
Figure 4b. Measurement and monitoring cost per credit and total number of credits.

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

Variable Name	Value	Source
Z	1.96 (95% confidence)	Normal tables
ε	Varies by agroecozone	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 agroecozone	Number of hectares that enter into contracts to supply C credits at a given price within an agroecozone. Obtained from simulation model results.
j	Varies by agroecozone	Number of strata within an agroecozone. Obtained from simulation model results.
N_j	Varies by agroecozone and stratum	Number of hectares within stratum j. Obtained from simulation model results.
$\widetilde{\sigma}_j$	Varies by agroecozone and stratum	Estimated standard deviation of C changes within each strata and agroecozone. Calculated from input data to Century model.

Table 2. Cost estimates for field sampling

Variable Name	Value	Assumptions and/or Sources
L	$232/day	Lead technician @ $17/hour over 8 hours = $136/day Driver/assistant @ $12/hour over 8 hours = $96/day
R	$70/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/day	Assuming a driving distance of 150 miles per day, fuel consumption of 15 miles per gallon and price of $1.65/gallon.
ND	50/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/sample	Estimate provided by Keith Paustian, Natural Resources Ecology Laboratory, Colorado State University.

Table 3. Population and total sample size '*n*' by Sub-MLRA – with varying price per tonne, error and confidence

Price/C-credit ($)	Sub-MLRA 52-high				Sub-MLRA 52-low				Sub-MLRA 53-high			
	Population	$\varepsilon=10\%$ 95% Confid.	$\varepsilon=5\%$ 95% Confid.	$\varepsilon=10\%$ 99% Confid.	Population	$\varepsilon=10\%$ 95% Confid.	$\varepsilon=5\%$ 95% Confid.	$\varepsilon=10\%$ 99% Confid.	Population	$\varepsilon=10\%$ 95% Confid.	$\varepsilon=5\%$ 95% Confid.	$\varepsilon=10\%$ 99% Confid.
10	158,524	861	3,377	1,476	283,708	1,884	7,381	3,236	108,137	785	3,067	1,346
20	225,828	741	2,923	1,271	334,914	1,724	6,777	2,961	122,276	760	2,977	1,303
30	277,276	683	2,699	1,175	388,611	1,630	6,426	2,803	131,647	735	2,888	1,264
40	336,517	649	2,561	1,112	458,085	1,548	6,117	2,661	139,296	724	2,840	1,240
50	372,671	626	2,477	1,073	494,068	1,515	5,991	2,605	148,722	714	2,806	1,225
60	406,601	616	2,442	1,059	542,506	1,483	5,876	2,554	154,220	707	2,781	1,213
70	443,312	609	2,410	1,043	577,104	1,429	5,667	2,461	158,933	702	2,763	1,206
80	465,561	603	2,389	1,035	600,631	1,396	5,534	2,403	161,813	698	2,744	1,198
90	485,585	600	2,378	1,029	624,158	1,399	5,542	2,406	163,384	697	2,739	1,195
100	496,153	599	2,378	1,029	642,149	1,399	5,541	2,406	163,908	695	2,737	1,194

Price/C-credit ($)	Sub-MLRA 53-high				Sub-MLRA 58-low				Sub-MLRA 58-high			
	Population	$\varepsilon=10\%$ 95% Confid.	$\varepsilon=5\%$ 95% Confid.	$\varepsilon=10\%$ 99% Confid.	Population	$\varepsilon=10\%$ 95% Confid.	$\varepsilon=5\%$ 95% Confid.	$\varepsilon=10\%$ 99% Confid.	Population	$\varepsilon=10\%$ 95% Confid.	$\varepsilon=5\%$ 95% Confid.	$\varepsilon=10\%$ 99% Confid.
10	154,526	3,146	11,849	5,351	214,256	997	3,919	1,711	189,820	1,307	5,109	2,239
20	177,471	2,883	10,987	4,917	237,362	927	3,646	1,590	209,611	1,242	4,871	2,133
30	197,905	2,703	10,372	4,619	271,843	864	3,412	1,486	232,890	1,199	4,711	2,062
40	212,122	2,600	10,018	4,445	300,904	817	3,231	1,403	244,696	1,156	4,543	1,984
50	233,194	2,499	9,671	4,277	312,982	790	3,122	1,358	254,592	1,152	4,528	1,977
60	244,433	2,399	9,310	4,110	329,261	771	3,052	1,326	265,388	1,108	4,368	1,904
70	258,949	2,366	9,202	4,057	338,189	756	2,984	1,295	277,083	1,086	4,282	1,865
80	264,100	2,349	9,135	4,023	341,865	741	2,934	1,272	286,978	1,064	4,196	1,827
90	269,250	2,322	9,043	3,982	345,016	736	2,915	1,265	288,778	1,048	4,134	1,801
100	272,996	2,290	8,922	3,925	346,066	726	2,878	1,248	292,376	1,032	4,068	1,770

Table 4a. Estimated cost of measurement and monitoring per credit – 10% error, 95% confidence

Price/credit ($)	Sub-MLRA 52-high		Sub-MLRA 52-low		Sub-MLRA 53-high		Sub-MLRA 53-low		Sub-MLRA 58-high		Sub-MLRA 58-low	
	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% 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

Table 4b. Estimated cost of measurement and monitoring per credit – 5% error, 95% confidence

Price/credit ($)	Sub-MLRA 52-high		Sub-MLRA 52-low		Sub-MLRA 53-high		Sub-MLRA 53-low		Sub-MLRA 58-high		Sub-MLRA 58-low	
	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% 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

MPQ=measurement and monitoring cost per tonne C.

Table 4c. Estimated cost of measurement and monitoring per credit – 10% error, 90% confidence

Price/credit ($)	Sub-MLRA 52-high		Sub-MLRA 52-low		Sub-MLRA 53-high		Sub-MLRA 53-low		Sub-MLRA 58-high		Sub-MLRA 58-low	
	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% of Price)	MPQ ($)	Measurement Cost (% 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	0.110	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	0.050	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	0.040	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

MPQ=measurement and monitoring cost per tonne C.

Table 5. Coefficient of variation in C and sample size (10% error, 95% confidence)

Price/credit ($)	Sub-MLRA 52-high		Sub-MLRA 52-low		Sub-MLRA 53-high		Sub-MLRA 53-low		Sub-MLRA 58-high		Sub-MLRA 58-low	
	CV	Sample Size	CV	Sample Size	CV	Sample Size	CV	Sample Size	CV	Sample Size	CV	Sample Size
10	1.49	861	2.22	1,884	1.43	785	2.89	3,146	1.61	997	1.84	1,307
20	1.38	741	2.12	1,724	1.40	760	2.76	2,883	1.55	927	1.80	1,242
30	1.33	683	2.06	1,630	1.38	735	2.66	2,703	1.49	864	1.76	1,199
40	1.29	649	2.00	1,548	1.37	724	2.61	2,600	1.45	817	1.73	1,156
50	1.27	626	1.98	1,515	1.36	714	2.56	2,499	1.43	790	1.73	1,152
60	1.26	616	1.96	1,483	1.35	707	2.50	2,399	1.41	771	1.70	1,108
70	1.25	609	1.92	1,429	1.35	702	2.49	2,366	1.40	756	1.68	1,086
80	1.25	603	1.90	1,396	1.34	698	2.48	2,349	1.38	741	1.66	1,064
90	1.24	600	1.90	1,399	1.34	697	2.46	2,322	1.38	736	1.65	1,048
100	1.24	599	1.90	1,399	1.34	695	2.45	2,290	1.37	726	1.63	1,032