CHANGING SOIL DEGRADATION TRENDS IN SENEGAL WITH CARBON SEQUESTRATION PAYMENTS

by

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

In Sudo-Sahelian Africa, erosion and nutrient mining are prominent causes of soil degradation. In Senegal, harvesting grains and crop residue from the land impact heavily on soil carbon content, while the insufficient replacement of soil nutrients with fertilizers contributes to negative nutrient balances. Given the economic perspective of the rational farmer and the dynamic nature of crop and soil management issues, this thesis used a regional case study in the Groundnut Basin of Senegal to do the following: describe and assess economic incentives specific the to the case study region; model the farmer's production and decision making process; design carbon contract policies and model them within the farmer's decision making process; simulate the interaction between the current agricultural marketplace and potential carbon policies; and to assess the role that carbon sequestration could play in helping the region deal with soil degradation problems, if and when international action is taken to reduce greenhouse gas emissions. Information from farmers in the region indicates that several factors constrain fertilizer use, including financial constraints and market imperfections. The result of these constraints is to reduce the productivity and increase the farm gate cost of fertilizers. The results of the simulation supported this hypothesis. Using data from the Groundnut Basin in Senegal, and employing an econometric-process simulation model, this study found that some carbon contracts could be used to reduce losses in soil carbon and productivity; however, only at high carbon prices ($180 USD/t carbon and higher). Transactions costs, the additional labor costs associated with residue incorporation, and groundnut residues prices all strongly influenced the results of the carbon contract policies, particularly where carbon prices are less than $100/t.

CHAPTER 1

NEW PERSPECTIVES ON CREATING INCENTIVES FOR THE ADOPTION OF SUSTAINABLE SOIL MANAGEMENT PRACTICES

Introduction

Declining soil organic carbon content, and resultant declines in soil fertility, are problems for many of the world's agricultural production systems (Oldeman, 1990) Although volumes of soil conservation research focus on this problem and alternative sustainable practices, this trend continues in many parts of the world today, notably in Sub-Saharan Africa (SSA).

A key process in many unsustainable agricultural systems is degradation of soils through loss of soil organic carbon (SOC). With cultivation, soils may lose 50% or more of their organic carbon content, depending on soil conditions and agricultural practices. Consequently, there is a potential to increase SOC in most cultivated soils. Soil carbon sequestration is defined as using plant photosynthesis to capture carbon dioxide (CO_2) from the atmosphere, and put it into soil carbon stocks. This is can be achieved by a variety of management practices including: increasing cropping intensity and fertilization; mulch farming; conservation tillage; cover crops; integrated nutrient management; and agroforestry (Lal, 2004).

The cycle of depletion of soil organic matter, declining crop yields, poverty and food insecurity, and soil and environmental degradation could be broken by improving soil fertility through enhancement of the SOC pool (Lal, 2004). Incentive mechanisms to encourage carbon sequestration could alleviate those problems, while satisfying international goals of greenhouse gas mitigation. A key question that needs to be answered before implementation is: at what cost can SOC losses be slowed or reversed?

There are several crucial factors to be considered in order to evaluate carbon sequestration's potential as an instrument to break the cycle of soil degradation. These include: the design of institutions that would convert global demand for reduced greenhouse gases into incentives for carbon sequestration (Young, 2003); externalities or "co-benefits" of new practices, such as erosion reduction, improved pollution control, and nutritional improvements; and, the technical SOC storage potential of soils. In the final case, although the SOC storage potential factor may be high, it could also be very expensive to reach. As a result, we must analyze both the SOC storage potential and the economic returns to adapting sequestering practices.

Contract design will play an important role in the successful implementation of a carbon sequestering initiative, as the payments must convey the intended incentives to large numbers of farmers managing small farms.

A number of studies have estimated the technical and economic potential for soil carbon sequestration in the United States (e.g., Pautsch *et al*. 2001; Antle *et al*. 2001, 2003; McCarl and Schneider 2001). Few studies have assessed soil carbon sequestration potential in developing countries. Antle *et al*. (2003) analyzed the potential for terracing and agroforestry to sequester carbon in hillside agriculture in Peru. Tschakert (2004) estimated carbon sequestration rates and economic returns to different management techniques for the Senegal groundnut basin, establishing the link between increased fertilizer usage, residue incorporation and reduced soil degradation.

Using simulation analysis, this thesis will examine the economic feasibility of slowing or reversing soil degradation through carbon sequestration payments in the Groundnut Basin of Senegal, a region typical of dryland subtropical Sub Saharan Africa. Farmers' participation in carbon sequestering contracts will be simulated with consideration of existing markets and institutions. Following the examination of the feasibility of carbon sequestration, we will simulate carbon supply under a variety of policy and technology scenarios, and assess the potential for farmers' participation in carbon contracts to slow or reverse the trend towards soil degradation in the region.

Food Security, Agricultural Production and Soil Degradation in Africa

Africa's population growth rate is the highest on the planet, while its agricultural productivity growth has fallen behind population growth and in some cases has declined absolutely. Approximately 180 million Africans suffer from malnutrition – an increase of 100% since 1970. Malnutrition exacerbates health problems such as HIV/AIDS, malaria and tuberculosis (Sanchez, 2002). The USDA Economic Research Service projects that the number of hungry people in SSA will rise in proportion to its anticipated population growth over the next decade (2004).

Addressing issues such as child survival, disease management, foreign investment, trade barriers and debt-relief are all significant and necessary to unraveling Africa's problems. However, interested parties cannot solve Africa's woes without first (or also) addressing agricultural productivity. As an economic sector, agriculture engages 70% of all Africans. In Sub-Saharan Africa, agriculture is the primary source of food, livelihood and foreign exchange earnings (Badian and Delago, 1995). In many rural areas, households depend upon their own production for food and fodder. Imports are a minor part of total food supplies; making domestic food production integral to food security in the region (Wiebe *et al.,* 2001). The food aid and foreign exchange earning capacity of West African countries are projected to decrease, the latter due to decreased tourism, low savings and investment rates, poor infrastructure and the growing burden of the HIV/AIDS epidemic (ERS, 2004).

Other regions of the world have reaped significant agricultural production gains through and since the Green Revolution, while African agriculture (particularly in the Sub Sahelian region) has floundered. Even though technology has improved over time, many of Africa's countries have been less able to actualize the benefits. Sanchez (2002) cites a recent study, stating that while adoption rates of improved crop varieties during the last 38 years have been similar in Asia, Latin America, the Middle East, and Sub-Saharan Africa, varieties are responsible for 66% to 88% of crop yield increases in the first three regions, but for only 28% in Sub-Saharan Africa.

Soil fertility depletion is regarded as the primary biophysical factor that limits food production on most African small farms (Drechsel *et al*., 2001).What is causing this trend, and how can it be reversed?

Population Pressure, Natural Resources and the Rational Farmer

Agronomists have long been warning of the serious human-induced soil degradation Sub Saharan Africa. In the 1930s, they "sounded the alarm" on rising erosion in farming areas of Africa with increasing population pressure (Koning and Smaling, 2005). Following World War II, strong agricultural prices stimulated farmer investment in land management. During this period, decolonization took precedence over environmental concerns. Policy agendas of the time stressed technology transfer and external input use, and downplayed the use of farmer's own knowledge (Kiome and Stocking, 1995).

Concerns over soil degradation rose again in the 1970's, a period characterized by general "eco-pessimism", as marked by the Club of Rome Report (Meadows *et al*., 1972) and Ehrlich's "Population Bomb" (1968).

Developmental economists attempted to explain the agronomists' findings that linked population pressure and soil degradation. According to Tiffen *et al*. (1994), there is considerable disagreement on whether this population growth thwarts per capita income growth and if it necessarily leads to natural resource depletion. The views of the pessimists have their roots in Thomas Malthus' theories. This group views natural resources as finite, and believes that population growth will cause smaller shares for each person. This capital dilution effect also applies to public services, such as education. In addition, there are diminishing returns to each input, holding technology constant. Innovations in technology are viewed as exogenous to the system, and cannot be counted on.

Tiffen's research in the Machakos region of Kenya supported an alternative view, originally expressed by Boserup (1965) with respect to agriculture and by Simon (1986) in reference to industrial societies. They found that increased population contributes to innovation, and their results also contradicted commonly held orthodoxies of African agriculture, including: population growth leads to environmental decline; increased commercial production is detrimental to food supply; investment in semi-arid areas does not pay as well as it does in humid areas; out-migration is negative; and that development depends heavily up on government intervention and external aid.

According to Koning and Smaling, not all agronomists supported the former view of population pressure causing soil degradation. Pieri (1989), for instance, suggested that farmers may use degrading practices when first settling new agricultural areas, but would eventually intensify or shift management practices as population pressure increased. Unfortunately, he found that these adjustments often did not result in reduced soil degradation. Others, including Bremen (1997), and economists such as Reardon *et al*. (1999), cite low farm gate prices that are insufficient for sustainable land management systems, which were caused by low world agricultural prices, the elimination of fertilizer subsidies, and anti-agrarian policy biases (Koning and Smaling, 2004).

In the 1990's, critical authors challenged the prevailing ideas on soil degradation. Historians, geographers, anthropologists, ethnobotanists, and some agronomists blamed the prevailing agronomist views for their "undue alarmism, neglect of the knowledgeablilty and rationality of African farmers, and subservience to bureaucratic interventions that did more harm than good" (Koning and Smaling, 2005). There is a growing recognition in natural resource management literature that many small farmer practices do have a rational basis. Older approaches, which favoured high technology transfer and external input use over local farmer knowledge, have been replaced by newer views, which stress the role of the farmer as steward. In the new view, "farmers may often make better decisions than the expert, not because of any greater analytical skills, but because of the experience gained in integrating a vast array of factors responsible for controlling production." Further, because of their reliance on the land, farmers are unlikely to manage their land in ways that would undercut their future and risk household livelihood and food security unless their immediate survival was threatened (Kiome and Smaling, 1995). This new perspective was concerned with the prevailing top-down bias of interventions, which interfered with the bottom-up initiatives of the farmers themselves. Their approach rejected the technocratic idea, in favor of a farmer-first approach for sustainable land management.

Critical authors emphasized the intricate strategies that farmers used to cope with soil degradation (Tiffen *et al*., 1994; Templeton and Scherr, 1999; Kiome and Stocking, 1995). Koning and Smaling cite arguments that critical authors have made, including:

- The direct link sometimes made between population growth and soil degradation is not always warranted. Cases have been made for a U-shaped relationship, where farmers mine their soils in places of low population pressure, but over time and with population densification, invest in land management as land becomes scarcer (Tiffen *et al*., 1994).

- Soil degradation may be a problem "for some people in some places" (Scoones, 1997), but agronomists have a much too linear and exaggerated view of the problem.

Less controversial than these arguments, Koning and Smaling summarize critical claims that are more universally accepted:

- Agricultural and environmental changes are far more complicated and dynamic than appears from much agronomic research.
- When areas are newly settled, farmers may not invest much in the soils initially. As population puts more pressure on the land resource, these farmers will attempt, not always successfully, to use more sustainable land management practices.
- Low-external-input systems are rational responses to existing farming conditions. Farmers exhibit flexibility by exploiting variation in the terrain, microclimates, crop and livestock system synergies, and by using locally available inputs.
- Many top-down interventions that attempted to reduce soil degradation by superseding or interfering with farmer's decisions have failed. For example, colonial-era environmental controls often frustrated farmers' attempts to manage environmental problems.

The current prevailing economic explanation for resource degradation is that economic incentives often encourage degradation and do not encourage conservation. This phenomenon has been ascribed to poor infrastructure and high transportation costs, adverse government policies, low prices (perhaps due to trade policy), market imperfections, lack of capital markets, insecure property rights and limited availability of fodder for grazing or fuel for cooking and heating (e.g. Lutz, Pagiola, and Reiche; Heath and Binswanger; Tiffen *et al*.). Although there are many similarities between regions within Sudo-Sahelian and Sub Saharan Africa, there are also many country-specific conditions faced by farmers. These factors will be discussed in greater detail with respect to Senegal in Chapter 4.

Soils evolve in complex ways, and attempts to improve the management practices of farmers should be linked to the knowledge of farmers, researchers and policy makers face new challenges. Given this new perspective, researchers and policy makers face new challenges. They must now attempt to understand the factors and conditions causing soil degradation, and ascertain how to design mechanisms that will provide farmers with the economic incentives to adopt more sustainable land use and management practices (Antle and Diagana, 2003).

Soil Degradation and Soil Carbon Sequestration

Soils are complicated physical, biological and chemical systems that life on earth relies upon for food production and other processes (Donovan and Casey, 1998). Soil fertility is a measure of the health of these soils, and their ability to support and nourish plants. Many natural factors influence soil fertility, including geology, climate, and hydrology. Human management can also influence soil fertility, either positively or negatively. Decreases in nutrient content, and in other physical, chemical and biological qualities of soils, can all lead to diminished fertility.

Soil degradation, a decline in soil fertility, results both from declining macro and micronutrients essential to plant growth, and from declining stocks of soil organic matter. Soil cultivation, and associated biological and physical processes, release soil organic carbon over time, often reducing stocks by 50% or more, depending on soil conditions and agricultural management techniques (Antle *et al*., 2004). Since these fields contain less carbon than in past equilibriums, it is possible to restore (at least in part) SOC to higher levels.

Most Sahelian (see Figure 13 on p.46) soils are naturally less fertile than soils in other parts of the world. Typically, they have low SOC, are macronutrient deficient, and because of their low clay and carbon contents, they tend to exhibit low Cation Exchange Capacity[1]. However, similar soils in other locations (e.g. south-eastern USA) have been made highly productive by implementing successful management techniques.

The decline[2] of soil fertility in SSA has been well documented by the scientific community (Stoorvogel and Smaling, 1990; Donovan and Casey, 1998; Gladwin et al., 1997; Lal, 2004). Both natural and man-made factors have contributed to this. Weathering, leaching, and surface runoff can all make nutrients less available to plants. Agricultural

[1] Cation Exchange Capacity (CEC) measures the ability of a soil to attract exchangeable cations (nutrient ions which include:(Ca^{++}), magnesium (Mg^{++}), potassium (K^{+}), sodium (Na^{+}), hydrogen (H^{+}) and ammonium (NH_4^{+})) to the negatively charged surfaces of its particles, and thereby make essential nutrients available to plants. Organic matter has the highest CEC of soil components, and the presence even of small amounts of organic matter can substantially improve the CEC of a soil (Rosen and Bierman, 1998). Higher soil CEC increases the efficiency of fertilizer use. In addition, it fosters improved biological diversity, which leads to more favourable soil chemical and physical conditions, which could include increased infiltration and water holding capacity, and reduced erosion (Donovan and Casey, 1998).

[2] There have been some detractors to this majority opinion; Niemeijer and Mazzucato (2002) completed a study in Burkina Faso which found evidence contradicting claims of wide-spread, severe soil degradation, and suggest a need to re-examine evidence of soil degradation in other Sahalian countries.

crops use nutrients, and many of these are removed when the crops are harvested. These nutrients can be replaced, at least in part, by mineral and organic fertilizers, crop residue incorporation, or, by different land tenure systems. Fertilizer consumption in SSA, which is associated with increased soil organic carbon, accounts for only 2.5% of global use. Traditionally, fallowing was the tenure system used to replenish soil fertility; however, population pressure and poverty have all but eliminated fallow systems in this part of the world (Faye et al., 2001). Now, the prevailing tillage-intensive continuous cropping regimes, marginal land extensification, overgrazing, residue harvesting and deforestation, all accelerate soil degradation (Donovan and Casey, 1998, Lal, 2004, Sanchez, 2002).

Table 1: Additional benefits of enhancing the soil carbon pool

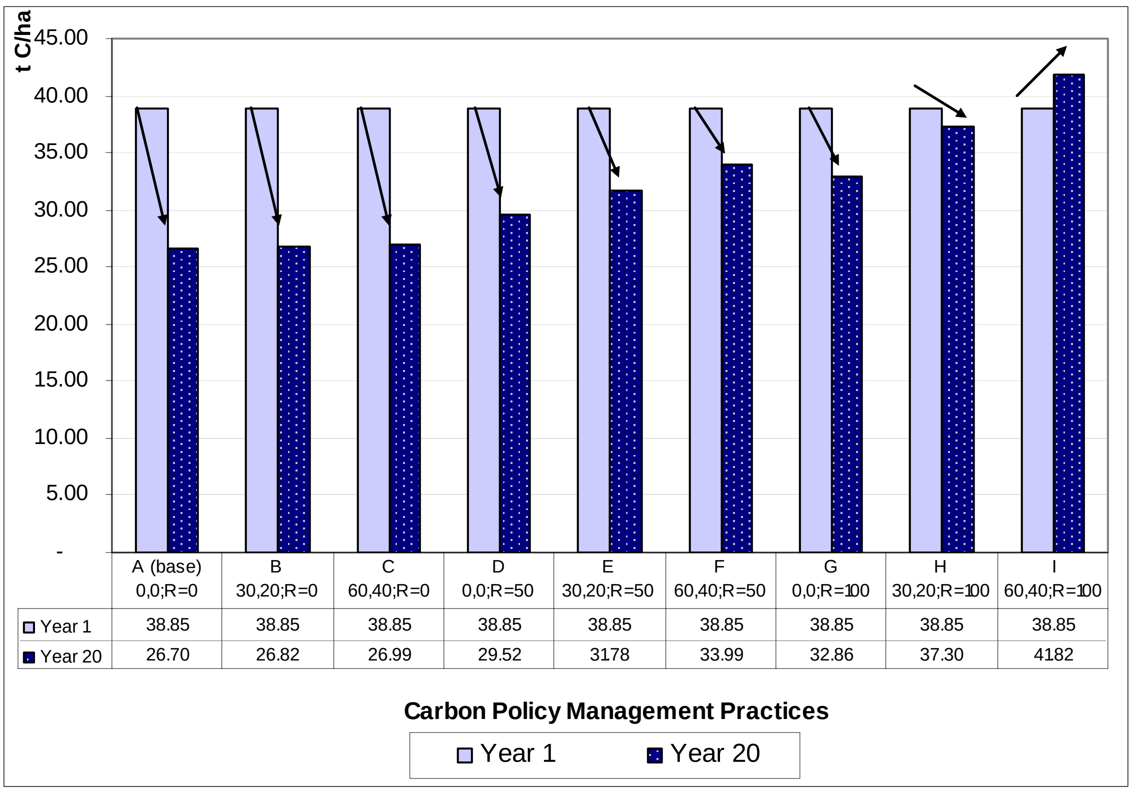
On-Site Benefits	Externalities, or “Off-Site Benefits”
Soil Quality	Air Quality
↑ **available water capacity**	↓ **rate of enrichment of greenhouse gases**
↑ **nutrient retention**	↓ wind-borne sediments
Improvement in soil structure and tilth	
Buffering against changes in pH	Desertification Control
↑ soil biotic activity	**Restoration of desertified lands**
Improvements in soil moisture and temperature regimes	Reversal of degradation trends
	Strengthening elemental recycling mechanisms
Agronomic/Forest Productivity	Biodiversity
↑ **crop yield**	↑ **soil biodiversity**
↑ **use efficiency of input (e.g., fertilizers, water)**	Improvement in wildlife habitat and species diversity on restored ecosystems
↓ losses of soil amendments by runoff, erosion and leaching	Improvement in aesthetic and cultural value
Sustainability and Food Security	Water Quality
More sustainable use of soil and water resources that have been drastically perturbed by past uses	**Decrease in transport of pollutants out of the ecosystem**
An important step in achieving food security	Biodegradation and denaturing of pollutants and contaminants
Additional income from trading C credits	Reduction in sediment load and siltation of water bodies
↑ **nutritional value of food** (especially micronutrients) and avoidance of hidden hunger	↓ non-point source pollution
	↓ risks of hypoxia in water bodies
	↓ damage to coastal ecosystems
	Low risks by floods and sedimentation to aquacultures (shrimp, fisheries etc.)

Source : Lal 2004

Besides improved soil fertility, soil carbon sequestration has many other benefits, including onsite effects and externalities. Lal (2004) compiled an extensive list of these potential benefits, as outlined in Table 1.

Figure 1 shows simulated carbon stocks in the case study region, given different levels of fertilizer use and residue incorporation. With the exception of the intensive practice, "I", all practices result in declining soil carbon balances.

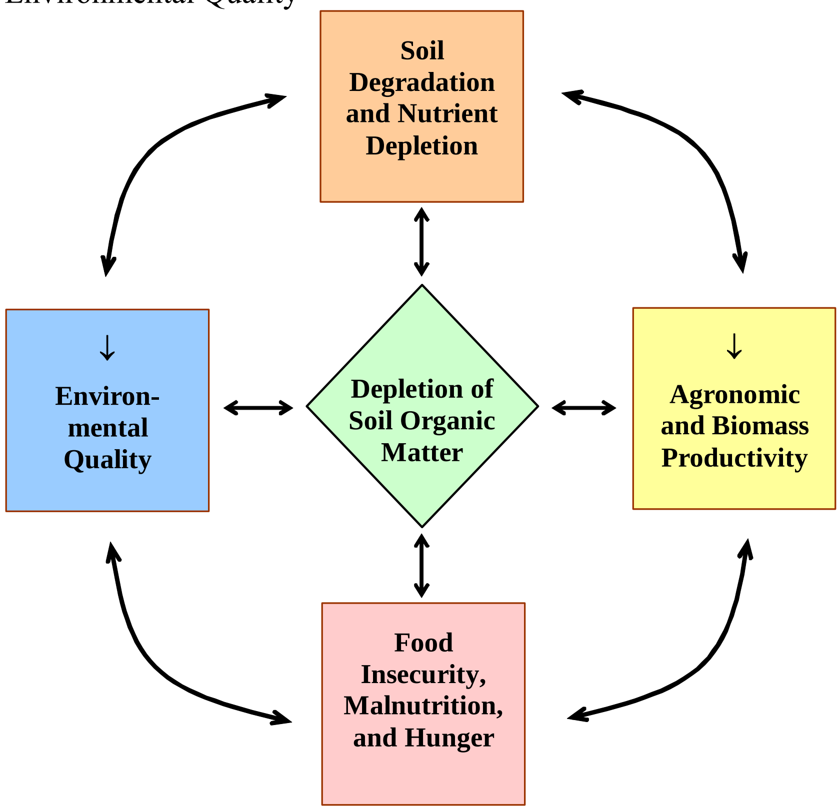
Figure 1: Average carbon stocks over time, given 9 different management practices



Management practice (groundnut fert kg/ha, millet fert kg/ha; R=residue incorporation)	
D: 0, 0; R=50%	G: 0, 0; R=100%
E: 30, 20; R=50%	H: 30,20; R=100%
F: 60, 40; R=50%	I: 60, 40; R=100%

Figure 2 illustrates the links between; nutrient depletion and soil degradation, soil organic carbon levels, agronomic productivity, environmental quality, and, food security and hunger. Particularly in SSA, where policy makers operate in a "second best" world of many institutional distortions (Gladwin et al., 1997), there may be a need to use external stimuli to move countries out of this cycle.

Figure 2: The Cycle of Soil Depletion, Food Insecurity and Agronomic and Environmental Quality



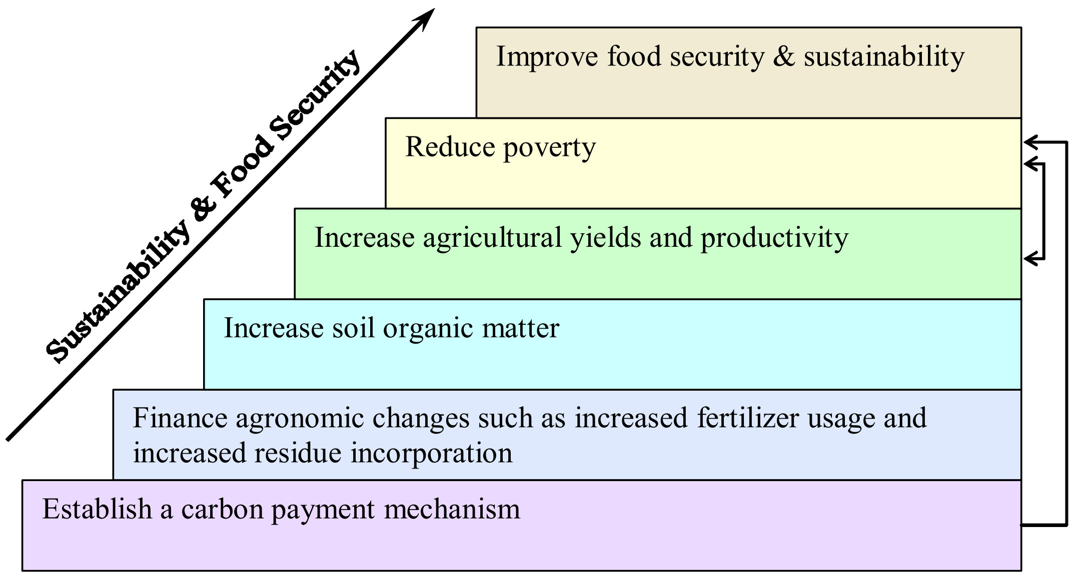
Source: *adapted from* Lal, 2004.

Additional influxes of income through a carbon trading system could overcome existing economic barriers to sustainable land use in the region. Lal (2004) writes:

> "The soil C sequestration potential of this win-win strategy is finite and realizable over a short period of 20 to 50 years. Yet, the close link between soil C sequestration and world food security on the one hand and climate change on the other can neither be overemphasized nor ignored."

This "win-win" strategy, where externally originating carbon payments are used to pay for carbon sequestering activities in SSA, and farmers there accrue the onsite benefits, may help to extricate the region from the cycle illustrated in Figure 2. Figure 3 shows the potential steps in this process.

Figure 3: Carbon payments, and the steps towards food security and sustainability



Many regard soil fertility depletion as the primary biophysical factor that limits food production on most African small farms (Drechsel *et al.*, 2001). What is causing this trend, and how can it be altered? If it is due to policy distortions, price levels and market failures, and other market conditions, could carbon payments be a mechanism to overcome these impediments? Farm households in degraded environments are some of the world's poorest. Because of this, incentive mechanisms for carbon sequestration in agricultural soils could simultaneously contribute to the goals of alleviating rural poverty, enhancing agricultural sustainability and mitigating greenhouse gas emissions (Soil Management CRSP, 2002).

The use of agricultural soil carbon sequestration has been limited under the Marrakesh Accords of the Kyoto Protocol (UNFCCC). The United States has not ratified the Kyoto protocol, further limiting its role in policies to mitigate GHGs. The purpose of this thesis is not to speculate about what role carbon sequestration may play under any specific policy regime. Instead, this thesis will asses the role that soil carbon sequestration might play in helping developing countries deal with soil degradation, if and when governmental, non governmental or corporate entities take actions to reduce GHG emissions.

Thesis Objectives

Human induced soil degradation has multiple forms, including: nutrient decline, erosion, salinization and physical compaction (ISRIC GLASOD, 2004). In Sudo-Sahelian Africa, erosion and nutrient mining are prominent causes of soil degradation. Nutrient mining occurs when more nutrients, such as nitrogen, phosphorus, potassium, carbon, and other micronutrients, are removed from the soil than are put back into the system. In the case of Senegal, harvesting grains and crop residue from the land impact heavily on soil carbon content, while insufficient replacement of soil nutrients with fertilizers leads to negative nutrient balances. Policies that encourage or enable farmers to incorporate crop residues into their soils, and to increase mineral fertilizer usage, would help to reduce or reverse these types of soil degradation in the region.

Given the economic perspective of the rational farmer, and the dynamic nature of crop and soil management issues, this thesis uses a regional case study in the Groundnut Basin of Senegal to do the following:

- To describe and assess the economic incentives facing farmers specific to the case study region. This study will examine institutions and conditions that impact farmers' decisions.
- To model the farmer's production and decision making process.
- To design carbon contract policies and model them within the farmer’s decision making process.
- To simulate the interaction between the current agricultural marketplace, and the new carbon policies.
- To assess the role that carbon sequestration could play in helping the region deal with soil degradation problems, if and when international action is taken to reduce GHG emissions.

CHAPTER 2

THE FARMER AND THE CARBON CONTRACT

Nutrient Mining, and the Role of Fertilizer and Crop Residues in Agricultural Systems

Nutrient mining, a form of human-induced soil degradation, is prevalent throughout Africa, including the Sudo-Sahelian region. Drechsel *et al*. (2001) define nutrient mining as:

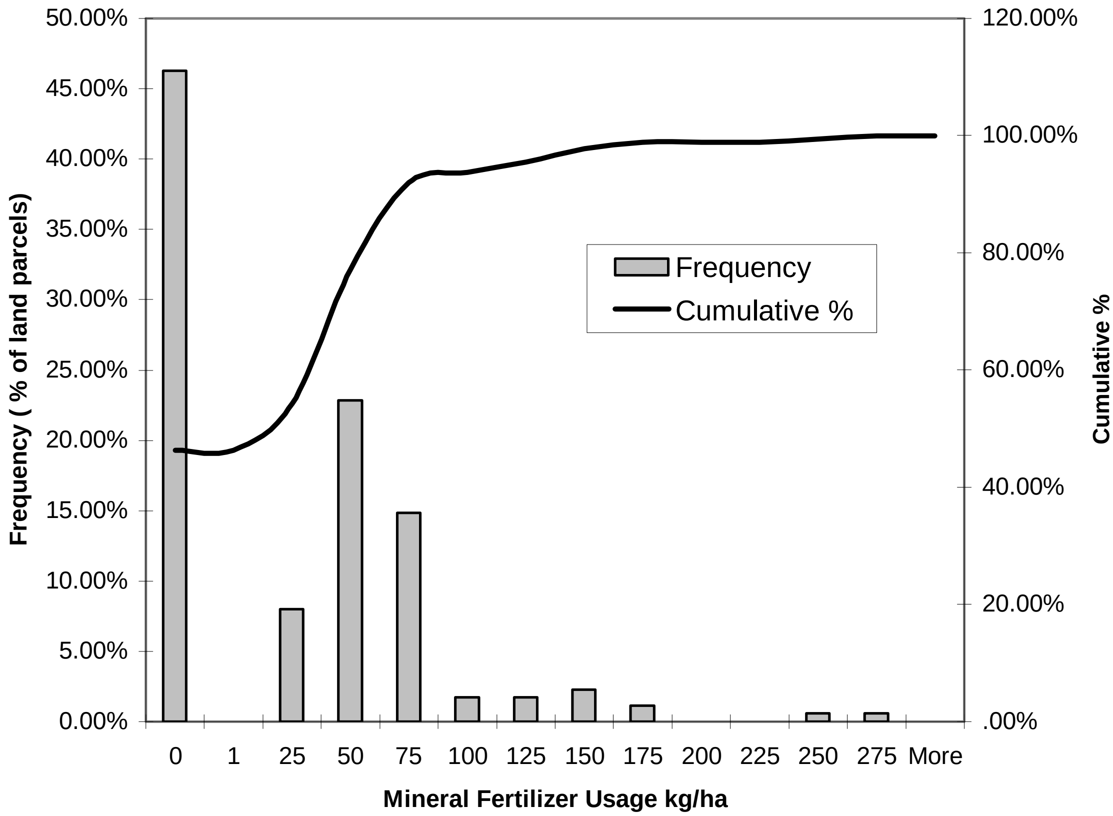
> "…the net loss of plant nutrients from the soil or production system due to higher nutrient outputs (through leaching, erosion, crop harvest, etc.) than inputs (e.g. through rainfall, manure, mineral fertilizer, fallow), resulting in a negative nutrient balance."

As described in Chapter 1, the majority of Sub Saharan Africa's soils are innately poor. Most of the region's farmers operated in shifting cultivation systems until the mid 1900's. Until then, soil nutrient balance was largely maintained by a system that interspersed crops with long periods of fallow. With population growth and extensification, permanent cultivation replaced fallow systems, and the nutrient equilibriums of those systems were upset. Without the use of fallows or other management practices that would add organic matter and nutrients to soils, soil organic carbon stocks will inevitably decline, often to less than 50 percent of natural conditions, in several years (Koning and Smaling, 2005).

Throughout the Sahel, organic matter and nutrients are removed by harvesting grains and by selling or burning the crop residues. While some processes, including organic fertilizer application, atmospheric deposition, and biological fixation of nitrogen, partially offset withdrawals from the system, they are not sufficient to sustain nutrient balances. Stoorvogel and Smaling (1990, 2000) found that nutrient balances throughout Sub Saharan Africa, including Senegal and other Sahelian Countries, were predominantly negative. Multiple authors, including Joa and Kang (1989), Batiano *et al*.(1998), and Swift *et al*. (1994), concur that a combination of mineral fertilizers, manure, and crop residues need to be incorporated to maintain or improve crop production (Koning and Smaling, 2005).

One reason for negative nutrient balances in Sub-Saharan Africa is that farmers use very low quantities of fertilizer relative to other agricultural regions. Average fertilizer use in SSA has been estimated at less than 15 kg per hectare as of 1994/95, compared to more than 200 kg in East Asia, 125 kg for Asia as a whole and 65 kg in Latin America (UNDP/UNECA Report in Diagana, 2003). Some farmers use no mineral fertilizer at all in a given year. Figure 4 shows fertilizer usage distribution among the Senegalese small holdings farmers used in the case study discussed in Chapter 4. This figure shows that about 46 percent of parcels had no mineral fertilizer applied, and that many who did apply fertilizer used relatively low rates.

Figure 4: Distribution and Probability of Fertilizer Usage in the Senegal ENEA sample



Instead of being incorporated into the soil, crop residues such as groundnut hay are harvested and used or sold as animal fodder and fuel (Stoorvogel & Smaling, 1990.) This removal of organic matter and nutrients from the system contributes to the declining quality of soils.

Farmers are choosing to use less mineral fertilizer and crop residues as inputs into their production systems than we would expect for a sustainable system. The parameters and reasoning behind these input usage decisions are examined in the next section.

Input Usage & the Rational Farmer

When farmers apply fertilizer or incorporate crop residue back into the soil, there is a multi-period stream of benefits and costs associated with these practices. According to economic theory, rational, risk-neutral farmers use mineral fertilizer such that $VMP_i = w_i$, subject to spatial and temporal availability constraints. Where there are dynamic effects of fertilizer and crop residue on SOC, the VMP can be interpreted as capturing all (discounted) future productivity effects. In the absence of market distortions, farmers are using fertilizer where their marginal benefit equals marginal cost (VMP_i=w_i). However, distortions caused by poor infrastructure, import taxes , lack of capital markets for wholesale and retail sectors, imperfect competition, and parastatal bureaucratic inefficiencies can increase the farm-gate cost and availability of fertilizer. As shown in Figure 5, market distortions that raise the price of fertilizer induce a reduction in quantity demanded. Lack of fertilizer availability at the appropriate time during the growing season, and lack of well-functioning short-term credit, reduce the ability of farmers to use fertilizer in a technically efficient manner. These factors effectively reduce fertilizer productivity, and thus shift the fertilizer VMP downward. Figure 4 shows that the combination of these two effects can reduce the quantity of fertilizer applied, and may even force the farmer to a corner solution where no fertilizer is applied. Farmers' "myopia", characterized by high discount rates and insufficient education and knowledge of future benefits, can also impact their perceived value of fertilizer.

To demonstrate these effects, consider the net present value of growing crops on a unit of land over T years:

$$(1)\ NPV = \sum_{t=1}^{T} D_t\ [p_t f(x_t,\ C(x_{t-1},\ x_{t-2},...)) - w_t x_t]$$

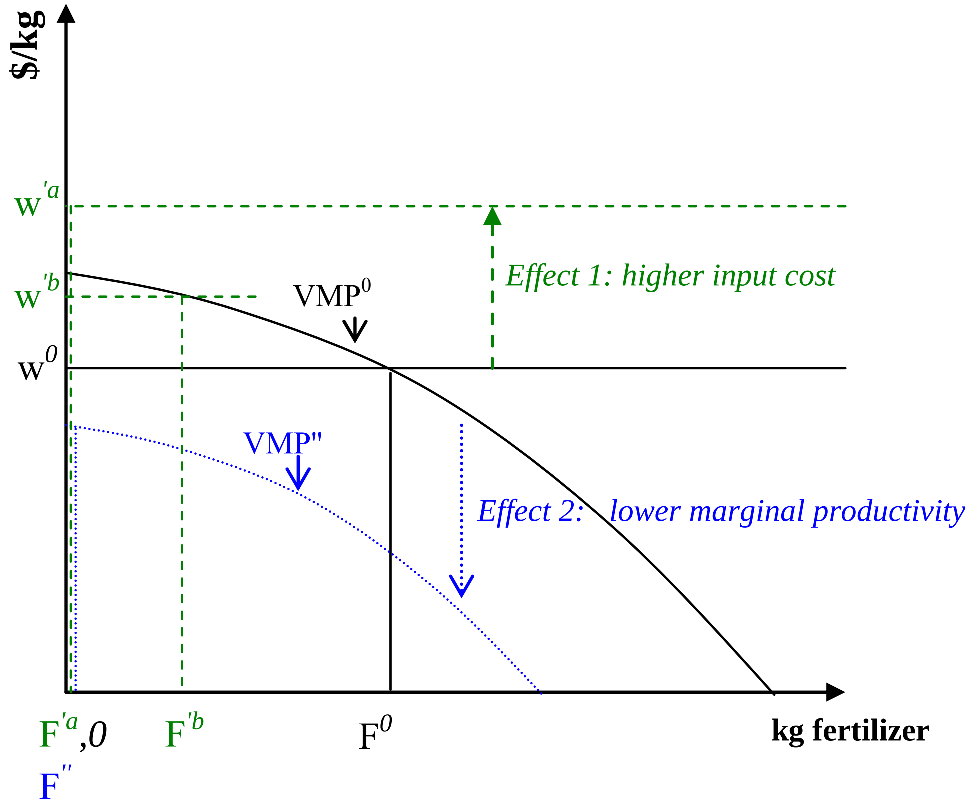
where $D_t = (1/1+r)^t$, r is the interest rate, p and w are output and input prices, x is the quantity of fertilizer, and C(.) is the stock of carbon which depends on past fertilizer applications. Differentiating with respect to x_1, the first-order condition for fertilizer use in period 1 is:

$$p_1 \cdot \partial f_1/\partial x_1 + \sum_{t=2}^{T} D_t\ p_t \frac{\partial f_t}{\partial C_t} \cdot \frac{\partial C_t}{\partial x_1} = w_1$$

The expression on the left-hand side is the value of the marginal product of fertilizer, composed of the usual terms (price times marginal product) plus the discounted value of the future impacts on productivity through carbon accumulation. As *r* increases, the future stream of VMP, beyond year t, diminishes. As a result, the perceived VMP drops as *r* rises, and farmers use less of the input.

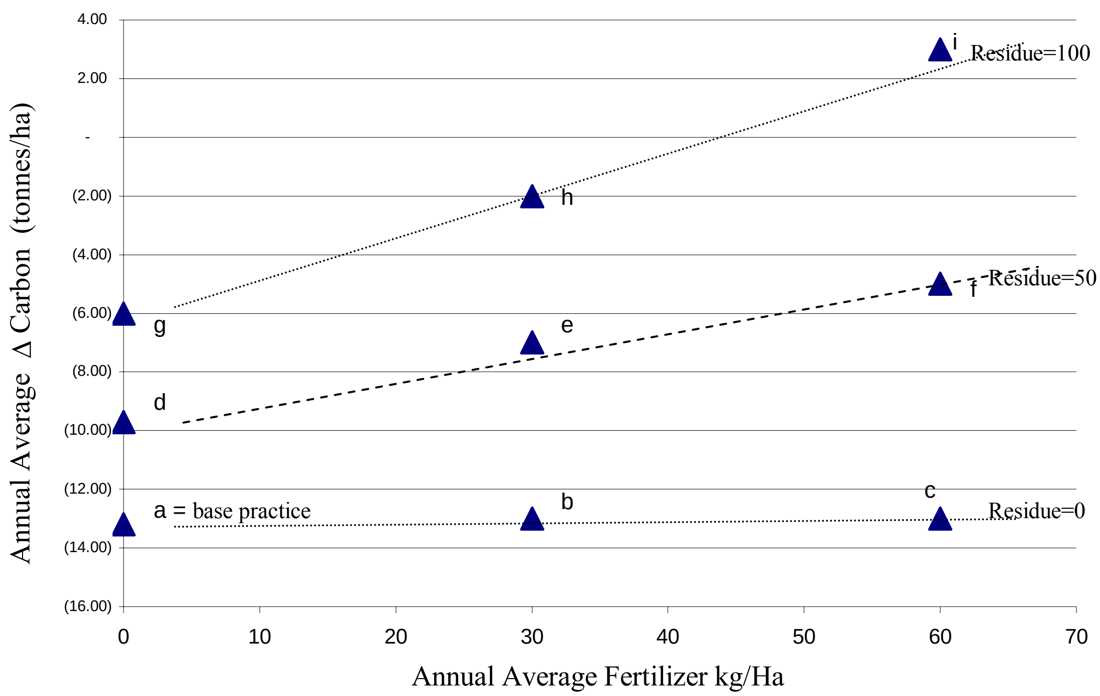
Figure 5 shows how shifts in the VMP and in fertilizer markets can lower or eliminate fertilizer usage. If the VMP of fertilizer is significantly suppressed by low output prices or other factors discussed above, then a farmer that would have used F^0 fertilizer with w^0 and VMP^0 will instead use no fertilizer (F") in the VMP" case. Similarly, where $VMP=VMP^0$ if farm gate fertilizer prices are higher than w^0, then farmers would reduce fertilizer usage to $F^{'b}$ or $F^{'a}$ kilograms per hectare.

Figure 5: Fertilizer usage with market distortions



The incorporation of crop residue is known to have a positive impact on soil organic matter and SOC (Stoorvogel & Smalling, 1990). Figure 6 shows simulated carbon changes in a sampled field, given nine different management practices. Residue=0,50,100 refers to zero, 50 percent and 100 percent groundnut residue incorporation levels. Points a,b,…, i refer to the carbon management contracts analyzed in Chapter 5 with different combinations of fertilizer applications and crop residues. Figure 6 shows that higher residue incorporation levels not only lead to more SOC, but also act synergistically with fertilizer usage to increase soil carbon.

Figure 6: Average annual changes in SOC with carbon contracts on a sample field (Generated by the DSSAT/CENTURY model; t=20 years)



In Senegal, there is a market for groundnut residue (hay) for livestock fodder, and it is also valued for on-farm feed. If farmers incorporated residue, they would face these opportunity costs, in addition to higher labor costs. As with fertilizer, farmers' high discount rates lead to short time horizons, and undervaluing SOC maintenance. Farmers' short-run VMP would be perceived as lower than it would be if they took into account the long-term productivity effects. For this reason, and because relatively strong livestock markets lead to high opportunity costs, residue incorporation is not common (if existent) in the region of study.

Dynamics, Adoption Thresholds and the Role of Incentives

In this section, we consider farmers' decisions to adopt management practices that sequester carbon (or slow the rate of carbon loss) in the soil. This analysis framework was developed by Antle *et al*. (2001) and Antle and Diagana (2004).

To increase soil carbon stocks, a farmer must change from a given long-term rotation system, *i*, (the historical land use baseline), and choose to adapt some carbon-intensive land use system, *k*. We assume management practice *i* is used up to time 0, resulting in soil carbon level C^i. The adoption of practice *s* at time 0 will cause C^i to rise to C^k at time T. At this time T, soil carbon levels reach a new equilibrium level (referred to as the "attainable maximum" by Ingram and Fernandes), until further management practice changes occur. Literature (Watson *et al*., 2000) suggests that the path from C^i to C^k is approximately linear over the time interval when most of the carbon is accumulated.

As discussed in Chapter 1, changes in management practices may have other productivity inducing benefits beyond soil carbon accumulation, which can include improvements in soil structure, water holding capacity, cation exchange capacity, and increased topsoil depth. These other benefits, however, tend to occur after some time lag. The magnitude of these long-term productivity effects, as well as farmers' discount rates and financial positions, play crucial roles in the profitability of conservation investments (Valdivia, 2002).

Carbon sequestration contracts could provide an additional financial incentive to adapt these new management practices. Two types of carbon contracts are discussed in the literature: per hectare contracts, where farmers are paid $\$g_t$ dollars for each hectare on which specific practices are adopted; and, per tonne contracts, where farmers are paid $\$P_t$ per tonne of C sequestered in each time period, regardless of the practice used (Antle *et al.*).

The net present value to the farmer of changing from system *i* to system *k* for T periods is given by:

$$NPV(i,k) = \sum_{t=1}^{T} D_t[NR(p_t, w_t, k) + g_t(i,k)],$$

where:

$$D_t = \left(\frac{1}{1+r}\right)^t,$$

r is the annual interest rate,

$NR(p_t, w_t, k)$ = the net return (restricted profit function) for system *k* in time *t*, given output prices p_t, and input prices w_t.

$g_t(i,k)$ = g_t if contracts are per hectare,

= $P_t \Delta C_t(i,k)$ if contracts are per tonne.

If the farmer does not participate in the carbon contract, and continues to manage land with system *i*, then $g_t(i,k) = 0$, and farmers earn NPV (*i*). Farmers will only enter the contract if NPV (*i,k*) > NPV(*i*). Risk can be incorporated into this decision analysis through risk premia or option values (Feng et al., 2004).

Assuming that expected NR(p,w,k), P, and $\Delta c(i,k)$ are constant over time, the multi-period problem presented above is equivalent to a sequence of single-period decisions over the same number of years. To see this, observe that

$$\text{NPV}_i = \text{NR}_i * \sum_{t=1}^{T}\left(\frac{1}{1+r}\right)^t.$$

$$\text{NPV}_k = (\text{NR}_k + g_k) * \sum_{t=1}^{T}\left(\frac{1}{1+r}\right)^t$$

A farmer will switch to practice k if NPV (i,k) > NPV(i). This condition implies:

$$\text{NPV}_k - \text{NPV}_i = (\text{NR}_k + g_k - \text{NR}_k) * \sum_{t=1}^{T}\left(\frac{1}{1+r}\right)^t > 0,$$

The discounting term can be factored out, leaving:

(2) $\text{NR}_k(\text{p,w},k) + g(i,k) > \text{NR}_i(\text{p,w},i)$.

There are several significant implications for analysis that follow from this equation.

First, assume that there are no carbon payments; g=0. In this case, a farmer will only adapt the conservation practice, *k*, if it provides higher net returns than the original conventional practice, *i*. If the productivity benefits are realized after a time lag, equation (2) shows that high farmer discount rates or high uncertainty of future benefits will lead to a case where farmers would bear the costs of adopting the practice, but would not attach value to the benefits. A lag between the adoption of conservation practices and the realization of benefits can lead to an *adoption threshold* (Antle and Diagana, 2003). On the other hand, if most of the benefits occur immediately (for example, if most of the productivity gains came immediately from using more fertilizer), then benefits will not be as susceptible to discounting or uncertainty, and the threshold effects would be lowered.

Second, where there is payment for carbon sequestration, then we can rearrange equation (2) to describe farmers who switch practices:

(2b) $g(i,k) > \text{NR}_i(\text{p,w},i) - \text{NR}_k(\text{p,w},k)$.

The right hand side of this expression is the farmer's opportunity cost for switching from system *i* to system *k*. The farmer will switch to practice *k* when the opportunity cost is less than the payment per period. For per tonne contracts, g(*i*,*k*)= PΔc(*i*,*k*), and the participation in these contracts can be expressed as:

$$\text{P} > \frac{\text{NR}(\text{p},\text{w},i) - \text{NR}(\text{p},\text{w},k)}{\Delta\text{c}(i,s)} \quad \textbf{(3)}$$

The right hand side of equation (3) is the farmer's opportunity cost per tonne of carbon. The farmer will participate when the price per-tonne C is higher than the farmer's opportunity cost per tonne C. In this case, the market price for carbon plays a pivotal role in farmers' decisions to participate (Antle and Diagana, 2003).

Significantly, equation (3) demonstrates that when carbon payments are made, it may be no longer necessary for the conservation practice to be privately more profitable than the conventional practices. In cases where rational farmers are apprised of the benefits of conservation practices, but they still do not adopt them, it is safe to assume that these practices are not as profitable as the conventional ones. In these cases, additional positive financial incentives are necessary to induce and maintain adoption.

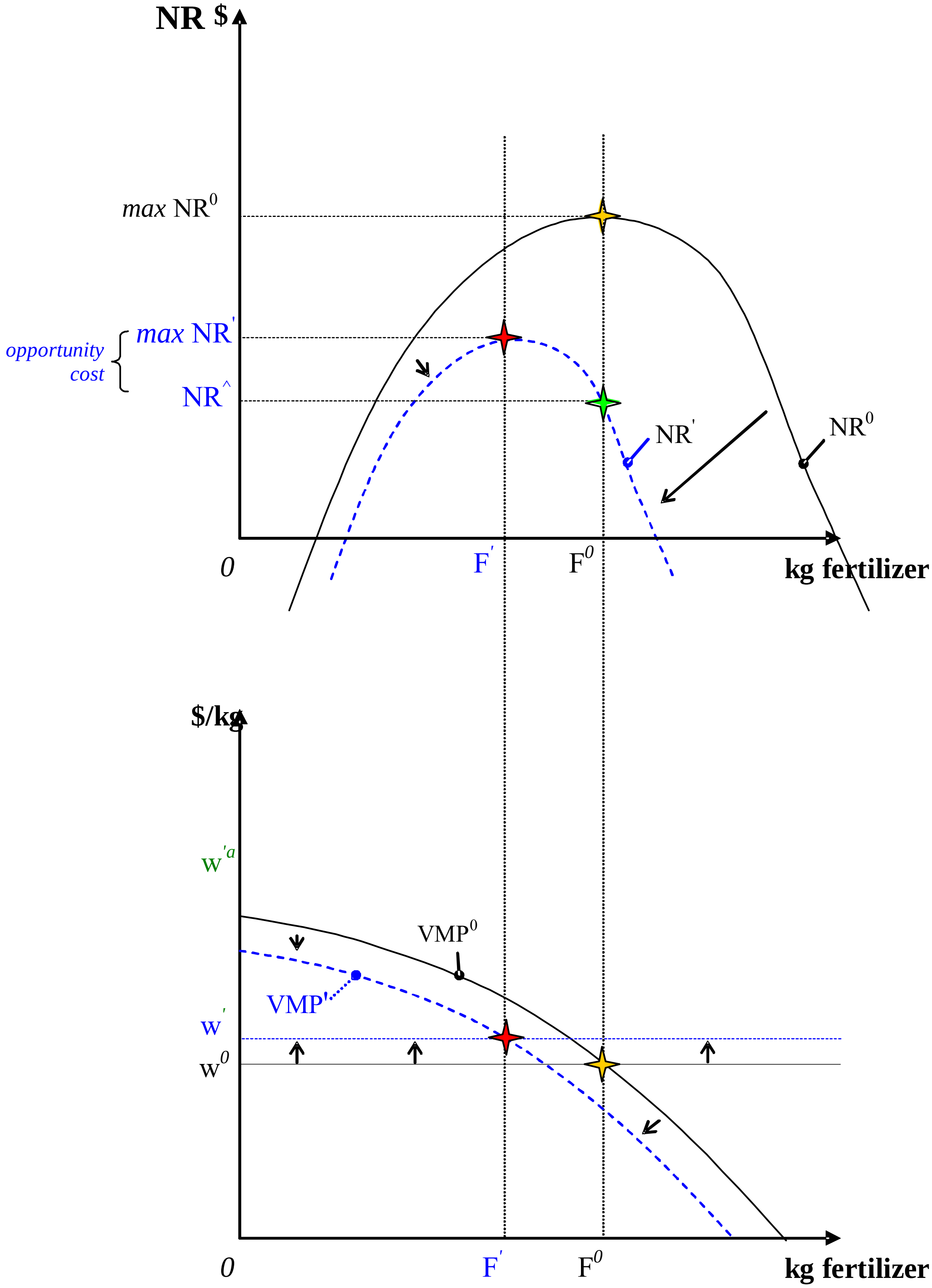
Carbon Contracts for Fertilizer and Residue Incorporation

In this analysis per-tonne carbon contracts will be issued for adoption of carbon-intensive management practices. Most of these possible contract scenarios will stipulate minimum levels of mineral fertilizer usage, in concert with some level of crop residue incorporation. On the whole, these contracts will encourage increased usage of mineral fertilizer, which many West African farmers use at levels far lower than the rest of the world. Long-term effects, such as carbon sequestration and those associated with increased soil organic carbon are significant and dynamic; however, they are small in comparison to the immediate short run productivity benefits of the increased fertilizer.

Figure 7 shows the net revenues, opportunity costs, and offset values required to increase fertilizer usage. In this case, market distortions and conditions cause the VMP and cost of using fertilizer to be VMP' and w', respectively. The profit function associated with these conditions is NR'. Farmers are profit maximizers, and will use demand F' kg of fertilizer per hectare.

Now, carbon contracts are offered to farmers, where, to fulfill these contracts, they must switch from their current management practices, *i*, to a carbon-intensive management system, *k*. This entails using fertilizer (and or residue) at rate F^0, which is greater than F'. There are two ways that this can be achieved. First, carbon payments can offset the opportunity cost of changing practices, as shown in the top panel of Figure 7. From equation (2b), the carbon payment, g, must be > (max NR' - NR^) for farmers to switch practices.

Figure 7: Net revenue and opportunity costs associated with fertilizer usage



Carbon contracts may also increase fertilizer (and / or residue) inputs by offsetting distortions and constraints in the input markets. If large-scale providers of carbon contracts could provide fertilizer at lower cost to farmers, and provide it in a timely manner, it is possible that farmers would use fertilizer at rate F^0 because it would be cheaper and more productive. In this case, farmers would be willing to enter carbon contracts simply to obtain access to fertilizer. In this case, carbon payments do not need to be positive to spur adoption of new practices because the opportunity cost of switching to the carbon-intensive practice is negative.

When there are profitable uses of crop residues as feed or fuel, residue incorporation carries a high price relative to the short-term agronomic benefits. In addition, if farmers have high discount rates, or do not have access to credit markets, they will tend to discount future benefits and thus will be likely to incorporate little if any residues into the soil. If a carbon payment was used to promote residue incorporation (in concert with fertilizer intensification), participating farmers would eventually capture the long-term agronomic benefits of the practices, which would eventually increase the profitability of the carbon-intensive management practices. An important empirical question is how large of an incentive would be required to induce farmers to incorporate enough crop residues to reduce or reverse the loss of SOC.

It is likely that a combination of carbon payments and market distortion offsetting can be used to increase carbon intensive management practices. In simulation, we expect that if the contracts simply make fertilizer temporally available to farmers, that some farmers will join the contracts and switch practices, even without a carbon payment. This would support the hypothesis that fertilizer availability is binding. We also expect, as carbon payments increase, more and more farmers will switch practices, and would increase the supply of carbon sequestration services.

In this analysis, we attempt to anticipate some of the possible farmer incentives associated with participating in carbon contracts, and the likely ability of each policy to induce farmers to undertake new management practices. While acknowledging the importance of transaction cost and permanence issues, this thesis aims to establish the economic potential of carbon sequestration, abstracting from these issues. We leave these problems to future work.

CHAPTER 3

THE SIMULATION APPROACH

Modeling Complex Systems

The scientific community recognizes that many economic, environmental and other biophysical phenomena are best described as complex systems. Biophysical models have been applied to agricultural production systems to model a restricted set of properties, including; crop growth (Whisler *et al.*, Ritchie), hydrologic transport and cycling (e.g., de Willigen *et al.*, Ghardiri and Rose), soil OM and nutrient dynamics (Paustian, Powlson *et al.*), and crop-livestock production systems (Thornton and Herrero) (Antle and Capalbo, 2002). Larger biogeochemical models, which incorporate all or most pertinent subsystems, characteristically focus on the dynamics of the nutrients, biomass and carbon within an ecosystem (e.g. Hunt *et al.,* Parton *et al*). Ecological processes, such as primary consumption, production, decomposition and energy transfers are concatenated at different temporal and spatial scales with mechanistic and empirical formulations. In these cases, however, human behavior and decisions are treated as exogenous, and their economic behavior is "conceptually outside the boundaries of the system" (Antle and Capalbo, 2002).

In the same way, boundary conditions or constraining variables in biophysical models are often endogenous to a system, yet economists typically take these biophysical variables as exogenous or represent them with simple empirical relationships (Antle and

Capalbo, 2002). Mathematical programming and econometric production models have been linked with biophysical models[3], usually by taking the output from one model (e.g. an input use decision for an economic model, or yield from a crop growth model), and using it as the input into another model.

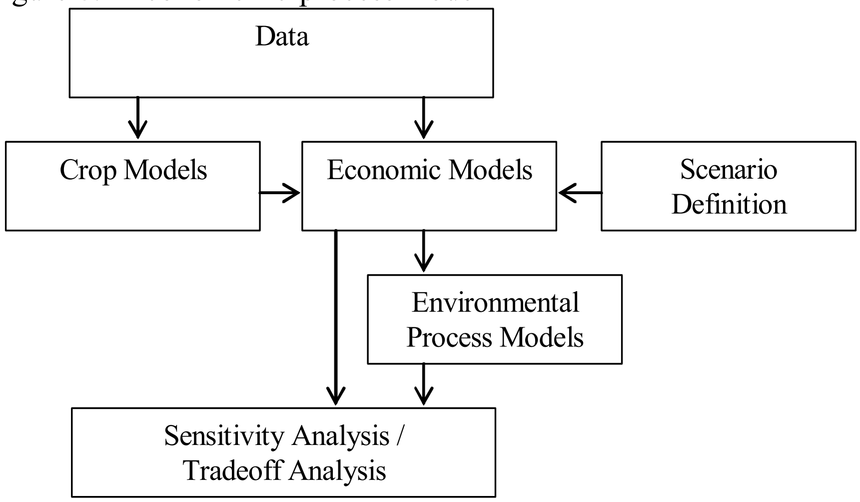
Integrated Assessment for Agricultural Production Systems

Antle and Capalbo (2001) described the integrated assessment paradigm for agricultural production systems. To paraphrase, soils and climate data are inputs into crop and livestock process models, which calculate site and time specific productivity. Outputs from the crop and livestock models, such as crop yield and livestock productivity, may then be inputs into economic models. Outputs from these crop and livestock model, and economic data are also used as inputs into economic production models. Outcomes of both of these model types (crop yield, livestock productivity, and land and input use decisions) may then be incorporated into environmental process models, which could model processes such as chemical leaching, and soil erosion. Assuming that the biophysical and economic data are representative of the land units and decision makers in a population, these models can then be used to aggregate environmental and economic outcomes for a region, demonstrating tradeoffs for policy makers within the region.

This multidisciplinary approach can be modeled with software that integrates the economic and biophysical models. In this case the Tradeoff Analysis Model and Software, version 3.1, will be used (Stoorvogel *et al*., 2001).

[3] See Antle and Capalbo for a review of this literature.

Figure 8: Econometric-process model



Source: Stoorvogel et al.(2001), Valdivia (2002).

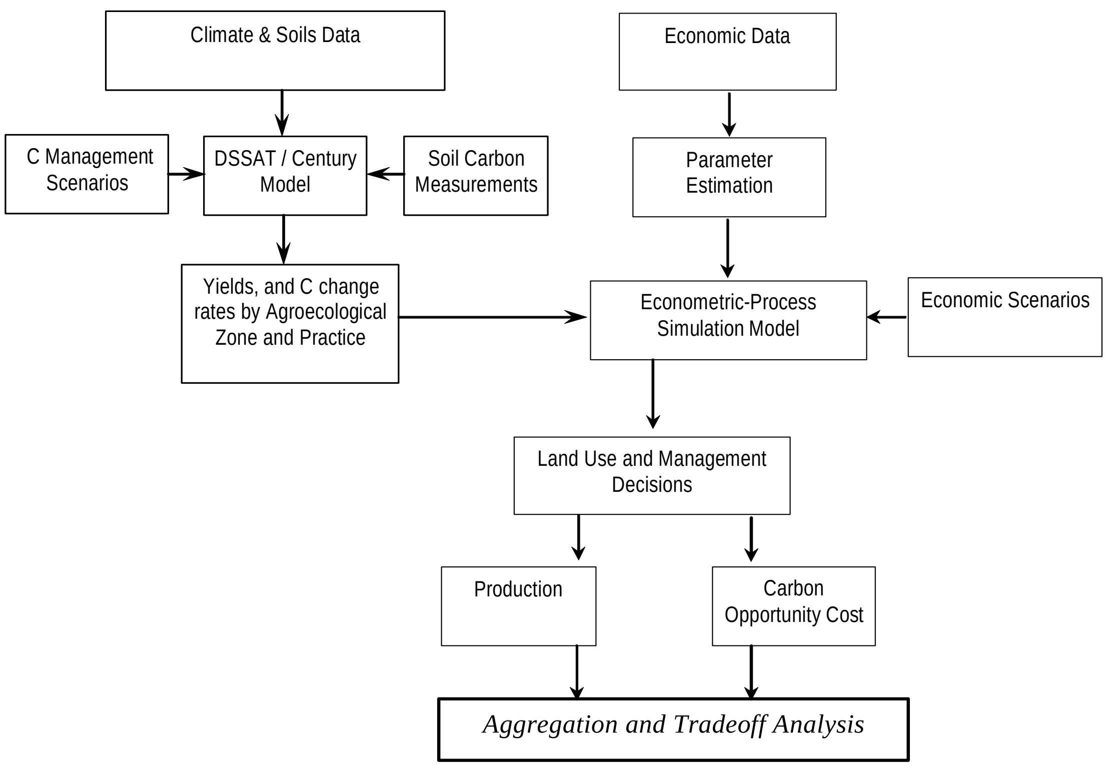
These models can utilize experimental, biophysical and/or farm survey data. *Inherent productivity* indices indicate the production capacity of a piece of land in a specific management regime. Soils and climate data are used in the crop simulation models to estimate site-and time-specific inherent productivity indices. Economic production models are estimated using farm survey data. The estimated economic production parameters, price distribution parameters (synthesized or estimated), and inherent productivity indices are combined as inputs into an econometric-process simulation model (Antle and Capalbo, 2001). Simulated management decisions from the economic simulation model are inputs into environmental process models, which estimate impacts on environmental indicators of interest.

Scenarios are defined by setting model parameters to represent particular sets of policy or technology conditions, such as mandatory crop residue incorporation and fertilizer subsidies. Environmental process model outcomes, such as changes in soil carbon, and predicted land use decisions and economic markers, such as tenure choice and net returns, can be aggregated to assess the environmental and economic impacts of each policy. Using the Tradeoff Analysis software, a set of parameters can be varied while holding others constant to conduct sensitivity analysis.

Methods

This sub-section contains a description of the relationship between economic and agronomic factors that enter the decision-making, or tradeoff framework.

Figure 9: Integrated Assessment Model of Carbon Sequestration



Source: Antle *et al.*, 2002

Figure 9 shows the conceptual structure of the integrated assessment model used, including the relationship between its parts. Economic models and components are depicted on the right side of the figure, while agronomic, soils, and environmental models are on the left.

Crop and Carbon Models

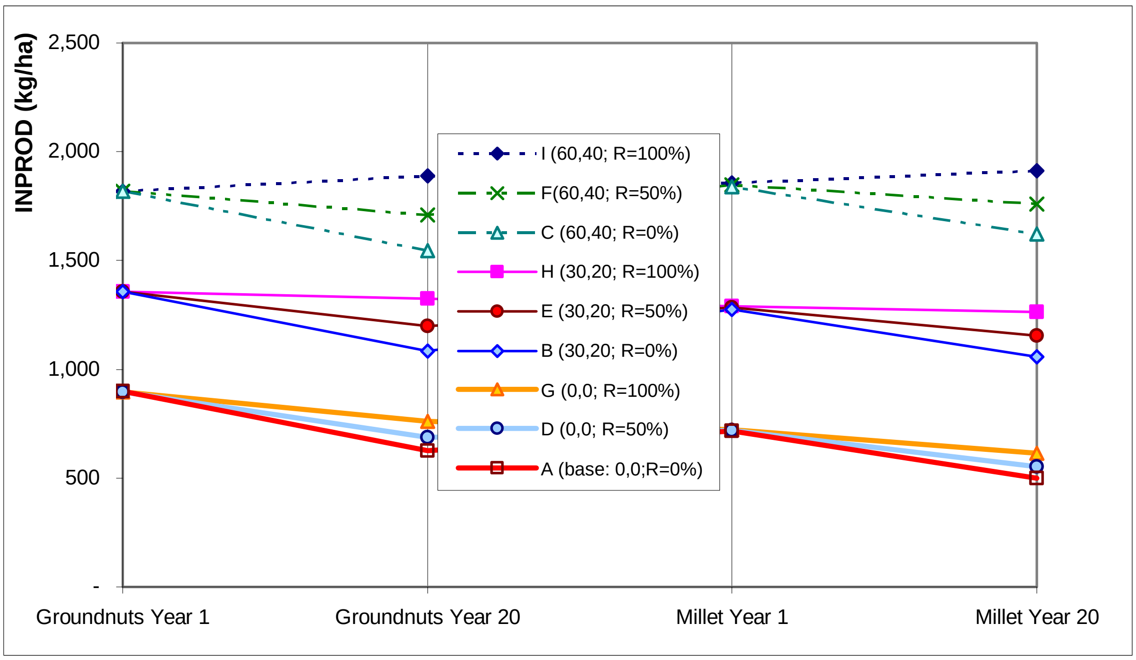
DSSAT/CENTURY. The DSSAT/CENTURY model (Gijsman *et al*., 2002) was used by a collaborating team of scientists to estimate soil carbon changes and inherent productivity for conditions representing each village in this study. The DSSAT/CENTURY model was developed by linking the DSSAT crop modeling system to the CENTURY model's method of simulating soil carbon dynamics. The DSSAT/CENTURY model was developed specifically for low input systems where most nutrients become available from soil organic matter (SOM) and residue turnover. The DSSAT/CENTURY model estimates changes in soil organic carbon stocks, using variables such as crop type, tillage mechanism, fertilizer usage, residue incorporation and rainfall. Using the model, initial and final values of soil carbon and crop yields were determined for each field, over a pre-determined time period (in this case, twenty years). The model was implemented using soils and climate data for the region and parameters for groundnut and millet crops from the region. The model was simulated for representative soil and climate conditions in each village represented in the study.

Modeling Changes in Inherent Productivity and Soil Carbon Stocks. The inherent productivity attributed to a field in any year, t, is:

$$\underset{0 \le t \le 20}{inprod_t} = inprod_0 + \frac{(inprod_{20} - inprod_0)}{20} \times t\ .$$

Figure 10 shows inherent productivity levels that were simulated over 20 years, given nine different management practices. These practices, which correspond to carbon contract requirements which will be analyzed in Chapter 5, mostly result in declining simulated inherent productivity. As with soil carbon stocks, only practice "I" results in sustained or improved inherent productivity. To correct for changes in inherent productivity that result directly from fertilizer increases, the intercept terms (year 1) of all management practices were set equal to the base policy, "A".

Figure 10: Inherent productivity levels given 9 different management practices

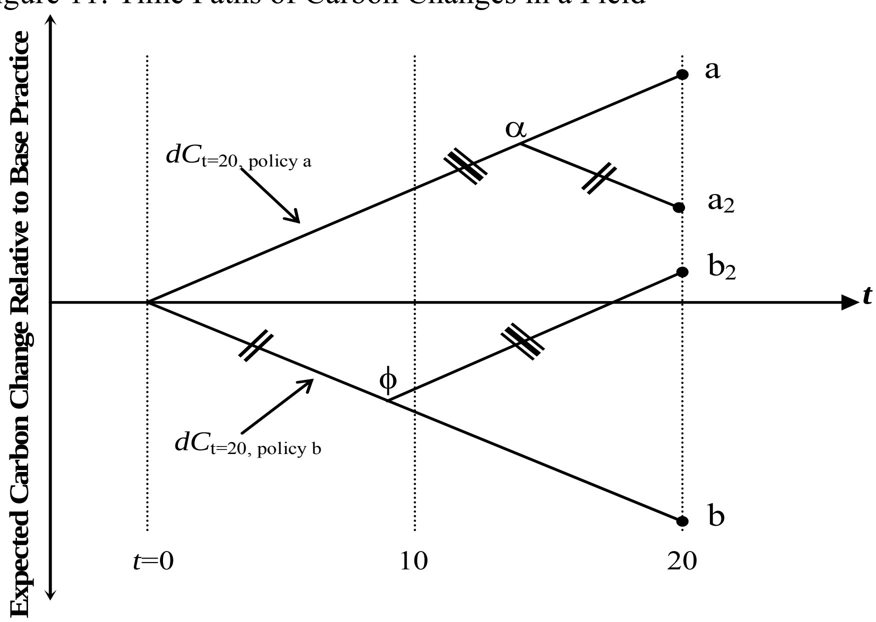


Expected Carbon change rates are calculated in a similar manner:

$$C_t = dcarb_t + C_{t-1}, \text{ where } dcarb_t = average(ctime_0, ctime_{20}).$$

Figure 11 shows potential paths of carbon sequestration for a field, given two land management practices, *a* and *b*. Path "a" shows the relative carbon change path of the field if management "a" was adapted in year one, and used continually for twenty years. Path "a_2" shows the decision to follow management "a" for fourteen years, and then switch to policy "b". Similarly, path "b" depicts exclusive use of management "b", while b_2 depicts the relative carbon change path of implementing management "b" for nine years, and then switching to "a." Unlike the inherent productivity numbers, all management practices start with the same value, so no intercept correction was needed for this simulated variable (see Figure 1 on page 13).

Figure 11: Time Paths of Carbon Changes in a Field



Two major simplifying assumptions are made here; first, expected soil carbon increases or decreases linearly; and second, it increases or decreases at the same rate, regardless of initial level. For example, it assumes that soil carbon decreases at the same linear rate if a farmer used policy "b" from year 0, versus starting at point α in year 14.

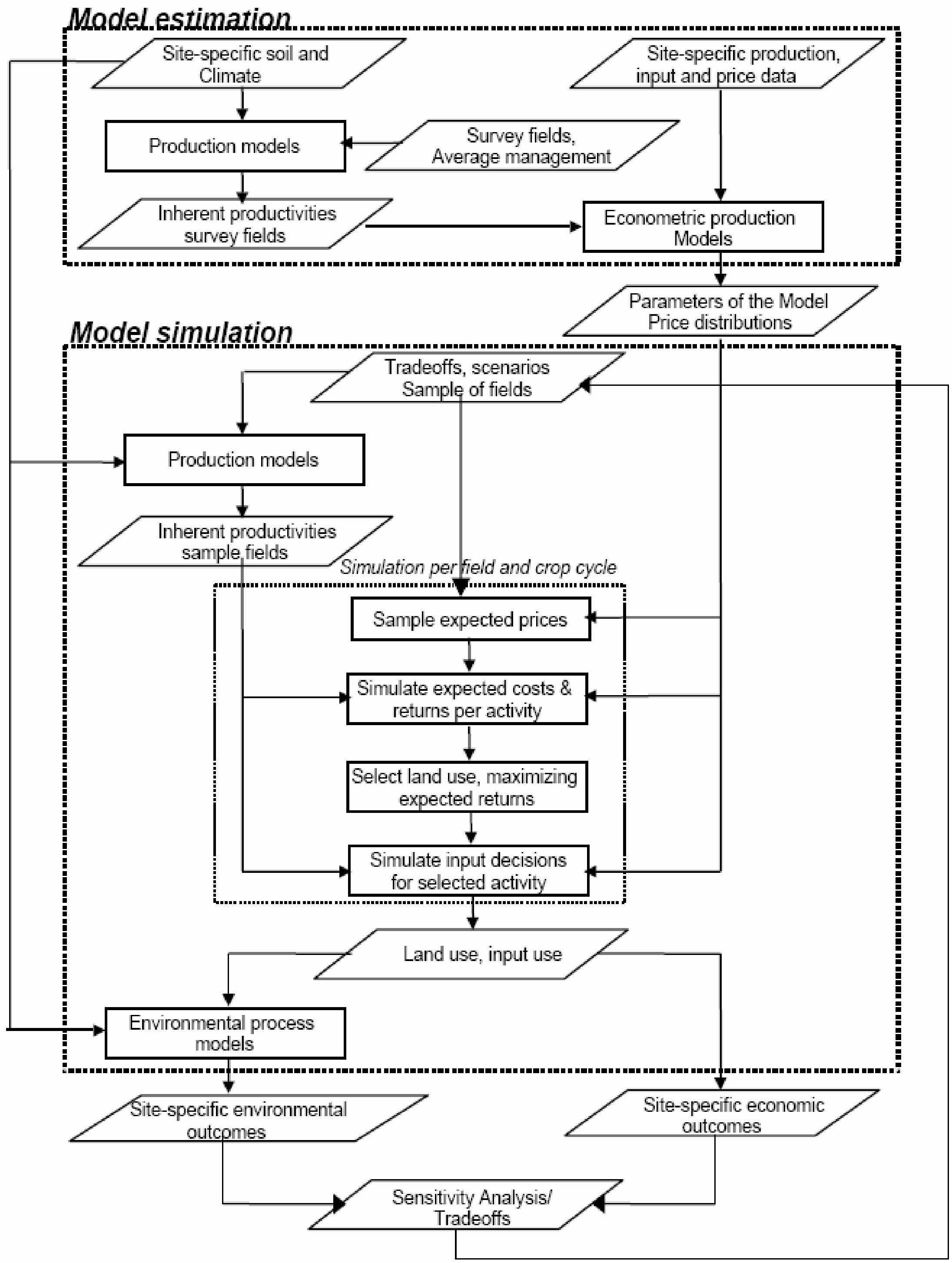
Economic Models: The Econometric Process Simulation Model

Antle and Capalbo (2001) developed the econometric process simulation model, which merges econometric production models, represented by supply and demand equations with discrete process-based land use decisions, represented by the threshold equation for contract participation, Equation (3).

In the *econometric process simulation model*, parameters and state variables are estimated in the biophysical and economic models, and those estimates are then used in simulation to predict discrete land use decisions for each field in each year. Figure 12 depicts the structure of the econometric process simulation model, with the upper half representing the estimation steps of the econometric models, and the lower part representing the simulation model structure. The latter model simulates the farmer's land use choice on a given field in a given year, and the related output and input usage corresponding to that choice.

The output can be interpreted as a "statistical representation of the population of land units in an agricultural region" (Antle and Capalbo, 2001) because of the stochastic nature of the sample data and the econometric models. In addition to this, because the simulation operates at the field scale using site-specific data, it can represent temporal and spatial variations in land use over time. These variations, such as tenure system, and crop rotations, can lead to different regional economic and biophysical outcomes over space and time.

Figure 12: Structure of the Econometric-Process Model



Adapted from Antle and Capalbo (2001).

Sensitivity Analysis of Soil Carbon Management Using Integrated Assessment Models

The General Approach. Agricultural systems are complex, dynamic systems, with biophysical and economics variables and parameters. Particularly in developing countries, the quality of data available to researchers can be less than perfect. This, in addition to inherent or unforeseen fluctuations in a system, can generate uncertainty in a model. Changes in parameters and exogenous variables can affect model outcomes (Valdivia, 2002).

Influences on the reliability, efficiency and robustness of a model vary from parameter to parameter. The appropriateness, or relevance, of a model highly depends on the sensitivity of outcomes with respect to its parameters. Valdivia (2002) cites several reasons to use analysis, including:

- Identifying critical thresholds, or values where the optimal strategy changes.
- Identifying sensitivity to important, changeable, variables.
- Testing the robustness of an optimal solution. This indicates the robustness with regards to changes in key parameters, and speaks to the relevance of those parameters and the model.

In an effort to understand the causal relationships within and between complex systems, integrated analysis combines, interprets, and communicates knowledge from diverse disciplines. Researchers have many tools for this approach, including computer-aided modeling, scenario analyses, simulation and experience-and expertise-based participatory integrated assessment (IPCC, 2001).

Comparisons of different models and model variants by the IPCC show that model results are very sensitive to alternative climate model inputs, which explains the large variance in yield estimates from crop models. Uncertainties in economic models alone are substantial, implying that the "economic impacts of climate change on agriculture are given a low degree of confidence" (Valdivia, 2002). As a result, integrated assessment and econometric modelers need to use sensitivity analysis to identify key assumptions and parameters, and focus research on those areas of the models. The *scenario analysis approach* is used in this thesis to conduct sensitivity analyses of the model.

Scenario Analysis

The scenario analysis approach, also call parametric analysis, assumes scenarios by specifying ranges and/or combinations of selected parameter values. The researcher solves the problem repeatedly, obtains a range of solutions, and observes sensitivities. From this, an approximation is chosen subjectively. Key parameters, distribution or range specifications, and the assignment of specific values such as maximums, are usually also obtained with this subjective method.

Scenarios are descriptions of possible future states that are described without ascribed probabilities. While these scenarios may contain sources of uncertainty, they are generally not explicitly acknowledged. Combinations of two or more scenarios can be used to construct ranges of possible outcomes that are sensitive to these sources of uncertainty.

The integrated simulation model applied in this thesis uses linked econometric and biophysical models. It allows comparisons of tradeoffs between prevailing and future economic and environmental outcomes. We conduct a sensitivity analysis with the information produced by an integrated assessment model by varying important parameters, including: input and output prices, yield responses, contract costs, and contract requirements.

CHAPTER 4

CASE STUDY: SENEGAL

General work has been completed regarding factors impacting Carbon sequestration in developing countries, however specific, “detailed case studies are needed to assess the economic feasibility of soil Carbon sequestration under conditions representing different parts of the world” (Antle & Diagana, 2003). This study will focus on the groundnut basin of Senegal.

Geography

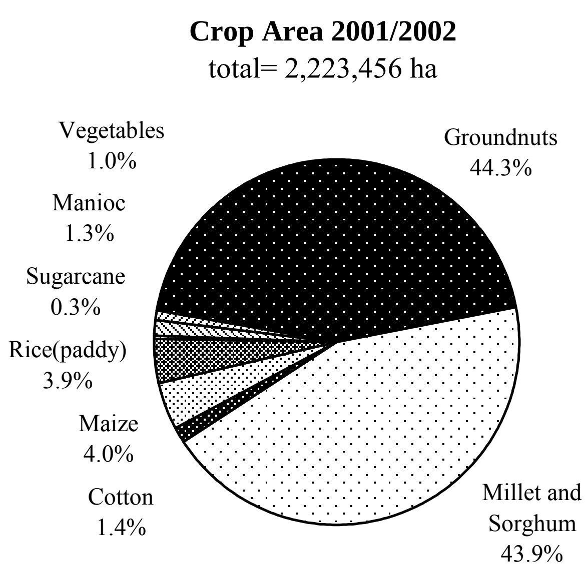
Senegal is located in the Atlantic Sahelian region of Sub Saharan Africa. Figure 13 depicts Senegal's location, and the Sahelian zone of Africa. Sub Saharan Africa is the region south of the Sahara Desert, which includes all nations of the Sahel and southwards.

Most of Senegal's crop production is dryland, or un-irrigated. Senegal's national crop composition is shown in Figure 14.

Figure 13: Map of Africa

Source: PERC, 2004, with Senegal emphasis by author

Figure 14: Crop Area in Senegal, 2001/2002 Crop Year



Source: IMF, 2003

The Groundnut Basin of Senegal is dominated by millet and groundnut production. Figure 15 shows the major agricultural zones of Senegal. This area represents roughly one third of Senegal's total landmass, and three quarters of its arable land (Kelly et. al., 1996; Akobundu, 1998). Overall, the GB accounts for 80% of Senegal's exportable groundnut crop, and 70% of its national cereal crop. Of the total cultivated area in the Groundnut Basin, groundnuts make up 50% of seeded acreage, followed by millet and sorghum (45%), with the remainder planted in maize, cassava and cowpeas (Badiane, 2001).

The Groundnut Basin is comprised of the following regions; the Northern, Central, and Southern Groundnut Basins, the Eastern Region and Casamance. Table 2 summarizes the characteristics of these regions. In the literature, there is some variation in the delineation and description of the different Groundnut Basin regions (Soufi, 2001). Overall, however, it can be said that both rainfall and soil clay content increase as one moves from North to South.

Figure 15: Map of Senegal, and Senegal's Groundnut Basin

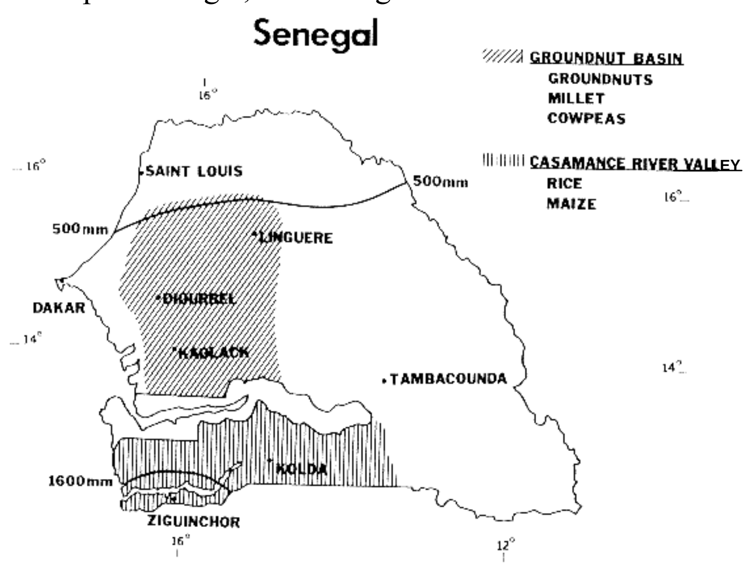


Table 2: Regions of the Groundnut Basin of Senegal

Region	Rainfall	Agricultural Products	Population Density
The Northern Groundnut Basin (Louga – Diourbel - Thies)	400 to 600 mm over a 30 to 45 day period.	Groundnuts, Millet	15 – 25 people/km^2
Central Groundnut Basin*** **(Thies – Diourbel – Kaolack - Mbour)** *** *location of sample*	**600 to 800 mm, over a 45-50 days period**	**Groundnuts, millet, cassava, cowpeas and livestock**	**80 – 100 people/km^2**
Southern Groundnut Basin (Sine and East Sine Saloum)	800 to 1,000 mm over a 55 to 70 day period	Groundnuts, millet, cassava, cowpeas, cotton, tobacco, sorghum and maize. High incidence of trypanosomiasis limits the potential for livestock raising.	15 – 35 people/km^2
Eastern Region	600 to 1,500 mm.	Groundnuts, sorghum, cotton and maize are grown in the Western region.	3.6 people/km^2
Casamance Region	-	Casamance is the most fertile region of the country. It specializes in long grain rice, maize and groundnut crops.	12 people/km^2 Lower Casamance: 80 people/km^2

Source: Badiane, 2001

Historical Background

Senegalese agriculture has changed substantially through the last century. The policies of the colonial and independent governments, as well as those imposed by Bretton Woods institutions are summarized in this section.

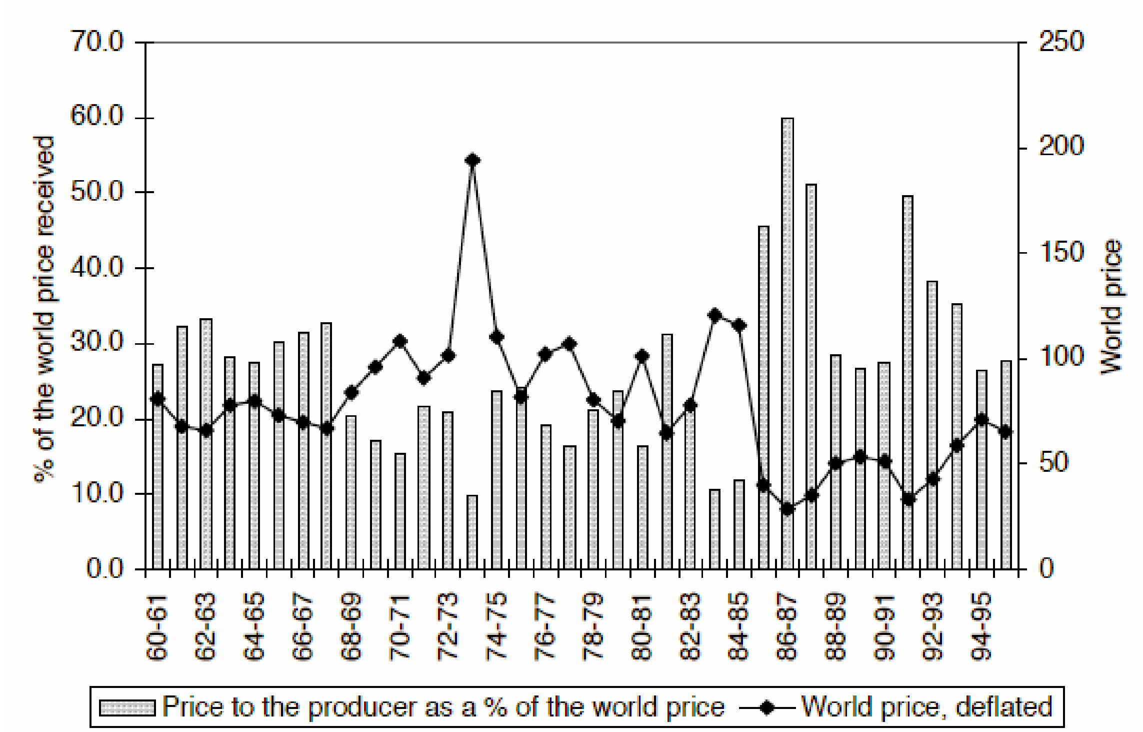
The Colonial Period. At the beginning of the 20th century, Senegal was a French colony. Groundnut production was left to the peasants, while the Government tried to spur economic development by investing in rail, road and harbour infrastructure development. The transport of groundnuts was financed by French merchant companies who operated with local, often Lebanese, agents. These agents also imported consumer goods and rice for the farmers to purchase. In order to offset the rural food deficit, which was created by farmers focusing groundnuts for export, and to supplement urban food needs, the colonial Government encouraged importation of broken rice from French Indo-China. During this period, credit was important to farmers, both for purchasing food during scarcity, and for groundnut seed, which is required in high ratios relative to output. Low prices and preparation ease soon made rice the preferred urban staple food and a significant millet complement in rural households (Faye *et al*., 2001).

French colonial rule left Senegal highly dependant on groundnut export revenues. For many years after Independence, Senegal's food strategy differed little from patterns established during the colonial period. Specialization in producing and exporting groundnut products to finance cereal importation was encouraged; and, there was substantial state involvement in production and marketing (Akobundu, 1998).

Independence. In 1960, Senegal gained independence as a nation. Demographically, there was a small, well educated urban elite who, because of the French education system, had been largely differentiated from rural peoples (Wilson & Fall, 2000). This elite and the political leadership were instilled with the prevailing socialist state planning ideas of the time.

The new government's *Programme Agricole* policies, which were in effect from the 1960s to the 1980s, used co-operative parastatals to organize and handle Senegal's farmers and their produce (Faye *et al*., 2001). In the 1960s, French firms were driven out of intermediary roles, while the co-operative parastatals were slowly given monopolies in domestic groundnut trade, farm inputs, rice and other cereals. As a result, farmers were required to be members of these co-operatives. ONCAD (*Office National de Commercialisation et d'Assistance*) was the large parastatal responsible for channeling credit and inputs downwards and groundnuts upwards. French firms retained control of the processing and exporting sectors. SATEC, which later became SODEVA (*Société de Développment et de Vulgarisation Agricole*), provided training services to farmers who were now using credit-provided animal-drawn equipment. With the *Programme Agricole*, all prices were fixed by the state. Large margins were set between export prices and farm gate prices, which financed the number of state employees, and increased the taxable profits of downstream industries (Faye *et al*., 2001). Pricing was based on the principle of paying farmers just enough to keep them producing groundnuts, but not enough for farm savings for investment, as these would be provided on state originated credit. Between 1970 and 1985, the price ratio of the groundnut producer price to the export price typically varied from 1:4 to 1:2 from 1970 to 1985 (Classin & Salin, 1991).

Figure 16: Farmgate and World Groundnut Prices



Source: Faye *et al.,* 2001 (p. 13)

Throughout this period, industrialization was viewed as the pathway to development, and the groundnut industry would provide the necessary capital. Government-funded research was largely invested in groundnut innovation, to the detriment of cereal production (Akobundu, 1998).

In the 1970s world groundnut prices rose, and government revenues from the industry increased. Because the development of the industrial sector was a dominant concern relative to the agricultural sector, the additional government funds were invested the industrial sector. This investment funded factories for textiles, phosphate fertilizer, fishmeal, groundnut oil and feedcake.

When the economic boom of 1974 -1976 ended, groundnut prices returned to approximately pre-1974 levels. Lower rainfall levels, from 1968 to the early 1970s undermined farmer's production capacity, leaving many farmers unable to repay their credit obligations. During that period, civil unrest led the Government to forgive farmer debt three times. This, in addition to inefficiencies and corruption within ONCAD, led to huge debts for that organization.

Structural Adjustment and Beyond. Senegal experienced a macroeconomic crisis from the late 1970's to the early 1980's. Responding to this, Senegal agreed to undergo structural adjustment measures imposed by the International Monetary Fund (IMF) and World Bank. These adjustments, and the associated *Nouveau Politique Agricole* (NPA) programs, took effect in 1985, and continued until 1994, when the currency, the *Franc de la Communauté Financière Africaine* (FCFA or CFA Franc) was devalued. These drastic reforms were aimed at using market forces to motivate farmer decisions - turning “peasants into farmers”. ONCAD was abolished in 1980; some agricultural extension services were phased out; large government fertilizer subsidies ended in 1984; and in 1985, credit supply was halted (Faye *et al.,* 2000). However, despite an overall trend towards less contribution, the government was still involved in input markets, output markets, and in the setting of price floors and ceilings for various crops.

In 1995, the Senegalese Government made a commitment to privatize the state-owned groundnut enterprise, the *Société Nationale de Commercialisation des Oléagineux* *du Sénégal* (SONACOS), although at the time no buyers could be found. The *Societé National de Graines de Semance du Sénégal* (SONAGRAINES), which is a descendant of the abolished input parastatal ONCAD, was downsized and transferred its seed procurement functions to official cooperatives and licensed traders, but in reality, both of these groups were "agents of SONACOS rather than independent and competing traders" (Kherallah *et.al*., 2002). Today, SONACOS still handles most of the unshelled groundnut and groundnut oil trade in Senegal, and is still state owned. Through SONACOS and SONAGRAINES, the Government continues to control producer prices, and a large portion of the marketing, processing and input supply channels to oil groundnuts in Senegal (Kherallah *et.al*., 2002).

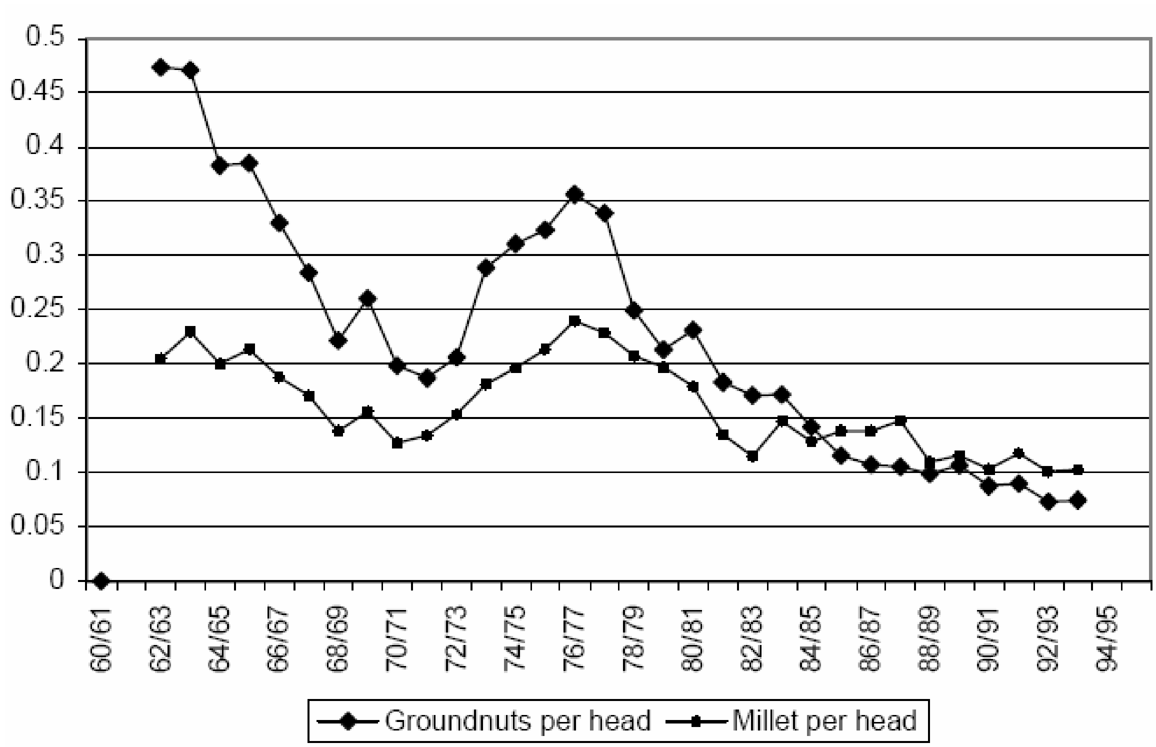
Crisis in Senegal

This section explores the perceived crisis in the natural resource based economies of Senegal. It will cover the fall in production, the drought, demographic changes, the elimination of subsidies, the fall in new land available for cultivation, and finally, the rise of soil degradation

Falling Production. Between 1960-1970 and 1990-1996, there was a 28% reduction in national groundnut production. This was due to both reduced acreage (19% less) and lower yields (11% less). Over that same period of time, there was a slight increase in millet production, but this was outstripped by population growth (Faye *et al.*, 2001). Figure 17 shows these trends for the Diourbel Region of the Groundnut Basin.

Besides minor changes in crop selection, these drops in production have been attributed to “changes in rainfall and poor resource management and environmental degradation leading to lower output, this being propelled by population growth and pressure on the resource base” (Faye *et al.,* 2001). However, economic factors such as prices also contribute to decreased production.

Figure 17: Production of groundnuts and millet per capita (Diourbel Region), in tonnes



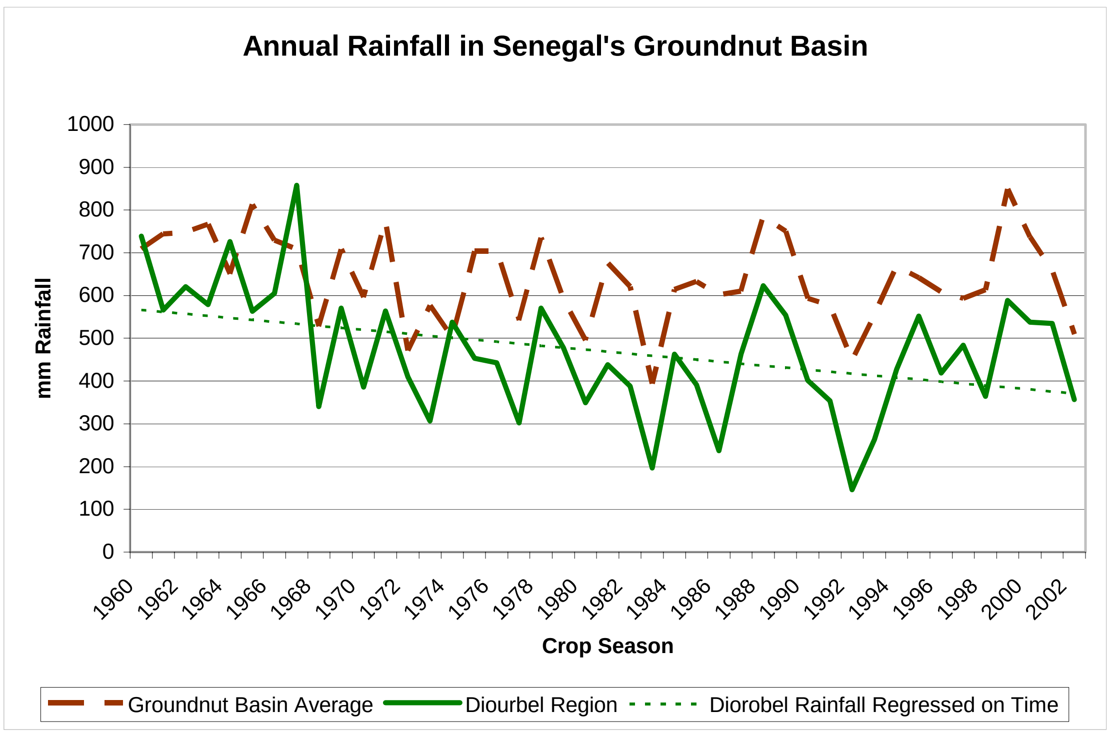
Source: Faye *et.al.,* 2001, p. 6.

<u>Drought in the Sahel</u>. The entire Sahelian region, including the region of study, has been subject to a prolonged drought. Figure 18 shows rainfall trends and levels in Senegal's groundnut basin over the past 30 years. The Diourbel region has experienced substantial demographic and climactic stresses (Mortimore *et al.,* 2004). This area, in the Central and

Northern Groundnut Basins, forms a major part of the groundnut-exporting region of Senegal.

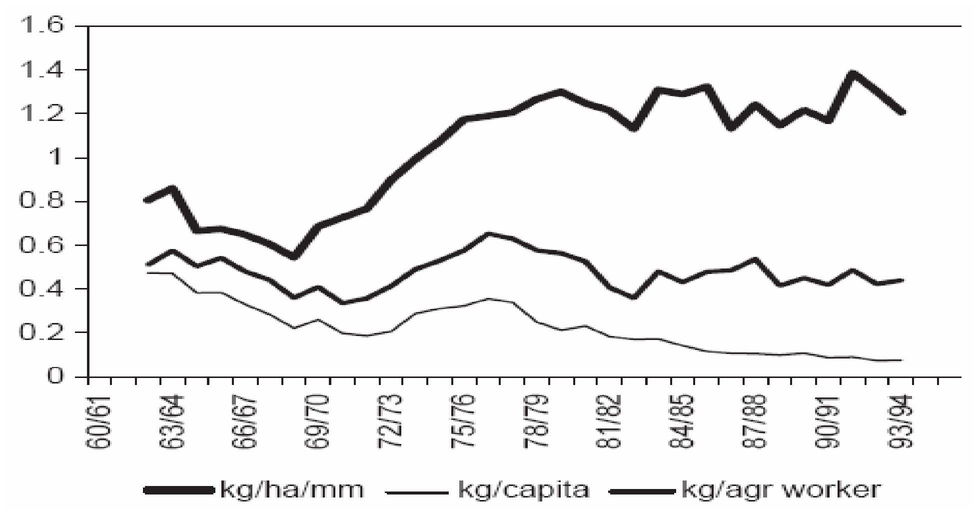
In response to this drought, drought tolerant varieties of groundnuts and millet that were developed for these regions, and adaptive management practices, increased the yield per mm of rainfall (Akobundu, 1998; Mortimore & Francis, 2005). Figure 19 shows millet trends over time, per capita, per agricultural worker and per mm rain on a per hectare basis.

Figure 18: Historic Rainfall Levels in Senegal's Groundnut Basin



Source: IMF, 2003.

Figure 19: Millet Yields in the Diourbel Region



Source: Mortimore and Francis, 2005.

Demographics and Population Pressure. The study area is populated by Wolof and Serer peoples on mixed crop and livestock farms. Among both groups, Islam is the prevalent religion, and many of both groups have followed the Mouride movement (Fall, 2002). In the 1930's, under French rule, Mouride leaders were significant in rural commerce, and were agents of urbanization. The Serer people have traditionally been much less hierarchical than the Wolof, who tend to operate with very stratified roles. Both groups practice extended family compound living, and income from off-farm jobs are important sources of money for the farm unit. In recent years, as agricultural fortunes have suffered, young men supplement household income by trading at *loumas*, (regional weekly bazaars), and/or working and peddling in urban centers, both in Senegal and abroad (Fall, 2000). Perry (2000) notes that these *loumas* appeared concurrently with the introduction of structural adjustment policies in Senegal. The diminished importance of parastatals in the rural marketplace gave rise to *loumas* as the local economic hubs.

This area has been subject to a high rate of population growth; the national growth rate is 2.4% per annum (WHO, 2004), and regional rural growth estimates range from 2.8% to 3.24% (Barry *et al*. 2000). People were living at variable densities of 46–151/km2 at the time of the 1988 census (Barry *et al*., 2000). Fields are small (about .5 ha) with cereals (mainly bulrush millet) grown for subsistence. Over 80% of the land has been under cultivation or short, 1-year fallows since 1954 or earlier (Ba *et al*., 2000). In recent years, fallow has dropped to very low levels (0.5-2%) in some areas, and has virtually disappeared in others.

The Groundnut Basin is proximate to Dakar, population 2.6 million (World Gazeteer, 2004). Between the Administrative Regions of Dakar, Diourbel, and Thiès, there are over 5 million of Senegal's 10 million people (see Table 3). This density not only puts pressure on rural area for land cultivation, but it also creates a large demand center for other regional resources and products.

Table 3: Population Statistics

Admin Region	**Population**	**km^2**	**persons/ km^2**
Dakar	2,613,700	550	4752
Diourbel	1,008,000	4,359	231
Thiès	1,461,700	6,601	221
3 Regions	**5,083,400**	**11,510**	**442**
Senegal	**10,624,800**	**196,722**	**54**

Price and Policy Roots of Production Decline. While population pressure and drought have placed significant pressure on the agricultural systems of Senegal, production has dropped for other reasons as well. Farmers, being rational, will adjust their management practices, including input usage, based on the prices and information before them.

Input Markets and Policies

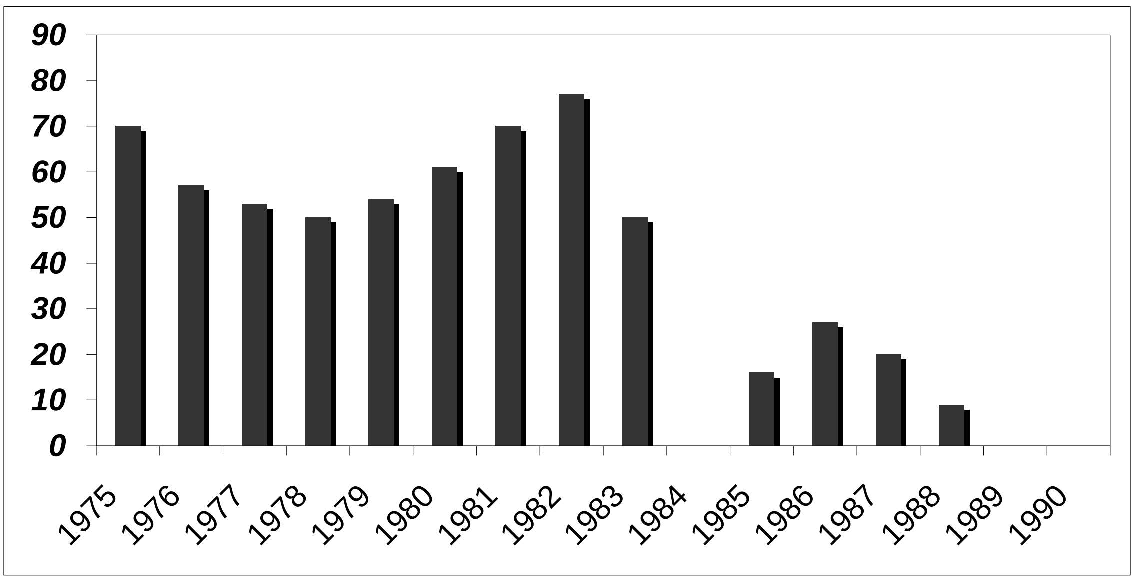
During structural adjustment, once government fertilizer subsidies were eliminated, prices rose, and in the absence of accompanying investments for physical and institutional infrastructure to support markets, the availability of inputs decreased (Diagana, 2003). In the Groundnut Basin,

> "Fertilizer, agricultural equipment, seeds, and credit were all subjected to different rules governing their supply and accessibility to farmers. Input supply policy became as variable as the weather while the government sought the magic combination of policies that would increase cereal production and involve the private sector in the input and output marketing activities of the agricultural sector."

(Akobundu, 1998, pp. 11-12)

Through this period, the documented lack of stability in policies pertaining to key inputs was a likely cause of decreased input use, and therefore decreased production. In response to the decreased fertilizer use, USAID/Senegal subsidized private sector fertilizer purchases by farmers from 1986 through 1989 on a declining basis (Kelly *et al.*, 1996). Despite this effort, overall fertilizer usage did not recover to earlier levels, as farmers did not have access to adequate credit markets to finance the private market purchases. When the CFA Franc was devalued in 1994, fertilizer became relatively more expensive, which again discouraged its use. Today, farmers still face liquidity constraints when buying fertilizer, as payments for government purchased groundnuts (via SONACOS) are not always made in time to purchase fertilizer for the next growing season.

Figure 20: Fertilizer Subsidy Rate in Senegal (% of full cost)

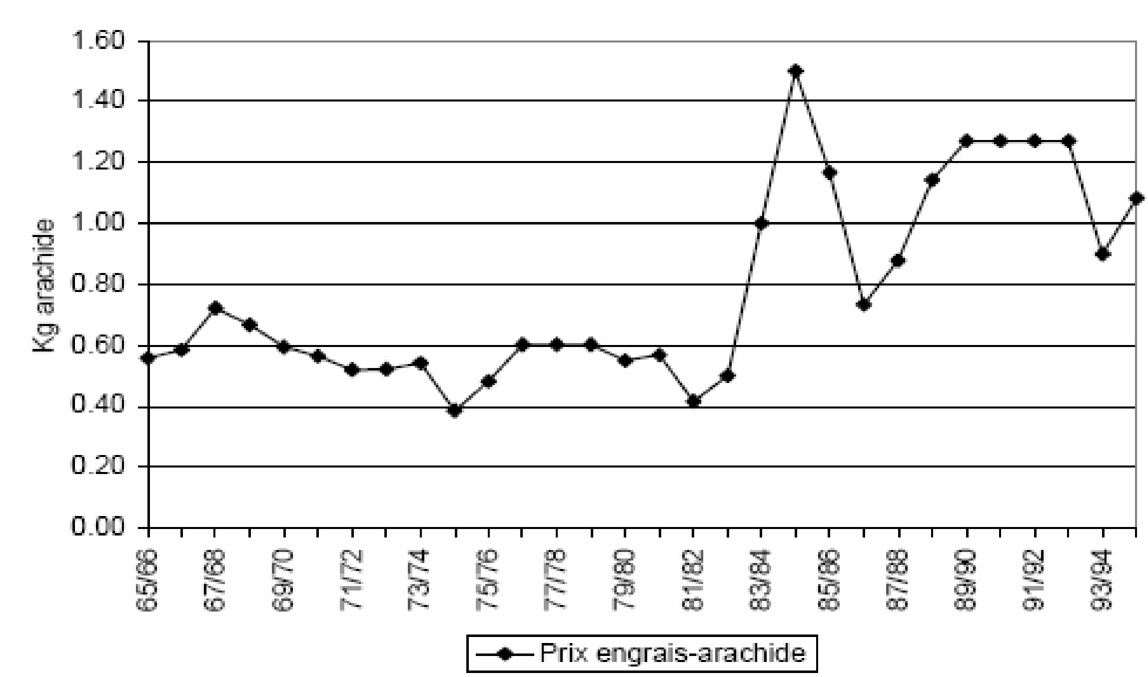


Data Source: (Kherallah *et.al*., 2000).

As discussed above, the policy changes associated with structural adjustment adversely affected input usage. In the case of fertilizer, subsidies have been eliminated, and private companies have not been fully able to fill the gaps efficiently. In combination with these higher fertilizer prices, there is evidence that government involvement in output markets suppresses output prices (see Figure 16). Figure 21 shows the relationship between fertilizer and output prices over time. As this ratio increases, farmers will use less and less fertilizer.

Other input markets have also been affected by policy changes. SONAGRAINES and its predecessors used to provide funding for extension and research services, as well as subsidies and credit services for certified groundnut seed. As the government has reduced and eliminated these services, this has also lead to decreased potential returns to fertilizer application. Also, given limited budgets and lack of credit, farmers tend to substitute higher seeding densities for fertilizer usage (Kelly *et al.,* 1996).

Figure 21: Kilograms of groundnuts necessary to purchase 1 kg of mineral fertilizer



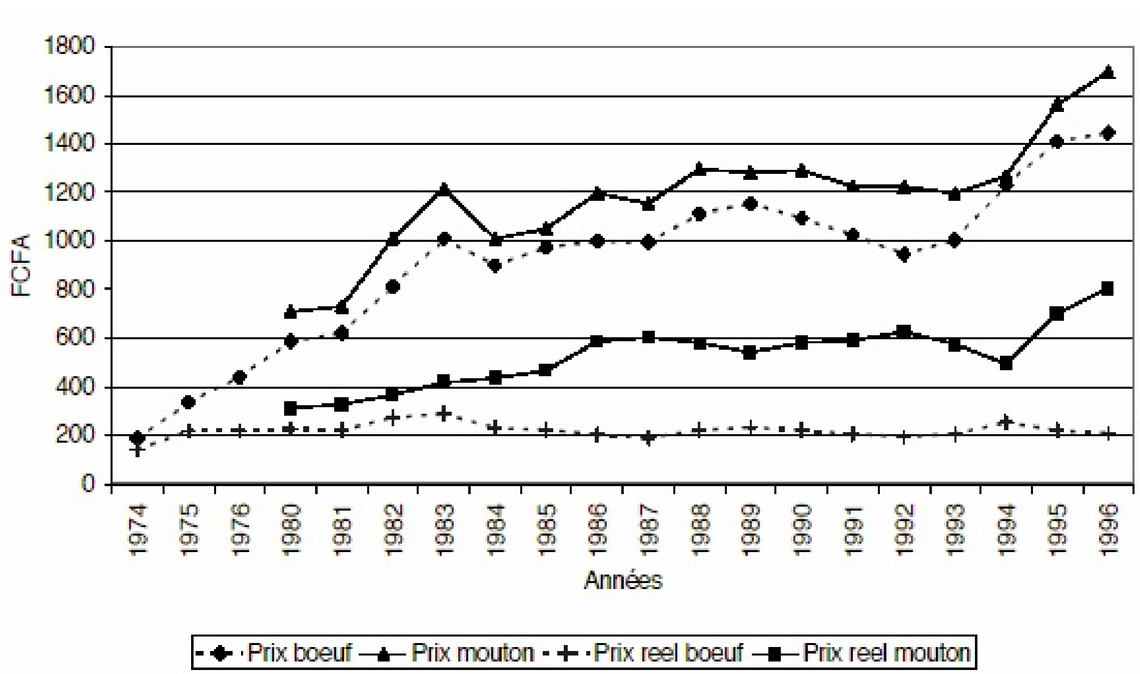
Legend: "kg arachide" = groundnuts (kg); "Prix engrais-arachide" = Price fertilizer/groundnuts

Source: Faye *et al.,* 2000, p. 13.

Crop Residue

Chapter 1 discusses how crop residue incorporation could play an important role in reducing or even reversing soil degradation trends. In the Groundnut Basin, groundnut residues are sold for animal fodder. Figure 22 shows how, from 1974 to 1996, real beef prices remained relatively constant, while real mutton prices increased. At the same time, livestock production, particularly that of small ruminants, increased significantly, as shown in Figure 23. Increasing population density and urbanization is driving this meat demand, and along with it, the demand for livestock feed. Consequently, this increases the opportunity cost of applying residue (hay) to cropland.

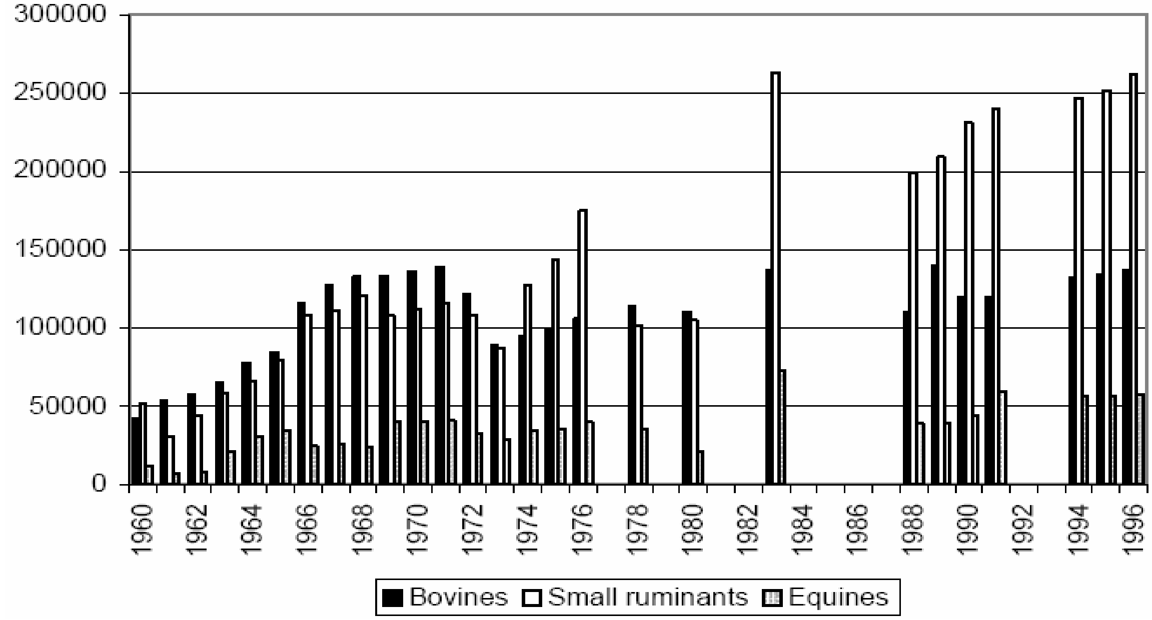
Figure 22: Meat Prices in Senegal



Prix boeuf, mouton = Price beef, mutton *Prix reel boeuf, mouton = Real prices*

Source: Faye *et.al.,* 2001, p.21.

Figure 23: Changes in Livestock owned, 1960-96, Diourbel Region



Source: Faye *et al.,* 2001, p.21.

Table 4 shows the mean yields, revenues, and opportunity cost of incorporating groundnut residues. Assuming that the costs of incorporation are the same as those for harvesting as transporting the residue, farmers would need a 7.7% increase in yields in their cropping system to compensate for incorporating all residues. If farmers incorporated residue, this would restrict supply into the animal feed market, and likely drive up prices further. This would increase the opportunity costs of the practice further.

Table 4: Average Yields & Revenues from the 2000 ENEA dataset

	GN Residue	**Groundnuts**	**Millet**	**Total Revenue**
Yield	1642	1194	1030	
Price	15	135	107	
Revenue CFA/ha	24630	161190	110210	296030
Revenue Share in 2 year rotation	8.3%	54.5%	37.2%	100%
		Groundnuts	**Millet**	**Both crops** *(2 yr rotation)*
Yield increase to offset incorporation of 100% groundnut residues		15.3%	22.4%	7.7%

Land Tenure

Given certain sets of rights, land tenure could affect the motivation to use fertilizer. Generally, renters have less incentive to make long-term investments in land quality than owners. However, rental is a relatively rare phenomenon in most African countries. Traditionally, senior village or Mouride officials grant usufruct rights to farmers, which tend to be secure enough to not dis-encourage investment. Structural adjustment brought with it new land tenure policies (Kherallah *et.al*., 2000).

Similarly, most land in Senegal belongs to the state, which grants usufruct rights rather than ownership to users. However, according to the current laws, traditional non-cultivation practices, such as long-term fallow, renting, gifting, collateral provision and loans, are limited to two years. Otherwise, usufruct rights may be revoked, and given to someone else. Tschakert (2001) notes that this law discourages de-facto users, especially in densely populated areas, from undertaking traditional fallow patterns. Temporary users (those gifted land, renting or borrowing land) have less incentive to invest fertilizer and soil quality because of their limited two year time horizon.

These new laws are enforced to differing degrees, and farmers have found ways to cope with them:

> "People have become more suspicious, but also more innovative. We have encountered farmers who fake cultivation, by sowing only 1/10 of their plot, and pretending a state of stubbornness close to mental illness -- with which administrative officials usually don't want to deal -- simply to let their land lie fallow. We have also met farmers who have lost precious land by voluntarily

> renting it out to needy neighbors who, after the critical period of two years, officially claimed the land and received it." (Tschakert, 2001).

According to the IIED (1999), despite the official extinguishing of the customary rights in Senegal, formalized and customary systems of tenure co-exist. Generally, the restrictions on customary land tenure rights occur in peri-urban areas and project development sites.

Private Markets

Since structural adjustment, farmers now deal with private companies. In many areas of the Sahelian and SSA, farmers face relatively high transportation and transactions costs when interacting in private markets (Kherallah *et al.*, 2002). Senegal has relatively good physical infrastructure, and is a port country, which reduces transportation costs relative to other countries in the region.

Today, fertilizer is sold privately in the Groundnut Basin. These private companies are different from past government supply avenues in that they so not have the same capacity to obtain credit to make wholesale purchases or the capacity to provide retail credit to farmers. Farmers have difficulty obtaining private market credit for farm purchases in Senegal. Land tenure is usufruct, leaving farmers without collateral. Family networks and informal credit are more prevalent in the region (Fall *et al.* 2000). Anecdotally, timeliness of delivery is a major problem within the private system.

Discussion

Climactic shocks, population pressure and government policies all play roles in farmers' decisions to degrade soils. Population pressure, and to some extent land tenure institutions, have caused farmers to abandon extensive traditional management systems which used fallowing as a means to maintain soil fertility. To offset this change in land management practices, farmers need to intensify their land usage with practices such as increased fertilizer and crop residue incorporation. Unfortunately, market conditions and government policies have not created the incentives for farmers to make these changes. Increased fertilizer and seed prices, minimal to non-existent credit markets, and currency devaluation all contributed to this. Droughts make fertilizer usage risky and less effective. Using the ENEA dataset from this region, Chapter 5 will examine whether carbon payments could help to offset some of these forces, and reduce or reverse soil degradation in the region.

CHAPTER 5

MODEL IMPLEMENTATION, SCENARIOS & RESULTS

In the Nioro region of Senegal most farmers plant millet and groundnuts in a simple alternating rotation, without the benefit of fallowing, residue incorporation, or significant levels of fertilizer. This system often depletes soils, and has low productivity potential. As discussed in Chapter 2, many of these farmers apply low rates of mineral nutrients. These low nutrient use rates are hypothesized to be explained by a number of factors, including availability constraints, high discount rates, and relatively high input prices. In addition, farmers remove most organic material from their fields because it is valuable as animal feed. Indeed, there is a growing demand for groundnut crop residues driven by the growing demand for animal protein. Thus, farmers face a significant opportunity cost to incorporate crop residues into their soils. The key question addressed in this chapter is whether the trend towards soil nutrient depletion can be slowed or reversed by offering farmers carbon contracts that provide farmers with an incentive to use more nutrients and to incorporate crop residues into soils.

This chapter utilizes an econometric-process simulation model to simulate farmers' willingness to participate in carbon contracts. The first part of this chapter describes the estimation of the production models for groundnut and millet crops, taking into account its salient features, including the low and zero rates of mineral fertilizer use observed. The second part of this chapter defines carbon contracts and simulates them using an econometric-process simulation model. Carbon supply curves for the region will be estimated, and we will attempt to answer questions posed earlier: first, is fertilizer availability a binding constraint? Second, could a carbon payment system induce carbon sequestration and help to reduce soil degradation in the region?

The Nioro Dataset

The data used in this analysis was obtained by farm survey from the Nioro region of Senegal and represents the 2001 growing season. The Nioro region of study is situated between 13º35' to 13º50' North and 16º00' to 16º30' West. The region is arid, with a rainy season that lasts from June until October. Average annual rainfall is approximately 750 mm (3"), and average annual temperature is 27.5ºC, ranging from 38ºC to 15ºC, averaged monthly. Elevations are low, ranging up to 40m above sea level (Diagana *et al.,* 2004).

Most soils of the Nioro region were formed from ironstone or the underlying sandstones of the Continental terminal. The soils on the glacis, collovu-alluvial terraces and bas-fonds are deep; whereas soils on the ironstone plateaus tend to be shallow and rocky. Clay content generally increases with depth, and all Nioro soils tend to be weathered, leached and rich in iron. Most of these soils are FAO classified as lixisols, ferralsols or leptosols (Meerkerk, 2003 in Diagana *et al.,* 2004).

Groundnuts and millet are the two main crops grown in this region, with minor acreages of sorghum, maize, tomatoes, melons and orchards. Fallow, though common in the past, is no longer common in crop rotations. Groundnuts are produced for sale, while millet tends to be a subsistence crop used for household consumption. There is a thriving animal fodder market in the region, and most groundnut residue (hay) is sold into it. There are virtually no tractors in this region; animal and human labor is predominant.

The data used in this thesis is a cross section from 2001 collected by ENEA (École Nationale de Economie Appliqué), an agricultural economics college in Senegal. Every year, ENEA students are sent into a region to collect household production and consumption data from a sample of rural households (their sample shifts locations every year, so it is not a panel dataset). This dataset has the advantage of not relying on farmer's memories of input usage, as enumerators are present during all phases of the growing season; however, there are obvious drawbacks to having multiple inexperienced enumerators collecting and compiling data.

The data available for this case study was extensive, but somewhat patchy in quality. The 2000 ENEA Nioro dataset was incomplete in some variables, including seed prices, labor costs, fertilizer costs, and some output prices. Several steps were taken to clean the data: extreme outliers were dropped from the sample; observations with extensive missing or indecipherable data were dropped; and, some outliers were replaced with plausible values. A distribution was constructed for each of these variables, using predominant levels from the Nioro dataset, and other Senegalese data, including country level aggregated price and quantity data for outputs and fertilizer. Tables 5 and 6 contain summary statistics for the cleaned data used in this analysis.

Table 5: Sampled Variables Used in Analysis (Nioro region of Senegal, 2000)

Fields with Groundnuts

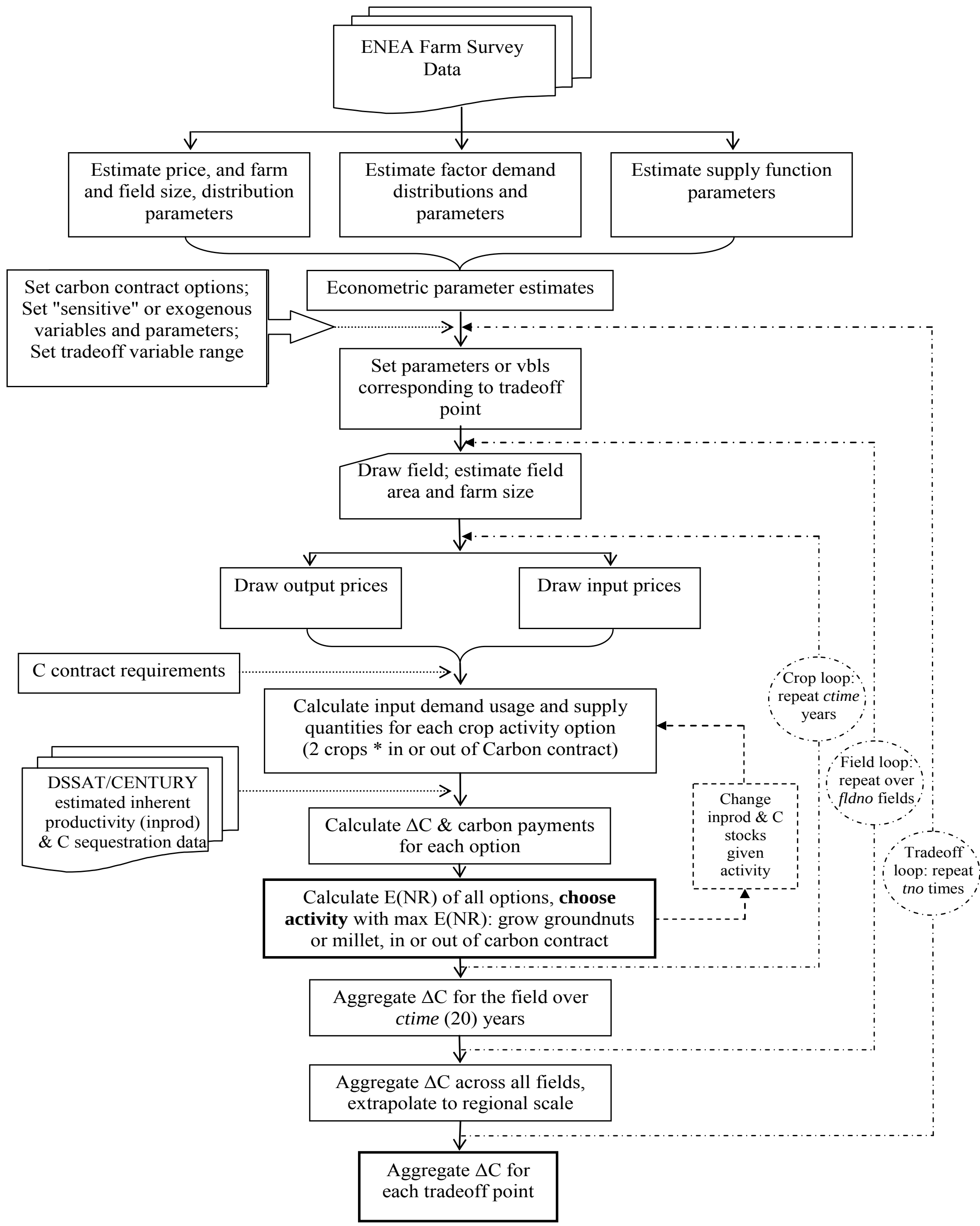
Description	Unit	n	Mean	Std Dev	Min	Max
Field Size	*ha*	96	1.31	1.02	0.19	6.12
Farm Size	*ha*	96	9.88	5.75	1.72	22.23
Grain Yield	*kg/ha*	96	1304.2	430.0	625.0	2887.0
Groundnut Hay Yield	*kg/ha*	70	1642.1	613.8	506.8	3806.1
Seed Price	*CFA/kg*	96	250.5	84.0	120.0	405.0
Fungicide Price	*CFA/kg*	96	748.8	421.8	10.0	1600.0
Mineral Fertilizer Price	*CFA/kg*	96	281.2	94.1	111.1	600.0
Seed Used	*kg/ha*	93	88.0	49.7	8.0	333.3
Organic Fertilizer Used	*kg/ha*	6	1053.0	1042.9	7.0	2000.0
Fungicide Used	*units/ha*	34	83.2	36.9	50	161.5
Fungicide Use Dummy	*O,1*	79	43.0%	0.498	0	1
Labor Used	*hours/ha*	82	65.1	36.9	10.0	205.1
Mineral Fertilizer Used	*kg/ha*	49	68.2	51.7	10.8	264.7
Fertilizer Use Dummy	*O,1*	79	62.0%	0.488	0	1
Crop = Groundnuts	-	96	1	0	1	1
Crop = Millet	-	96	0	0	0	0
Previous Crop Fallow	-	96	2.1%	0.144	0	1
Previous Crop Millet	-	96	74.0%	0.441	0	1
Previous Crop Maize	-	96	6.3%	0.243	0	1
Previous Crop Groundnuts	-	96	6.3%	0.243	0	1
Village Dummy 1	-	96	5.2%	0.223	0	1
Village Dummy 2	-	96	7.3%	0.261	0	1
Village Dummy 3	-	96	0.0%	-	0	0
Village Dummy 4	-	96	13.5%	0.344	0	1
Village Dummy 5	-	96	21.9%	0.416	0	1
Village Dummy 6	-	96	6.3%	0.243	0	1
Village Dummy 7	-	96	6.3%	0.243	0	1
Village Dummy 8	-	96	5.2%	0.223	0	1
Village Dummy 9	-	96	11.5%	0.320	0	1
Village Dummy 10	-	96	2.1%	0.144	0	1

Table 6: Sampled Variables Used in Analysis (Nioro region of Senegal, 2000)

Fields with Millet

Description	Unit	n	Mean	Std Dev	Min	Max
Field Size	*ha*	92	1.30	0.83	0.06	4.50
Farm Size	*ha*	92	6.50	4.81	0.06	22.23
Grain Yield	*kg/ha*	79	1030.1	484.5	304.0	2600.0
Seed Price	*CFA/kg*	79	108.2	21.6	75.0	250.0
Fungicide Price	*CFA/kg*	79	754.0	549.9	10.0	4000.0
Mineral Fertilizer Price	*CFA/kg*	79	295.8	55.1	50.0	555.6
Seed Used	*kg/ha*	74	6.7	8.0	1.3	50.0
Organic Fertilizer Used	*kg/ha*	16	612.7	658.0	12.5	2000.0
Fungicide Used	*units/ha*	25	26.8	40.9	0.5	150.0
Labor Used	*hours/ha*	74	48.3	32.1	12.3	162.1
Mineral Fertilizer Used	*kg/ha*	44	51.8	27.5	14.1	152.1
Fertilizer Use Dummy	*O,1*	92	47.8%	0.50	0	1
Crop = Groundnuts	-	79	0	0	0	0
Crop = Millet	-	79	1	0	1	1
Previous Crop Fallow	-	79	5.1%	0.221	0	1
Previous Crop Millet	-	79	8.9%	0.286	0	1
Previous Crop Maize	-	79	0.0%	-	0	0
Previous Crop Groundnuts	-	79	81.0%	0.395	0	1
Village Dummy 1	-	79	10.1%	0.304	0	1
Village Dummy 2	-	79	10.1%	0.304	0	1
Village Dummy 3	-	79	2.5%	0.158	0	1
Village Dummy 4	-	79	6.3%	0.245	0	1
Village Dummy 5	-	79	19.0%	0.395	0	1
Village Dummy 6	-	79	5.1%	0.221	0	1
Village Dummy 7	-	79	7.6%	0.267	0	1
Village Dummy 8	-	79	6.3%	0.245	0	1
Village Dummy 9	-	79	6.3%	0.245	0	1
Village Dummy 10	-	79	3.8%	0.192	0	1

Figure 24: Structure of the Econometric-Process Simulation Model



Structure of the Analysis

Figure 24 shows the steps used to carry out this analysis. The simulation uses estimated biophysical and economic parameters in order to simulate the land-use decisions and corresponding outcomes for each field, across space and time. One hundred draws are made from the sample set of fields. In order to simulate the spatial heterogeneity faced by farmer, farm size, field area, and input prices are spatially varied.

Farm size and field size are modeled as spatially-varying lognormal distributions, with the mean of the logged variable varying by village. These village effects were estimated with OLS, and are reported in tables 7 and 8. Output and labor prices are modeled as spatially varying log normal random variables. Village effects on seed, fungicide, and fertilizer prices are estimated using OLS; these parameters are reported in tables 9 to 11.

Table 7: OLS results of millet seed price distribution

Millet seed price (V12) OLS Estimation
Dependent Variable: Log millet seed price (CFA/kg)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Village intercept	4.5556	0.0317	143.86	<.0001
Village Dummy 1	0.3594	0.0571	6.3	<.0001
Village Dummy 2	0.2067	0.0571	3.62	0.001
Village Dummy3	0.0496	0.1001	0.5	0.622
Village Dummy 4	0.1705	0.0679	2.51	0.015
Village Dummy 5	0.0163	0.0470	0.35	0.729
Village Dummy 6	0.0173	0.0743	0.23	0.816
Village Dummy 7	0.1847	0.0633	2.92	0.005
Village Dummy 8	0.1157	0.0679	1.7	0.093
Village Dummy 9	0.1705	0.0679	2.51	0.015
Village Dummy 10	0.1984	0.0838	2.37	0.021

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
11	68	1.2273	0.018	0.1343	79	0.4626	0.3835

Table 8: OLS estimates of groundnut seed price parameters

Groundnut seed price (V11) OLS Estimation
Dependent Variable: Log groundnut seed price (CFA/kg)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Village intercept	5.638	0.063	90.07	<.0001
Village Dummy 1	-0.120	0.140	-0.86	0.3924
Village Dummy 2	-0.533	0.123	-4.34	<.0001
Village Dummy3	0.000	0.000	.	.
Village Dummy 4	-0.276	0.100	-2.76	0.007
Village Dummy 5	-0.079	0.088	-0.90	0.3713
Village Dummy 6	0.342	0.130	2.62	0.0103
Village Dummy 7	-0.368	0.130	-2.82	0.0059
Village Dummy 8	-0.247	0.140	-1.76	0.0817
Village Dummy 9	-0.362	0.105	-3.45	0.0009
Village Dummy 10	-0.850	0.208	-4.10	<.0001
Restrict	0	0	<------	Biased

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
10	86	6.7384	0.0784	0.2799	96	0.426	0.3659

Table 9: OLS estimates of fungicide price parameters

Groundnut fungicide price (V4) OLS Estimation Dependent Variable: fungicide units (CFA/unit)				
Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Village intercept	5.363	0.349	15.380	<.0001
Village Dummy 1	0.942	0.780	1.210	0.230
Village Dummy 2	1.655	0.685	2.420	0.018
Village Dummy3	0.000	0.000	.	.
Village Dummy 4	-0.009	0.556	-0.020	0.987
Village Dummy 5	1.294	0.487	2.660	0.010
Village Dummy 6	1.083	0.726	1.490	0.140
Village Dummy 7	-1.600	0.726	-2.200	0.030
Village Dummy 8	1.178	1.157	1.020	0.312
Village Dummy 9	1.001	0.586	1.710	0.091
Village Dummy 10	0.852	1.157	0.740	0.464
Restriction	0	0	<------	Biased

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
10	83	201.9	2.4328	1.5597	93	0.2393	0.1568

Table 10: OLS estimation of mineral fertilizer price parameters

Fertilizer NPK price (V6) OLS Estimation Dependent Variable: Log mineral fertilizer price (CFA/kg)				
Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Village intercept	5.724	0.050	114.400	<.0001
Village Dummy 1	-0.010	0.099	-0.100	0.917
Village Dummy 2	0.055	0.094	0.590	0.556
Village Dummy3	0.004	0.224	0.020	0.988
Village Dummy 4	0.046	0.088	0.520	0.603
Village Dummy 5	-0.322	0.072	-4.490	<.0001
Village Dummy 6	-0.011	0.110	-0.100	0.918
Village Dummy 7	-0.070	0.102	-0.680	0.495
Village Dummy 8	-0.062	0.110	-0.570	0.571
Village Dummy 9	-0.469	0.092	-5.110	<.0001
Village Dummy 10	-0.027	0.147	-0.190	0.853

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
11	164	15.5986	0.0951	0.3084	175	0.2544	0.209

Table 11: OLS estimates of farm size parameters

Farmsize (Fsize) OLS Estimation
Dependent Variable: Log farm size (ha)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Village intercept	2.104	0.097	21.610	<.0001
Village Dummy 1	-0.646	0.199	-3.250	0.001
Village Dummy 2	-0.062	0.188	-0.330	0.742
Village Dummy3	-0.767	0.435	-1.760	0.080
Village Dummy 4	0.563	0.172	3.280	0.001
Village Dummy 5	-0.193	0.140	-1.380	0.170
Village Dummy 6	0.216	0.213	1.010	0.312
Village Dummy 7	-0.762	0.199	-3.830	0.000
Village Dummy 8	-0.851	0.213	-3.990	0.000
Village Dummy 9	-0.201	0.179	-1.120	0.263
Village Dummy 10	-0.670	0.286	-2.350	0.020

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
11	162	58.3268	0.36	0.6	173	0.3082	0.2655

Table 12: OLS estimates of field area parameters

Field Area (AREA) OLS Estimation
Dependent Variable: Log area (ha)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Village intercept	-0.691	0.202	-3.420	0.001
Village Dummy 1	0.690	0.216	3.200	0.002
Village Dummy 2	0.384	0.198	1.950	0.053
Village Dummy 3	0.771	0.462	1.670	0.097
Village Dummy 4	0.011	0.187	0.060	0.954
Village Dummy 5	0.130	0.148	0.880	0.381
Village Dummy 6	0.559	0.225	2.480	0.014
Village Dummy 7	0.025	0.218	0.120	0.907
Village Dummy 8	0.296	0.235	1.260	0.210
Village Dummy 9	0.438	0.189	2.320	0.022
Village Dummy 10	0.133	0.305	0.440	0.664
Farmsize	0.292	0.083	3.540	0.001

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
12	161	64.1821	0.3986	0.6314	173	0.172	0.1155

For each field, farm size and field areas are drawn from the estimated distributions which use village information. Fertilizer, seed and fungicide prices are estimated using the OLS determined village effects. These parameters will remain with the field through all years, through all tradeoff variable (carbon price) loops. For each growing season, output and labour prices are sampled from non village-dependant distributions. Expected supply and input use are simulated, given these sampled prices and estimated parameters of the production models.

Expected net revenues (ENRs) for each crop are calculated using these calculated production, input demand, and cost quantities. If alternative management options (such as carbon sequestration contracts) are available to farmers, then the expected net returns will be calculated for each available activity, for each crop, and the activity and crop corresponding to the maximum ENR is selected.

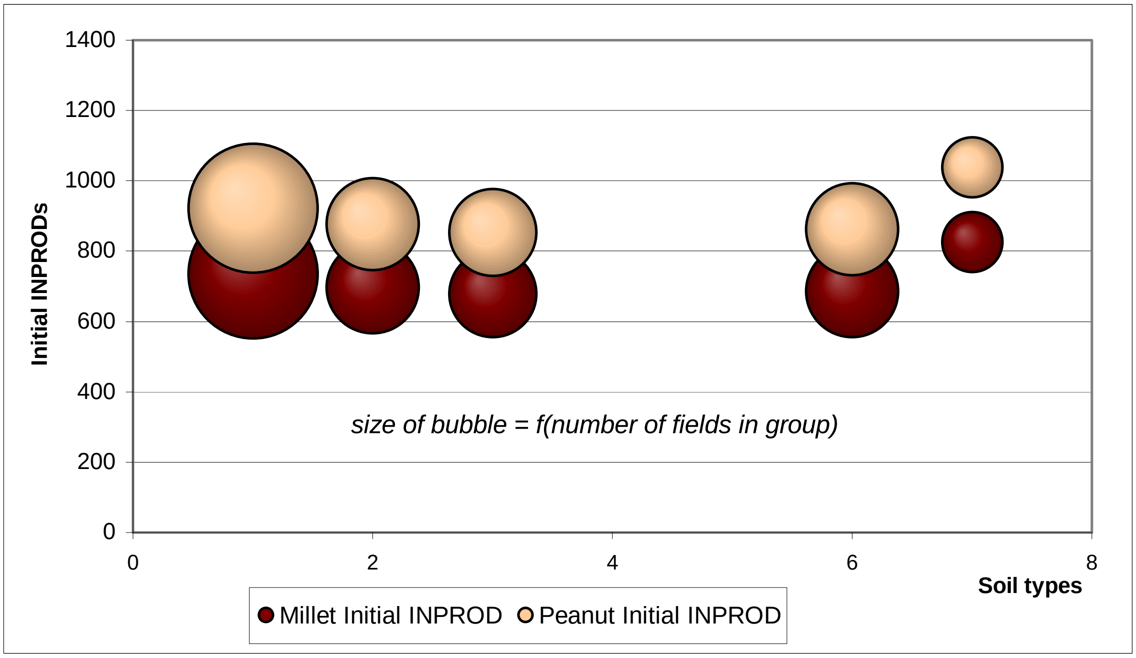
After the model has simulated land usage, activity choice, production quantities, input consumption and environmental changes for all draws from the sample, the same procedure will be repeated on the same field for *ctime* cycles (20 years in this case). In each subsequent year, output prices are again drawn, and the same economic parameters are used to calculate ENRs for each activity. The activity choice simulated in the previous year affects successive ENRs, through crop rotational effects (estimated econometrically in the economic models), and changes in inherent productivity. If an activity that altered the inherent productivity path, such as entering a carbon contract, was chosen previously, then this will impact expected productivity in the next year.

In this simulation, carbon prices are varied from zero to \$200/tonne (0 to 100,000 CFA/tonne) to derive carbon supply curves. In the simulation model structure, the carbon price is defined as a "tradeoff variable" and each tradeoff point corresponds to a different price. For each tradeoff point, another loop of the model (*i* fields * *ctime* years) is run, and the results are aggregated. Results are scaled up to the regional level (there are approximately 103,000 hectares of millet and groundnut production in the Nioro region), and in this way carbon supply curves are generated.

Biophysical Parameters: Inherent Productivity

Inherent productivity (INPROD) values were estimated using the DSSAT/CENTURY model, as described in Chapter 1, using soils and climate data for each village. These values, which are the predicted yields for each crop, exhibit relatively little variation. There are five different soil types, and therefore five different simulated inherent productivity and carbon paths for each management practice. Figure 25 shows the five initial inherent productivities for both of the crops. This grouping of the inherent productivities leads to clusters of farms with identical proxies for biophysical parameters. When farmers make discrete choices (such as whether to use fertilizer, or participate in a carbon contract, etc.), the inherent productivity variable can cause simulated groups of farmers to make similar decisions. Later in this analysis, this causes supply curves to assume a step-function shape (for example, see Figure 27).

Figure 25: Inherent productivity data, by soil type and crop



Econometric Specification and Estimation of
Groundnut and Millet Production Models

A key issue identified in Chapter 2 is the low, and often zero, rates of mineral fertilizer use in the Senegal groundnut/millet system. Conventional, neoclassical production models do not allow for zero input use. This section describes how a conventional log-linear specification of factor demand and output supply equations was adapted to account for the zero-input problem.

The approach taken here is a pragmatic one, aimed at the development of a well-behaved simulation model that captures farmers' behavior in this system. Elaborate econometric procedures, e.g. with mixed discrete-choice and continuous choice equations, are not considered for two practical reasons. First, the data available for this analysis undoubtedly contain significant measurement errors; and second, the simulation of complex systems discrete and continuous choice models is not empirically tractable.

OLS (Ordinary Least Squares) was used to estimate each of the economic equations, including input demand functions and supply functions. These are modeled as constant elasticity functions with non additive error terms. Given these non additive errors, these functions are non linear in the parameters, and therefore nonlinear least squares is used. These errors are assumed to have mean (0) and constant variance. Equations were estimated separately, and most equations contained non-linear elements. Generally, input demand is a function of input prices, output prices, and agronomic potential and other fixed effects.

Table 13 shows the OLS results of demand for seed and labor in the groundnut and millet crops.

Table 13: OLS estimates of groundnut seed demand parameters

Groundnut seed demand (X1) Non-Linear OLS Estimation
Dependent Variable: groundnut seed (kg/ha)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Intercept	-4.968	5.701	-0.870	0.387
Log (area)	-0.302	0.064	-4.740	<.0001
Log (seed price)	-1.046	0.159	-6.570	<.0001
Log (fertilizer price)	0.197	0.140	1.410	0.163
Fungicide use dummy	-0.141	0.094	-1.500	0.137
Previous millet dummy	-0.127	0.137	-0.930	0.358
Log (farm size)	0.135	0.063	2.160	0.034
Log (inherent prod.)	2.043	0.848	2.410	0.019

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
8	69	85767.3	1243	35.2563	77	0.4822	0.4297

Table 14: OLS estimates of labor demand parameters in groundnut fields

Groundnut labor demand (X5) Non-Linear OLS Estimation
Dependent Variable: groundnut labour (person days/ha)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Intercept	13.208	5.617	2.350	0.022
Log (area)	-0.348	0.069	-5.070	<.0001
Log (seed price)	-0.439	0.155	-2.840	0.006
Fungicide use dummy	-0.045	0.080	-0.560	0.576
Log (fertilizer price)	-0.507	0.129	-3.920	0.000
Previous millet dummy	-0.028	0.146	-0.190	0.849
Log (farm size)	-0.266	0.072	-3.680	0.001
Log (inherent prod.)	-0.472	0.878	-0.540	0.593

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
8	61	34134	559.6	23.6553	69	0.662	0.6232

Table 15: OLS estimates of millet seed demand parameters

Millet seed demand (X1) Non-Linear OLS Estimation
Dependent Variable: millet seed (kg/ha)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Intercept	-4.304	14.308	-0.300	0.764
Log (area)	-0.278	0.191	-1.460	0.149
Previous groundnut dummy	-0.007	0.263	-0.030	0.980
Log (farm size)	-0.198	0.112	-1.770	0.081
Log (inherent prod.)	0.981	2.171	0.450	0.653

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
5	83	3690.5	44.4636	6.6681	88	0.2096	0.1715

Table 16: OLS estimates of labor demand parameters in millet fields

Millet labor demand (X5) Non-Linear OLS Estimation
Dependent Variable: X5

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Intercept	6.808	8.923	0.760	0.448
Log (area)	-0.313	0.108	-2.890	0.005
Log (fertilizer price)	0.047	0.223	0.210	0.834
Organic fertilizer dummy	-0.160	0.164	-0.980	0.331
Previous groundnut dummy	-0.012	0.165	-0.070	0.941
Log (farm size)	0.005	0.070	0.070	0.942
Log (inherent prod.)	-0.485	1.372	-0.350	0.724

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
7	81	61185.8	755.4	27.4842	88	0.1956	0.136

Modeling Zeros in Input Demand. Because of the prevalence of zero application rates for mineral fertilizer, a probit model was used to estimate the likelihood that producers would use fertilizer. This probit model is used to simulate the use/non-use decision of the farmer. Distribution of use and demand for groundnut fungicide (X4) was also estimated in the same two-step probit/OLS fashion.

In the simulation model, once a farmer is determined to use mineral fertilizer or pesticide, a conventional input demand equation is simulated to estimate the quantity applied. These input demand equations are estimated for the part of the sample where positive input application rates are observed. These demand equations may be subject to sample selection bias. Theoretically, if there are unobserved variables that explain use/non-use of the input (e.g., credit constraints, input availability, location) and if these variables are correlated with explanatory variables in the model (e.g., farm and field size, productivity, prices) then the error term in the input demand equations may violate the standard conditions of statistical independence from the explanatory variables.

One procedure used for sample selection correction is the *Heckit method*, after the work of Heckman (Wooldridge, 2003). The Heckit procedure was run on the model, by first estimating probit equations, calculating the inverse Mill's ratio, and then estimating the input demand equations including the inverse Mill's ratio as an explanatory variable. The estimated parameters of the inverse Mill's ratio were statistically insignificant, indicating that error covariance was not a problem in the model. In addition to this, the other parameter estimates had similar values to those in the truncated OLS model. As a result, a probit and OLS method was used to estimate these discrete choice demand models. Table 17 and Table 18 show the estimated probit models of fertilizer usage.

Table 17: Probit Model for fertilizer use in groundnut fields (modeling the probability of no fertilizer usage: X6D1=0)

Variable	**DF**	**Estimate**	**Std Error**	**95% Confidence Limits**		**Chi Square**	**Pr > ChiSq**
-	1	-4.728	5.795	-16.086	6.630	0.670	0.415
Log(field area)	1	-0.414	0.221	-0.847	0.020	3.500	0.061
Log(farm area)	1	0.271	0.251	-0.220	0.762	1.170	0.280
Log(fertilizer price)	1	1.608	0.528	0.574	2.642	9.290	0.002
Log(inherent productivity)	1	-0.670	0.762	-2.163	0.824	0.770	0.380

Dependent Variable:	X6D1	**Name of Distribution:**	Normal
n total, n with X6>0:	79, 49	**Log Likelihood:**	- 45.8127

Table 18: Probit Model for fertilizer use in millet fields (modeling the probability of no fertilizer usage: X6D2=0)

Variable	**DF**	**Estimate**	**Std Error**	**95% Confidence Limits**		**Chi Square**	**Pr > ChiSq**
-	1	34.951	19.628	-3.519	73.421	3.170	0.075
Log(field area)	1	-0.110	0.227	-0.555	0.335	0.240	0.628
Log(farm area)	1	0.021	0.178	-0.327	0.369	0.010	0.906
Log(seed price)	1	-2.770	1.085	-4.895	-0.644	6.520	0.011
Log(fertilizer price)	1	0.999	0.569	-0.116	2.113	3.080	0.079
Log(inherent productivity)	1	-4.205	2.779	-9.653	1.242	2.290	0.130

Dependent Variable:	X6D2	**Name of Distribution:**	Normal
n total, n with X6>0:	92, 44	**Log Likelihood:**	-57.437

These probit models of fertilizer usage provide economically sensible parameter estimates. In the case of groundnuts, only field area and fertilizer price parameters were statistically significant. Field area is positively correlated with usage, which runs against the conventional wisdom that small plots, generally closer to the home, tend to be farmed more intensely. Higher fertilizer prices, of course, are associated with non-usage. This is consistent with the ideas put forth in Chapter 2, namely that farmers who face high prices are more likely to be at a corner solution. Although the inherent productivity parameter estimate is not statistically significant, it is negative, which is consistent with the idea that fertilizer use is positively related to productivity potential. Labor costs and time constraints would create thresholds, where it could be more productive for a farmer to apply more or all of their fertilizer on some fields, and none at all on others, rather than a lower average level across all fields.

Table 18 shows the results of the millet probit model where the intercept, seed price, fertilizer price and inherent productivity parameter estimates were statistically significant. As seed prices increase, the probability of fertilizer usage increases (as non-usage drops). This could be the result of farmers expecting higher output prices, since millet seed and millet output markets are positively related. The fertilizer price and inherent productivity parameters have the same signs, and likely the same causes, as in the groundnut case.

The Fertilizer Demand Function. The following mineral fertilizer demand function was estimated using OLS, with the sample truncated to where fertilizer usage (X6) is greater than 0.

Generally, Mineral Fertilizer Quantity = *f {intercept, log (field area), log (groundnut seed price), log (fertilizer price), previous millet crop dummy variable, log (farm size), log (inherent productivity in year 1)}*

From the factor share equation:

$$X6 = e^{(\text{F01} + \text{FAREA1*ln(AREA)} + \text{FV11*ln(V1)} + \text{FV61*ln(V6)} + \text{FPRML1*PR\_ML} + \text{FFSIZE1*ln(FSIZE)} + \text{FINP1*ln(INP101)})}$$

Table 19 shows the estimated results of the fertilizer demand equations. In the groundnut model, the estimated parameters for field area, fertilizer price, and the previous crop being millet dummy were statistically significant. In the case of millet, the parameters for field area, seed price, and farm area were significant.

In Senegal, larger fields are typically located further away from the village, and tend to be farmed less intensively than those closer by. This is consistent with the estimated parameters, FAREA1 and FAREA2, which were (-.39) and (-.57) respectively.

The farm size parameter was significant and positive in the millet equation. In this case, farm size could be a proxy for greater farm household wealth, which would lead to more access to credit and capital to make fertilizer purchases. In the case of groundnuts, the parameter for fertilizer price was highly significant and negative. This demonstrates downward-sloping input demand curves. For millet, seed price was negative and significant. This is likely because farmers substitute seed density for fertilizer usage (Kelly et al., 1996). In groundnuts, the seed price parameter was small, positive and insignificant. Finally, in the groundnut equation, the millet rotation dummy variable was negative and significant. Two factors influence this effect; the agronomics of crop rotations, and financial constraints. If farmers grew millet the year before, it is likely that their soils have lower nitrogen balances than if they grew groundnuts (groundnuts are a leguminous crop, which has nitrogen fixing capability). For this reason, we could expect a positive value on this parameter. However, because groundnuts are a cash crop, and millet is not, it is likely that farmers will have lower financial reserves after growing millet. This second effect appears to be dominant, and for this reason we see a negative algebraic sign on this parameter. The statistical insignificance of inherent productivity is of concern. This was probably a result of little variation in inherent productivity numbers across fields

Table 19: OLS estimates of groundnut fertilizer demand parameters (where X6>0)

SAS Non Linear OLS Model Procedure **– Groundnut Model**

Dependent Variable: fertilizer use (kg/ha) where X6>0 (n=49/79 groundnut fields)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Intercept	7.22603	4.9777	1.45	0.154
Log(field area)	-0.3914	0.1487	-2.63	0.0118
Log(groundnut seed price)	0.098841	0.4337	0.23	0.8208
Log(fertilizer price)	-0.81154	0.2842	-2.86	0.0067
Previous millet crop dummy	-0.57985	0.264	-2.2	0.0336
Log(farm area)	-0.19658	0.1658	-1.19	0.2424
Log(inherent productivity)	0.203069	0.5685	0.36	0.7227

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
7	42	49815	1186.1	34.4394	49	0.611	0.5554

Table 20: OLS estimates of millet fertilizer demand parameters (where X6>0)

SAS Non Linear OLS Model Procedure **– Millet Model**

Dependent Variable: fertilizer use (kg/ha) where X6>0 (n=44/93 millet fields)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Intercept	10.19454	8.6724	1.18	0.2473
Log(field area)	-0.56996	0.1338	-4.26	0.0001
Log(millet seed price)	-1.05445	0.526	-2.000	0.052
Log(fertilizer price)	-0.1323	0.106	-1.250	0.218
Log(organic fertilizer)	-0.07754	0.162	-0.480	0.635
Log(farm area)	0.166472	0.092	1.820	0.077
Log(inherent productivity)	-0.12485	1.214	-0.100	0.919

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
7	37	18130.5	490	22.136	44	0.442	0.351

Table 21: Estimated groundnut fungicide use discrete choice and input demand parameters

Probit Model for Fungicide Usage with the Groundnut Crop
(modeling the probability of no fungicide usage: X4D=0)

Variable	**DF**	**Estimate**	**Std Error**	**95% Confidence Limits**		**Chi Square**	**Pr > ChiSq**
-	1	36.73	20.23	-2.92	76.39	3.30	0.07
Log(farm area)	1	-0.24	0.23	-0.68	0.21	1.08	0.30
Log(fertilizer price)	1	-1.38	0.46	-2.27	-0.49	9.18	0.00
Log(inherent productivity)	1	-4.17	2.98	-10.01	1.67	1.96	0.16

Dependent Variable:	X4D	**Name of Distribution:**	Normal
n total, n with X4>0:	79,34	**Log Likelihood:**	-46.7170

Groundnut Model : SAS Non Linear **OLS Model Procedure**

Dependant Variable: fungicide units/ha, where X4>0 (34/79 fields)

Variable	**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
Intercept	8.890	12.207	0.730	0.473
Log(field area)	-0.117	0.126	-0.930	0.361
Log(fertilizer price)	-1.033	0.422	-2.450	0.021
Previous millet dummy	-0.166	0.181	-0.920	0.367
Log (farm size)	0.236	0.151	1.560	0.131
Log (inherent prod.)	0.148	1.938	0.080	0.940

Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
6	28	33057.6	1180.6	34.3603	**34**	0.2648	0.1335

Supply Equations

Conventional production function or supply function models do not allow for zero input use. To estimate fertilizer productivity with both zero and positive application rates, the supply function is specified as a function of a (0,1) dummy variable for fertilizer use. The parameter on this dummy variable measures the average productivity of fertilizer in the fertilizer-using group. To simulate fertilizer supply response, this mean productivity of fertilizer is applied to all observations that use more than the mean application rate (X6*) in the fertilizer-using group. For application rates below X6*, fertilizer productivity is approximated by a linear relationship between zero and the mean level for the user group (see Figure 26).

Figure 26: Crop yield and carbon sequestration returns to fertilizer use

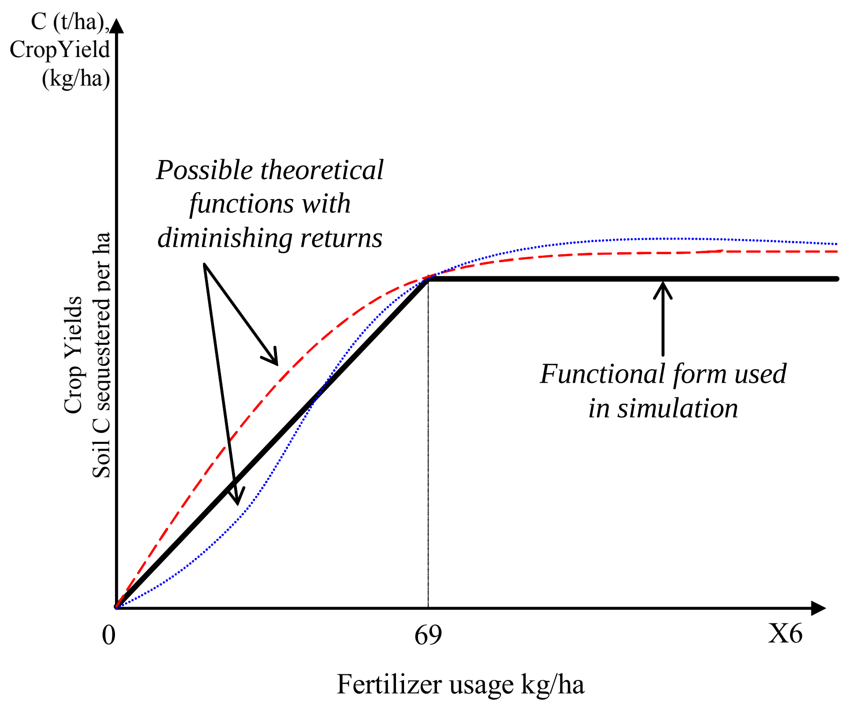


Table 22 shows the parameter estimates of the supply function. The parameter QX6D1 is estimated to be 0.23, implying that farmers that use mineral fertilizer in groundnut production obtain on average approximately 23 percent higher yield than farmers not using fertilizer.

Table 22: OLS estimated groundnut grain supply parameters

Groundnut Grain Supply (QR1) Non-Linear OLS Estimation Dependent Variable: groundnut grain yield (kg/ha)							
	Variable			**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
	Intercept			3.275	0.607	5.400	<.0001
	Log(field area)			-0.096	0.045	-2.130	0.036
	Log(groundnut seed price)			0.015	0.103	0.150	0.883
	Fertilizer use dummy			0.228	0.069	3.310	0.001
	Previous millet dummy			0.181	0.089	2.040	0.045
	Log(Inherent productivity)			0.500	0.000	.	.
	Restriction			3.081	1.732	1.780	0.075
Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
5	74	7179536	97021	311.5	79	0.1786	0.1342

Table 23: OLS estimated groundnut residue supply parameters

Groundnut Residue Hay Supply (QB1) Non-Linear OLS Estimation Dependent Variable: groundnut residue yield (kg/ha)							
	Variable			**Estimate**	**Std Err**	**T Value**	**Pr > |T|**
	Intercept			0.192	0.942	0.200	0.839
	Log(field area)			-0.071	0.053	-1.350	0.182
	Log(groundnut grain supply)			0.515	0.135	3.810	0.000
	Fertilizer use dummy			0.239	0.087	2.750	0.007
	Log(Inherent productivity)			0.500	0.000	.	.
	Restriction			3.296	1.515	2.180	0.029
Model d.f.	**Error d.f.**	**SSE**	**MSE**	**Root MSE**	**n**	**R^2**	**R-bar^2**
4	75	1.9E+07	257061	507	79	0.2972	0.2691

Table 24: OLS estimated millet grain supply parameters

Millet Grain Supply (QR2) Non-Linear OLS Estimation
Dependent Variable: millet grain yield (kg/ha)

Variable	Estimate	Std Err	T Value	Pr > |T|
Intercept	-1.117	5.847	-0.19	0.85
Log(field area)	0.095	0.067	1.42	0.16
Log(millet seed price)	0.859	0.370	2.32	0.02
Fertilizer use dummy	0.053	0.096	0.55	0.58
Organic fert. use dummy	0.013	0.107	0.13	0.90
Previous groundnut dummy	-0.118	0.115	-1.02	0.31
Log(Inherent productivity)	0.609	0.821	0.74	0.46

Model d.f.	Error d.f.	SSE	MSE	Root MSE	n	R^2	R-bar^2
7	85	13460238	158356	398	92	0.108	0.045

In these equations, several of the parameters had an algebraic sign opposite to what theory predicts. These include the previous crop dummy variable, although it is statistically insignificant. Agronomically, we would expect this rotation effect to be positive, as the similar effect is in the groundnut equations. In addition, the inherent productivity parameter in the groundnut model was negative but again statistically insignificant. The inherent productivity scores are predicted yields from the biophysical models. Theory implies that these parameters should be between zero and unity (as is true for the inherent productivity parameter in the millet model). As a result, we restricted the groundnut inherent productivity parameter to 0.5. Sensitivity analysis will be used to test the implications of these restrictions on our final results. The following section describes the policy options, and key policy, biophysical, economic, and variable assumptions that are identified for sensitivity analysis. Results of these analyses are then aggregated, using the Tradeoff analysis software, and implications are discussed.

Carbon Contract & Policy Analysis

There are several different combinations of policies that will be examined. The major elements of these policies are groundnut residue incorporation, in combination with different minimum mineral fertilizer levels. They include these elements:

a. Farmers are paid ($0 to upper limit) to participate in a contract, where their fertilizer usage quantity is specified,
b. An NGO or other intermediary will provide fertilizer to farmers under contract, at an appropriate time in the growing season, and,
c. Farmers must incorporate some groundnut residues back into the field, rather than using them for feed or selling it into the animal fodder market.

Table 25: Carbon policy management practice requirements

Scenario	*Fertilizer Requirement*		*Groundnut Residue Incorporation Requirement**
	Millet	*Groundnut*	
A	0	0	0
B	20	30	0
C	40	60	0
D	0	0	50
E	20	30	50
F	40	60	50
G	0	0	100
H	20	30	100
I	40	60	100
Groundnut Residue Incorporation codes: * 0=none, 1= 50% of groundnut grain yield, 2= 100% of groundnut grain yield			

In effect, several things are varying: the amount of a lump sum carbon payment, the availability of fertilizer, the required minimal fertilizer rate, and the amount of residue that must be incorporated into the field.

Implementation Issues

Buyers of carbon contracts would not want farmers to opt in and out of carbon sequestration programs to ensure that the carbon is stored permanently.

Initial information problems are not significant in the area of study because almost no farmers are in the "incumbent" position of already sequestering carbon. Residue incorporation is rare in the groundnut basin, and this is the catalyst which leads most of the carbon sequestration in this agricultural system. Even farmers using 70 kg/ha of fertilizer can greatly increase their net carbon sequestration rate by incorporating residue. As a result, there are no perverse incentives for incumbent fertilizer users to temporarily stop or misrepresent their fertilizer usage in order to qualify for carbon contracts.

Contract Design and Incentives

An important set of contract design issues concerns the flexibility farmers have to enter and exit contracts, whether farmers will be penalized for defaulting on contracts, and the impact that flexibility has for the amount of carbon that is sequestered. We assume that contracts would require farmers to maintain the prescribed practices (fertilizer applications and residue incorporation) for the duration of the contract. Carbon accumulation is a relatively slow process, often taking 20 to 30 years for soil carbon to converge to a new equilibrium after farmers change practices.

Moreover, as explained in Chapter 1, soil carbon is likely to be lost if those practices are not continuously maintained. Therefore, we would expect carbon contracts to require maintaining practices for a relatively long period, and contract duration is assumed to be 20 years in this analysis. However, farmers may either choose not to maintain the practice continuously, or may not be able to do so, because of unanticipated changes in economic or environmental conditions. When this happens, one could argue in principle that farmers should be penalized for the carbon that is released back into the atmosphere. It is not clear, however, whether it would be politically or administratively feasible to implement such penalties. In this analysis we consider two possible approaches to contract default. First, farmers are required to stay in the contract for the duration of the contract; opting out is not an option (this will be used in most of the analysis). Second, farmers may be allowed to enter and leave contracts without penalty, but when they stop complying with the practices specified by the contract, they will not receive payments.

Carbon Rates and Carbon Payments. To calculate the carbon payment, changes in carbon sequestration rates had to be estimated. The DSSAT/CENTURY crop and soil carbon model estimated trends in soil carbon that were negative for all dataset and policy management practices, with the exception of policy I.

Figure 6 (p. 24) shows that Carbon changes are approximately a linear function of fertilizer usage and residue incorporation, in the form:

$$\text{carbon}=\alpha+\beta*X6,$$

given a residue incorporation level (α and β vary with each level of residue incorporation).

The carbon rate attributed to using 30 kg/ha fertilizer is approximately the average of the 0 and 60 kg/ha rates, given the same residue incorporation level. The annual expected change in carbon for policy is modeled to be:

$bcrate_p$= (estimated carbon year 20- estimated carbon year 1)/20,

where *p* denotes the management practice prescribed by the contract

$Ecrate_p$ is the annual expected change in carbon, relative to *status quo* (practice A):

$ecrate_p$= $bcrate_p$- $bcrate_{A.}$

Annual carbon changes are calculated by taking the intercept (points A, D, and G on Figure 6), where fertilizer=0 for each residue level, and calculating a slope term for the function by averaging the ecrates of the 0 and 60 kg/ha practices. For example, if all groundnut residues are incorporated, (res_inc = 2), then the annual carbon change is:

$$Carbon_{res\_inc=2}(X6) = ecrate_g + \frac{(ecrate_i - ecrate_g)}{60\ kg/ha} * X6 .$$

To calculate the change in Carbon, relative to what it would have been outside of the policy, we calculate the amount of carbon that would have been sequestered otherwise (with no residue incorporation), and subtract that from the calculation above.

$$DCarb(X6) = Carbon_{res\_inc=2}(X6N) - Carbon_{res\_inc=0}(X6),$$

where X6N is the fertilizer used in contract, and X6 is the amount of fertilizer that would have been used otherwise.

Finally, carbon payments were calculated by multiplying the price of carbon by the calculated Dcarb.

Results of Simulation

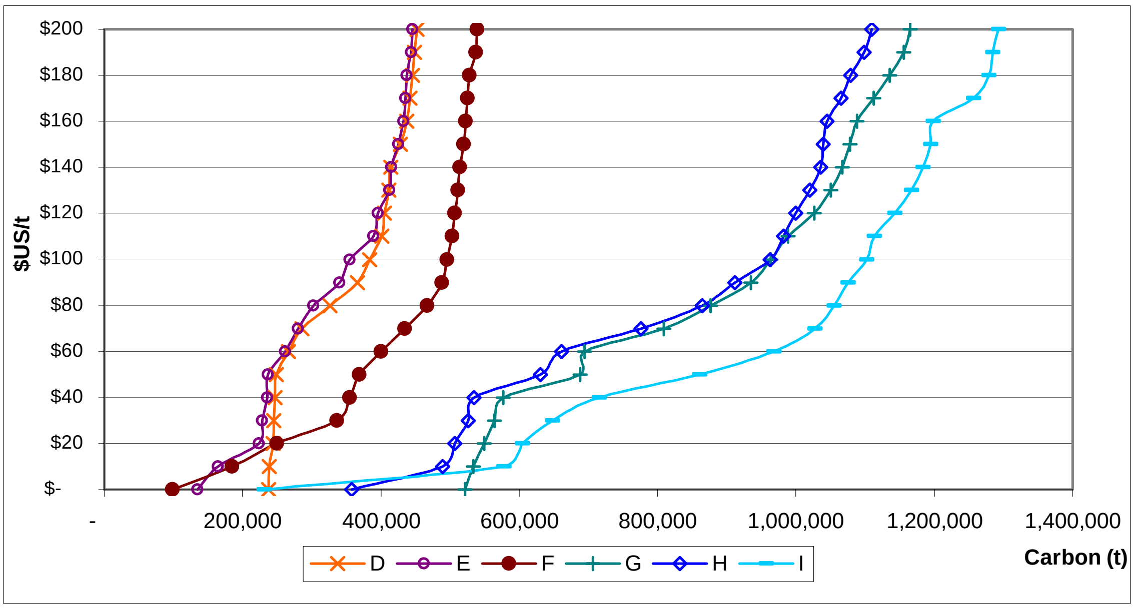
The simulation was run across 21 tradeoff points, where the price of carbon per tonne ranged from $0 to $200 USD; over 100 sample field draws; over 20 years. 31 scenarios, with different sets of policy restrictions, prices and other parameters of interest, were run for the sensitivity analysis of the simulation results. SAS (v.9) was used to estimate parameters, and run the simulations.

Base Policy Results

To begin, the nine carbon contract policy scenarios discussed earlier in this chapter were simulated. Figure 27 and Figure 28 show the carbon supply curves simulated for the Nioro region. With Policy A, which required no residue incorporation and had no fertilizer requirements or provision, 0% of farmers participated and zero carbon was supplied. This is to be expected, as it models the *status quo*, and without further incentives, farmers have no reason to change practices. Policies B and C supplied trivial amounts of carbon, both due to the very low carbon sequestration potential of those management practices. The simulated supply curves are upward sloping, and diverge because of the differing carbon potential of each policy. For example, contract I (fertilizer = 60, 40; res_inc=2) will generate more per hectare than policies, such as E and H, which use half as much residue.

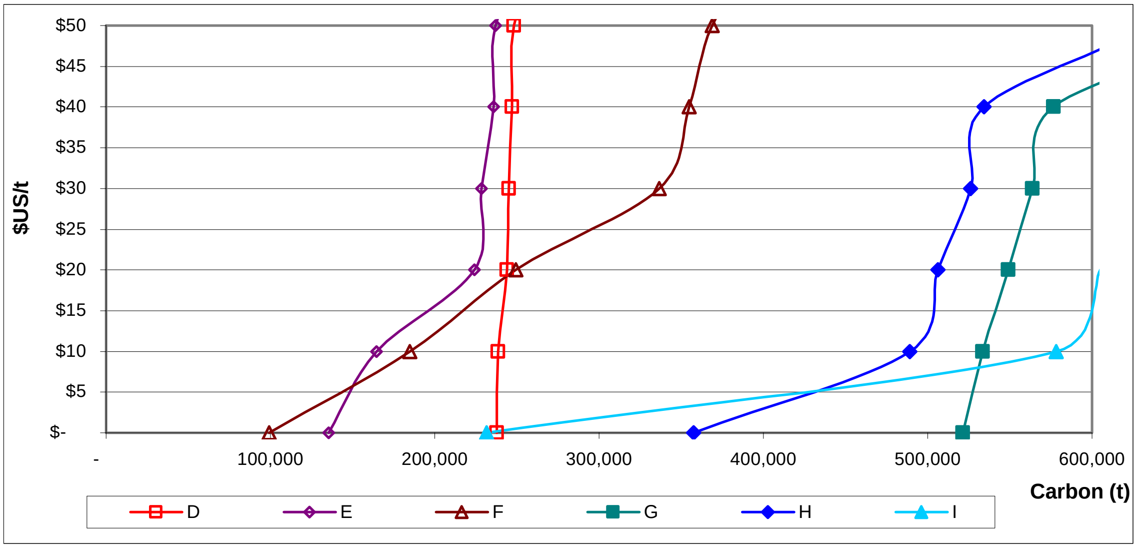
All policies with positive residue incorporation exhibited upward sloping supply curves that supplied positive amounts of carbon at all positive price, even $0/t. As described earlier, the bunching of the inherent productivity observations leads to clusters of farms with identical proxies for biophysical parameters. Because of this, when farmers make discrete choices, such as whether to participate in a carbon contract, the inherent productivity variable can cause simulated groups of farmers to make similar decisions. This causes the step-function shape that can be observed in the estimated supply curves.

Figure 27: Carbon supply with 6 residue-incorporating carbon contract policies



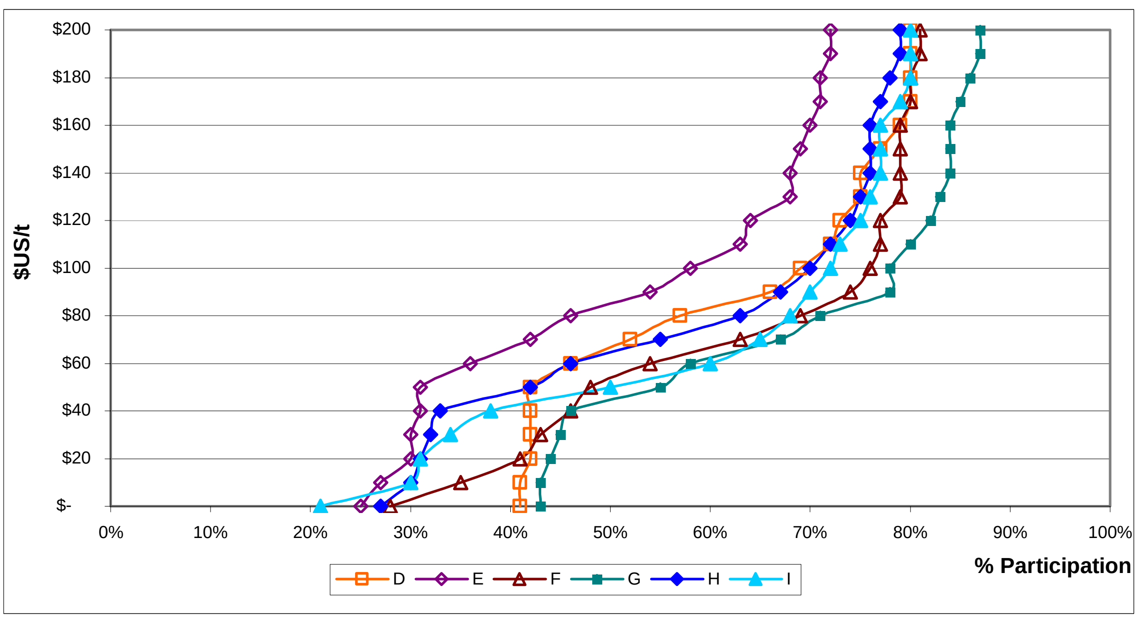
Policy: (groundnut fert kg/ha, millet fert kg/ha; R=residue incorporation)	
D: 0, 0; R=50%	G: 0, 0; R=100%
E: 30, 20; R=50%	H: 30,20; R=100%
F: 60, 40; R=50%	I: 60, 40; R=100%

Figure 28: Detail of carbon supply with 6 residue-incorporating carbon contract policies



Policy: (groundnut fert kg/ha, millet fert kg/ha; R=residue incorporation)	
D: 0, 0; R=50%	G: 0, 0; R=100%
E: 30, 20; R=50%	H: 30,20; R=100%
F: 60, 40; R=50%	I: 60, 40; R=100%

Figure 29: Contract participation in 6 residue incorporating carbon contract policies



Policy: (groundnut fert kg/ha, millet fert kg/ha; R=residue incorporation)	
D: 0, 0; R=50%	G: 0, 0; R=100%
E: 30, 20; R=50%	H: 30,20; R=100%
F: 60, 40; R=50%	I: 60, 40; R=100%

Figure 27, Figure 28, and Figure 29 show that contract participation with policies D to I is positive when the price of carbon is \$0/t. Farmers enter contracts for access to fertilizer, even when carbon payments are zero, which implies that constraints on access to fertilizer are relaxed with participation in carbon contracts, as hypothesized in Chapter 2. Once these policies relaxed supply constraints, farmers increased their usage.

Contracts D and G, which require 0 fertilizer and residue incorporation levels 1 and 2, respectively, encourage more participation and C sequestration than their higher fertilizer counterparts at the \$0/t carbon price level. In the case of D and G, because farmers are not forced to incorporate higher levels of fertilizer, but still have access to whatever fertilizer they require; more farmers will enter these contracts at low carbon price levels. With all contracts, participation and carbon supply increase with the price of carbon. Figure 27 shows that at higher price levels, more input use (i.e. policy I) results in more carbon sequestration (i.e. policy E).

Sensitivity Analysis

Not all variables and parameters used in the analysis had known distributions, either because they could not be statistically estimated, or perhaps because the statistically estimated values were suspect. Sensitivity analysis is used to asses the affects of these parameters. From this, we can compare and see how robust the original results of the previous section are to our assumptions. Table 26 contains a complete listing of scenarios tested.

Table 26: Scenario guide

Scenario	X6C		RES_INC	TRANCOST	MAN_CST	PB1C	X6KINK1	X6KINK2	QINP1	QBINP1	Exit & Entry
	Groundnuts	*Millet*									
A	**0**	**0**	**0**	1000	110	1	69	48	0.5	0.5	restricted
B	**30**	**20**	**0**	1000	110	1	69	48	0.5	0.5	restricted
C	**60**	**40**	**0**	1000	110	1	69	48	0.5	0.5	restricted
D	**0**	**0**	**1**	1000	110	1	69	48	0.5	0.5	restricted
E	**30**	**20**	**1**	1000	110	1	69	48	0.5	0.5	restricted
F	**60**	**40**	**1**	1000	110	1	69	48	0.5	0.5	restricted
G	**0**	**0**	**2**	1000	110	1	69	48	0.5	0.5	restricted
H	**30**	**20**	**2**	1000	110	1	69	48	0.5	0.5	restricted
I	**60**	**40**	**2**	1000	110	1	69	48	0.5	0.5	restricted
FT1	60	40	1	**5000**	110	1	69	48	0.5	0.5	restricted
IT1	60	40	2	**5000**	110	1	69	48	0.5	0.5	restricted
FL90	60	40	1	1000	**90**	1	69	48	0.5	0.5	restricted
IL90	60	40	2	1000	**90**	1	69	48	0.5	0.5	restricted
FL150	60	40	1	1000	**150**	1	69	48	0.5	0.5	restricted
IL150	60	40	2	1000	**150**	1	69	48	0.5	0.5	restricted
IPB50	60	40	2	1000	110	**.5**	69	48	0.5	0.5	restricted
IPB90	60	40	2	1000	110	**.9**	69	48	0.5	0.5	restricted
IPB110	60	40	2	1000	110	**1.1**	69	48	0.5	0.5	restricted
IPB150	60	40	2	1000	110	**1.5**	69	48	0.5	0.5	restricted
IPB200	60	40	2	1000	110	**2**	69	48	0.5	0.5	restricted
IPB250	60	40	2	1000	110	**2.5**	69	48	0.5	0.5	restricted
IKINK9	60	40	2	1000	110	1	**62**	**43**	0.5	0.5	restricted
IKINK12	60	40	2	1000	110	1	**83**	**58**	0.5	0.5	restricted
FPARM25	60	40	1	1000	110	1	69	48	**0.25**	**0.25**	restricted
IPARM25	60	40	2	1000	110	1	69	48	**0.25**	**0.25**	restricted
FPARM75	60	40	1	1000	110	1	69	48	**0.75**	**0.75**	restricted
IPARM75	60	40	2	1000	110	1	69	48	**0.75**	**0.75**	restricted
INOUT_F	60	40	1	1000	110	1	69	48	0.5	0.5	**free**
INOUT_I	60	40	2	1000	110	1	69	48	0.5	0.5	**free**

Variables of Interest for Sensitivity Analysis

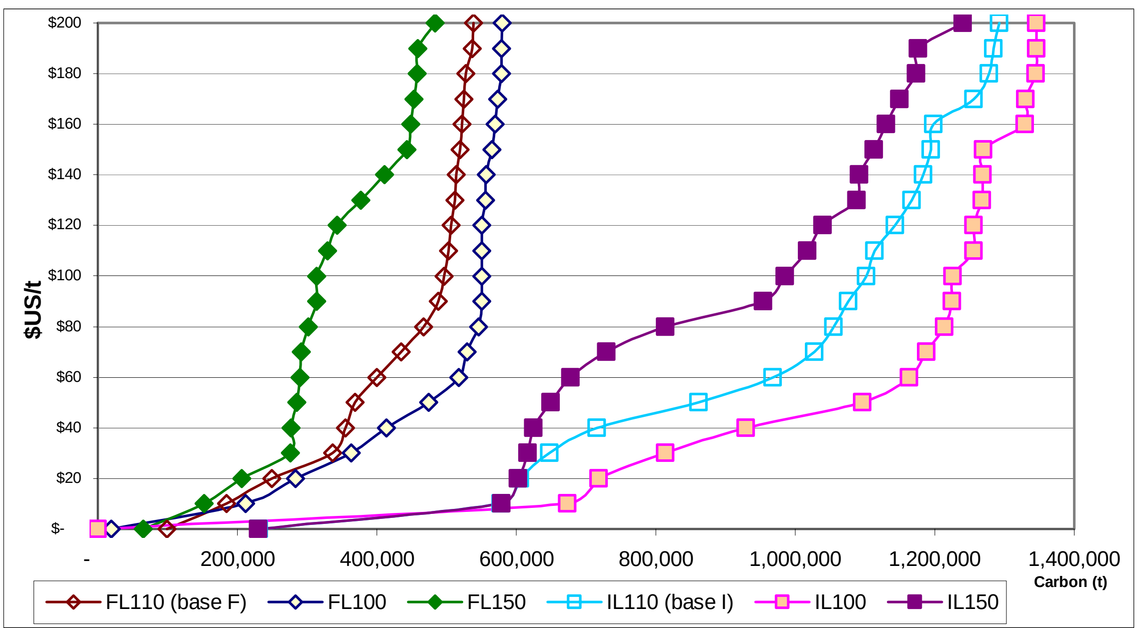
- **X6C**. This is the minimum amount of fertilizer that must be applied if participating in the carbon contract. Farmers participating in contracts will have access to any amount of fertilizer equal or greater than X6C. This will be available to farmers at prevailing (sampled from the dataset) prices.
- **RES_INC**. This indicates how much groundnut residue farmers must incorporate into the soil. 0, 1, 2 indicate 0%, 50% and 100% of yield respectively.
- **TRANCOST**. This is the cost of participating in carbon contracts. We assume that when carbon prices are greater than zero, there will be a lump-sum transaction cost applied each year.
- **MAN_CST**. This parameter is used to scale labor cost in order and test the results' sensitivity to this input.
- **PB1C**. This parameter is a scaling factor on the market price of crop residues.
- **X6KINK1, X6KINK2**. These are the points at which the fertilizer response functions concatenate, as discussed before and shown in Figure 26.
- **QINP1**. This inherent productivity parameter in the groundnut supply function was estimated to be negative , but not statistically significant. Agronomically, this is not possible, so three values between 0 and 1 will be tested.

- **QBINP1**. Same as QINP1, but with the inherent productivity parameter in the groundnut residue supply equation
- **Exit & Entry**. This sets whether farmers can enter and exit contracts freely from year to year, or if they must remain either in or out after they choose initially.

Sensitivity Analysis Results

Labor Costs. We do not know how much more labor would be involved in incorporating groundnut residues relative to the current practice of harvesting them. Figure 30 shows carbon supply sensitivity to increasing overall labor costs by 0% (FL100, IL100), 10% (F,I), and 50% (FL150, IL150). At lower carbon prices, the results are somewhat sensitive, particularly in the case of policy I, which prescribes full residue incorporation. Further studies need to be completed in order to obtain accurate labor cost values.

Figure 30: Carbon supply with different labor costs of residue incorporation.

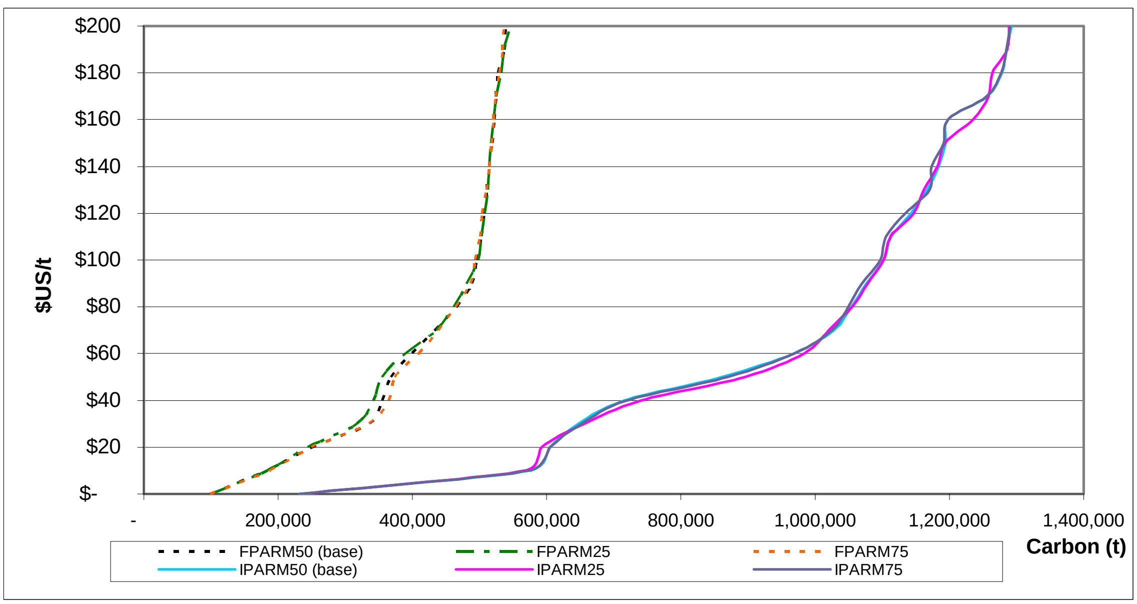


Policy: (groundnut fert, millet fert; R=residue incorporation; L= labour cost inflator)

FL110: 60,40;R=50%; L=110% (base F)	IL110: 60,40;R=100%; L=110% (base I)
FL100: 60,40;R=50%; L=100%	IL100: 60,40;R=100%; L=100%
FL150: 60,40;R=50%; L=150%	IL150: 60,40;R=100%; L=150%

Inherent Productivity Parameter Sensitivity. As shown in Table 22, and discussed earlier, the estimated parameters for inherent productivity in the crop supply equations were negative for both groundnut grain and residue production. For the original policies, these parameters were restricted to 0.5. Figure 31 shows the results of varying these restricting these parameters to 0.25 and 0.75, along with the results using the 0.5 value. The results show little sensitivity to these changes. This is because the returns to being in and out of contract are affected similarly by changes in the INPROD parameter.

Figure 31: Carbon supply sensitivity to PPARM levels



Policy: (groundnut fert kg/ha, millet fert kg/ha; R=residue incorporation; PARM values)	
FPARM50: 60, 40; R=50%; PARM=.50 (base)	IPARM50: 60, 40; R=100%; PARM=.50 (base)
FPARM 25: 60, 40; R=50%; PARM=.25	IPARM 25: 60, 40; R=100%; PARM=.25
FPARM 75: 60, 40; R=50%; PARM=.75	IPARM 75: 60, 40; R=100%; PARM=.75

Transaction Costs. There will be some cost of administering carbon contracts, which were modeled as lump-sum annual per-hectare costs to farmers in the contracts. The value used in the original policy analysis was 1000 CFA/ha, or $2 USD. Figure 32 and Figure 33 show the sensitivity of the results to increasing this cost to $10 USD/ha. Series "FT1", representing the practice with 30 kg/ha fertilizer,50% residue incorporation and $10/ha transaction costs, bends backwards because transactions costs are $0/ha when carbon prices are $0/ha – when prices increase to $10 and $20/t, this is not enough to offset the threshold created by the higher transaction cost. Higher transactions costs resulted in lower participation rates and sequestration rates, particularly in the lower carbon price ranges.

The results were particularly sensitive in the lower ranges. For example, at $20/t Carbon, participation ranged from 15% to 41%. This shows that the cost efficiency of potential carbon programs is important.

Figure 32: Carbon supply sensitivity to contract transaction costs

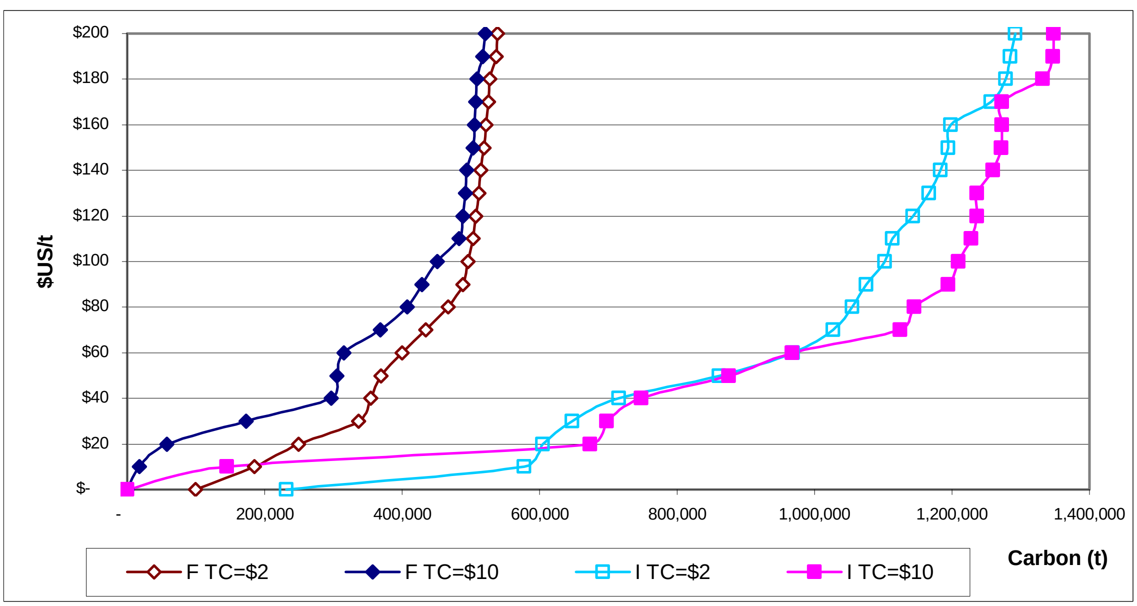
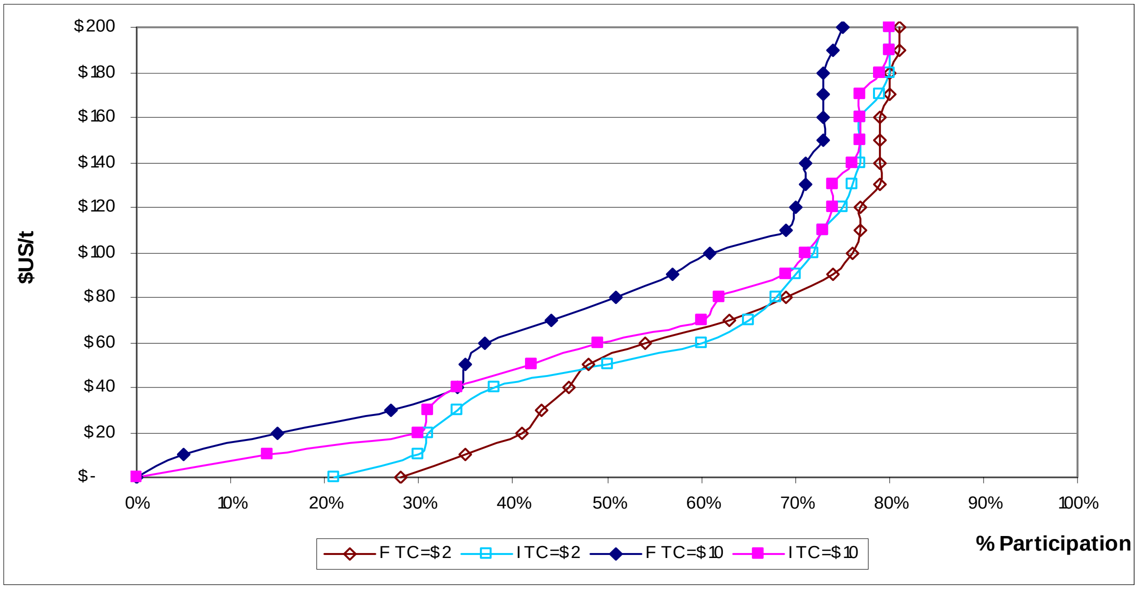


Figure 33: Contract participation sensitivity to contract transaction cost levels



Entry and Exit from Contracts. Next, we tested the effects of allowing farmers to exit and enter freely from carbon contracts. Figure 33 shows the result of this analysis. In this case, the “INOUT” series varied significantly from those with the base assumption of restricted exit and entry. This implies that design and specification of exit and entry rules in these contracts is essential to final policy outcomes.

Figure 35 shows how crop choice changes with the option to exit and enter freely. In both the "I" and "F" contracts, more millet is grown in the free entry/ext cases, especially at higher carbon prices. One possible hypothesis to explain this is that carbon rates are calculated as uniform across both groundnuts and millet, with the assumption that farmers will grow both in a relatively even rotation. Even though there are agronomic advantages to rotating crops, farmers may be growing more millet than groundnuts under contract because they receive carbon payments, and do not have to incur opportunity costs of incorporating the residue.

Figure 34: Participation sensitivity to entry and exit restrictions

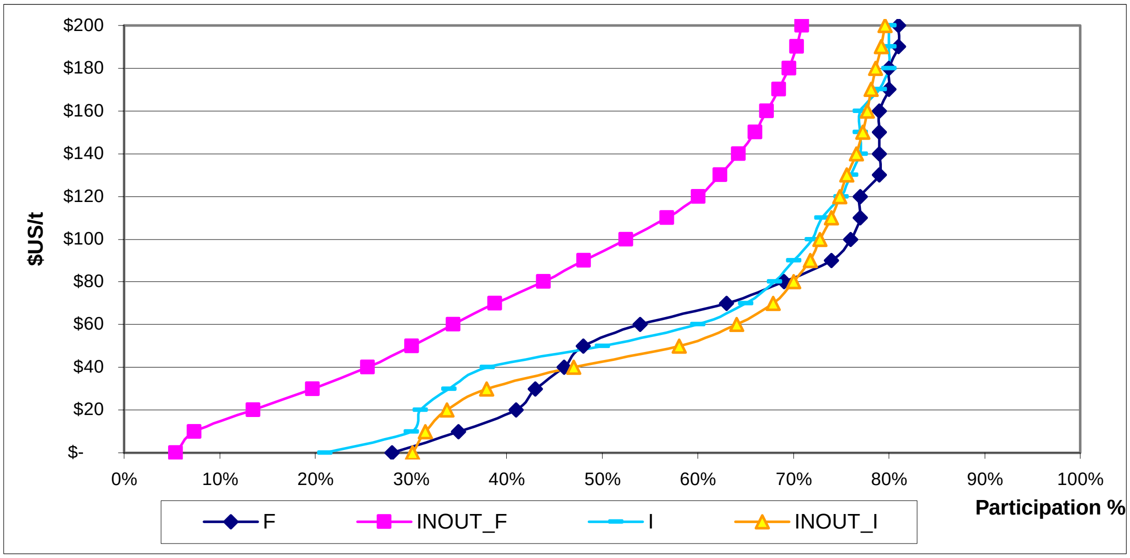
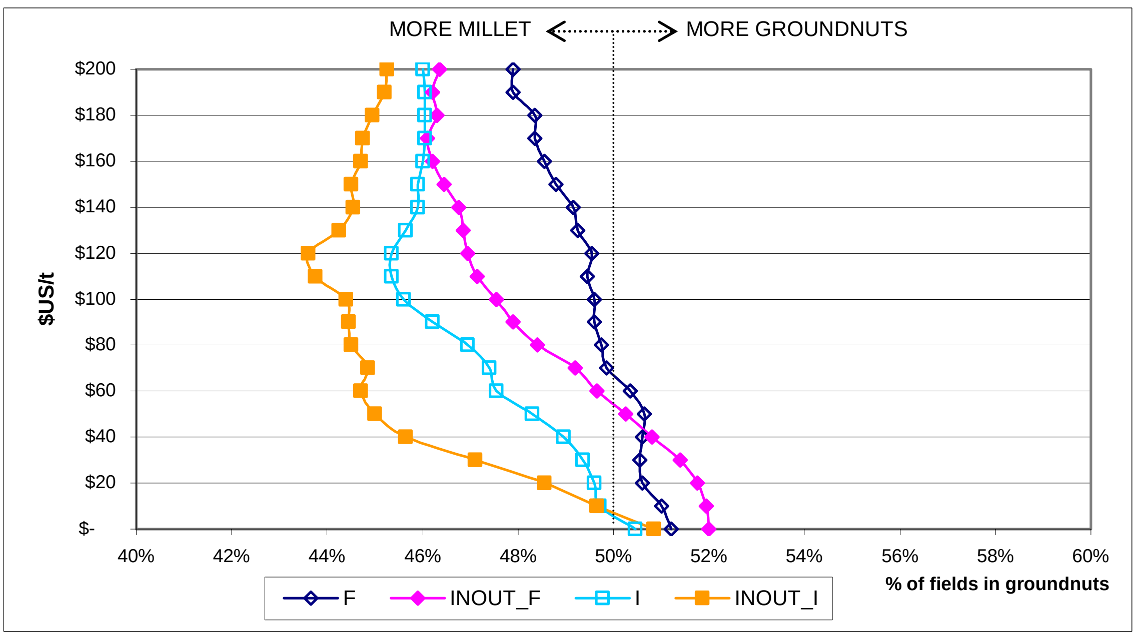


Figure 35: Crop choice composition with and without entry/exit restrictions



Fertilizer Response Functions. Figure 26 shows the fertilizer response function imposed in the simulation model. In the sensitivity analysis we tested three different sets of kink points for this function, for each crop. The base level used for most of the scenarios was 69 kg/ha in groundnuts, and 48 kg/ha in millet. We also tested 90% and 120% of these levels (62 and 43 kg/ha; 83 and 58 kg/ha) to see if this assumption affected the results. Figure 36 shows the resultant participation levels, and Figure 37 show s the carbon supply curves associated with contract "I" (60, 40 fertilizer; 100% residue). From these figures, it is apparent that this specification has little impact on the results.

Figure 36: Contract "I" participation with 3 different fertilizer response functions (X6KINK)

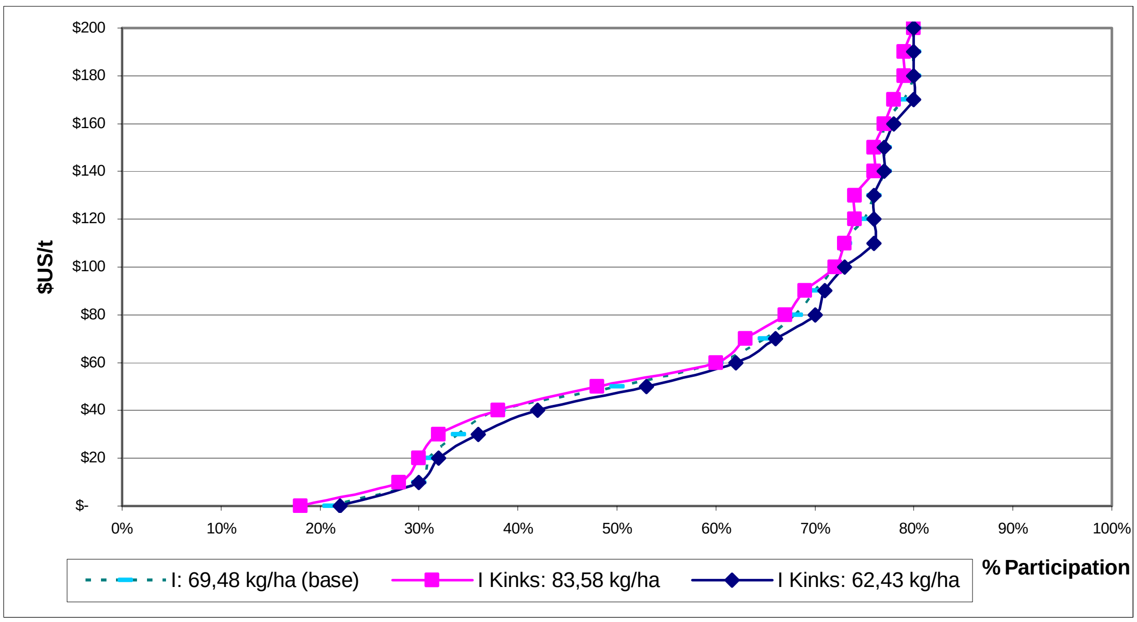
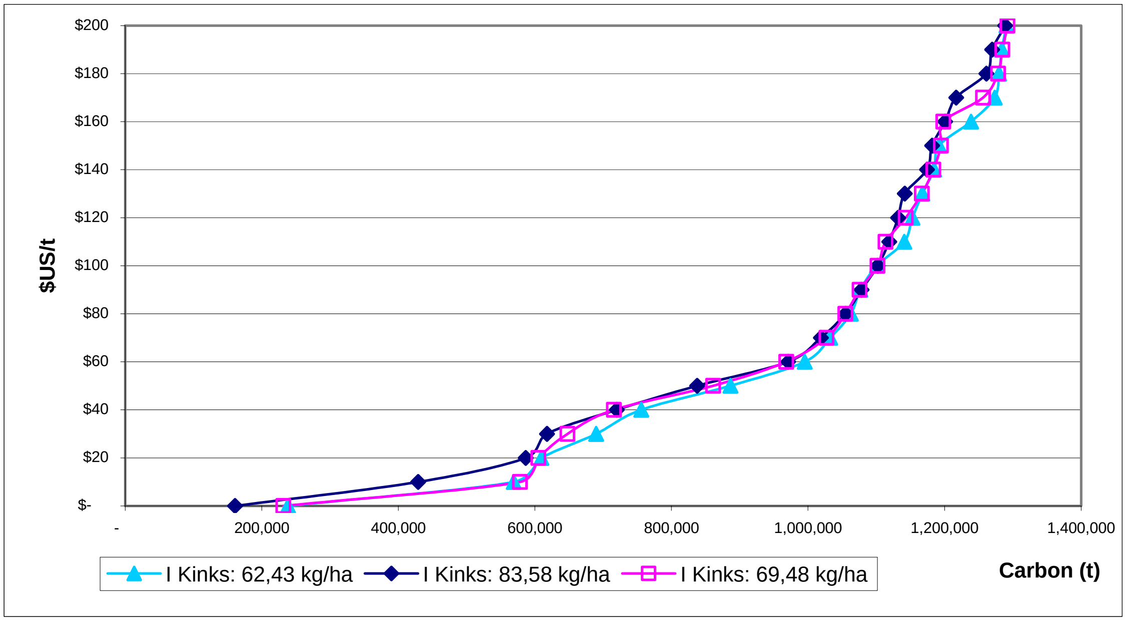
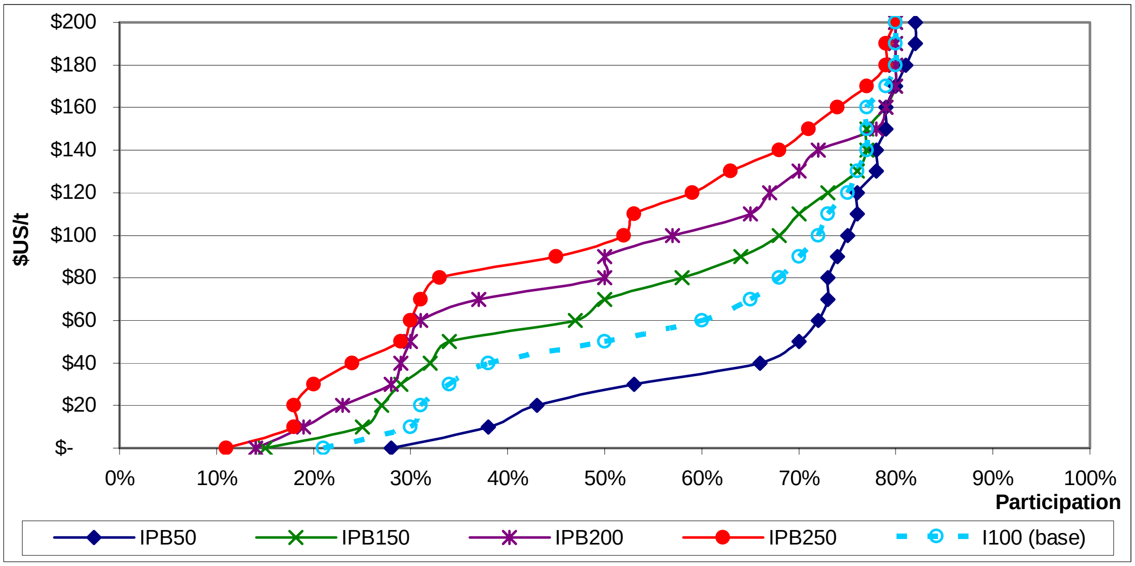


Figure 37: Carbon supply with 3 different fertilizer response functions (X6KINK)



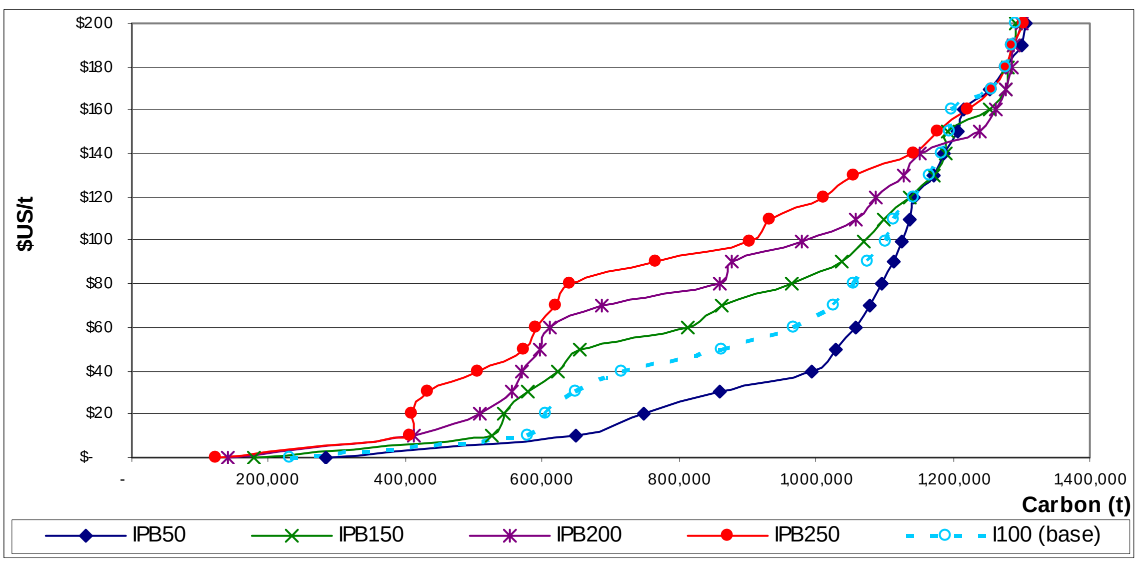
<u>Groundnut Residue Prices.</u> Finally, we examined how groundnut residue prices impacted the results. This price has the potential to increase with carbon sequestration programs, for reasons of endogenaity discussed in Chapter 4. Figure 38 and Figure 39 show how this price can impact the results substantially, particularly in the lower and intermediate carbon price ranges. As expected, as this price rose, participation and carbon supply shifted inwards.

Figure 38: Contract participation sensitivity to groundnut residue price (PB1C)



All "I" policies, requiring 60kg/ha, 40kg/ha (fert. on groundnuts, millet) and 100% residue incorp'n		
IPB50: Price(GN Residue) = 50%	IPB150: Price(GN Residue) = 150%	IPB200: Price(GN Residue) = 200%
IPB250: Price(GN Residue) = 250%	I100: Price(GN Residue) = 100% = Base "I" Simulation	

Figure 39: Carbon supply sensitivity to groundnut residue price (PB1C)



All "I" policies, requiring 60kg/ha, 40kg/ha (fert. on groundnuts, millet) and 100% residue incorp'n		
IPB50: Price(GN Residue) = 50%	IPB150: Price(GN Residue) = 150%	IPB200: Price(GN Residue) = 200%
IPB250: Price(GN Residue) = 250%	I100: Price(GN Residue) = 100% = Base "I" Simulation	

Discussion

From the sensitivity analysis, it is apparent that certain assumptions and variables are highly influential on supply responses. For example, if groundnut residue prices increase substantially for exogenous or endogenous reasons, this will cause adoption rates (and therefore carbon sequestration rates) to be much lower at a given price level. Other factors, such as entry and exit restrictions, costs of administering the program and transactions costs can also impact participation and sequestration rates, particularly at lower price levels.

Labor costs also play an important role in determining outcomes of policies. For this reason, it is important that agronomists and economists effectively estimate the costs of participating in the contract management practices, particularly the costs of incorporating residue.

The results of this type of analysis can be used by policy makers to assess carbon sequestration potential in Senegal's Groundnut Basin. World carbon prices, which will be determined by the institutions and restrictions placed on polluters, are largely exogenous to small countries like Senegal. For that reason, it is useful to see how much carbon sequestering and storing services a region can supply, given a range of possible prices.

Policy "I", which required at least 60 kg/ha and 40 kg/ha fertilizer on groundnut and millet fields, and 100% groundnut residue incorporation, was the only management regime that could increase (or, for that matter, maintain) simulated SOC and inherent productivity levels on a given field. For this reason, we are particularly interested in the simulated adoption of it in the region. Figure 40 shows average simulated Carbon stocks over time, comparing *status quo* management ("A") and "I" type management.

Figure 40: Carbon stocks with "A" and "I" management requirements

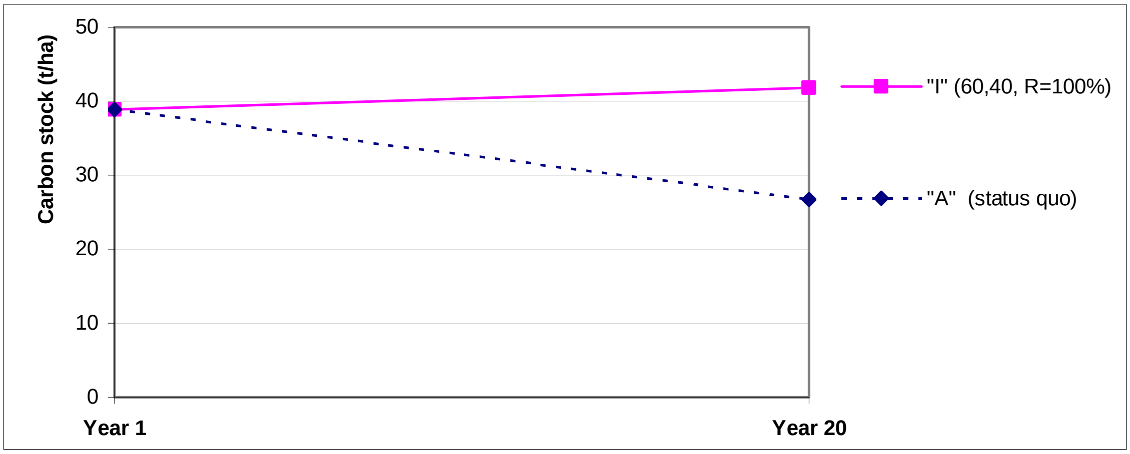


Figure 41: Average carbon stocks, given different carbon prices and corresponding adoption rates of type "I" contract requirements

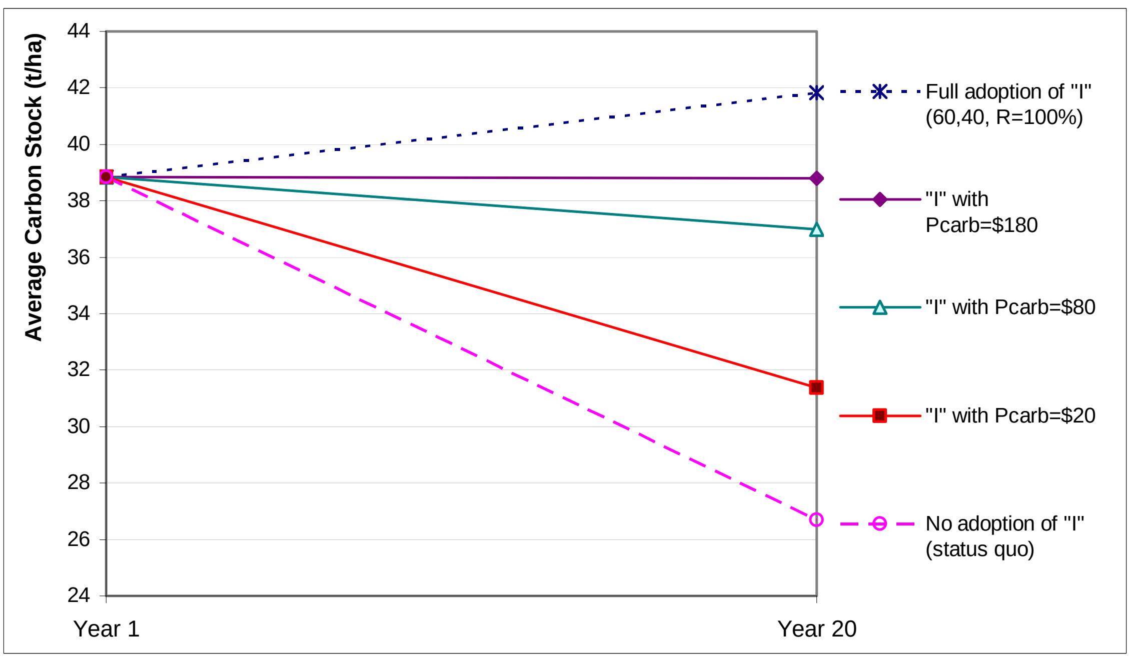
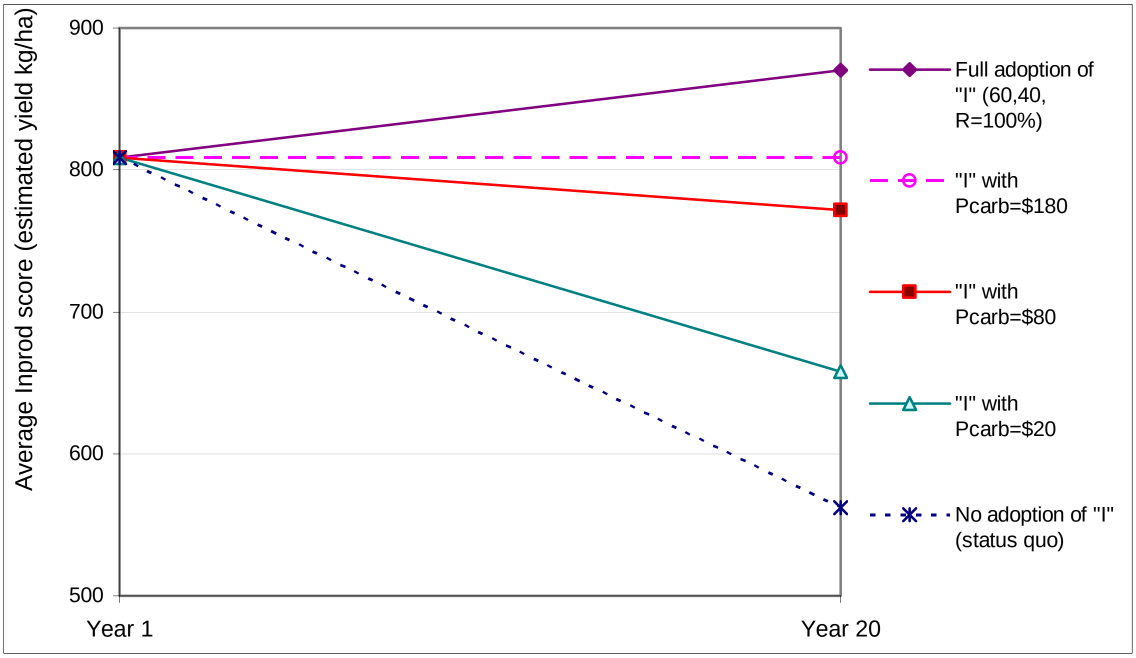


Figure 41 shows how the carbon stock of the average field would change, given three different carbon price levels; $20, $80 and $180 USD/tonne. Each of these prices would lead to higher Carbon stocks than if no carbon contracts were available. Although net carbon sequestration occurs at all prices with "I" contracts, only high prices (i.e. $180/t) cause enough adoption to essentially stop SOC losses in the region.

Figure 42: Average inherent productivity, given three carbon prices and corresponding adoption rates of type "I" contract requirements



Note: These inherent productivity scores are standardized to the same intercept, and averaged across fields and between crops.

Carbon price levels would affect inherent productivity similarly. At all carbon prices, offering carbon contract "I" would mitigate losses in land productivity. Given high carbon prices, farmers could sustain, or even increase the inherent productivity of their fields. Figure 42 shows these effects.

CHAPTER 6

CONCLUSION

Human induced soil degradation has multiple forms, including: nutrient decline, erosion, salinization and physical compaction (ISRIC GLASOD, 2004). In Sudo-Sahelian Africa, erosion and nutrient mining are prominent causes of soil degradation. Nutrient mining occurs when more nutrients, such as nitrogen, phosphorus, potassium, carbon, and micronutrients, are removed from the soil than are put back into the system. In the case of Senegal, harvesting grains and crop residue from the land impact heavily on soil carbon content, while insufficient replacement of soil nutrients with fertilizers leads to negative nutrient balances. Policies that encourage or enable farmers to incorporate crop residues into their soils, and to increase mineral fertilizer usage, would help to reduce or reverse these types of soil degradation in the region.

Given the economic perspective of the rational farmer and the dynamic nature of crop and soil management issues, this thesis used a regional case study in the Groundnut Basin of Senegal to do the following: describe and assess economic incentives specific the to the case study region; model the farmer's production and decision making process; design carbon contract policies and model them within the farmer's decision making process; simulate the interaction between the current agricultural marketplace and the new carbon policies; and to assess the role that carbon sequestration could play in helping the region deal with soil degradation problems, if and when international action is taken to reduce greenhouse gas emissions.

In Chapters 2 and 4, we hypothesized that farmers are using insufficient quantities of fertilizers for several reasons. Information from farmers in the region indicates that several factors constrain fertilizer use, including financial constraints and market imperfections. The result of these constraints is to reduce the productivity and increase the farm gate cost of fertilizers. The results of the simulation supported this hypothesis. The carbon contracts that were simulated allowed farmers unrestricted access to fertilizer at market prices. Even when carbon prices were $0/tonne, farmers still participated in contracts, and used more fertilizer than they would have in a *status quo* environment.

The larger question that this thesis attempted to address was: can payments for carbon sequestration services mitigate and/or reverse soil degradation trends in this region?

Using data from the Groundnut Basin in Senegal, and employing an econometric-process simulation model, this study found that some carbon contracts could be used to reduce losses in soil carbon and productivity; however, only the most intensive management policy “I” resulted in sustained carbon stocks and simulated productivity levels, and that only occurred at high Carbon prices ($180 USD/t carbon and higher). Furthermore, the adoption of this practice, which requires farmers to incorporate at least 60 kg/ha of fertilizer in groundnut fields, 40 kg/ha in millet fields, 100% of groundnut residues into the soil, was found to be sensitive to the assumptions maintained in the analysis. For example, if groundnut residue prices, contract monitoring transactions costs, or labor costs rose significantly, these could decrease participation in the carbon contract activities, and thereby reduce average carbon stocks in the region.

Transactions costs, the additional labor costs associated with residue incorporation, and groundnut residues prices all strongly influenced the results of the carbon contract policies, particularly where carbon prices are less than $100/t. With this in mind, it is important for policy makers to both further assess what these costs would be, and to develop policies that would minimize their effects. Although this study examines many possible parameters relevant to farmers in the region, further studies that account for endogenous price effects, transactions costs, and actual agronomic implementation costs, would be beneficial extensions to this analysis.

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