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Pricing Benefit Externalities of Soil Carbon Sequestration in Multifunctional Agriculture

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"Multifunctionality" emphasizes the benefit externality properties of nonfood products that coincide with agricultural commodity production, some of which also have public-good properties. However, determining the willingness to pay for local benefit externalities is seen as necessary but daunting. This paper pursues the idea that the valuation process might first start by estimating the incentives required to supply various levels of a benefit externality. With the use of carbon sequestration through the adoption of no-till cultivation as an example of a multifunctional benefit externality, mathematical programming is used to derive representative price schedules. The implication for incentive prices are examined in light of risk aversion.

Key Words: carbon sequestration, externalities, multifunctionality, quadratic programming

JEL Classifications: C61, D62, Q12, Q21

There has been increasing interest in the past several years, especially in Europe and Japan, in a variety of positive nonfood products and services generated in conjunction with agriculture production activities. This comes at a time when agriculture's overall economic contribution to national prosperity is declining or small and as populations become more heavily concentrated in urban areas. The social benefits of rurality to urban people, especially in densely populated areas where the natural environment has been managed for hundreds of years, are thus becoming synonymous with agricultural activity. Put differently, agriculture is said to produce *multiple functional outputs,* of which some are traded in (commodity) markets and others are not. The beneficial outputs of multifunctional agriculture are described as relating to environmental health, the scenic environment, food security, rural development, and social institutions (OECD). Although these outputs are welfare enhancing and "consumed" by members of the larger community, there is no market mechanism to compensate producers for that consumption. It has been therefore advanced that there is a constructive role for government to enact transfers to agricultural producers to support and encourage the continued or enhanced production of these multiple, beneficial outputs.

Although farm support has nearly always been forthcoming, the traditional mechanism has been, in general, unimaginatively focused solely on commodity production, is often of such a design as to hasten the decline of the very family farm characteristics of agriculture that it was proposed to protect, and frequently

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exacerbated the extent of negative by-products generated by agriculture (Freshwater). The discussion of beneficial nonfood farm outputs and an emphasis on the increasingly important societal role of agriculture beyond the provision of primary outputs has led to the idea that perhaps the wrong commodity has been sustained and that appropriate adjustments in support policy toward the other jointly produced products of agriculture would better serve the welfare interests of the family farm and society. What is needed, therefore, are ways through which producers could be provided with the incentives, normally monetary compensation, to adjust or maintain production structures that enhance or increase the supply of desirable agricultural nonfood outputs, reduce the supply of negative ones, or both.

This suggestion has raised considerable debate, particularly in trade circles, about the likely distortions imposed on commodity markets resulting from what might appear to be thinly disguised farm support subsidies. Closely related are concerns about how to appropriately measure demand and willingness-to-pay for these types of goods, which are essentially local in nature and might require an immensely expensive valuation effort (Randall).

This paper approaches the debate by viewing the multiple product characteristic of agriculture as a classic economic problem of externalities. This implies the existence of market inefficiencies, so long as the externalities are not trivial (Bruce). Rather than focusing on the demand side, this paper takes as its starting point the question of what prices or payments must be received by agricultural producers to induce them to supply certain quantities of beneficial nonfood outputs. To do so, externalities are essentially transformed into commodities that can be valued (Meyer). Success in this exercise would meet the objective of demonstrating a method to providing some reasonable contextual supply response parameters from which willingness-to-pay assessments and public expenditure assessments could begin.

The empirical framework is one of mathematical programming with the use of a "representative farm" for a particular area that is consistent with the notion that there is an important spatial dimension to the demand for largely local, nontraded goods. The results are then extended to consider producer risk aversion and stochastic returns in the traded commodity, but not in the nontraded externality.

Defining Multifunctionality as Externalities

It has long been recognized that agriculture generates an output quantity that exceeds the traditional measure of its now meager relative contribution to gross domestic product for the production of food and fiber (Bohman et al.). The additional outputs are nonfood items and services that result from a variety of joint product relationships of primary agricultural production activities. For the most part, the additional outputs are by-products incidental to the profit-maximizing goals of producers because there are no markets for them.

However, this is nothing more than the recognition that agricultural production generates externalities, potentially positive or negative, that depend on the choice of product, production technology, and input use. That positive externalities create a benefit for other people without compensation suggests market incompleteness. Market incompleteness results from it being difficult to exclude anybody from enjoying the benefit externalities provided by agricultural production. Furthermore, although the benefit externalities are largely local in nature, they are also primarily nonrival. To the extent that these are also characteristics of public goods, then from a public welfare perspective, it suggests that the benefits will be typically underproduced relative to social optima. These statements provide the crux of the economic arguments contained in the definition of multifunctionality, whose key elements are: "(i) the existence of multiple commodity and non-commodity outputs that are jointly produced by agriculture; and (ii) the fact that some of the non-commodity outputs exhibit the characteristics of externalities or public goods, with the result that markets for these goods do not exist or function poorly" (OECD, p. 13).

The types of noncommodity outputs include items such as agriculture's contribution to biodiversity, view-shed or open space provision, greenhouse gas abatement, soil and water quality, preservation of the cultural heritage, and contribution to rural viability. In general, multifunctionality is viewed as being derived from high marginal cost farms (Atance and Bardají). In other words, large-scale factory farms are not likely to be contributors to the types of rural, environmental, and cultural amenities that people desire.

That agricultural benefit externalities constitute a form of public good has resulted in the suggestion that public policy might well impose some type of subsidy to increase the supply, the usual policy prescription when some attribute has a public good element of being unpriced but freely consumed and therefore underprovided in the marketplace. This argument hinges on the belief that even positive externalities create market inefficiencies. Traditionally, agriculture has been used as the example of a near perfect market: many price-taking producers producing roughly homogeneous goods leading to a Walrasian equilibrium satisfying the Pareto efficient conditions for welfare maximization. This does not hold if we recognize that an externality exists, even a public good externality, and does indeed suggest that some market inefficiencies exist, possibly requiring government intervention (Bruce).

Explicit and direct support for joint products has not been without controversy and raises many difficult issues. Among the most vocal opponents are those concerned with potential or actual trade distortions generated in the traded commodity markets due to the joint production relationship, especially since decoupling is now the mantra of domestic agricultural support policy. Various studies have attempted to resolve this uncertainty by detailing the nature of the production relationships and conditions contributing to traded commodity distortions. Critics charge that claims of public good provision by agriculture is thinly disguised farm subsidies, a mechanism to bypass World Trade Organization restrictions on domestic support. Furthermore, it might not be obvious that agriculture is the best mechanism through which to provide some public goods and that other more direct measures could be efficient in their provision (Blandford and Boisvert; Bohman et al.). In general, the view among detractors is that support to multifunctional agriculture for the increased supply of nonfood products will simply generate greater commodity production. However, to not provide for the supply of welfare-enhancing public-type goods could, in itself, be trade distorting.

Benefit Externality Valuation

Valuation of many types of public goods is quite complicated. Randall has described the potential difficulty faced by economists assessing the willingness-to-pay for jointly produced agricultural attributes, both in terms of acceptable methodology and the shear size of such an endeavor. Moreover, how do the characteristics of noncommodity goods, including their social demand, change over space and time? Values attached to various attributes provided by agriculture differ by location and population (Goodhue, Guillaume, and Klonsky; Randall). Valuation also depends importantly on income, from a public finance perspective, when assessing the willingness-to-pay for local public goods.

According to Randall, the appropriate starting point in valuation is willingness-to-pay estimation of a value function. In this paper, however, the view is taken that willingness-to-pay tells us little about the willingness-to-supply a public good by a private producer. In fact, it might be considerably simpler to estimate a supply function, which is still conceptually consistent with the idea of a value function. Knowing the value of the subsidy to a producer that generates the desired supply response provides two important benefits. First, it serves as a guide in designing willingness-to-pay surveys, and second, it enables a fairly good approximation of the total budget outlay required to achieve some level of public benefit externality.

Local Implementation

Some commentators have cautioned that there is little public and governmental support for national spending on programs that are implemented at local or regional levels for the benefit of local people and the environment (Freshwater). That is, willingness-to-pay for local public goods will become lower the farther away one is from the specific location in question. Although support for a public good provision is indeed local for many items, such as city parks, there are also numerous examples of nationally funded programs that are implemented on a local level and which often provide monetary or in-kind incentives and compensation to private landowners for some desired change in behavior (Antle et al. 2001). A few such examples include the Conservation Reserve Program, Wetlands Reserve Program, Environmental Quality Incentive Program, Water Quality Incentive Projects, and wildlife habitat programs.

As a generalization, therefore, the idea that multifunctionality cannot be successfully implemented for local public goods because of a lack of national willingness-to-pay or an inability of many local jurisdictions to fund them is not tenable. Indeed, the programs listed above demonstrate that willingness-to-pay exists and that redistribution between regions, for the enhancement of public goods, does take place.

Carbon Sequestration as a Multifunctional Activity

In the empirical application to follow, the use of agricultural soils to sequester atmospheric carbon is used as the multifunctional activity that we want to value. This activity is an appropriate example, in that it contains all the definitional characteristics of benefit externalities and multifunctionality.

Greater awareness and concern about human impact on the earth's life systems has emphasized the potentially damaging effects of high and increasing concentrations of greenhouse gases in the atmosphere, in particular CO_2. The primary source of carbon release is the burning of fossil fuels; however, there are many other sources. Historically, U.S. agriculture has been a source of carbon release from the intensive tillage of prairie grasslands and the clearing and burning of forest areas for cultivation (Donigian et al.; U.S. Department of Energy). Carbon incorporated into the soil profile, known as soil organic carbon (SOC), is released in gaseous form when soil is turned and exposed to oxygen. Facilitated by tillage, rapid decomposition of plant matter and soil erosion also contribute to carbon release (U.S. Department of Energy).

Agricultural tillage practices have in fact changed very little over time, although the implements have become larger and more efficient. Conventional tillage, in which the soil profile is inverted, is thought to have several important benefits for agricultural producers. Exposed to the air, black soils warm sooner, contributing to rapid seed germination. Wet soils dry more rapidly when turned, enabling other field operations to proceed sooner. Planting is made easier when seedbed preparation involves the incorporation of surface organic material into lower soil profiles through tillage.

Conventional tillage, however, contributes to serious soil erosion problems, both from wind and surface water. The alarming loss of material from even the most productive soils, but especially from vulnerable soils, resulted in research and extension efforts that led to the development of a variety of conservation tillage practices (e.g., reduced, strip, zone, and no-till technologies). Conservation tillage is generally described as any tillage and sowing technique that maintains an organic surface residual cover of 30% or greater after the planting operation (Reicosky). Although conservation tillage came about primarily for control of erosion, it was also found to be the primary method of transforming agricultural production from a carbon source to a carbon sink (i.e., carbon accumulation in the soil profile exceeding release due to disturbance; Allmaras et al.). Throughout this paper, conservation tillage and no-till is used interchangeably, although no-till does refer to that tillage practice causing the least disturbance of the soil profile.

Carbon release rates from conventional moldboard plowing are substantial, sometimes exceeding the carbon input from the prior year's crop. In several experiments, Reicosky found the initial carbon release to be 49 g CO_2 m^{-2} h^{-1} on average from highly productive Minnesota soils. Release rates fell to about 7 g CO_2 m^{-2} h^{-1} after 5 hours, but measurable release rates persisted as long as 28 days after plowing. In contrast, initial carbon release of a conservation till planting operation was 29–32% of the moldboard plow release. The carbon sink potential of agricultural soils therefore depends on carbon sequestration rates from plant incorporation exceeding releases from the tillage operation.

Rates of carbon sequestration resulting from plant absorption of atmospheric CO_2 that is incorporated into above- and belowground structures depend on the interaction of many factors in addition to tillage practice. These include soil type, precipitation, temperature, crop variety, and planting density. In addition, enhanced crop rotations incorporating a greater number of different crops, the use of green cover crops as mulch, winter cover crops, animal waste application, and reduced use of open fallow also increase the rate of SOC accumulation (Donigian et al.; U.S. Department of Energy). However, enhanced crop rotation after the adoption of no-till cultivation is found to contribute little additional SOC accumulation (Reicosky). Conversion to no-till agricultural production is thus the principle means of SOC accumulation in soil systems.

Carbon sequestration is not constant over time. Empirical studies have found several equilibrium levels corresponding to distinctly different rates of absorption. The highest rates occur during the period immediately following conversion of tillage techniques from conventional to no-till and endure from 5 to 10 years. Sequestration rates then fall eventually to near zero within 15 to 20 years (West and Post).

With this information, several observations can be drawn about SOC sequestration in agricultural soils. First, although there are limits to the total capacity of SOC sequestration, substantial initial carbon release allows agriculture to be a significant sink over the next 15 years. Furthermore, conversion to no-till cultivation in agricultural production is a low-cost and stable method of sequestering carbon relative to other methods, particularly aboveground stores, with gains that can be realized in a relatively short time (Antle et al. 2002). Increased SOC through no-tillage practices has other social and private benefits as well, including higher long-term soil fertility, reduced erosion, reduced leaching of nitrogen, and water filtration action (Schneider). Hence, there are many public good characteristics of producer adoption of no-till cultivation for carbon sequestration that is a natural joint product of a particular crop production technology.

No-Till Adoption and Yields

As cited, initial adoption of no-tillage production technology was mainly aimed at erosion control, with other benefits realized subsequently. Current adoption of conservation tillage techniques in the United States stands somewhere between 19% and 25% of total available cropland (Hellwinckel, Larson, and Ugarte; Reicosky). For significant carbon sequestration to take place, adoption of no-till cultivation by agricultural producers will have to increase and be maintained.

In a frictionless and full-information setting, optimizing farmers will have already adopted cultivation technologies that maximize the profits of their enterprise, which might or might not include no-till cultivation. Public policy intended to encourage expansion of no-till practices would need to provide compensation that at least covers the opportunity cost of switching to a lower profitability practice (Antle et al. 2001, 2002). However, although agricultural producers might indeed act as profit maximizers, they do so in an environment beset with risk and uncertainty, not only with respect to their own production activities but also with regard to the perceived benefits of no-till technologies. Herein, we may find further explanation regarding the reluctance of some producers to adopt no-till practices and clues on how to structure the incentives and compensation for switching.

The literature on conservation tillage adoption is not definitive in the assessment of the agronomic and economic benefits to producers of doing so, with the exception of highly erodible land where no-till adoption has clear benefits for the producer. The conclusions offered by various analysis depends, in part, on whether the criteria for decision making focuses on crop yields or whole-farm and enterprise returns.

Many crop budgets indicate higher net returns to no-till management over conventional tillage, but this appears to be less related to absolute crop yield advantages than to savings relating to equipment size and operating expenses, field day advantages, cropping pattern interactions, herbicide application rates, and fertilizer treatments (Ekman; Popp et al.). For example, a study that combined agronomic trials with enterprise budgets to analyze several combinations of production methods, including conservation tillage, in soybean production in Arkansas found that neither yields nor net returns were systematically and significantly affected by tillage method (Popp et al.). In some instances, mean yields are assumed identical when planting and harvesting periods coincide between no-till and conventional tillage methods (Lee, Brown, and Lovejoy). Agronomic findings, however, indicate that yield relationships between cultivation methods result from complex interactions of management practices with soil characteristics, weather conditions, crop type and pattern, and initial field conditions. A small sampling of available agronomic studies illustrates this point.

Average yield reductions of 7% are observed for no-till continuous corn in cool wet soils characteristic of the northern corn belt (Vetsch and Randall). However, reductions of 3% or less are possible with modified no-till systems (zone and strip tillage) while maintaining desirable residual organic cover. However, in the same region, corn yields are not affected when following soybeans in rotation. Sims et al. concur that tillage might be needed to maintain yields when soils are fine and slow to warm but that no-till production of irrigated corn is viable in the drier climates of Nebraska. However, higher rates of nitrogen application are needed to prevent yield reductions associated with no-till. For nonirrigated corn in southwestern Quebec during years of above average precipitation, Mehdi, Madramootoo, and Mehuys found that corn yield and biomass were not affected by tillage system even when organic residuals hindered initial plant emergence and delayed maturity in no-till systems. They anticipate, however, that no-till systems will produce higher yields under average to moderate precipitation. Krall, Nachtman, and Miller, studying irrigated corn following alfalfa in Wyoming, found that no-till corn sown into sod treated with preplant herbicide produced yields comparable to conventional tillage. The effect of residual cover on yields during the first transition year from Conservation Reserve Program land in Nebraska has important interaction effects with tillage for corn and sorghum (Shapiro et al.). Soybean yields, however, were not affected under no-till systems because of warmer soils associated with later planting dates and the availability of postemergence herbicides. Schillinger, Cook, and Papendick found that Pacific Northwest spring barley sown into standing stubble produced yields equal to or higher than conventional tillage when uniform stands where achieved. However, they did find important differences depending on the type of no-till seed drill equipment used. Finally, Vyn and Janovicek address issues of nutrient stratification, particularly of potassium, in long-term no-till systems on corn yields in southern Ontario. They found no yield advantage to conventional tillage on long-term no-till soils compared with no-till that included potassium in the starter fertilizer mix or when using a modified no-till system such as strip tillage.

The preceding examples highlight the complex relationship of tillage with site and weather-specific characteristics that affect grain yield response (Antle et al. 2001, 2002). These physical relationships combined with required adjustments in management practices affect the costs or benefits of no-till adoption for each producer.

When mean yield differences between cultivation methods are insignificant, Hellwinckel, Larson, and Ugarte suggest that incentives to no-till adoption will need to be ongoing. Schneider identifies producer risk aversion and "stickiness" with respect to traditional farming methods as additional factors inhibiting no-till adoption. Adoption of new production techniques might also be delayed if the transition involves costs that potentially threaten business survival, such as mistakes made while adjusting management. This effect is represented as a learning curve by Upadhyay and Young, who model it as a linear decreasing yield penalty. However, the authors assume higher long-run profits and focus on the conditions of successful transition, including the form of equipment acquisition and speed of adoption.

Another explanation for slow no-till adoption comes from the theory of investment under uncertainty. The traditional Marshallian rule calls for investment when the present value of future returns is greater than or equal to the investment cost or, alternatively, when the net present value (NPV) of an investment is greater than zero. However, no-till adoption has all the characteristics of an investment in which it might be rational to delay adoption of the new technology even when the usual investment rule calls for it (Dixit and Pindyck). The characteristics of an investment that generates an option value to delay include those in which the investment is at least partially irreversible because it is industry specific (such as no-till seed drilling equipment), there is uncertainty over future returns (e.g., ambiguity surrounding yield or cost advantages of no-till practices in a particular area), and it is possible to wait for more information without losing the possibility of making the investment in the future. Option value increases the threshold that discounted returns must exceed before investment takes place and provides a sound economic explanation for why rational producers might not adopt no-till technologies.

At first brush, positive option value suggests that incentives for no-till adoption and SOC sequestration will need to be large. However, payment for benefit externalities will hasten adoption, and at potentially lower cost, for two reasons. First, there is the obvious result that the additional revenue stream will increase the NPV of the investment. Second, if the additional revenue stream is also nonstochastic, the overall uncertainty of the project, and especially the degree of downside risk, is reduced, leading to a lower option value of waiting; that is, the investment threshold itself is reduced. Therefore, a lower but certain payment schedule for SOC sequestration might be sufficient to ensure no-till adoption.

Adoption of no-till technologies might also seem unattractive to producers on the basis of their subjective probability assessment of yield or income outcomes relative to the performance of their current practice. For example, it is known that the heuristics producers use in forming subjective distributions overestimate mean yields, whereas yield variance is underestimated (Buzby et al.; Dismukes, Allen, and Morzuch), a bias that potentially leads to management decision errors. Lee, Brown, and Lovejoy also show that producer assessment of income mean and variance are consistently more favorable than the objective distributions derived from individual farm models for both conventional and no-till operations.

However, another important observation is possible from an examination of the subjective distributions contained in the work of Lee, Brown, and Lovejoy. In their study, subjective income distributions were elicited from producers for both conventional and no-till practices regardless of the producers' actual choice. This information allows one to see how producers judge the outcome of moving from one tillage practice to another, but from the perspective of the current tillage choice. Table 1 presents the mean and coefficient of variation (CV) for each individual's subjective income distribution under conventional and reduced tillage. Use of the CV allows a direct comparison of the perceived variation in income between the two cultivation practices. The last column calculates the difference in the mean and CV from the perspective of the current tillage choice and reveals, with minor exceptions, a systematic bias in favor of the

Table 1. Comparison of Subjective Income Distributions by Cultivation Practice and Farm Size

Size	Conventional		Reduced		Difference	
(acres)	Mean ($)	CV	Mean ($)	CV	Mean ($)	CV
Conventional						
700	18,871	0.058	15,155	0.099	3,716	0.041
455	−6,728	0.001	−6,848	0.032	120	0.031
377	−7,588	0.001	−7,746	0.005	158	0.003
350	200	0.805	200	0.805	0	0.0
330	9,608	0.007	9,339	0.03	269	0.023
266	4,839	0.013	4,794	0.015	45	0.002
120	8,454	0.028	8,005	0.022	449	−0.006
100	8,516	0.079	8,178	0.090	338	0.011
80	998	0.001	818	0.001	180	0.0
Reduced						
930	26,666	0.064	32,261	0.036	5,595	0.029
930	32,626	0.188	41,481	0.13	8,855	0.058
785	16,258	0.036	16,902	0.029	644	0.008
633	18,191	0.057	19,060	0.074	869	−0.017
288	20,886	0.013	20,974	0.012	88	0.001
270	13,579	0.013	13,353	0.004	−226	0.008

Source: Data from Lee, Brown, and Lovejoy (Table 2, p. 844).

currently employed tillage technology. That is, those producers who practice conventional tillage believe that their mean income would decrease by moving to reduced tillage and that the variability in their income would increase. Similarly, producers currently employing reduced tillage technology believe that moving to conventional tillage would result in a mean income reduction and an increase in income variability.

In general, the percent decrease in mean income ranges between 0% and 21% and averages about 8% when moving from the producer preferred technology to the other. This observation adds additional substance to the idea of stickiness of traditional farming methods, in which, on the basis of subjective distributions, current practice is considered most beneficial. The results also suggest that once the transition to conservation tillage is made, there exists a similar subjective bias against reconversion.

Methodological Approach

The method of determining a value to apply to a unit of benefit externality is inspired by Meyer, who proposed modeling an externality as an additional commodity in a mathematical programming setting in order to take advantage of information contained in derived dual variables. The essential economic problem is to discover what minimum price is required to obtain a certain level of externality production for which no prior "price-discovering" market exists. The approach draws on the duality property between a production function and a cost function in that each contains information that describes the other (Varian). When a constrained optimization problem is solved, the dual of the primal (e.g., the corresponding minimization of a maximization problem) is simultaneously solved with the information obtained through the constraints of the primal. The solution values of the minimization problem are just the shadow prices of the constrained resources in the primal maximization problem. By interpreting the shadow prices as the marginal cost associated with a unit increase of a constraint, we are then able to understand something about a producer's short-run supply curve.

Given a description of the joint production technology involving a benefit externality, we should be able to find the dual minimum cost values of meeting a certain externality production level in the process of maximizing the profit function of the farming enterprise, subject to other resource and institutional constraints. Optimal resource allocation problems in agriculture such as this constitute a classical application of predictive mathematical programming, which is the empirical tool employed in the analysis (Hardaker, Huirne, and Anderson; Schneider).

In this application, a profit-maximizing, joint product, representative farm resource allocation problem is specified that incorporates nonrecourse production yield risk. Yield risk is an objective function coefficient risk source and is modeled in the expected value-variance (E-V) framework. In this formulation, risk-averse producers are assumed willing to accept lower expected returns for a decrease in variance of expected returns, depending on their degree of risk aversion. Furthermore, the conditions under which maximization of the E-V model is equivalent to maximization of expected utility are assumed to be met (Hardaker, Huirne, and Anderson; Freund). The incorporation of risk will be important in this application because the returns to carbon sequestration are nonstochastic and are anticipated to have strong effects on the incentives to undertake no-till activities.

Following the matrix notation of McCarl and Spreen, the standard form of the E-V quadratic programming model is

$$\begin{aligned} \text{Max } Z &= \bar{C}X - \Phi X'SX \\ \text{s.t. } AX &\leq b \\ X &\geq 0, \end{aligned}$$

where X are producer's choice variables, $\bar{C}X$ is expected income, Φ is the risk aversion coefficient, $X'SX$ is variance of expected income, and b are resource constraints.

Because there are no known prices for SOC sequestration to guide resource allocation decisions, a minimum requirement constraint is imposed that must first be satisfied before profit maximization can take place. In setting a minimum requirement, the assumption is made that there are costs associated with no-till adoption relative to conventional tillage. The minimum constraint will be met in the least cost fashion to achieve a specified level of output given the form of the no-till penalty, other farm-specific constraints, and SOC sequestration rates.

Under risk neutrality, the partial derivative of the optimized objective function with respect to the constraints yields the marginal value of limiting resources, the shadow price, which is equivalent to the Lagrangian multiplier from any constrained optimization problem. When the constraint is a minimum requirement, the partial derivative can be interpreted as the marginal cost of meeting the requirement. By iterating over a range of minimum constraint levels, the resulting marginal costs (or minimum cost of a certain level of production) can be mapped and constitute the producer's short-run supply curve for the benefit externality.

Empirical Model

Two experiments are undertaken in the application to derive values associated with conversion to no-till cultivation and subsequent carbon sequestration. This is conducted within the framework of an optimal farm resource allocation model previously developed and described by Dillon. The quadratic programming model incorporates crop yield risk using E-V analysis and consists of a representative mixed crop farm enterprise operating on 1,350 acres in Henderson County, KY. Crop enterprises include corn, wheat, soybeans, and double-cropped soybeans following wheat. A crop rotation requirement ensures that no more than half the available land is planted in corn, with the balance in soybeans, wheat, or both. However, crop and production choice is expanded to include a number of different varieties, different planting densities, and sowing dates that have an effect on expected crop yields. In addition, labor use is further constrained by incorporating considerations of days suitable for field work. In this application, the possibility of double-cropping soybeans is removed because suitable data regarding carbon sequestration were not available for this practice. It should be noted that this initial model assumes that no-till production technology is in place.

New Activity Vectors

The first experiment involves incorporating vectors to describe the joint production characteristic of crop production and carbon sequestration in tons of SOC per acre by crop type. This is achieved by adding new crop production activities representing no-till practices and redefining the existing crop production activities as occurring under conventional tillage. This procedure preserves the richness in the original model in terms of crop production alternatives (i.e., plant variety, sowing date, sowing density, and suitable field days).

In this experiment, it is assumed that all producer benefits of conventional tillage are subsumed under a mean yield advantage of 5%. This considerably simplifies the analysis and might not be completely unrealistic if producer stickiness, in terms of no-till adoption, can be represented by a subjective yield distribution that is slightly higher under conventional tillage. The 5% yield advantage works out to about a 7% mean income advantage, which is slightly less than the average subjective income advantage found previously for conventional versus no-till. However, even if differences are nonexistent, the option value of delaying the investment could prevent adoption. Yield variation between no-till and conventional tillage are assumed to be the same. This would induce a further bias against no-till if yield variation is considered to be less severe than under conventional tillage practices.

Finally, a minimum requirement for SOC sequestration is added, which is increased over successive iterations until maximum annual sequestration potential or saturation is reached given sequestration rates and crop rotation requirements. Risk neutrality is assumed in this step. This procedure yields a range of shadow prices attached to the constraint at each level, which is interpreted here as the implicit marginal cost of SOC sequestration given the state of technology.

These modifications can be summarized as

$$\sum_{\mathrm{E}} \sum_{\mathrm{V}} \sum_{\mathrm{P}} \sum_{\mathrm{S}} X_{\mathrm{E,V,P,S}} \mathrm{SOCyield}_C \geq \mathrm{SOCmin} \quad \forall C,$$

where $\mathrm{SOCyield}_C$ are carbon sequestration rates by crop, SOCmin is the carbon sequestration requirement, E is the enterprise activity index, V is the variety index for soybeans and corn, P is the plant population index, S is the sowing date index, and C is the expanded crop index.

The second experiment then removes the minimum requirement constraint but includes carbon sequestration as a joint production economic activity in which prices per ton of SOC are varied over the range of shadow prices found in the first experiment, again under risk neutrality, and the voluntary level of SOC sequestration is then observed. Given duality, the resulting carbon sequestration supply schedule should be similar to that found in the first experiment. Finally, risk aversion is introduced to observe how stochastic farming returns from crop production with nonstochastic returns from carbon sequestration affect the incentives for producers to adopt no-till technology and store carbon.

Modifications to the empirical model can be summarized as

$$\sum_{\mathrm{E}} \sum_{\mathrm{V}} \sum_{\mathrm{P}} \sum_{\mathrm{S}} X_{\mathrm{E,V,P,S}} \mathrm{SOCyield}_C - \mathrm{SOCbal} = 0 \quad \forall C,$$

$$\sum_{\mathrm{YR}} \frac{1}{N} Y_{\mathrm{YR}} + (\mathrm{SOCbal} * \mathrm{SOCpr}) - \bar{Y} = 0,$$

where SOCbal is total carbon sequestered per year, SOCpr is price per ton of carbon, $\bar{Y}$ is the average net returns across years, Y_{YR} is net returns by year, YR is the year index, and N is the number of observations in the data set.

Carbon Sequestration Rates

Sequestration rates under no-till vary widely depending on many factors, as discussed previously. However, West and Post provide

Table 2. Sequestration Rates by Crop (g CO_2 m^{-2} yr^{-1})

	Corn	Soybean	Wheat
No-Till Cultivation	90 ± 59	84 ± 52	74 ± 52
Rotation Reduction	20 ± 12	20 ± 12	20 ± 12
Adjusted Rates	70	64	54
Tons SOC $acre^{-2}$ yr^{-1}	0.312	0.285	0.241

Source: Data from West and Post.

mean estimates and confidence intervals for a variety of crops and cropping systems on the basis of an extensive analysis of previous empirical research. Table 2 provides the sequestration rates used in the empirical model, which are assumed to reflect sequestration potential in the first 15 years following no-till adoption with enhanced crop rotation. Crop type is shown to be an important variable in sequestration potential. Corn provides the highest level, followed by soybeans and then wheat. Although the confidence intervals around the mean estimates are relatively large, it is interesting to note that they are fairly uniform over crop types. The initial farm resource allocation model imposes a prior crop rotation regime, so the base sequestration rates are adjusted downward to reflect SOC sequestration potential given existing management practice. A uniform lower value was selected because the crop rotation depicted is not particularly rigorous and involves just three crops. Finally, the mean adjusted rates are converted to annual tons of SOC per acre for use in this analysis.

Risk Aversion Parameter

Risk aversion is a characteristic of a diminishing marginal utility of wealth and thus a preference for current wealth. The risk aversion parameter in the E-V model, Φ, is thus a numerical expression of a producer's risk-return preference describing the rate at which mean returns are penalized in exchange for reduced variance. McCarl and Spreen outline a variety of methods to arrive at a value for the risk aversion parameter when a producer's utility function is unknown. Of these, the initial model uses the procedure described in McCarl and Bessler that relies on the assumption of normality of net returns over all states of nature to arrive at an upper bound parameter based on confidence intervals and is

$$\Phi = \frac{2Z_\alpha}{S_y},$$

where Z_α is the value of a one-tailed standard normal distribution at the α level of significance and S_y is the standard deviation of net returns. The standard deviation is recomputed from the initial model to reflect changes in the variance of net returns from the removal of the double-cropped soybean activity and used to generate a new risk aversion parameter. A relatively low risk aversion level of $\alpha = .60$ is chosen for this illustration and can be interpreted as the probability that the realized value of net returns will fall within one standard deviation of the mean 60% of the time. Therefore, $Z_\alpha = 0.253$, and with the newly computed $S_y = 72{,}912.53$, the risk aversion parameter becomes $\Phi = 6.9 \times 10^{-6}$. For reference, the mean value of net returns is $316,663.47 for conventional tillage with the 5% yield advantage assumption.

Results and Discussion

In the first experiment, the shadow price for various levels of yearly carbon sequestration is found by iteratively imposing minimum quantity constraints. The shadow prices attached to each constraint level can be interpreted as a marginal benefit resulting from the relaxation of the constraint at the margin. The derived schedule is depicted in Figure 1. The schedule is increasing, which reflects the higher opportunity costs of changing production activities in order to meet the more demanding constraint. The schedule is not smooth because

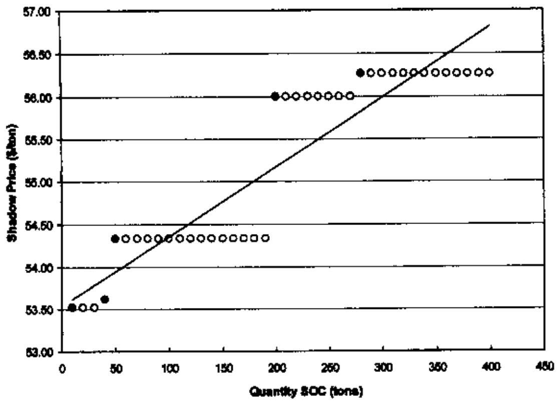

Figure 1. Short-Run Marginal Cost Curve

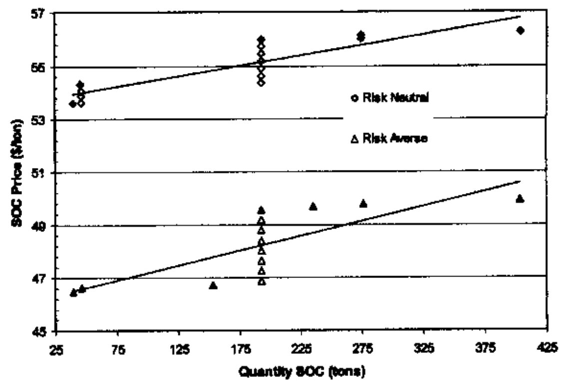

Figure 2. Risk-Neutral and Risk-Averse SOC Supply Response Ranges

in a math programming setting, production activity relationships are fixed. The five points identified in black show where the constraints just impose a new higher level of opportunity cost of carbon sequestration. The horizontal points to the right indicate that the marginal benefit to the producer of relaxing any higher level of constraint is constant over a certain range.

The results show that a minimum constraint for the first ton of SOC imposes a marginal cost of $53.52 per ton. Maximum carbon sequestration is reached at approximately 403 tons given the crop area, sequestration rates, and crop rotation requirement and is associated with a shadow price of $56.26 that starts at approximately the 274-ton constraint level. Total opportunity cost of a coercive minimum requirement is found as the area under the curve and yields an average cost of approximately $55.21. Because the constraint is coercive, the marginal benefit price of relaxing it from the saturation point would not be enough to voluntarily bring about that level of sequestration, but rather the 274 tons as indicated in the figure.

The shadow price ranges provided by the constrained model serve as the basis for price ranges in the second experiment that provides compensation per ton of carbon sequestered, first in a risk-neutral environment and then in a risk-averse environment. The risk aversion level used is quite low (60%), lower than one might expect to be realistic in practice (Dillon), but it is used to show the magnitude of effects over small changes.

Figure 2 depicts the voluntary SOC supply response to price changes given producer risk attitude. As anticipated, the supply response in the risk-neutral case contains the reference points found when imposing a minimum constraint. Under 60% risk aversion, the prices at every level are lower everywhere from the risk-neutral case for an equivalent amount of carbon sequestration, as is predicted by theory. This occurs because returns from carbon sequestration are nonstochastic and thereby contribute importantly to income variance reduction. In addition, the difference between the two supply schedules appears to be greater at low levels of carbon sequestration than at higher levels of carbon sequestration. An average cost of $55.72 per ton is found under risk neutrality, which drops to $48.66 per ton under risk aversion. This price falls into the range offered by other empirical studies (see Antle et al. [2001] for a brief review).

In both the risk-neutral and risk-averse scenarios, no-till soybeans are brought into the basis first in response to payments for carbon sequestration. Area to no-till soybeans increases until the limit is reached as defined by the rotation requirements, indicating that soybeans are the least cost method of carbon sequestration given differences in conventional and no-till production, even though no-till corn has a higher carbon yield. No-till corn enters the solution next, whereas wheat does not enter the solution at all.

These results and derived supply schedules show that, because of risk aversion among agricultural producers, the level of monetary incentive and total budgetary outlays required to induce multifunctional carbon sequestration might be lower than anticipated, but this depends importantly on assumptions about the level of producer risk aversion.

Further Work

Although this paper demonstrates a method to estimate the value for the voluntary supply of a specific benefit externality in a particular location, the analysis suffers from several shortcomings. The entire problem for the case of carbon sequestration can be made more realistic by initially modeling a representative farm where conventional tillage is the norm. Specifically, subsuming all benefits to conventional tillage under a uniform yield advantage masks important cost differences between the two tillage technologies. For example, labor requirements are different because no-till requires only two field operations. There could also be differences in machinery size requirements and associated operating costs. Crop yield functions should reflect site-specific characteristics under different tillage scenarios. Carbon sequestration rates might also need to be reexamined in light of local soil types and with the possibility of modeling enhanced crop rotation schedules. Biophysical simulation methods, calibrated to a particular area, could help realistically fill the gaps where relevant location-specific data are missing or incomplete.

A second important consideration is contract form. Monitoring and enforcement are important transaction costs that vary widely depending on contract design and location of administration. The success of programs for the production of local benefit externalities most likely lies in their being locally administered, which lowers monitoring costs and enables adjustments to prevailing resource conditions. Wu and Babcock outline the relevant issues for contract design when the policy objective is to correct for market failure in the interest of public welfare. Their approach is explicit in considering site-specific resource endowments and focuses on the principles of voluntary participation and self-selection in contract design. In practice, not all producers will be induced to participate at politically acceptable price levels, but this should not be of concern so long as adequate provision of the desired benefit externalities is generated by those who do participate.

The contract form implicit in this paper is an annual per ton payment for sequestered SOC. Although useful for examining the costs of carbon sequestration, implementation of a per ton payment scheme is likely difficult because stored carbon is difficult to observe, payments vary by soil type and crop, and the payment scheme is probably less intuitive, for example, than per acre payments for no-till adoption. Furthermore, there are important implications of option value in contract design and duration of payments that would benefit from further study. For example, if payments are offered to overcome the value of waiting, the possibility also exists that once no-till conversion takes place, payments could be phased out with little likelihood that producers would switch back to conventional tillage.

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