Poverty, Risk and the Adoption of Soil Carbon Sequestration

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Abstract

In this paper we explore the incentives of low income agricultural producers to adopt soil carbon sequestration, focusing particularly on the impact of risk. A dynamic optimization model of the farm level decision to adopt conservation is then presented, where farmers' optimize over the expected utility of profits from agricultural and carbon sequestration activities. Carbon sequestration adoption impacts on agricultural productivity are modeled as a combination of the technological impacts of adopting a new farming system and the productivity impacts of changes in soil carbon on agricultural output. Comparative static results indicate that increases in the price for carbon sequestered in the soil and the discount rate have an unambiguous impact on equilibrium soil carbon levels with the former leading to higher carbon levels and the latter leading to lower levels. The impact of increases in the price of agricultural output and risk aversion are ambiguous, depending on the relative strength of the productivity and technology effects of adoption. The paper concludes with a discussion of the implications of the theoretical and empirical findings for the design of payment mechanisms to induce low income farmers to participate in carbon markets.

1. Introduction

Sequestering carbon in soils through the adoption of agricultural practices broadly known as “conservation agriculture” is an important means by which the process of global climate change may be mitigated. (Lal 1999; Batjes 1999) At the same time, the agricultural practices used to supply soil carbon sequestration often lead to more profitable and sustainable agricultural production systems for both small and large producers, characterized in many cases by more stable and higher agricultural yields. (FAO 2004) Additional environmental benefits in the form of and improved ecosystem functioning are also commonly associated with such agricultural production systems. (FAO 2004; FAO 2001a; FAO 2001b) The global public benefit associated with climate change mitigation from carbon sequestration has been increasingly recognized, defined, and valued in recent years, accompanied by the development of institutions to facilitate payments for mitigation services. Developing countries in particular are thought to have a tremendous potential to supply soil carbon sequestration at low and competitive prices in markets for carbon emission reductions. (Lal 1999; Reicovsky 2004 ;Ringius 2002)

Soil carbon sequestration is of particularly interest in the context of poverty alleviation, since degraded lands in dryland areas are a good potential source of carbon sequestration, with the potential to simultaneously increase agricultural productivity in areas characterized by high poverty incidence and limited options to improve livelihoods outside of the agricultural sector. Payments for the supply of climate change mitigation services through soil carbon sequestration offer the potential to meet both environmental and socio-economic objectives through the same set of activities. The adoption of conservation agricultural production systems can generate both private and public goods: e.g. higher and more stable returns to agriculture and climate change mitigation respectively. Payments for the public good component in the form of payments for soil carbon sequestration, can be used to augment the private benefits of conservation agriculture compared with traditional practices, creating incentives to adopt . Alternatively, conservation agriculture may represent a more productive and stable farming system than the alternative even without supplementary carbon payments, but not be adopted due to the presence of financial or social barriers. Here, payments for carbon sequestration may be most effective as a means of overcoming these constraints.

One key barrier, particularly for poor farmers who are highly risk-averse, is the uncertainty associated with the adoption of conservation agricultural practices. Conservation agriculture requires new and more intensive management input, yields may become more volatile and costs for herbicides or labor inputs for weed control may increase during a transition phase from conventional agricultural practices. Risk averse farmers are often reluctant to make a major change in their farming practices due to the potential risk to yields, income and food security that are involved, even if it is only for a limited period.. (Bishop-Sambrook et. al. 2004; ACTN 2004; FAO 2001a) In this paper we explore the role of risk in the decision to adopt agricultural practices that generate soil carbon sequestration, focusing particularly on poor farmers. We assess the likely impacts of risk as well as other factors on the supply of sequestration from poor farmers and discuss how payments for carbon sequestration may be designed to stimulate supply response from this group. The paper is organized as follows: in section II we describe the technical potential of conservation agriculture as a potential source of soil carbon sequestration supply. In Section III, we assess the private benefits from adopting conservation agriculture, including the potential demand for soil carbon sequestration services, as well as the private costs and returns to agricultural production. In Section IV we present a household model of the decision to adopt conservation agriculture and supply soil carbon sequestration which incorporates risk.. In Section V we conclude with a discussion of the results of the previous sections and their implications for the role of risk in the potential supply of soil carbon sequestration from poor farmers, and suggestions for the design of carbon payment programs.

2. Technical Background

*A. Conservation agriculture: one option for soil carbon sequestratio*n

Conservation agriculture is but one of several options available for increasing soil carbon sequestration. albeit one of the most productive sources of sequestration from agricultural crop lands (See Table 1 below) Simply increasing the application of inorganic or organic fertilizer, or changing from agricultural to grassland or agro-forestry land uses, increasing the length of fallow periods, and refraining from converting lands to agricultural production are all examples of land use management changes that can increase soil carbon sequestration. (FAO 2004; Ringius 2002; Lal, 1998) In this article we focus on conservation agriculture as a potential source of carbon sequestration since it is a system that does not require a change of land use out of agricultural crop and food production and requires relatively little external inputs. Both of these features are important in considering appropriate strategies for poor farmers in developing countries where agricultural markets and financial services for agriculture are not well-functioning. Growing food for own consumption is a widely practice strategy among poor farmers to reduce the risk of food insecurity. Poverty is usually correlated with small land holding size, and a limited capacity to convert some land to non-crop alternatives, thus a strategy that maintains the capacity to produce food crops is important in many agricultural development contexts Another important reason for promoting conservation agriculture (although not one focused upon in this study) is the environmental benefits it can generate aside from climate change mitigation. These include improved watershed functions, particularly flood control and reduction of water contamination, as well as biodiversity conservation. (FAO Conservation Agriculture Fact Sheet)

B. Soil carbon sequestration as an output of conservation agriculture

Conservation agriculture is a term that covers a broad range of agricultural practices that protect and stimulate biological functioning of the soil as a means of attaining high and stable productivity, in contrast to conventional agricultural practices that either rely upon capital inputs to maintain productivity, or involve the depletion of soil resources , frequently resulting in declining levels of agricultural productivity. (FAO 2001b pg. 3) The two key features of a CA system are a reduction or elimination of tillage, and an increase in the coverage on the soil surface. (FAO 2001b pg. 3) The process of improving soil functions by building up soil organic matter (SOM) with CA adoption also increases soil organic carbon (SOC) which results in an increase in carbon sequestration, and/or a decrease in carbon emissions. The adoption of a permanent soil cover helps protect the soil from sun, wind, and water erosion. The change in tillage practices reduces the amount of soil carbon that is dispersed into the atmosphere as a result of churning the soil. Together these practices feed soil biota, microorganisms, and fauna, which improve the ability of the land to engage in its own nutrient balancing, thereby stabilizing the soil ecosystem. In short, the adoption of conservation agricultural practices increases the amount of carbon being introduced into the soil through surface organic materials, and decreases the amount of carbon that is removed from the soil by protecting the land surface from weather events and the avoidance of tillage that leads to atmospheric carbon releases.

C. Soil carbon sequestration potential by agro-ecological zone

Soils are the largest carbon reservoir of the terrestrial carbon cycle. (FAO 2001b) Soils contain about three times more carbon than vegetation and twice as much as that present in the atmosphere. Soil carbon sequestration increases the carbon content of soils through a set of land management practices that add organic content to the soil or reduce soil carbon losses from decomposition and mineralization. One estimate of the potential impact of improved land management over the next 50 to 100 years is sequestration of up to 150 Pg of carbon, which is the equivalent of the total amount of carbon emitted since the mid 19th century from land use change. (FAO 2001b; Lal 1999) However, it is important to note that while the total amount of carbon that can be sequestered from improved soil management is quite large, the amount which can be generated per hectare per year, per land area is relatively small, particularly in comparison to sequestration from increasing above-ground biomass (e.g. reforestration or afforestation). Due to this low productivity, as well as other features of the carbon market discussed below, several studies have noted that the economic potential for soil carbon sequestration supply are considerably lower than the technical estimates. (Ringius 2002; Schlesinger, W.H. . 2000)

Comparative figures of the sequestration productivity per hectare by source are shown in Table 1 below.

The potential rate of carbon sequestration is sensitive to agro-ecological conditions, with higher rates in humid temperate areas than semi-arid and tropical areas. (Pretty and Ball 2001; Lal 1999) According to Lal 1999, the adoption of conservation agriculture techniques that involve reduced tillage and coverage of at least 30% of the land area can be expected to generate 0.5 -1.0 t C/ha/yr in humid temperate conditions, 0.2 - 0.5 t C/ha/yr in humid tropics, and 0.1 - 0.2 t C/ha/yr in semi-arid zones (Lal, 1999). The differences between agricultural and forest sequestration in drylands and tropical areas, in terms of the average carbon sequestration productivity by land use change, is shown in the table below (taken from Lal 1999).

Table 1.

Main effects of land management practices or land use on carbon sequestration (t/ha/yr). Drylands and tropical areas [from Lal, 1999]

	Drylands (3 billion ha)	**Tropical Areas (2 billion ha)**
CROPLANDS 700 million ha.		
Conservation tillage	0.1/0.2	0.2/0.5
Mulch farming or plant cover	0.05/0.1	0.1/0.3
Conservation agriculture	0.15/0.3	0.3/0.8
Composting	0.1/0.3	0.2/0.5
Nutriment management	0.1/0.3	0.2/0.5
Water management	0.05/0.1	
GRASSLAND AND PASTURES 3 billion ha.	0.05/0.10	0.1/0.2
AFFORESTATION		4 to 8
AGROFORESTRY 1 billion ha.		0.2/3.1 (max. 9)

Rates of soil carbon sequestration from conservation agriculture are variable over agro-ecological conditions, as well as the specifics of the farming system adopted. A difference in crops included in a rotation can have a major impact on sequestration rates. (Ringius 2002)

Despite their sequestration productivity disadvantage (relative to humid areas), carbon sequestration in drylands can be attractive due to their extensive coverage (43% of the earth's surface), high residence time for soil organic matter, and their large capacity for sequestering carbon before reaching a new equilibrium, due to historic patterns of use that have left these areas highly degraded. (FAO 2004) Sections III and IV discuss the farm-level incentives to supply soil carbon sequestration services in more detail.

3. The Costs and Potential Benefits of Sequestering Carbon

In order to model the farmer's decision to adopt agricultural practices for soil carbon sequestration, it is first important to understand the key components of the returns to newly adopting these practices. In this section, we describe the potential returns to supply soil carbon sequestration and to increasing agricultural productivity, as compared with the costs of adoption.

A. The market for soil carbon sequestration services

Two key forces are driving the emerging market for carbon sequestration services: 1) legally binding commitments to reduce carbon emissions, and 2) the potentially lower cost of emission reduction credits from carbon sequestration relative to other possible means – particularly in the short run. Several exchanges of carbon offsets are being set up, but the one of most relevance for developing countries is the Clean Development Mechanism of the Kyoto Protocol. This mechanism allows developed countries with binding emissions reductions to offset their carbon emissions with the purchase of carbon emission reduction credits (CERs) from developing countries. Carbon sequestration from afforestation and reforestation is one potential source of CERS, however under the current commitment period ending in 2012, sequestration from soils is not allowed. Including soil carbon into the CDM for the next commitment period is currently under discussion but uncertain.

Other non-Kyoto sources of payments for CERs from soil carbon sequestration in developing countries have emerged, although the trading volume is quite limited. The Biocarbon Fund, recently established by the World Bank with a capitalization of $53.8million for the first phase, has two separate windows for financing: one targeted to land-use changes that qualify for credits under the CDM, and another which allows a broader menu of land uses to be considered, including agricultural soil carbon sequestration. (World Bank 2002).

The prices that are being paid for CER credits varies widely by source of demand and type of offset. The ecosystem marketplace reported prices of around $7/tCO2, up from a range of $3 to $6.5 per ton in 2004. (Ecosystem marketplace website) The Chicago Climate Exchange, a voluntary exchange of carbon offsets including U.S., Canada and Mexico which allows soil carbon sequestration reported prices ranging from $2.3/Cton - $2.65Cton for 2005. (Chicago Climate Exchange Website)

CER prices from carbon sequestration are disadvantaged relative to other sources of carbon offsets due to their reversibility. Carbon stored as a result of sequestration can be released back into the atmosphere with a reversal in the land use change that generated the sequestration; e.g. if farmers revert to conventional tillage. The risk of reversibility is being managed by the creation of temporary offsets that must be renewed after a fixed period of time. Temporary credits are priced lower than other CERS. The BioCarbon Fund has set an indicative price of $4/Cton for temporary CERs under their CDM compliant window, and $3/CTON for CERS under Window 2, where soil carbon sequestration could be funded. (World Bank 2002)

Market-based sources of demand for CERS require additionality: the sequestration generated should be additional to what would have occurred under a baseline "business as usual" case. Sequestration projects thus require baseline setting, monitoring and verification in order to generate certified CERs, as the source of demand is based on having verifiable sources of emissions reductions. The costs of monitoring and verification insoil carbon sequestration projects are substantial, increasing significantly for smaller project sizes. Mooney et. al. 2004 estimated per hectare costs of monitoring for a 1,000 hectare project at between $5 to $8 hectare, using data from soil carbon projects in the U.S.

The Global Environment Facility is a non-market source of demand for carbon sequestration services, providing global public sector intervention to stimulate the production of global environmental goods such as climate change mitigation.
GEF is funded by contributions from donor countries**.** In 2002, 32 donor countries pledged $3 billion to fund operations between 2002 and 2006. (GEF website) GEF funds the "incremental" or additional costs associated with transforming a project with national benefits into one with global environmental benefits, such as climate change mitigation. Soil carbon sequestration activities qualify for funding under the Land Degradation and Integrated Ecosystem Management operational areas. Payment levels and form vary between projects; there is no one set price for carbon sequestration. GEF projects do not require the type of monitoring and verification required for the market based projects, although they do require regular reporting of quantifiable indicators of project impact.

At this point in time, market-based demand for CERs from soil carbon sequestration in developing countries is quite limited. This could change, but considerable uncertainty persists on future levels and sources of demand for CERS from soil carbon sequestration. Even if prices for CERs from sequestration do rise substantially, the transactions costs of supplying to the market are high. As more experience with sequestration projects in developing countries is gained, and the rules of the markets more clearly and firmly established, transactions costs could fall, however given the considerable uncertainty that still exists on both the demand and supply of the CER market any assumptions on price movements can only be speculative. Funding from non-market sources such as the GEF are another potential source of demand for soil carbon sequestration services, which may be more suitable for soil carbon sequestration payments due to high transactions costs in the market based setting.

B. Economic costs

The adoption of conservation agriculture (CA) changes the agricultural technologies and input mix employed in agricultural production. Changes occur in labor, capital, energy, pesticide and herbicide and fertilizer costs. (FAO, 2001a).

A reduction in input costs is cited as one of the most important impacts of CA adoption, but in the short run, during a transition phase, these costs can increase. It is important to note that the size and even the sign of these cost changes depend, in part, on the agricultural practices that prevailed before the switch. Switching out of a capital intensive production system is quite different than switching out a low input, low productivity system. The latter situation is the most likely to be the case of poor agricultural producers, and thus the one we focus upon. Agro-ecological conditions also play an important role in determining the size of these cost differences.

A reduction in labor requirements is one of the most important aspects of changing to CA in the context of poor agricultural producers in developing countries. (Bishop-Sambrook et. al. 2004) In the case of Brazil, which has over 14 million hectares in CA production, decreases in labor use on the order of 10-60% per hectare per year were observed, depending on the crop and region (Pieri et. al. 2002) Labor savings is one of the primary motivating factors in the promotion of CA in Africa, as a means of helping address the impact of HIV AIDS on the reduction in agricultural labor forces. (Bishop-Sambrook et. al. 2004) ACTN, 2004) For those that previously tilled the land with a hand-hoe, the labor savings can be rather substantial, assuming that weed control, particularly in the transition phase, is managed with herbicides and not manual labor. Studies in developing countries have found substantial cost savings in labor with CA adoption, although in several examples labor input rose during a transition phase of one to three years. (Bishop-Sambrook et. al. 2004; ; Ekboir et. al. 2002)

Insect control tends to be equally important in conventional and CA systems, although some evidence indicates that pest pressures are reduced under the latter systems, resulting in lower pesticide costs. (Ekboir et. al 2002; FAO 2004) The two practices differ in their use of herbicides. Herbicides may be used to combat weeds that are no longer controlled through tillage, and new adoption of conservation agriculture can therefore necessitate an increase in herbicide use, particularly during the transition phase. The extent of this increase will depend on how badly the weed infestation of the field was in the beginning, how much weeding is performed by hand or how well other weed management tools (soil cover, crop rotation) are implemented from the beginning. There is evidence that herbicide use will decline over time, perhaps eventually falling to levels below conventional agriculture (FAO, 2001a).

The adoption of conservation agricultural practices requires some capital investment, and this is often cited as a factor preventing low income agricultural producers from adopting the technology. (Bishop-Sambrook et. al. 2004; Pieri et. al. 2002; ACTN 2002) The purchase or rental of no-till planters that plant directly through a ground cover greatly reduces labor requirements but requires a capital expenditure. Capital costs associated with the adoption of conservation agriculture from a low input subsistence system include purchase or rental of mechanized and non-mechanized planters that can seed through soil mulch, although in some cases, particularly in Africa, the planting tools of the traditional farming system have been used. (Ekboir et.al.2002)

During the transition phase, fertilizer use in CA agriculture can increase, depending on whether green manure crops are used in the rotation and how effective they are. (ACTN 2002). However increases in the soil fertility associated with the adoption of CA has resulted in a decreased need for fertilizer inputs over the long run in study sites in Brazil and Africa. Fertilizer applications were cut by 30% in the case of maize and 50% for soybeans in one long term study of CA adoption in Brazil. (ACTN 2002) Fertilizer use has been found to increase in CA systems in developed countries however. (Uri, 1997) Furthermore, the application of fertilizer in conservation agricultural systems requires greater management skills, suggesting that the costs of fertilizer *per application* may also rise with the adoption of these systems. (ACTN 2002)

As the adoption of conservation agricultural practices yields cost savings on some inputs and cost increases on others, the net effect is ambiguous, depending on factors such as agro-ecology and conventional systems in place. Evidence on the relative cost of conservation agriculture production in developing countries is sparse, while that from the U.S. and Canada give mixed results. Some studies have found evidence of small long-run cost saving (Crosson, 1981; Uri, 1997), while others have found the adoption of conservation practices to be cost-increasing (Zentner et al., 1991; Stonehouse and Bohl, 1993). The net effect depends critically on the form of CA that is adopted (partial or full adoption of the system) as well as the previous farming system, and on agro-ecological conditions, including climate, soil type, topology, and the level of soil degradation, that dictate potential crop types and agricultural input requirements. High adoption rates in some areas (e.g. Latin America) together with the limited empirical studies of CA adoption in developing countries indicate that significant reductions in input use are achievable by a transition from traditional to conservation agriculture under a wide range of circumstances.

C. Agricultural benefits from CA adoption

In this section we focus on the private benefits of CA adoption in the form of improved levels and stability of agricultural yields, focusing particularly in dryland areas. Current farming systems in the drylands of developing countries often rely on mining soil resources, depleting organic carbon and other nutrients, and thereby resulting in losses in productivity and unsustainable systems. These areas and farming systems are characterized by highly degraded soils, low agricultural productivity and high rates of poverty. (FAO 2004) A fairly limited range of options exists for improving rural livelihoods in these areas at this point, and improving agricultural productivity is a critically important part of any effort to reduce poverty in the area.

Conservation agriculture practices that generate soil carbon sequestration also impact agricultural productivity by improving both biological and chemical components of the soil. Soil carbon sequestration is associated with increased levels of soil organic matter (SOM) which has a direct impact on soil fertility. (FAO 2001b) Organic matter, and the biological activity that it generates, have a major influence on the physical and chemical properties of soils (Robert, 1996). Aggregation and stability of soil structure increase with organic matter content. These, in turn, increase the infiltration rate and available water capacity of the soil, as well as resistance against erosion by water and wind (Reicovsky 2004) . Soil organic matter also improves the dynamics and bioavailability of main plant nutrient elements. Agricultural productivity co-benefits can also be high in soils with low cation exchange capacity (CEC). CEC increases with organic matter, particularly in drylands areas, and by increasing the bio-availability of other nutrients such as phosphorus and inhibiting the toxicity of others such as aluminium, its impact on agricultural yield can be quite significant (Tieszen et. al. 2004; FAO 2001b; Robert 1996)

Much like the case for carbon sequestration productivity, the impact of soil carbon on agricultural yields also depends on agro-ecological conditions. These yield effects can be quite significant in dryland areas, where increasing soil organic matter may impact water holding capacity and availability of a range of nutrients. Despite some careful empirical work examining the relationship between soil erosion (related to levels of soil carbon levels) and agricultural productivity (e.g. Wiebe 2003.), considerable uncertainty remains about the precise relationship between soil carbon levels and agricultural productivity. In general however, soil carbon sequestration is always associated with a positive increase in SOM, which may lead to improved agricultural productivity through a variety of pathways: by increasing water holding capacity or CEC, as well as improving soil textures and reducing erosion risk. The relationship between SOM changes and changes in any of these parameters, and the ultimate impact on agricultural productivity depends on the soil type, climate and production system.

The mechanism by which carbon sequestration through the adoption of CA affects agricultural productivity can be best understood by examining two distinct elements of the process. The first is the set of human actions which need to be taken to generate sequestration, which includes all the production activities that must be altered to switch to a conservation agricultural system. We refer to the impact from this element as the 'technology' effect, as it is a direct result of adopting new agricultural practices, or technologies. The second is the result of the biophysical change in the level of SOM and its impact on agricultural productivity that is generated as a result of the adoption of sequestering land use practices. We refer to the impact from this element as the 'productivity' effect, as a higher level of soil organic carbon is associated with more productive soils.

As discussed in the section on economic costs above, farmers undergo a transition period in the adoption of CA. During this period of transition (approximately 1-5 years), the soil ecosystem adjusts from one equilibrium to another. Soil-borne pests and pathogens may create new problems in the process of changing the biological equilibrium. (FAO Conservation Agriculture Fact Sheet) Weed control in the first 1-2 years of adoption can be a significant problem, requiring increased use of herbicides and/or increased labor for weeding. (FAO 2001b) Average agricultural yields generally remain unaffected, but yields can be more susceptible to pest and diseases, with a consequent increase in yield volatility (FAO Conservation Agriculture Fact Sheet). This susceptibility is a direct result of the instability of the soil ecosystem. Once the ecosystem has reached its new post-adoption equilibrium, this heightened level of susceptibility ceases to exist. In short, the adoption of sequestration activities does not affect average agricultural yields but does increase pressure to respond to different or sometimes even new pest or disease problems for a brief period following adoption. The increase in soil carbon content as a result of sequestration activities, in contrast, affects both average yield and its volatility. Increases in the level of soil carbon tend to increase average yields, albeit at a decreasing rate. Increases in the level of soil carbon also decrease the susceptibility of yield, primarily to weather shocks, also at a decreasing rate. Thus, the addition of carbon to the soil essentially pays a "double dividend" with regards to agricultural yields: average yields increase and yield volatility decreases.

Combining both the 'technology' and the 'productivity' effect reveals the net impact of carbon sequestration on agricultural yields. In the initial phase after adoption, average agricultural yields rise slowly as a result of increased soil carbon levels, but may become more volatile as a result of the recent disruption to the soil ecosystem, and as farmers become familiar with the new production system. In the subsequent phase, the 'technology' effect dissipates and average yield increases while the volatility of yield decreases and input use (fertilizer and pesticides) also decreases. The degree to which volatility effects are important will depend, in part, on farmers' risk preferences, the length of the transition phase, and the exposure to weather and pest shocks. The length of the transition phase, weather and pest risk and the magnitude of average yield increases will, in turn, depend on local agro-ecological conditions.

4. Modeling Soil Carbon Sequestration Decisions

A. A Household Model of Soil Carbon Sequestration Supply with Risk

In this section, we develop a basic model of optimal soil carbon sequestration supply from the adoption of conservation agriculture for small farmers. The distinction of 'small' farmers is meant to convey the importance of production stochasticity and producer risk preferences. Specifically, we assume that farmers maximize their expected utility from profits, $EU(\pi)$, rather than profits directly. Profits in this case are generated from both agricultural output and payments for sequestering carbon in the soil, where $U'(\pi)>0$ and $U''(\pi)<0$. As such, the farmer's land can be viewed as a multiple-use resource whose optimal management will require the farmer to consider the returns to each activity and the (possibly) competing demands that they place on her land (Zivin et al., 2000).

Suppose that agricultural yield in any given period is equal to $f(S,C_t)+2g(S,C_t)\Theta$, where θ is a stochastic weather variable with an expected value of zero (Just and Pope, 1978). S is a composite measure of exogenous land quality which includes soil type, land slope, local temperature and rainfall conditions, and C_t is the amount of carbon in the soil in period t.[1] Expected yield f is assumed to be increasing in all variables at a decreasing rate (i.e. f'(S)>0, f''(S)<0,f'(C)>0, f''(C)<0). The function g can be thought of as a measure of sensitivity to weather. Weather sensitivity is assumed to be decreasing in land quality and soil carbon levels at an increasing rate (i.e. g'(S)<0, g''(S)>0, g'(C)<0, g''(C)>0). Let p_a represent the market price per unit of agricultural output. For simplicity, we will also assume that this price represents the per unit value of agricultural output consumed by the farmer, which is tantamount to assuming that all farmers have market access and that food production levels always exceed the subsistence demands of the household. We will discuss the implications of relaxing this assumption when we analyze the properties of equilibrium carbon sequestration levels. Profits from agricultural production can be expressed as $\pi_a = p_a f(S, C_t) - 2p_a g(S, C_t)\sigma_\Theta^2$. Taking a second-order Taylor-Series approximation of $EU(\pi_a)$ yields the following expression:

$$(1) \qquad EU(\pi_a) \cong p_a f(S, C_t) - rp_a g(S, C_t)\sigma_\Theta^2$$

where r is the Arrow-Pratt measure of risk aversion. Utility from agricultural production is increasing in average yield and decreasing in the variability of yields. This type of utility function is frequently used in finance (Markowitz, 1987) and can be viewed as a special case of the more general class of mean-standard deviation utility functions. The properties of these utility functions and their consistency with expected utility theory are discussed in great detail elsewhere (Meyer, 1987).

In addition to revenue from agricultural output, farmers can earn money for sequestering carbon in the soil. Let p_c denote the price per unit carbon sequestered. Note that only incremental carbon units above baseline are eligible for payment. Thus, farmer revenue from sequestering carbon can be expressed as $p_c\widetilde{C}$,where $\widetilde{C} = C_t - C_0$ and C_0 represents baseline carbon levels established as part of the carbon payment program.[2] Carbon augmentation is achieved through investment in sequestering activities, Φ_t, such that $\dot{C} = h(\Phi_t, S)$. The amount of soil carbon growth as a result of sequestration activities depends on land quality, where $h'(\Phi) > 0, h''(\Phi) < 0, h'(S) > 0, h''(S) < 0$. The cost of sequestration has two parts. First, there is a direct per unit cost of sequestration activities,

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[1] Note that soil carbon is intentionally excluded from our measure of land quality, as we wish to examine its impacts on agricultural yield and yield volatility separately.

[2] If the baseline is based on actual carbon levels at the commencement of the program, it will be important that rules are defined to avoid an endogenous rush to mine carbon from the soil before joining the program. An alternative approach that avoids this problem is to define the baseline using agroecological modeling.

which we will denote q_Φ.[3] This cost should be viewed as the per period costs – the management, labor and input costs – of operating a farming system of sequestration intensity Φ.[4] Second, the undertaking of sequestration activities temporarily raises the yield variability during the transition phase. Adopting sequestering practices may generate yield volatility in two ways: by disturbing the previous soil ecosystem equilibrium, which, in turn, makes agricultural yields more susceptible to weather shocks or because of imperfect adoption of the new system due to incomplete information, lack of inputs and the farmers' process of learning the new technology. When the soil ecosystem equilibrium is restored, this volatility effect disappears. For simplicity, we model this volatility impact as a one period shock to agricultural yield variability immediately following a change in sequestration activities, denoted $m\dot{\Phi}$. Thus, the new expression for crop yield susceptibility to weather shocks is $m\dot{\Phi}$ times the pre-sequestration yield volatility measure $g(\ )$.

Expected utility for the farmer from engaging in both agricultural production and carbon sequestration in the soil can now be expressed as follows:

$$(2) \qquad EU(\pi) \cong p_a f(S,C_t) - rp_a g(S,C_t) m\dot{\Phi}\sigma^2_\Theta + p_c\tilde{C} - q_\Phi \Phi_t .$$

The objective of the farmer is to choose sequestration activities to maximize expected utility subject to the equation of motion for soil carbon growth. Letting δ denote the discount rate, this objective can be expressed by the following current-value Hamiltonian.

$$(3) \qquad \tilde{H} \cong \left\{p_a f(S,C_t) - rp_a g(S,C_t) m\dot{\Phi}\sigma^2_\Theta + p_c\tilde{C} - q_\Phi \Phi_t + \mu[h(\Phi_t,S)]\right\}e^{-\delta t}$$

The first-order conditions for this maximization problem can be expressed as:

$$(4) \qquad \frac{\partial \tilde{H}}{\partial \Phi} = -rp_a g(S,C_t) m\sigma^2_{\Theta t} - q_\Phi + \mu\frac{\partial h}{\partial \Phi} = 0$$

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[3] In our earlier discussion, we noted that the operating costs of conservation agriculture may fall over time. While we do not formally model this cost dynamic, the implications are potentially important, as they would strengthen the disincentive to adopt sequestration activities while leading to increased levels of sequestration among those who still find it profitable to engage in these activities. The relative magnitudes of these changes on the intensive and extensive margins, and thus aggregate soil carbon levels, will depend on how quickly operating costs fall over time.

[4] Note that, in our model of agricultural profits without sequestration, input costs are normalized to zero. Thus, q_Φ can be viewed as the incremental costs of operating a system of sequestration intensity Φ relative to the costs of operating a system where Φ=0.

$$(5) \qquad \dot{\mu} - \delta\mu = -\frac{\partial \widetilde{H}}{\partial C} = -\left\{ p_a \frac{\partial f}{\partial C} - rp_a \frac{\partial g}{\partial C} m\dot{\Phi}\sigma_\Theta^2 + p_c \right\}$$

$$(6) \qquad \dot{C} = h(\Phi_t, S),$$

where the assumption that soil carbon has no value beyond its price from the sequestration program and its contribution to agricultural productivity suggests the following transversality condition: $\lim_{t\to\infty} \mu(t) = 0$. Equation (4) states that the disutility from an increase in the volatility of yields as a result of sequestration activities plus the direct cost of sequestration activities equals the marginal productivity of sequestration in terms of carbon production times the shadow value of soil carbon. The interpretation of equation (5) is that the change in the shadow value of carbon in the soil is equal to the discounted value of carbon content in the soil from the previous period minus the impact of a change in carbon on expected utility (the expression in brackets). This latter carbon effect includes the impact soil carbon has on average yields, the volatility of yields, and the revenue a farmer receives directly from carbon payments. Equation (6) is simply a restatement of the equation of motion for soil carbon

B. Model Dynamics and Steady-State Analysis

In this section, we will derive the steady-state solution for the farmer's problem and then examine the properties of this equilibrium. Before proceeding, we first analyze the equilibrium paths of sequestration activities and soil carbon levels. The latter is simply (6) above. The sequestration path is obtained by taking a time derivative of (3) and substituting this expression and (6) into (5). Considerable manipulation yields the following:

$$(7) \quad \dot{\Phi} = \frac{rp_a \frac{\partial g}{\partial C} hm\sigma_\Theta^2 + \left[p_a \frac{\partial f}{\partial C} + p_c \right]\left[\frac{\partial h}{\partial \Phi} \right] - \delta\left[rp_a g(S, C_t) m\sigma_{\Theta t}^2 + q_\Phi \right]}{\left[\frac{\partial^2 h}{\partial \Phi^2} \Big/ \frac{\partial h}{\partial \Phi} \right]\left[rp_a g(S, C_t) m\sigma_\Theta^2 + q_{\Phi t} \right] + \left[\frac{\partial h}{\partial \Phi} \right] rp_a \frac{\partial g}{\partial C} m\sigma_\Theta^2}$$

Figure 1 contains a phase-plane diagam, which illustrates the path dynamics. The carbon isocline indicates that sequestration is independent of carbon levels. Sequestration levels are decreasing at an increasing rate in carbon levels along the sequestration isocline. The directionals make clear that the steady-state equilibrium (Φ_*, C_*) is a saddle point defined by covergent isosectors II and IV and divergent isosectors I and III. All points in isosectors II and IV will converge to the steady-state solution as $t \to \infty$. Rather intuitively, when carbon levels are initially low (high), high (low) levels of sequestration will lead to the steady-state equilibrium.

INSERT FIGURE 1

The steady-state solution corresponds to the case where $\dot{C} = \dot{\Phi} = 0$. Thus, setting (6) and (7) equal to zero and combining provides a concise expression describing the steady-state equilibrium.

$$(8) \qquad \delta = \frac{\left[p_a \dfrac{\partial f}{\partial C} + p_c \right]\left[\dfrac{\partial h}{\partial \Phi} \right]}{\left[q_\Phi + r p_a g m \sigma^2_{\Theta t} \right]} \equiv \frac{\dfrac{\partial U}{\partial C}\dfrac{\partial h}{\partial \Phi}}{\dfrac{\partial U}{\partial \Phi}}$$

In steady-state equilibrium, the discount rate is equal to the marginal utility gained from an additional unit of carbon (which includes benefits from carbon payments as well as agricultural yield impacts) times the marginal productivity of sequestration in producing soil carbon divided by the marginal disutility from engaging in sequestration, i.e. the costs of sequestration. In other words, the opportunity cost of capital equals the economic return on sequestration – a result frequently referred to as the Golden Rule of Capital Accumulation. If this were not true, farmers could reallocate their portfolio of activities and increase their utility.

C. Comparative Statics and Implications for the Poor

For simplicity, let U denote $EU(\pi)$ as defined by equation (2), with $U'(C)$ representing the productivity effect and $U'(\Phi)$ representing the technology effect from sequestration. Consider first the marginal effect of changing the price per unit of carbon sequestered. Totally differentiating (8) and applying the Implicit Function Theorem yields:

$$(9) \qquad \frac{dC}{dp_c} = \frac{-\left[\dfrac{\partial^2 U}{\partial C \partial p_c} \dfrac{\partial U}{\partial \Phi} \right]}{\left[\dfrac{\partial^2 U}{\partial C^2} \dfrac{\partial U}{\partial \Phi} - \dfrac{\partial U}{\partial C} \dfrac{\partial^2 U}{\partial \Phi \partial C} \right]}.$$

The denominator of this expression can be manipulated such that its sign depends on whether the elasticity of the marginal benefit from an additional unit of soil carbon is larger or smaller than the elasticity of the marginal cost of sequestration on the marginal benefit from an additional unit of soil carbon per unit of sequestration. The second-order restrictions on the maximization problem ensure that this expression will be negative for all interior solutions. Thus, the latter effect is larger than the former. The bracketed expression in the numerator is clearly positive, thereby making the sign of (9) positive. Rather intuitively, increases in the price of carbon yield higher levels of soil carbon sequestration. Assuming that all agents will be offered the same carbon payment, this effect should affect rich and poor farmers in a similar manner.

Now, consider the marginal effect of changing the price of agricultural output on equilibrium carbon sequestration levels. Again, totally differentiating (8) and applying the Implicit Function Theorem yields:

$$(10) \qquad \frac{dC}{dp_a} = \frac{-\left[\dfrac{\partial^2 U}{\partial C \partial p_a}\dfrac{\partial U}{\partial \Phi} - \dfrac{\partial^2 U}{\partial \Phi \partial p_a}\dfrac{\partial U}{\partial C}\right]}{\left[\dfrac{\partial^2 U}{\partial C^2}\dfrac{\partial U}{\partial \Phi} - \dfrac{\partial U}{\partial C}\dfrac{\partial^2 U}{\partial \Phi \partial C}\right]}$$

As in (9) above, the sign of the denominator is negative. The sign of the numerator is ambiguous. Higher output prices make the augmentation of soil carbon more attractive because it increases agricultural yield and decreases long-term yield volatility, but less attractive because the sequestration activities that must be undertaken to increase soil carbon levels increase short-term yield volatility. The ultimate impact of an increase in agricultural output prices on equilibrium soil carbon levels will depend on the magnitude of the positive ‘productivity’ effect relative to the magnitude of the negative ‘technology’ effect. The discount rate also plays an important role, as the technology effect occurs at the moment that sequestration activities are altered, while yield impacts accrue over time.

Earlier, we stated that the assumption of a fixed market price for agricultural output was equivalent to assuming that food production levels always exceed the subsistence demands for the household. If, as we might expect, this assumption is not true for poor farmers, then it must be true that the value that they place on agricultural output is higher than the market price. Otherwise, they would be selling at least some fraction of their output in the market.[5] Thus, we can think of the poor farmer as one who implicitly faces a higher price for (i.e. places a higher value on) agricultural output. The implications of this for equilibrium soil carbon levels will depend on the sign of (10). If, *ceteris parabus*, the yield effect prevails, poor farmers will sequester more carbon than wealthier farmers. If the technology effect dominates, poor farmers will sequester less carbon.

We can also examine the impact of the discount rate on equilibrium soil carbon levels. This impact can be characterized as follows:

$$(12) \qquad \frac{dC}{d\delta} = \frac{\left[\dfrac{\partial U}{\partial \Phi}\right]^2}{\left[\dfrac{\partial^2 U}{\partial C^2}\dfrac{\partial h}{\partial \Phi}\dfrac{\partial U}{\partial \Phi} - \dfrac{\partial U}{\partial C}\dfrac{\partial h}{\partial \Phi}\dfrac{\partial^2 U}{\partial \Phi \partial C}\right]}$$

The denominator, as before, is negative and the numerator is positive. Increases in the discount rate unambiguously decrease the amount of carbon sequestered in the soil. This result is rather intuitive as the negative impacts from disturbing the agricultural ecosystem – the technology effect – accrue in the short-term while the positive benefits from an increase in agricultural yield and a decrease in yield volatility accrue over a longer time horizon. If discount rates are decreasing in wealth (Lawrance; Ogaki and Atkeson), then poor farmers will sequester less carbon than rich ones. In our setting, these high discount rates among the poor could be motivated by a host of factors, including credit constraints, insecure land tenure, or shortened planning horizons due to survival concerns.[6]

Next, we consider the impact of a marginal change in the coefficient of risk aversion on equilibrium soil carbon levels. Again, totally differentiating (8) and applying the Implicit Function Theorem yields:

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[5] For simplicity, we are assuming that the transaction costs associated with market access are not prohibitively large.

[6] The interested reader should see Shiferaw and Holden and Lipper 2001 for a more detailed discussion of conservation decisions, discount rates, and the rural poor.

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$$(12)\qquad \frac{dC}{dr} = \frac{-\left[\dfrac{\partial^2 U}{\partial C \partial r}\dfrac{\partial U}{\partial \Phi} - \dfrac{\partial U}{\partial C}\dfrac{\partial^2 U}{\partial \Phi \partial r}\right]}{\left[\dfrac{\partial^2 U}{\partial C^2}\dfrac{\partial U}{\partial \Phi} - \dfrac{\partial U}{\partial C}\dfrac{\partial^2 U}{\partial \Phi \partial C}\right]}$$

The denominator is negative and the sign of the numerator is ambiguous. Like the impact of agricultural output prices, increases in the degree to which a farmer is risk averse has two opposing effects. Increasing soil carbon levels becomes more attractive due to the long-term benefits associated with decreased yield volatility. On the other hand, the sequestration activities that must be undertaken to increase soil carbon levels increase volatility in the short-run, creating a disincentive to sequester for more risk-averse farmers. In general, risk aversion is assumed to decrease with wealth (Hennesey 1997; Bar-Shira et al, 1997). Thus, poor farmers will tend to sequester more carbon than wealthier farmers when the soil carbon effect on volatility dominates the sequestration activity effect on volatility. When the technology effect dominates, poor farmers will sequester less. Again, the discount rate will play an important role, as the timing of these two effects is not the same.

Finally, we can examine the impact of land quality on equilibrium soil carbon levels. This impact can be characterized as follows:

$$(13)\qquad \frac{dC}{dS} = \frac{-\left[\left(\dfrac{\partial^2 U}{\partial C \partial S}\dfrac{\partial h}{\partial \Phi} + \dfrac{\partial U}{\partial C}\dfrac{\partial^2 h}{\partial \Phi \partial S}\right)\dfrac{\partial U}{\partial \Phi} - \dfrac{\partial U}{\partial C}\dfrac{\partial h}{\partial \Phi}\dfrac{\partial^2 U}{\partial \Phi \partial S}\right]}{\left[\dfrac{\partial^2 U}{\partial C^2}\dfrac{\partial h}{\partial \Phi}\dfrac{\partial U}{\partial \Phi} - \dfrac{\partial U}{\partial C}\dfrac{\partial h}{\partial \Phi}\dfrac{\partial^2 U}{\partial \Phi \partial C}\right]}$$

Changes in land quality will have an ambiguous impact on equilibrium soil carbon levels. The impact depends fundamentally on how the marginal benefit from an additional unit of soil carbon changes with land quality and on how the marginal benefit from additional sequestration activities changes with land quality, $\frac{\partial^2 U}{\partial C \partial S}$ and $\frac{\partial^2 h}{\partial \Phi \partial S}$, respectively. The literature seems to suggest that both of these functions are increasing at low levels of land quality and decreasing at high levels. In other words, as one moves from low quality land to slightly improved land, the marginal benefit from soil carbon increases, as does the marginal productivity of sequestration activities. As one moves from high quality land to even higher quality land, the marginal benefit from an additional unit of soil carbon is declining, as is the marginal productivity of sequestration activities. A graphical representation of these marginal impacts with land quality on the x-axis would reveal an s-shaped curve, revealing increasing returns to scale at low levels of soil quality and decreasing returns to scale at high levels of soil quality (Antle 2002)

Given these relationships, it is straightforward to verify that at low levels of land quality, improvements in land quality will yield higher levels of soil carbon sequestration. At very high levels of land quality, improvements in land quality yield sufficiently small impacts on agricultural yields and the productivity of sequestration activities (i.e. sufficiently negative marginal impacts) so as to decrease equilibrium levels of soil carbon. At intermediate land quality levels, improvements in land quality will again yield higher levels of soil carbon sequestration, albeit with an impact not nearly as large as that for farmers on low quality land. The implications of these results for the poor depend on the types of lands that the poor tend to inhabit. Those who live on land of intermediate quality will sequester the most carbon. Those on very low or very high quality lands will sequester the least. In terms of the implications for the poor, there is considerable controversy over the nature of the relationship between land quality and poverty, and studies have shown conflicting results, party due to differences in scale of analysis. (Lipper 2001) A negative relationship between poverty and land quality is more frequently found in micro level studies. Except in cases of extremely poor land quality, poor producers are thus likely to be on lands suitable for soil carbon sequestration.

The results of the comparative static analysis and their implications for the participation of poor agricultural producers in the adoption of soil carbon sequestering land use practices are summarized in Table 2.

Table 2. Summary of Comparative Static Analysis Results on Equilibrium Carbon Levels

Effect	**Sign**	**Note**	**Poverty Implication**
Price of carbon	Positive	Increase in carbon price results in increased carbon levels	Same for all income levels
Price of ag. output	Ambiguous	Results depends on relative strength of productivity and technology effects	Poor farmers have a higher value of ag. output (subsistence)
Discount rate	Negative	Higher discount rates lead to lower carbon levels	Poor more likely to have higher discount rates
Coefficient of Risk Aversion	Ambiguous	Result depends on relative strength of productivity and technology effects	Poor are more risk averse
Land Quality	Ambiguous	Result depends on land quality effect on marginal increase in soil carbon and in soil carbon impact on ag. productivity	Poor often located on degraded lands

5. Discussion: Poverty, Risk and Soil Carbon Sequestration Supply

Our analysis has indicated that under current market conditions the returns to soil carbon sequestration $p_c\left[\widetilde{C}\right]$ are likely to be small, due to a combination of low prices for CERs from sequestration as well as low sequestration productivity rates from soil carbon. Using the indicative numbers presented in sections II and III, assuming that a farmer could sequester between .15 to .3 CTons/HA/year from CA adoption, for a period of 20 years and the price paid is the Biocarbon indicative price of $4 CTon, a farmer could make between $12 to $24 per hectare, which is a small amount, even in the context of agricultural systems with low agricultural productivity. One study from Senegal that projected returns to soil carbon sequestration at between $1.4 to $31 per year, per household, found that this would represent only a very small fraction of total household income: between .2 and 4 percent. (FAO 2004 pg. 80) Thus payments for soil carbon sequestration are likely to most important as a support to the adoption of CA systems that generate a positive private benefit to agricultural production.[7]

The results from the household model give insight to the critical determinants of CA adoption – and the potential barriers to the poor. They indicate that higher carbon prices and lower discount rates unambiguously increase the supply of soil carbon sequestration. They also indicate that the relative strength of what we have called the "technology" and "productivity" effects of adopting conservation agriculture is the key determinant of the impacts of changes in agricultural output prices, risk aversion and land quality on the decision to adopt CA and supply soil carbon sequestration. Enhancing the strength of the productivity effect, and in particular for poor producers, reducing the negative impacts of the technology effect are critical to induce the adoption of CA and the supply of soil carbon sequestration.

The productivity effect is an outcome of biophysical relationships between various components of CA technology interacting with the soil and agro-ecosystem. Identifying the spatial distribution of poverty with the biophysical conditions most likely to generate improvements in agricultural productivity and stabilization of crop yields, and using this to target programs is an important means by which positive productivity effects can be

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[7] This low per hectare price of soil carbon and the potentially high price of monitoring also raises concerns about the feasibility of payments directly based on the amount of carbon sequestered. If the transaction costs of such payments are too high, payments will need to be made on proxies for soil carbon sequestration. Insofar as these measures are inaccurate, the proxy approach will introduce more uncertainty into the adoption process, thus creating an additional disincentive for participation by risk averse farmers.

strengthened. In particular, it is important to define the aspects of land quality which are most likely to generate a positive agricultural benefit and map these against the distribution of wealth. In addition, information on the biophysical conditions under which improvements in agricultural productivity and soil carbon sequestration are highly correlated would identify locations where CA adoption will be most beneficial to producers.

The negative impacts of the technology effect on adoption stems from the possibility of higher yield volatility during a transition phase. This volatility can be expected to have a strong negative impact on the adoption behavior of the poor, who generally have higher levels of risk aversion, as well as higher discount rates. Our analysis suggests that fixed payments for soil carbon sequestration – while insufficient to stimulate CA adoption in the absence of agricultural co-benefits – could induce some farmers to supply carbon by reducing the costs of operating a CA system. An annual payment alone, however, will be insufficient to achieve optimal sequestration as the agricultural productivity risk associated with transitioning to CA will inhibit poor farmers from participating in the carbon market. Structuring carbon payments to provide insurance against yield volatility for CA adopters, particularly during the transition phase, could induce poor farmers to participate. Optimality would require both insurance against the productivity risk as well as an annual carbon payment equal to the external benefits from sequestration. Of course structuring insurance contracts is not simple and problems with moral hazard and adverse selection can pose serious problems in the effectiveness of insurance schemes. (Skees et. al. 1999; McCarthy 2005) However this concept of using payments to support insurance services is likely to be important for other environmental services as well, where uncertainty is a factor determining the decision to adopt the land use associated with ES provision, and the returns to the service at the farm level are relatively low.

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