Influence of Project Scale and Carbon Variability on the Costs of Measuring Soil Carbon Credits

Siân Mooney,[a] John Antle,[b] Susan Capalbo,[c] and Keith Paustian[d]

[a]*Department of Agricultural and Applied Economics, University of Wyoming*

[b,c]*Department of Agricultural Economics and Economics, Montana State University*

[d]*Department of Soil and Crop Sciences and Natural Resource Ecology Laboratory*
Colorado State University

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Siân Mooney*
John Antle**
Susan Capalbo
and
Keith Paustian***

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Corresponding Author: Siân Mooney
Assistant Professor
Dept. Agricultural and Applied Economics
University of Wyoming
P.O. Box 3354
Laramie, Wyoming 82071-3354
Phone: 307-766-2389
Fax: 307-766-5544
E-mail: smooney@uwyo.edu

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*Assistant Professor, Department of Agricultural and Applied Economics, University of Wyoming, Laramie, Wyoming 82071.
** Professor and University Fellow, Resources For the Future; and Professor respectively, Department of Agricultural Economics and Economics, Montana State University, Bozeman, Montana 59717.
***Professor, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado 80523.

Abstract

A large body of research suggests that US cropland soils can also sequester significant amounts of C and are a promising source of C-credits. This paper presents a framework for assessing the transactions costs associated per-hectare and per-credit contract types and addresses the potential magnitude of transactions costs associated with measuring soil C credits under a per-credit contract within the dry-land crop region of Montana. In the empirical analysis, we estimate the total measurement costs for soil C-credits and investigate how changes in contract (and region) size as well as increases in C-credit variability affect total measurement costs. The empirical analyses suggest that increasing the size of the contract and aggregating credits over a larger number of producers can lower measurement costs associated with the per-credit contract, even in the face of increasing C variability thus contracts for large quantities of soil credits increase the likelihood that the per-credit contract remains more efficient than the per-hectare contract. However, these empirical results reflect the specific data and conditions present within the case study region. The theoretical expectation is that sample size and measurement costs can either increase or decrease as the population to be sampled increases. Thus the measurement costs associated with a per-credit contract could respond differently from this analysis across the spatial extent of the US.

Key words: Carbon sequestration, economics, measurement cost, project size, carbon variability, carbon contract, transactions costs.

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Under the Kyoto protocol, countries are required to reduce their emissions of carbon dioxide (CO_2) and other greenhouse gasses (GHG), thought to contribute to global warming. By December 2002, 101 countries had ratified the Kyoto protocol, representing 43.9 percent of 1990 CO_2 emissions. When 55 percent of CO_2 emissions are represented, the protocol will be implemented. One of the major emitters of GHG, the US, has not ratified the protocol, however many US firms and individual States are taking voluntary actions to reduce their greenhouse gas (GHG) emissions or purchase emissions credits from other sources (Rabe 2002; Rosenzweig and others 2002). Firms have an incentive to purchase credits to offset their emissions, even in the absence of a formal market, if they anticipate that reductions in GHG emissions will be mandatory in the future. Early trades can provide participants with experience in an emerging market and serve to inform the policy debate.

Most trades within the US to date have involved carbon (C)-credits generated by the energy and forest sectors (PacificCorp 1997; Terry and others 2002). However, a large body of research suggests that US cropland soils are a promising source of credits (Lal and others 1998) and can sequester significant amounts of C. Several studies have shown that by changing agricultural management practices more C can be sequestered in agricultural soils, creating credits at a cost that is competitive with the forestry sector (Antle and others 2002; Antle and others 2001; Pautsch and others 2001). Agricultural soil C sequestration has received less attention in the emerging GHG market in part, because there are many contractual and implementation issues that need to be resolved before credit trades can occur. Contracts for credit generation using agricultural practices have many characteristics that differ from contracts for credits from other sequestration sources. For example, consider two comparable land areas, with similar numbers of landowners, one in cropland agriculture and the other forested. In general we would expect that each hectare in agriculture would generate fewer credits than each forested hectare; this suggests that many more agricultural producers than forest landowners are needed to achieve a given number of credits. It is likely that contracts for agricultural soil credits may include many producers with land holdings spanning a large geographic region, in contrast to contracts that purchase credits from other sources. Exceptions could occur if an area contains a large number of small forest plots and a small number of large agricultural units. A second characteristic important for agricultural soil credit contracts is that the rate of C accumulation in agricultural soils cannot be identified easily through visual inspection. In contrast, the accumulation of credits in forest biomass is indicated by the presence of growing trees. The transactions costs associated with aggregating small carbon quantities from many producers and developing monitoring schemes that can detect changes in below ground carbon could increase the total cost of trading credits from agriculture. These costs will affect the overall cost and competitiveness of agricultural soil credits.

Very little research has examined the costs of aggregating credits from several producers into one contract, however more work has focused on measuring credits. Several guidelines have been developed for measuring and monitoring credit accumulation within forestry and agro forestry projects (MacDicken 1997; Vine and others 1999; Brown 1999). These guides concentrate on measuring and monitoring above ground C stored in woody biomass and do not address soil C. A few studies have examined the costs of measuring soil credits (examples are: Smith 2002; Mooney and others 2002; McConkey and Lindwall 1999). Mooney and others

(2002) develop a measurement protocol for soil credits under contracts that pay producers for each unit of additional soil C sequestered by a change in their cropping systems and apply this protocol to the dry-land cropping area in Montana. Their empirical analysis showed that measurement costs are a small percentage of total credit value and that these costs are unlikely to reduce the competitiveness of agricultural soil C sequestration as a source of credits. The analysis considered the sensitivity of measurement costs to different sample error and confidence values as well differences in the spatial heterogeneity of carbon values between areas. Measurement costs were found to vary with the price paid for carbon credits, and the degree of spatial heterogeneity exhibited by C changes within any given contract area.

This paper builds on Mooney and others (2002) and extends the analysis to examine how changes in contract size and soil C variability will affect contract measurement costs. We assume that within a given agricultural region, every hectare that changes management practices in response to a payment for C credits is aggregated to form a single contract. We find a counter intuitive result that as the number of hectares to be sampled increases, the sample size decreases, similarly, if two smaller contracts (or regions) are aggregated into a single contract covering their entire area, measurement costs for the larger region are less than the sum of the measurement costs over the individual smaller regions, because fewer samples are required for the larger area. Thus the same total quantity of carbon can be measured at lower cost. If we increase soil C variability the relationship between contract size and measurement costs can change. Although these empirical results appear counter intuitive, we show that the relationship between sample size, measurement costs and population size is indeterminate and that these results are not as counter intuitive as they first appear. Instead, they are driven by the biophysical and economic conditions in the case study region.

In the next section we discuss how contract design influences transactions costs and determines the extent and cost of measurement and verification activities. This is followed by a conceptual framework for assessing the costs of measuring a change in soil C over the contract period, and a description of the models and data used in the empirical analysis. The remaining sections present the empirical results and conclusions.

Relationship between Contract Design and Transactions Costs

Although there are many ways to design contracts for agricultural soil C credits, per-hectare and per-credit contract design have received a lot of attention in several papers, for example; Antle and Mooney (2002); Antle and others (2003) and Pautsch and others (2001). Under a per-hectare contract, producers are offered a payment to change from their current management practices to others thought to sequester additional soil C. Payments are not tied to the actual quantity of C that is sequestered but are entirely dependent on an observed change in practice. Many existing agricultural programs such as the conservation reserve program, favor arrangements that are similar to per-hectare contracts. In contrast, the per-credit contract is performance based and pays producers for each unit of additional C sequestered in the soil as a result of changing management practices. Antle and others (2003); Antle and Mooney (2002) and Pautsch and others (2001) have demonstrated that per-credit contracts are more efficient than per-hectare contracts; that is, a given number of C credits can be purchased at a lower cost under a per-credit contract in the absence of transaction costs. An efficient contract will purchase credits up to the point where the cost of producing the last credit is equal to its price. Producers receive the same payment for every credit produced. Under a per hectare contract, producers are given a uniform payment for each hectare in the contract regardless of whether it sequesters a small or large amount of C, thus the payment per credit differs depending on the productivity of each hectare. The difference in the cost of purchasing a given number of credits using either contract type is a measure of the efficiency difference between the two contracts.

The way in which contracts are designed significantly influences their day-to-day implementation and associated transactions costs. Table 1, outlines some of the transactions costs that could be incurred implementing either a per-hectare or per-credit contract for soil C credits. Both contracts will have transactions costs associated with negotiating the specific contract terms between buyers and sellers, aggregating sellers into larger units that sell their pooled credits and monitoring that producers have made a change in production practice or land use consistent with the terms of the contract. We assume that these costs will be similar across both contract designs. However, the need to measure the number of credits is unique to the per-credit contract design because payments are tied to the number of credits produced. In contrast, under a per-hectare contract design payments are triggered by a change in practice and are not tied to the number of credits produced, thus it is not necessary to measure the number of credits. This is consistent with existing agricultural programs such as the conservation reserve program (CRP) that seeks to reduce soil erosion. Under the CRP, payments are triggered by changes in practices and not related to the quantity of erosion reduction. If the per-credit contracts are associated with large measurement costs, this could offset their efficiency gains.

[Table 1 about here]

Conceptual framework – total measurement costs

Economic theory suggests that individual producers adopt those land use and production practices on each hectare that maximize their economic profit. To sequester additional soil C, producers must change these practices and will do so only if this results in a net economic benefit. Producers will weigh the economic costs of changing from their existing production system to another that sequesters more C, against the revenue they receive from selling credits.

Consider a per-credit contract where a buyer offers to pay producers P dollars for each additional credit they generate over a contract period of T years. Producers will enter into this contract if the revenue they receive exceeds the costs of producing the credits. On a given hectare of land, *j*, the cost of changing production practices is the difference between the discounted profit over T years from the original production system π_{j0}, and the profit from the subsequent production system π_{jS}, i.e. $\pi_{j0} - \pi_{jS}$. Let ΔC_j represent the number of credits created on hectare *j* over T years due to the change in production practices. The total revenue from selling these credits is $P\Delta C_j$. If $\pi_{j0} - \pi_{jS} < P\Delta C_j$, that is the cost associated with a change in practice is less than the revenue received from selling credits, the producer will enter that hectare into a contract to supply C credits. In an earlier section we stated that credits produced on each individual hectare are likely to be aggregated into larger quantities thus, measurement of the total contract amount will take place at the regional rather than individual scale. Within a given region of size R hectares, the percentage of hectares that adopt a per-credit contract can be represented by *s*(P). We expect that increases in the price offered per credit will increase the percentage of hectares within the region adopting the per-credit contract i.e. $\frac{ds(P)}{dP} > 0$. The total number of hectares participating in a per-credit contract within a region is

$s(P)R$, and the total credits produced under this contract scheme within a given region is $C_c = \sum_{j=1}^{s(P)R} \Delta C_j$.

Under a per-hectare contract, the producer receives a payment *h* for each hectare that is switched to an eligible practice. If $\pi_0 - \pi_S < h$, i.e. the costs of changing production practices are less than the payment for switching practices, the producer will enter that hectare into a per-hectare contract. If the percentage of hectares entering the contract is *s*(h) (where $\frac{ds(h)}{dh} > 0$); the total area under contract is *s*(h)R and the total quantity of carbon sequestered under this contract scheme within a single region is $C_h = \sum_{j=1}^{s(h)R} \Delta C_j$.

Relationship between total contract cost and measurement cost

The total contract cost (TC_m) of purchasing credits is the sum of the direct credit purchase cost (TCC_m) i.e. the cost attributable solely to purchasing credits, transactions costs (T_m) and measurement costs (M_m) (following table 1), i.e. $TC_m = TCC_m + T_m + M_m$. Where *m* is an index denoting the type of carbon contract and can be equal to *h* (a per hectare contract) or *c* (a per credit contract) i.e. *m* = *h*, *c*. If we evaluate the cost of purchasing K credits under a per-credit and the per-hectare program $\left(K = \sum_{j=1}^{s(h)R} \Delta C_j = \sum_{j=1}^{s(P)R} \Delta C_j \right)$ using results from Antle and others (2003); Antle and Mooney (2002) and Pautsch and others (2001) we expect that $TCC_c |_k \leq TCC_h |_k$ i.e. the total purchase cost of K credits under the per credit program is less than the total purchase cost of K credits under the per hectare contract in the absence of other costs.

Under the per-hectare contract $M_h = 0$ because payments are dependent on a change in management practice, not the number of credits produced. We make the simplifying assumption that other transactions costs under either contract are likely to be similar i.e. $T_c \approx T_h$. In the presence of transactions costs, the per-credit contract will remain more efficient that the per-hectare contract, $TC_c|_k < TC_h|_k$, if $M_c|_k < (TCC_h|_k - TCC_c|_k)$ that is, if the measurement costs associated with the per-credit contract system are less than the difference in the direct credit purchase cost of K credits under the per-credit and per-hectare contracts, figure 1. The magnitude of $M_c|_k$ can only be determined empirically and will vary between regions. However, theoretical investigations coupled with empirical applications can identify factors that have the greatest influence on measurement costs. In the next section we describe a measurement protocol that we use to empirically determine M_c at a range of credit prices, under a per-credit contract design.

[Figure 1 around here]

Measurement protocol

Mooney and others (2002) propose a combination of predictive biophysical and economic modeling coupled with repeated field samples to measure credit accumulation under a per-credit contract. Under this proposed measurement scheme, total measurement costs are a function of the number of samples required, *n*, the cost per sample, CS, and the frequency of sampling over the duration of the contract, W so that:

(1) $M_c = M(n, CS, W)$.

We expect that M_c is increasing in all its arguments.

Using a stratified random sampling scheme for a finite population, the total sample size, *n*, needed to estimate the number of credits supplied under a single contract can be calculated using (2) (McCall 1982).

$$(2) \qquad n = \frac{Z^2 (\sum_{f=1}^{F} N_f \tilde{\sigma}_f)^2}{N^2 \varepsilon^2 + Z^2 \sum_{f=1}^{F} N_f \tilde{\sigma}_f^2}$$

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 that supply credits under the contract

f = index identifying strata where f = 1,……, F; each stratum represents a change between a pair of crop systems

N_f = total number of hectares in the *f*th stratum

$\tilde{\sigma}_f$ = initial estimate of the standard deviation of change in C over 20 years resulting from a crop system change in the *f*th stratum

ε = measurement error

Thus, the total sample size, *n*, is dependent on the number of hectares that enter into contracts to sequester soil carbon within a region; the number of hectares that are within each stratum representing possible crop system changes, the acceptable degree of error, desired confidence level and variability of soil carbon changes within each stratum. Many of these factors will vary with the price offered per credit and the spatial extent of the sampled region.

Sample costs, CS, will vary with the method used for sampling, the ease of sampling in each location and the total number of samples required among other factors. The frequency of measurement, W, over the contract lifetime is at a minimum equal to 2. The first sample is taken to determine a baseline at the beginning of the contract and the second sample at the conclusion of the contract to assess the total change in C over the contract duration. W may take on values greater than 2 reflecting interim measurement efforts over the life of the contract. In the next section we describe the empirical model, the contract duration and the frequency of measurement events assumed for the empirical analysis.

Models, Data and Scenarios

We use an econometric production simulation model (Antle and others 2003; Antle and Capalbo 2001) to estimate the number of hectares that participate in per-credit contracts to sequester soil C at five different credit payments ($10 per credit to $50 per credit, increasing in $10 increments). The simulation model represents producer land use and management choices in response to a range of payments offered for credits. Century, a crop–ecosystem model, designed to study soil dynamics (Parton and others 1994; Paustian and others 1996), is coupled with the economic model and provides estimates of the average rate of soil C sequestration in response to changes in crop practices. Economic production data are collected at the field level using a survey of 425 farms that are statistically representative of 3 major land resource areas (MLRAs) within Montana. The biophysical data for Century was collected by further dividing each MLRA into high and low rainfall areas, making 6 sub-MLRAs represented in the econometric simulation model, figure 2. A detailed description of these data underlying both the economic model and Century is found in Antle and others (2003) and Antle and others (2001).

[Figure 2 around here]

Soil carbon sequestration rates under seven different cropping systems are supplied by the Century model for each sub-MLRA and used to construct an estimate of the soil C variability for each stratum, *f*. Each stratum, *f*, represents a change between a pair of crop systems. For example, starting with a single crop system such as continuous spring wheat, the producers could adopt any of several different cropping systems that increase soil C. Each before and after pair of crop systems constitutes a different stratum (Table 2). In general, changes from a crop-fallow system to a continuous cropping system result in higher rates of C sequestration and thus generate credits.

[Table 2 around here]

The variance within each stratum associated with a change from the original crop system to a subsequent system that sequesters more carbon, VAR_{s-o} is calculated as in (3). We have no information to suggest the degree of 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 overestimate VAR_{s-o} and lead to higher sampling rates.

(3) $VAR_{s-o} = Var_o + Var_s - 2COV_{o,s}$

In this paper we assume that two technicians can collect approximately 50 samples per day using a soil probe mounted to a truck. Once the samples are collected we assume they are bagged and transported to laboratory, air dried, ground and their C content is measured. Based on these assumptions Mooney and others (2002) estimate that a single sample costs approximately $16.37. This estimate of sample cost (CS) is also used in this study for purposes of comparison. We also assume a contract duration of 20 years with sampling in years 1, 5, 10 and 20, so the sampling frequency, W equals 4.

The framework developed earlier and the models described in this section are used to estimate M_c, the cost of measuring soil credits under a per-credit contract for six contract regions (sub-MLRAs) within the major small grain-producing region of Montana. Two scenarios are examined. First we explore how an increase in the size of the contract region influences measurement costs. Specifically we combine high and low rainfall sub-MLRAs to form a complete MLRA and examine how measurement costs at the MLRA scale compare with those at the sub-MLRA scale. Second we examine the influence of a cumulative 5 percent increase in within stratum C sequestration variance as credit prices increase at the MLRA and sub-MLRA levels. For each $10 increase in the payment offered for each credit the variance associated with each pair of crop system changes is increased by an additional 5 percent.

Results

In this section we present the empirical results generated by the coupled economic and Century models. In all cases, sample sizes are calculated assuming a 10 percent error and 95 percent confidence level; payments for credits range between $10 and $50 per credit, increasing in $10 increments.

Population size, sample size and total measurement costs – sub-MLRA region

Table 3 shows the number of hectares that enter into contracts to supply credits at each payment level, and the total sample size required to estimate the mean accumulation of credits within each contract region. When we increase the payment per credit, P, it is profitable for more hectares to enter into contracts within each region. In the case of finite population sampling (used in this study) an increase in the number of hectares adopting contracts also increases the population to be sampled. In each sub-MLRA the population size increases at a different rate reflecting differences in the biophysical conditions and economic opportunities within each area. Sample sizes required to implement the measurement scheme range between a low of 626 samples in sub-MLRA 52-high at a payment of $50 per credit to a high of 3,146 in sub-MLRA 53-low at a payment of $10 per credit, table 3. Counter intuitively, the sample size required for each contract is inversely related to the number of hectares (population size) within each contract under the assumption that Z, and $\tilde{\sigma}_f$ in (2) are held constant.

[Table 3 around here]

Table 4 presents an example illustrating how this result occurs in response to a $10 per credit and $50 per credit payment in sub-MLRA 52-high. When the credit payment increases, more hectares switch management practices to increase soil C resulting in a corresponding increase in N. In addition, the types of crop system changes differ because of differences in producer response to high and low payment levels causing both increases and decreases in the values of N_f. In addition, changes in N_f and N also increase the size of ε n this example. The cumulative effect of these changes is to increase the size of the denominator in (2) at a faster rate than the numerator, table 4. As a result, the sample size required to measure soil C credits decreases as population size increases.

[Table 4 around here]

N_f, N and ε are functions of P, the price offered per credit, thus *n*, the sample size, is also a function of P (among other arguments). The sign of $\frac{\delta n}{\delta \mathrm{P}}$ is dependent on changes in N_f, N and ε (holding $\tilde{\sigma}_f$ constant). Although we expect that $\frac{\delta \mathrm{N}}{\delta \mathrm{P}} > 0$ (the number of hectares within a contract for credits increases as the price of credits rises), the signs on $\frac{\delta \mathrm{N}_f}{\delta \mathrm{P}}$ and $\frac{\delta \varepsilon}{\delta \mathrm{P}}$ can be positive or negative. This is illustrated by the data presented in table 4. In the case of a change in crop system from spring wheat fallow or barley fallow to winter wheat fallow (SWF/BLF to WWF), N_f is positive when P increases from \$10 to \$50, while N_f is negative for a change to continuous winter wheat (SWF/BLF to CWW). Several other examples can be found in table 4. The sign on each $\frac{\delta \mathrm{N}_f}{\delta \mathrm{P}}$ is empirically determined by the biophysical and economic conditions within each region. As mentioned earlier, the sign of $\frac{\delta n}{\delta \mathrm{P}}$ is dependent $\frac{\delta \mathrm{N}_f}{\delta \mathrm{P}}$, $\frac{\delta \mathrm{N}}{\delta \mathrm{P}}$ and $\frac{\delta \varepsilon}{\delta \mathrm{P}}$ (holding $\tilde{\sigma}_f$ constant), therefore it is not possible in general to sign $\frac{\delta n}{\delta \mathrm{P}}$ because both $\frac{\delta \mathrm{N}_f}{\delta \mathrm{P}}$ and $\frac{\delta \varepsilon}{\delta \mathrm{P}}$ can take positive or negative values. In this example, we made the simplifying assumption of a constant variance $\tilde{\sigma}_f$ within each stratum at each credit payment level. As the payments for credits increase and the population to be sampled also increases, it is likely that σ_f, the true within stratum standard deviation, will also change. However the direction of this change is also uncertain as the population increases. This further compounds the problem of signing $\frac{\delta n}{\delta \mathrm{P}}$, *a priori*. Thus, although our result that sample size decreases as the population level increase does appear to be counter intuitive it can be explained by the complex interactions between many interacting variables described in the previous paragraphs.

When the total sample size decreases, total measurement cost will also decline. In each contract region the total sample cost decreases at a decreasing rate when the credit price is increased, figure 3. Total measurement costs range between a low of $41,000 in sub-MLRA 52-high to $206,000 in sub-MLRA 53-low, figure 3. The number of credits created range between 0.73 MMT (million metric tons) in sub-MLRA 53 low to 3.2 MMT in sub-MLRA 52-high. Measurement costs are a very small percentage of the total value of credits within any area. For example, at a payment level of $10 per credit, approximately 1.2 million credits are produced in sub-MLRA 52-high. Their total purchase price would be $12 million (1.2 million credits multiplied by $10 per credit), while the associated measurement cost is $41,000, or less than 1 percent of the total credit value.

[Figure 3 around here]

Change in region size from sub-MLRA to MLRA

Each MLRA represents the combined area of its sub-MLRAs. For example sub-MLRA 52-low and sub-MLRA 52-high are combined to form MLRA 52. The other MLRAs are formed in a similar way. The total population to be sampled at each price level within these larger MLRA regions is simply the total number of hectares that change management practices in response to a payments for credits in each sub-MLRA, table 2. This reflects the fact that the decision to enter each hectare into a per-credit contract is not influenced by the size of the region, only the size of the payment. The total sample sizes required to implement a measurement scheme at the MLRA level range between 847 samples in MLRA 52 to 1,483 samples in MLRA 53 and are inversely related to credit prices and population size similar to the sub-MLRA regions, table 3. In addition, the total sample size at the MLRA scale, at any price level, is less than the sum of the samples needed at the individual sub-MLRA scale. For example at a price of \$10 per credit the total number of samples required to measure C in sub MLRAs 52-high and 52-low is 2,745. While the number of samples required to implement a measurement scheme in MLRA 52 are 1,109. In general, table 3 shows that the sample size required at the MLRA scale is 40 percent to 60 percent smaller than the sum of the samples needed to measure soil credits under a per-credit contract at the sub-MLRA scale. This is because at every payment level, each stratum contains a larger number of hectares, increasing the size of the denominator in (2) more than the size of the numerator similar to the effect observed when payment levels increase within a single sub-MLRA, table 4.

Figure 3 presents the summed cost of sampling each sub-MLRA and the total measurement cost when each MLRA is sampled as a single region. The total measurement costs at the MLRA level are also 40 to 60 percent less than the total measurement costs at the sub-MLRA level as you would expect, mirroring the difference in sample size presented in table 3. These results suggest that aggregating producers into larger contract groups can reduce total measurement costs under a per-credit contract design.

Cumulative increase in variance

In the previous analyses, the within stratum variance, $\tilde{\sigma}_f$, remained constant as credit payments and the total number of hectares engaged in per-credit contracts increase. In reality we expect that σ_f will change as the population to be sampled changes, however the magnitude and direction of change will depend on the characteristics of the population. In this analysis, we examine the effect on measurement costs of a cumulative 5 percent increase in the within stratum variance each time there is an increase in the payment for credits. In response, the total sample size and total measurement costs, figure 4, increase for every contract region. Measurement costs range between a low of $49,110 in sub-MLRA 52-high at a payment of $40 per credit to a high of $206,000 in sub-MLRA 53-low at a price of $10 per credit. Interestingly, total measurement costs no longer decline over the entire payment range considered. All sub-MLRAs with the exception of sub-MLRA high have U shaped curves; their measurement costs decline initially and then start to increase at higher credit prices. Interestingly, even when within stratum variability increases with population size, it is still possible to have declining measurement costs over some range of credit payments. In contrast to the first analysis, sub-MLRA 53-high experiences an increase in measurement costs over the entire range of payments considered. These results support our earlier analysis that indicates $\frac{\delta n}{\delta \mathrm{P}}$ can take positive and negative values.

[Figure 4 around here]

At the MLRA level, measurement costs range between a low of $66,462 at payments of $40 per credit in MLRA 52 to $100,249 in MLRA 53 at a payment of $50 per credit. Similar to the sub-MLRA case, the shape of the total measurement cost curves have also changed, with MLRAs 52 and 58 exhibiting U-shaped curves. In MLRA 53 total measurement costs are strictly increasing in response to the changes in variance.

Comparing the summed sub-MLRA costs to those at the MLRA level we see that the percentage change in total measurement cost at each price level is larger for the summed sub-

MLRA areas than the MLRAs. This suggests that the sample size required to measure a large population is not as sensitive to changes in the variance of each stratum within the population.

Conclusions

Many studies have examined the relative efficiency of per-hectare and per-credit contract designs in the absence of transactions costs. In this paper we present a framework for assessing the additional transactions costs associated with each contract type and identify the conditions that are needed for the per-credit contract to remain more efficient than the per-hectare contract in the presence of these costs. We also present a framework for measuring agricultural soil credits under a per-credit contract design. In the empirical analysis we apply the framework to the dry-land crop-producing region of Montana and estimate the total measurement costs for soil credits. In addition we investigate how changes in contract (and region) size as well as increases in C variability affect total measurement costs.

Results from the empirical application suggest that as the price offered per credit increases, there is greater incentive for more producers to participate in credit contracts and thus the population to be sampled increases. In the first analysis, a constant within stratum variance is assumed for C at each price level. The empirical results from this analysis indicate that total measurement costs decline as the price of credits is increased. When the within stratum C variance was increased at each payment level we found that total measurement costs in many areas initially showed a decrease but at higher credit prices begin to rise. Finally, a third analysis showed that measurement costs over one large contract region are significantly less than costs if the region was split into smaller areas and sampled separately. These, initially, counter intuitive empirical results suggest that increasing the size of the contract and aggregating credits over a larger number of producers can reduce measurement costs associated with the per-credit contract (in this analysis measurement costs were reduced by 40 to 60 percent), even in the face of increasing C variability thus contracts for large quantities of soil credits increase the likelihood that the per-credit contract remains more efficient than the per-hectare contract. However, these empirical results reflect the specific data and conditions present within the case study region. The theoretical expectation is that sample size can either increase or decrease as the population to be sampled increases. Larger sample sizes lead to larger measurement costs while smaller sample sizes lead to smaller measurement costs, *ceteris paribus*. Thus the measurement costs associated with a per-credit contract could respond differently from this analysis, across the spatial extent of the US. This suggests that regional characteristics will drive the costs of C credit measurement and the influence of measurement costs on the relative efficiency of the per-credit and per-hectare contract designs.

Extensions to the current work 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 potential for spatial autocorrelation between hectares that could reduce the sample size necessary to measure the contracted credit quantity.

There are many other issues that could influence measurement and other transactions costs. A change in cropping practices is likely to change emissions of other GHGs. In a full GHG accounting framework changes in net credits and changes in other gases would need to be measured, having the potential to further increase measurement costs.

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Literature Cited

Antle, J.M., S.M. Capalbo, S. Mooney, E.T. Elliott, and K.H. Paustian. 2002. A Comparative Examination of the Efficiency of Sequestering Carbon in U.S. Agricultural Soils. *American Journal of Alternative Agriculture* 17.

———. 2001. Economic Analysis of Agricultural Soil Carbon Sequestration: An Integrated Assessment Approach. *Journal of Agricultural and Resource Economics* 26:344–367.

———. 2003. Spatial heterogeneity, contract design, and the efficiency of carbon sequestration policies for agriculture. *Journal of Environmental Economics and Management,* in press.

Antle, J.M., and S. Mooney. 2002. Designing Efficient Practices for Agricultural Soil Carbon Sequestration. *Agriculture Practices and Policies for Carbon Sequestration in Soil.* J.M. Kimble, R. Lal, and R.F. Follett, eds., pp. 323–336. Boca Raton, FL: CRC Press LLC.

Antle, J.M., and S.M. Capalbo. 2001. “Econometric-Process Models for Integrated Assessment of Agricultural Production Systems.” *American Journal of Agricultural Economics* 83(May):389–401.

Brown, S. 1999. Guidelines for Inventorying and Monitoring Carbon Offsets in Forest Based Projects. Winrock International, Morrilton, AR. http://www.winrock.org/reep/Guidelines.html.

Lal, R., L.M. Kimble, R.F. Follett, and C.V. Cole. 1998. *The Potential of U.S. Cropland to Sequester C and Mitigate the Greenhouse Effect.* Chelsea MI: Ann Arbor Press..

MacDicken, K.G. 1997. “A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects.” Winrock International Institute for Agricultural Development, http://www.winrock.org/REEP/PDF_Pubs/carbon.pdf.

McCall, C.H., Jr. 1982. *Sampling and Statistics Handbook for Research.* Ames IA: The Iowa State University Press.

McConkey, B., and W. Lindwall. 1999. “Measuring Soil Carbon Stocks: A System for Quantifying and Verifying Change in Soil Carbon Stocks due to Changes in Management Practices on Agricultural Land.” Agriculture and Agri-Food Canada, http://www.agr.gc.ca/policy/environment/eb/public_html/pdfs/climate_change/sinks.pdf.

Mooney, S., J.M. Antle, S.M. Capalbo, and K.H. Paustian. 2002. Contracting for Soil Carbon Credits: Design and Costs of Measurement and Monitoring. Staff Paper 2002-01, Department of Agricultural Economics and Economics, Montana State University–Bozeman, May.

PacifiCorp. 1997. “PacifiCorp’s Commitment to the Environment: CO_2 Initiatives.” Portland OR, October.

Parton, W.J., D.S. Schimel, D.S. Ojima, and C.V. Cole. 1994. “A General Model for Soil Organic Matter Dynamics: Sensitivity to Litter Chemistry, Texture and Management.” *Quantitative Modeling of Soil Forming Processes.* R.B. Bryant and R.W. Arnold, eds. SSSA Special Publication Number 39. Madison WI: Soil Science Society of America.

Paustian, K., E.T. Elliott, G.A. Peterson, and K. Killian. 1996. “Modelling Climate, Co_2 and Management Impacts on Soil Carbon in Semi-arid Agroecosystems.” *Plant Soil* 187:351–365.

Pautsch, G.R., L.A. Kurkalova, B.A. Babcock, and C.L. Kling. 2001. The Efficiency of Sequestering Carbon in Agricultural Soils. *Contemporary Economic Policy* 19:23–134.

Rabe, B.G. 2002. Greenhouse and Statehouse: The Evolving State Government Role in Climate Change. Pew Center on Global Climate Change, Arlington VA, http://www.pewclimate.org/projects/states_greenhouse.pdf

Rosenzweig, R., M. Varilek, B. Feldman, R. Kuppalli, and J. Janssen. 2002. The Emerging International Greenhouse Gas Market. Pew Center for Global Climate Change, Arlington VA, http://www.pewclimate.org/projects/trading.pdf, 2002.

Smith, G.R. 2002. “Case Study of Cost versus Accuracy When Measuring Carbon Stock in a Terrestrial Ecosystem.” *Agriculture Practices and Policies for Carbon Sequestration in Soil*. J. Kimble, ed. Boca Raton, FL: CRC Press LLC.

Terry, D., C, Guinn and M. Lee. 2002. State and Local Net Greenhouse Gas Emission Reductions Programs. Case Study Database. Pew Center for Global Climate Change, Arlington Virginia, http://www.pewclimate.org/states/index1.cfm. Viewed December 2nd 2002.

Vine, E., J. Sathaye, and W. Makundi. 1999. “The Monitoring, Evaluation, Reporting, Verification and Certification of Climate Change Forest Projects.” LBNL-41877. Lawrence Berkeley National Laboratory, Berkeley CA.

Table 1. Potential sources of additional transactions costs under per-tonne and per-hectare contracts for soil carbon credits

Cost category	Per-credit contract	Per-hectare contract
Legal - drawing up contracts - negotiating with producers	X	X
Aggregation - aggregating individual producers into larger contract groups	X	X
Monitoring - verifying producers have made a change in land use	X	X
Measuring - estimating the number of C credits sequestered over the contract period	X	Unnecessary

Table 2. Crop system pairs (X) that form each stratum, *f*

Initial crop system	Subsequent crop system				
	SWF/BLF	WWF	GR	CSW/CBL	CWW
SWF/BLF		X	X	X	X
WWF			X	X	X
GR				X	X
CSW/CBL					X

SWF = spring wheat fallow, BLF = barley fallow, WWF = winter wheat fallow, GR = grass
CSW = continuous spring wheat, CBL = continuous barley, CWW = continuous winter wheat

Table 3. Total population to be sampled and the corresponding sample size at 10 percent error, 95 percent confidence

Credit Price $/MT	Sub-MLRA 52 high	Sub-MLRA 52 low	MLRA 52	Sub-MLRA 53 high	Sub-MLRA 53 low	MLRA 53	Sub-MLRA 58 high	Sub-MLRA 58 low	MLRA 58
	Population size (hectares)								
10	189,820	283,708	473,528	108,137	154,526	262,664	214,256	189,820	404,076
20	225,828	334,914	560,742	122,276	177,471	299,748	237,362	209,611	446,974
30	277,276	388,611	665,887	131,647	197,905	329,552	271,843	232,890	504,732
40	336,517	458,085	794,602	139,296	212,122	351,418	300,903	244,696	545,600
50	372,671	494,068	866,739	148,722	233,194	381,916	312,982	254,592	567,574
	Total sample size (hectares)								
10	861	1,884	1,109	785	3,146	1,483	997	1,307	1,370
20	741	1,724	993	760	2,883	1,399	927	1,242	1,289
30	683	1,630	924	735	2,703	1,327	864	1,199	1,240
40	649	1,548	874	724	2,600	1,289	817	1,156	1,185
50	626	1,515	847	714	2,499	1,260	790	1,152	1,140

Table 4. Sample size calculations at \$10/tonne C and \$50/tonne C, Sub-MLRA 52 high

Strata representing each crop system change	\$10/tonne C N_f	\$50/tonne C N_f	$\tilde{\sigma}_f$	ε_f
SWF/BLF to WWF	28,923	8,900	10.52	0.20
SWF/BLF to GR	7,787	6,118	11.21	0.53
SWF/BLF to CSW/CBL	95,114	266,432	10.62	0.88
SWF/BLF to CWW	5,562	28,924	11.26	1.07
WWF to GR	1,112	556	11.43	0.33
WWF to CSW/CBL	17,799	50,617	10.86	0.68
WWF to CWW	1,112	10,012	11.48	0.87
GR to CSW/CBL	0	0	11.52	0.35
GR to CWW	0	0	12.11	0.54
CSW/CBL to CWW	1,112	1,112	11.58	0.19
Sample Size Calculations				
Z	1.96	1.96		
$\varepsilon^2 = \left(\frac{\sum_{f=1}^{F} N_f \varepsilon_f}{N} \right)^2$	0.50	0.71		
$N^2 = \left(\sum_{f=1}^{F} N_f \right)^2$	25,129,858,579	138,883,920,119		
$\left(\sum_{f=1}^{F} N_f \tilde{\sigma}_f \right)^2$	2,877,440,475,204	16,017,803,482,720		
$\sum_{f=1}^{F} N_f \tilde{\sigma}_f^2$	18,159,194	43,001,474		
$n = \frac{Z^2 (\sum_{f=1}^{F} N_f \tilde{\sigma}_f)^2}{N^2 \varepsilon^2 + Z^2 \sum_{f=1}^{F} N_f \tilde{\sigma}_f^2}$	861	626		

SWF = spring wheat fallow, BLF = barley fallow, WWF = winter wheat fallow, GR = grass
CSW = continuous spring wheat, CBL = continuous barley, CWW = continuous winter wheat

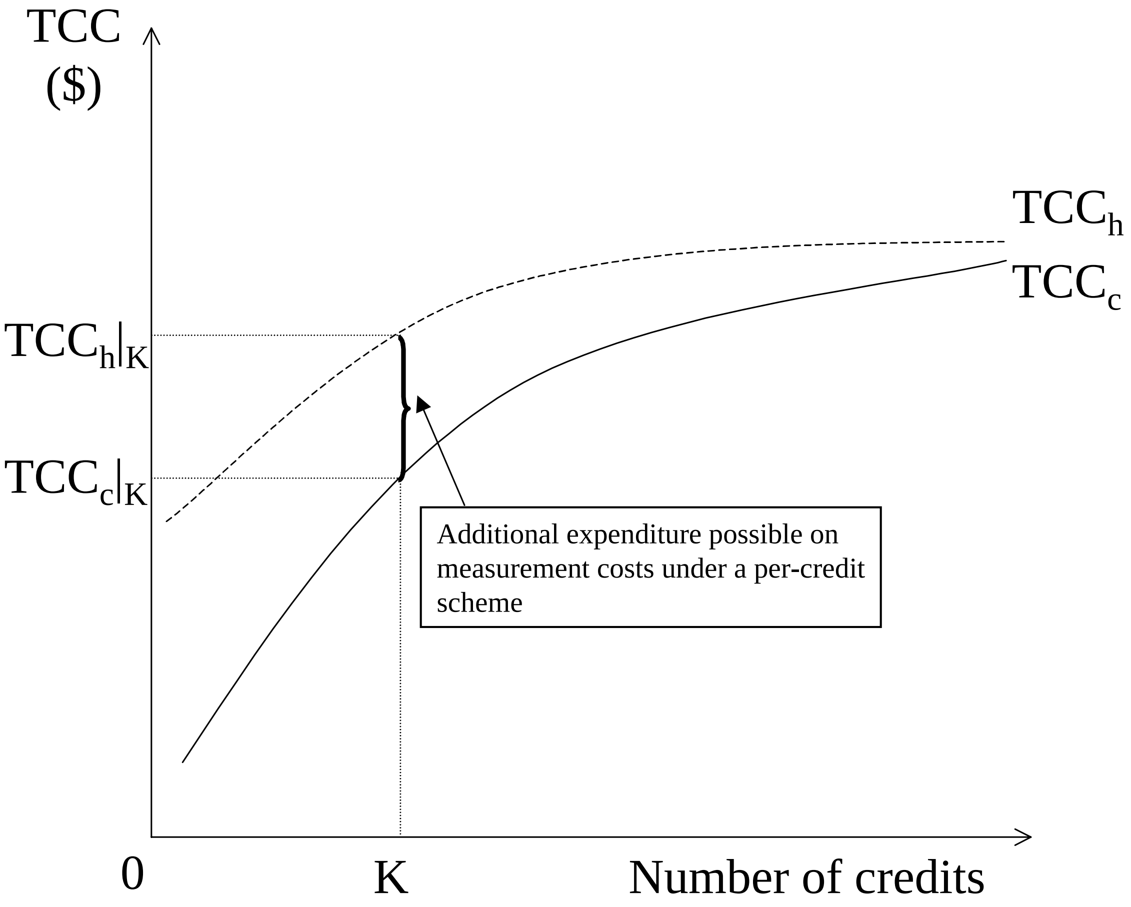


Figure 1. Total credit cost under a per credit ($TCCc|_K$) and per-hectare ($TCC_h|_K$) contract for K credits

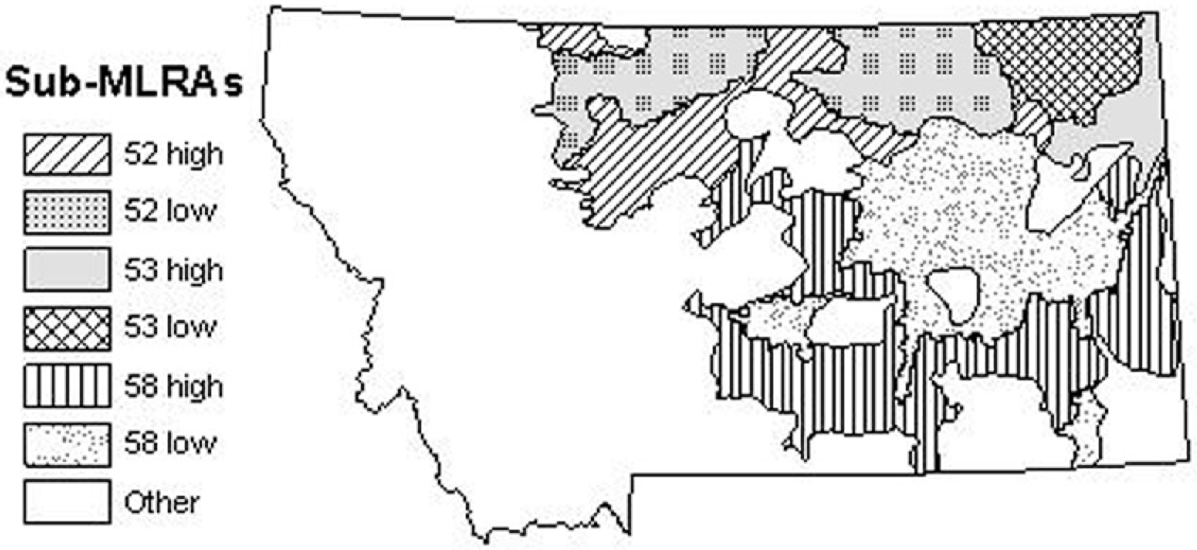
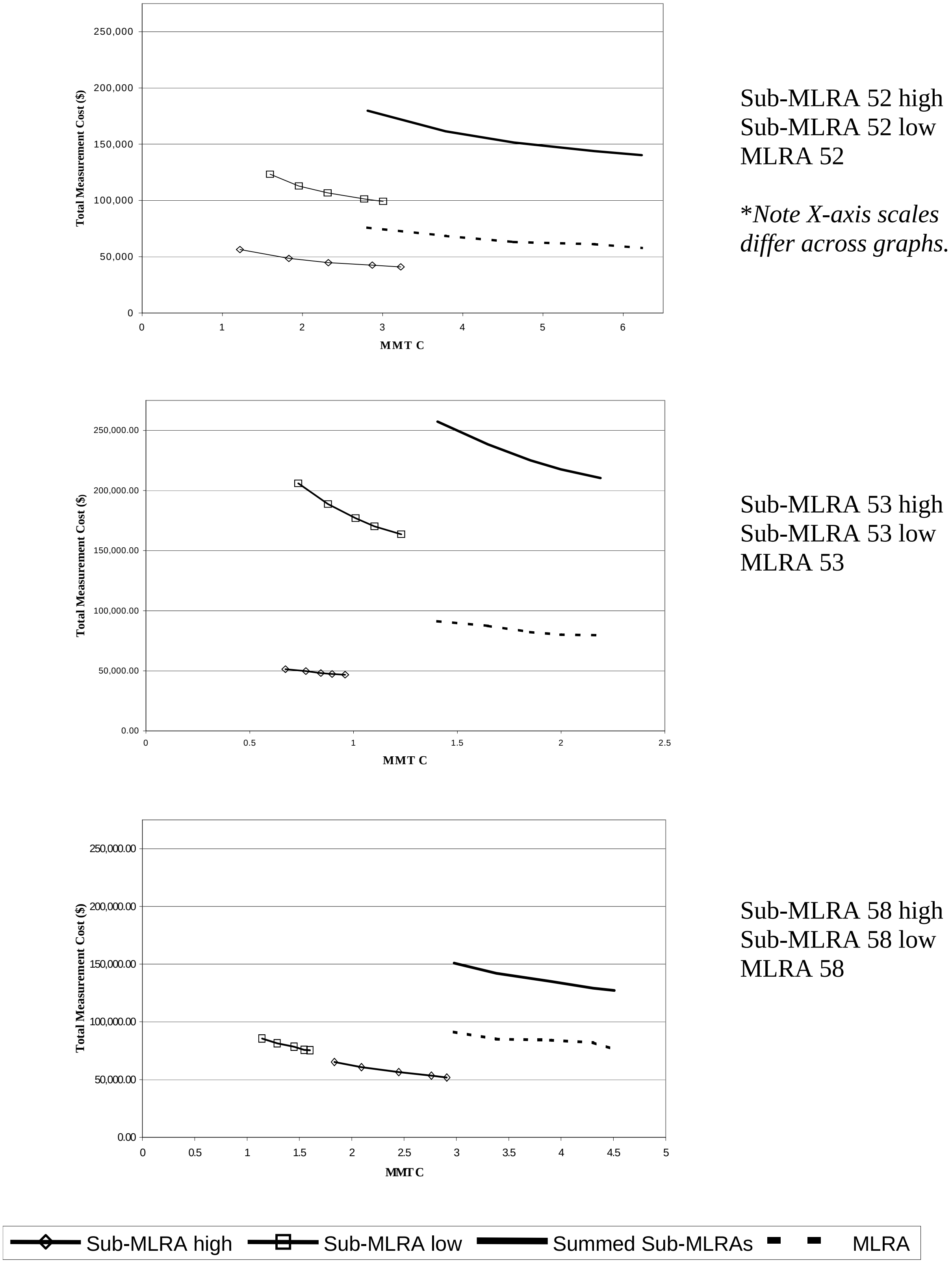


Figure 2. Sub-MLRA areas within Montana



Sub-MLRA 52 high
Sub-MLRA 52 low
MLRA 52

**Note X-axis scales differ across graphs.*

Sub-MLRA 53 high
Sub-MLRA 53 low
MLRA 53

Sub-MLRA 58 high
Sub-MLRA 58 low
MLRA 58

Figure 3. Total measurement cost by sub-MLRA, summed sub-MLRAs and MLRA

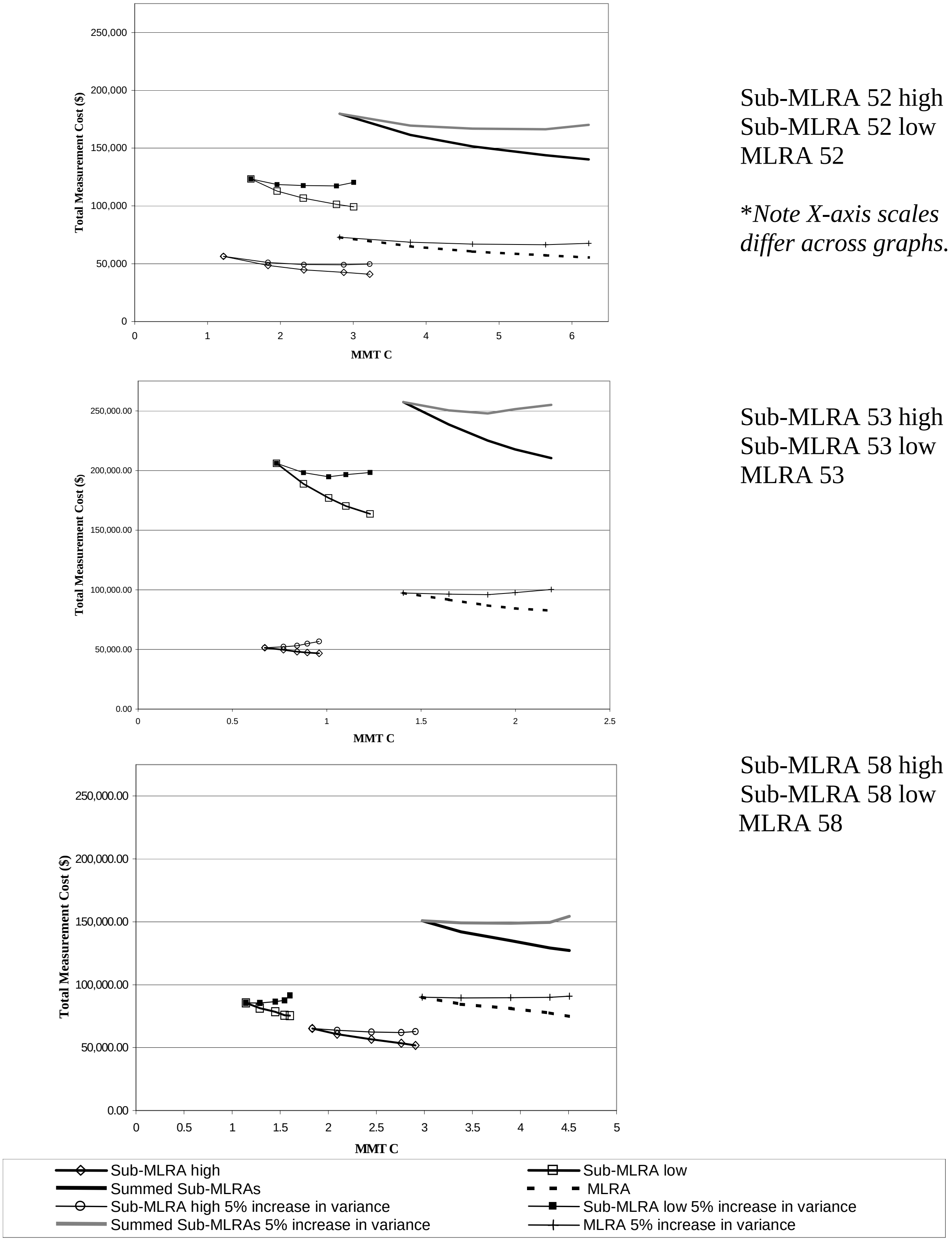


Figure 4. Total measurement cost with 5 percent increase in variance