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Carbon Sequestration, Carbon Markets, Technical Efficiency and Maize Production Using Conservation Agriculture in Mozambique

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To the Graduate Council:

I am submitting herewith a thesis written by Timoteo Eduardo Simone entitled "Carbon Sequestration, Carbon Markets, Technical Efficiency and Maize Production Using Conservation Agriculture in Mozambique." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Economics.

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Dedication

To my parents, Arão Simone Mbulu and Mónica Franzes, for their love, wise guidance and prayers.

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Abstract

Conservation agriculture practices are a promising sustainable farming system being promoted by various organizations in Mozambique. This thesis analyzes the impact of adoption of conservation agriculture practices on maize production technical efficiency, carbon sequestration and farmer income. The technical efficiency estimation utilizes data from a household survey conducted in Manica and Tete provinces of Mozambique. Soil carbon simulations use information from various sources including the household survey, European Energy markets and local meteorological data from the National Oceanic and Atmospheric Administration.

The second chapter of the thesis evaluates the technical efficiency of maize production using conservation agriculture practices. This section applies data envelopment analysis to estimate maize production technical efficiency scores of fields managed with conservation and conventional farming practices. The results suggest that the technical efficiency scores of fields managed with conservation agriculture practices is higher than fields managed with conventional practices.

In the third chapter, carbon sequestration in fields managed using various farming practices, including conservation agriculture, are simulated. The simulation results suggest that adopting conservation agriculture practices results in higher soil carbon accumulation. Scenarios with longer conservation practices use as well as using higher fertilizer rates resulted in higher soil organic carbon. This chapter also evaluates the income benefits of a hypothetical payments for environmental services program for conservation agriculture practices adopters, concluding that there is a potential for increasing farmers income through payments carbon sequestration in fields managed with conservation agriculture practices.

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Chapter 1 - Introduction

1.1. Problem identification

Production of various food crops has increased significantly in the past few decades. Expansion of global cropped acreage and intensification on existing productive land has supported growing agricultural production levels (Tilman, 1999). But many people, particularly in developing countries, are still food insecure (Brown, 1981; Rosegrant et al., 2001), defined as the lack of access to sufficient amounts of food (Maxwell and Smith, 1992). It is estimated that in sub-Saharan Africa, 24% of the population, about 200 million people, are food insecure (FAO et al., 2013). The challenge of meeting current and future food demand is exacerbated by an increasing world population combined with a dwindling resource base (Brown, 1981; Foley et al., 2011; Godfray et al., 2010).

Tillage-based intensive farming systems combining improved plant varieties, chemical fertilizers, herbicides, and pesticides can increase agricultural productivity (Kassam et al., 2010). However, some of the practices such as tillage on highly erodible land may cause long term environmental damage from erosion and fertility loss (Huggins and Reganold, 2008; Kassam et al., 2010). Deterioration of water quality may also occur in high-input intensive farming systems due to leaching of pesticides, and salinization caused by chemical fertilizers (Wood et al., 2000). Degradation of resources and increasing population pressure may lead to increased farming in marginal lands that is more prone to erosion, less fertile and is less suitable for farming (Grepperud, 1996).

Climate change is an emerging threat to global food security. Climate change is expected to modify agro-ecological conditions, possibly requiring adoption of different farming practices to adapt to the changes in the environment (Brown and Funk, 2008; Schmidhuber and Tubiello, 2007). Smallholder farmers in developing countries will be more vulnerable to climate shocks

because they usually have less capital, labor, and other resources, making it more difficult for them to adapt to climate change (Bohle et al., 1994). Thus, there is interest in developing farming systems that respond to food production demands. However, focus is increasingly also given to alternative farming systems that conserve soil and water resources, have minimal environmental impact, and help farmers adapt to changing climatic conditions (Cleaver and Schreiber, 1994; Pretty, 1999; Smit and Skinner, 2002; Wood et al., 2000).

This thesis evaluates the case of conservation agriculture practices (CAPs) in Mozambique. Specifically, the research evaluates agricultural input use efficiency and greenhouse gas (GHG) emission reductions through carbon (C) sequestration on farms using CAPs in the Tete and Manica provinces of Mozambique. Since 1996, the Mozambique government and non-governmental organizations (NGOs) have made efforts to develop sustainable agriculture in Mozambique by promoting the adoption of CAPs such as minimum tillage practices with cover crop or crop rotations and mulching in the existing farming systems (Grabowski, 2011). Use of CAPs is believed to protect soil from wind, water, and mechanical erosion (Erenstein et al., 2008; Hobbs, 2007; Hobbs et al., 2008; Nhancale et al., 2006), increase yield (Thierfelder et al., 2012), decrease labor input use (Harman et al., 1985), and sequester CO_2 as soil organic carbon (SOC) (Bayer et al., 2006).

The incorporation of CAPs into agricultural systems is a promising sustainable farming solution to increase efficiency of use of resources, improve soil fertility and quality through soil organic matter build up in currently farmed arable land, and stabilize crop production. But in many countries adoption of CAPs by smallholders remain relatively small compared to total cropped acreage (Friedrich et al., 2009; Kassam et al., 2012). In Mozambique, the farmer decision to adopt CAPs is constrained by resource endowment, and adoption is often influenced

by the costs of adopting CAPs which may include herbicides and specialized equipment (Giller et al., 2009; Grabowski, 2011; Rockstrom et al., 2009; Wall, 2007).

Several studies have focused on the effects of CAPs adoption on crop yields in Mozambique (Thierfelder et al., 2014; Wall and Thierfelder, 2009), but the effect of CAPs on overall input use efficiency is little understood. This thesis investigates the technical efficiency of farmers using CAPs. Findings help answer the question of whether adopting these practices can improve resource efficiency use in Mozambique or not, given the current technological level of agricultural practices typical to the country. This thesis also simulates C sequestration on farms using CAPs. A payments for environmental services (PES) program for farmers with C sequestration on CAPs managed fields is used to evaluate the potential of these payments in increasing smallholder farmer household incomes and incentivizing the adoption of CAPs.

1.2. Research objectives

This thesis has three objectives: it evaluates the ceteris paribus correlation of adoption of conservation agriculture practices and crop production technical efficiency, analyzes the effect of conservation practices on carbon sequestration, and simulates the impacts of payments for environmental services programs on farmer incomes. These objectives are accomplished by analyzing maize production efficiency and the accumulation of soil organic carbon on fields managed using conservation agriculture practices. The second chapter analyzes resource use for conservation agriculture practices adopters and compares the technical efficiency in fields managed using conservation agriculture practices to efficiency in fields managed using conventional farming practices. The third chapter tracks soil organic carbon through simulations considering use of different farming practices, including conservation agriculture and different fertilizer rates. This chapter also analyzes potential net benefits to adopters of conservation

agriculture practices who participate in a hypothetical payments for environmental services program for carbon sequestration.

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Chapter 2 - Maize Production Technical Efficiency and Conservation Agriculture Practices in Manica and Tete, Mozambique

Abstract

This study analyzes the technical efficiency of smallholder maize production using conventional and conservation agriculture practices in Mozambique. Conservation agriculture practices integrate minimum tillage, crop residue management, and crop rotation practices into farming systems. The analysis investigates the potential of conservation agriculture technologies for increasing the technical efficiency of smallholder maize farmers using a cross-section household survey. A non-parametric data envelopment procedure estimates field-level technical efficiency scores for maize production. Regression analysis is subsequently used to study the association between technical efficiency scores with household demographic, farm characteristics and conservation agriculture practices. On average, the technical efficiency scores associated with fields managed using conservation agriculture practices exceed those of conventionally managed fields. Access to loans and participation in maize markets are positively correlated with technical efficiency scores for all farms.

2.1. Literature review

Agriculture in Mozambique

Mozambique has one of the fastest growing economies on the African continent (Sonne-Schmidt et al., 2009). From 2003 to 2009, Mozambique's gross domestic product growth averaged 7% per year (Arndt et al., 2012). Still, most households live at or below absolute national poverty levels and are food insecure (Arndt et al., 2006; Cunguara and Hanlon, 2012; Garrett and Ruel, 1999). Recent economic growth is partially attributable to increased foreign investment in natural resource exploitation (Sonne-Schmidt et al., 2009) but agriculture remains central to economic activity in rural areas (Cunguara, 2011). The agricultural sector is an important focus of policies designed to alleviate poverty and to address chronically low levels of agricultural productivity (Arndt et al., 2010; Cunguara and Kelly, 2009; Jeje et al., 1998; Tschirley and Benfica, 2001; Tvedten et al., 2010).

Agricultural production in Mozambique is dominated by smallholder subsistence farmers, with 53% of all farming occurring on plots smaller than 1 ha and another 44% on fields between 1 and 5 ha (Falcão, 2009). Maize is the second most important staple crop in Mozambique following cassava (Donovan and Tostão, 2010), but Maize is the most commonly grown crop for markets and home consumption in the Manica and Tete provinces, the regional focus of this research. Low access to chemicals, fertilizer, herbicides, mechanization and improved seed varieties constrain the growth of Mozambique's agricultural sector (Ehui and Pender, 2005; Falcão, 2009; Howard et al., 2003; Tarp et al., 2002; Uaiene, 2008). Irrigation is the most commonly used technology, with 14% of farm households irrigating and 11% using animal traction. Only 3%, 5% and 4% of smallholder farmers use manure, pesticides, and fertilizer, respectively (Falcão, 2009).

Advantages of conservation agriculture practices

The benefits of conservation agriculture practices (CAPs) such as minimum tillage, crop rotation, mulching with crop residues are widely recognized. Friedrich et al. (2009), Kassam et al. (2009) and Thierfelder et al. (2012) concluded that CAPs increase soil organic matter and increase yields. Conservation agriculture practices promote soil nitrogen fixation, water retention, and minimize soil temperature variation (Sims et al., 2009). Conservation agriculture practices also improve the soil-water balance, thereby moderating demand for irrigation (Harman et al., 1985; Thierfelder and Wall, 2010). Erenstein et al. (2008) summarized the International Maize and Wheat Improvement Center's (CIMMYT) experiences with CAPs that focused on production and soil fertility in South Asia, Mexico and Southern Africa. In this earlier study, CIMMYT researchers concluded that the benefits from CAPs adoption were ambiguous in Southern Africa. For instance, CAPs significantly reduced labor demand for field management activities when chemical weed controls were used (Ekboir et al., 2002), but not when weeds were removed manually (Rockstrom et al., 2003), which is probably because weed density is usually higher in fields where weeds are controlled manually (Muoni et al., 2013). Crop residue retention on fields in semi-arid regions also involves tradeoffs with livestock production because of the importance of crop residues to supplement animal diets (Jaleta et al., 2013; Valbuena et al., 2012). Livestock are also valued as a source of household wealth (Haan et al., 1997), insurance against income variability (Dercon, 1998), animal traction (Sansoucy, 1995) and manure fertilizer (Giller et al., 1996). In these particular cases, the medium or long term gains from retaining crops residues on fields may not offset the financial and food security benefits from feeding livestock crop residues (Giller et al., 2009).

Studies about production efficiency in Africa and Mozambique

The literature documenting the advantages of CAPs is substantial but the empirical evidence examining the potential of CAPs to increase on-farm production efficiency in sub-Saharan Africa suggests mixed results. Mazvimavi et al. (2012) verified gains in labor productivity on farms using minimum tillage, crop rotation, and crop residue maintenance on soils, concluding that these conservation practices increased the technical efficiency of smallholder maize producers. Analysis of cotton and sorghum field trials using CAPs did not substantiate significant yield differences (Baudron et al., 2012). Chiona (2011) evaluated different tillage systems and concluded that practicing zero-tillage decreased overall technical and allocative (or cost) efficiency of maize production. However, basin planting, a minimum tillage practice, and conventional tillage increased input use efficiency but decreased allocative efficiency. Finally, mulching may increase technical and allocative efficiency while rotating crops may decrease both types of efficiency in cotton production (Kabwe, 2012).

Previous research examining smallholder farmer agricultural production efficiency in Mozambique focused on the role of credit, extension, fertilizer use, irrigation, pesticides, infrastructure, and household and farming characteristics. For example, Uaiene (2008) found that the use of modern farming technologies, including irrigation, improved seed varieties, animal traction, and chemical inputs increased smallholder farmer technical efficiency. Zavale et al. (2005) investigated the determinants of allocative efficiency of smallholder farmers that used improved and traditional maize varieties. Their research concluded that household characteristics, including family size, education, and farmer age were associated with higher allocative efficiency scores. Smaller farms and the use of inputs including pesticides, fertilizer and irrigation tended to be relatively more cost efficient. Zavale et al. (2005) also concluded that

credit and improved rural infrastructure were positively correlated with the allocative efficiency of maize production.

Minimum tillage, crop rotation and crop residue retention practices are often promoted as a package, but previous studies in sub-Saharan Africa evaluated the correlation between these and technical efficiency separately. This study diverges from that trend and evaluates the correlation between use of all these three conservation practices on fields and technical efficiency scores. The technical efficiency of agricultural production using CAPs has not been previously evaluated in Mozambique. This thesis contributes to the empirical work on technical efficiency in Mozambique by analyzing the effect of CAPs on input use efficiency.

This research estimates the technical efficiency of smallholder maize farmers in the Manica and Tete provinces of Mozambique who adopted CAPs. Data envelopment analysis (DEA) is used to compare the technical efficiency scores of maize producers using CAPs with producers who used conventional maize production methods in 2011. Ordinary Least Squares (OLS) and Two Stage Least Squares (2SLS) regressions are used to analyze the association between CAPs adoption and technical efficiency scores, holding farm operator and other production practices constant. Estimating technical efficiency scores associated with CAPs farming may reveal the potential of these practices for augmenting smallholder farmer agricultural productivity in Mozambique by conserving soil resources.

2.2. Data

This research uses data from a household survey conducted in 2012 in the Manica and Tete provinces of Mozambique. In Tete, the survey was conducted in the districts of Angonia

and Tsangano. In Manica, farming households in the Barue district were surveyed. In total, 22 villages were surveyed in both provinces.

The survey was conducted by researchers from the University of Tennessee with the collaboration of local enumerators, community leaders, the Government of Mozambique, and two non-governmental organizations (NGOs). Community leaders identified households that received CAPs training. All households that practices CAPs were surveyed. A systematic random sampling procedure was used to interview households that had not adopted CAPs (Lohr, 2009). In total, 10% of the population of the 22 villages was surveyed (558 households).

The focus of this study however, is on the subsample of villages where CAPs extension efforts had been ongoing since 2008. At the time of the survey, CAPs extension efforts led by government and non-government agencies were ongoing in 12 of these villages. Focusing on the villages with previous exposure to CAPs technologies allows comparison of maize production using conservation and conventional farming practices among farmers producing under relatively similar socioeconomic environments. There were 280 households in the subsample. The analysis focuses on field-level technical efficiency of maize production. In the sample of 280 households, 172 fields were managed with CAPs, while 415 fields were managed using farming practices typical to the region.

2.3. Methods

2.3.1. Data envelopment analysis of technical efficiency

Koopmans (1951) and Debreu (1951) pioneered the approaches for measuring technical efficiency (cited in Färe et al., 1994). For Koopmans, an input-output combination is *technically efficient* if an increase of an output or decrease of an input is possible only by decreasing some

other output or increasing some other input, respectively. Debreu (1951) suggested estimating production efficiency as a radial index that measures the maximum feasible *equiproportionate* reduction in all variable inputs (an input directed measure) or the maximum feasible *equiproportionate* increment of all outputs (an output directed measure).

Farrell (1957) made an important contribution to efficiency measurement by demonstrating a closely related component of technical efficiency; allocative or cost efficiency. Allocative efficiency measures the ability of producers to choose an input-output combination that minimizes production costs, given prevailing input and output prices (Färe et al., 1994). Allocative efficiency is not analyzed in this research because cost data for some inputs was unavailable.

The distinction between the concepts of technical and allocative efficiency is illustrated in Figure 2-1, where the isoquant TT′ represents single output production of a farm using two inputs, *x* and *y* (Farrell, 1957).

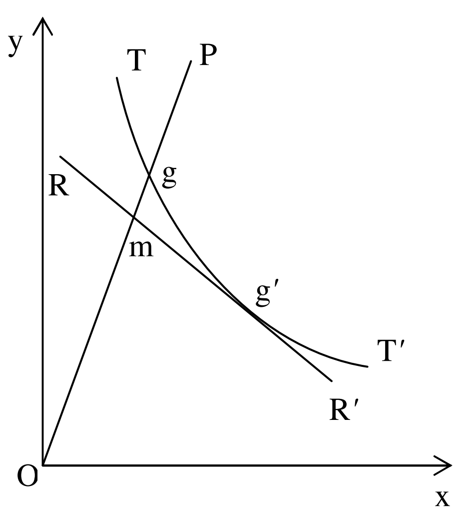

Figure 2-1. Technical and allocative efficiencies (Farrell, 1957).

The line segment *OP* passes through points *m* and *g*; thus the triplet (*m*, *g*, *P*) represents farms that use the same ratio of inputs to produce a given output level. Production at *P* is inefficient because it is possible to produce the same output using less of both inputs, which happens at a point closer to or on the isoquant, for example *g*. Thus, the difference between the origin and point *P* (*OP*) and the origin and point *g* (*Og*) indicates the production inefficiency of the farm operating at point *P*. Conceptually, technical efficiency is a ratio of these distances and is bounded between 0 and 1:

$$TE_i = g_i P_i / OP_i \,, \text{ or } \quad \frac{OP_i - Og_i}{OP_i} = 1 - \frac{Og_i}{OP_i}, \tag{2.1}$$

where *TE* measures technical efficiency and *i* indexes a farm. A farm operating at point *g* is technically efficient because *g* lies on the isoquant where the farm produces the highest achievable output using the current technology, but this farm is allocatively inefficient because production costs could be reduced by producing at g' where the isoquant intercepts the input price ratio RR'. Thus, g' satisfies the requirements for technical and allocative efficiency.

A non-parametric DEA algorithm is used to estimate the technical efficiency scores of fields managed with CAPs and conventional farming practices. The DEA algorithm is estimated as a linear programming model, measuring the relative output-oriented performance in terms of technical efficiency. Inputs including labor, fertilizer, field size, and seed and maize output vectors are used to construct a piece-wise production surface over the data points, resulting in a production frontier characterizing field-level technical efficiency. Fields with production deviating from the production frontier are inefficient. The inefficiency of an individual field is therefore measured by the distance of this field's production and input use to the efficient

production frontier (Coelli and Rao, 2005). This method of measuring inefficiency does not consider the effect of data measurement errors or differences in efficiency that may not be attributable to managerial skills but to external off-site factors that affect farming (Berger and Humphrey, 1997). In central Mozambique for instance, rainfall was above average from November to January during 2010. However, in February and March 2011 crop development was affected by poor rains (Ministério da Agricultura-GoM 2011). The influence of extreme weather conditions cannot be accounted for in typical cross-sectional DEA analyses (Uaiene, 2008). On the other hand, DEA does not require *a priori* assumptions about functional forms, the curvature of production surfaces, or the distribution of sampling errors (Berger and Humphrey, 1997).

The output-directed technical efficiency for field *j* managed by household *i* is the solution to the linear program (Coelli et al., 2005):

$$\begin{aligned} & \max \theta_{ij} \\ \text{s.t.} \quad & -\theta_{ij} y_{ij} + Y\lambda_{ij} \geq 0 \\ & x_{ij} - X\lambda_{ij} \geq 0 \\ & \iota_1 ' \lambda_{ij} = 1 \\ & \lambda_{ij} \geq 0 \end{aligned} \tag{2.2}$$

where $\theta_{ij} \geq 1$ is the proportional output increase that could be achieved by the *i-th* household on its *j-th* field. There were 172 and 415 fields managed using CAPs and conventional practices, respectively, among the 280 households surveyed in communities exposed to CAPs training. The vector y_{ij} is a (1×1) vector of maize output under CAPs or conventional farming practices; and Y is the $(1 \times ij)$ matrix of maize output in every *j-th* field of all *i* farms. The variable x_{ij} is a $k \times$

1 vector of inputs used by the *i-th* farm in the *j-th* field; X is the $k \times ij$ matrix of inputs used by all i farms in all of its fields; and λ_{ij} is a $ij \times 1$ vector of output and input weights used to calculate the technical efficiency scores. Finally, $\square_1$ is an $ij \times 1$ vector of ones. Given a solution to this problem for farm-field combination ij, the technical efficiency score of each field managed by a household is calculated as $\frac{1}{\theta_{ij}}$. The third constraint is a convexity constraint that differentiates constant returns to scale (CRS) and variable returns to scale (VRS) assumptions about the production technology. Including this constraint relaxes the assumption of CRS. The CRS assumption maintains that a proportional increase in inputs results in same proportional increase in outputs. Conditions such as imperfect markets and financial constraints may result in production functions exhibiting VRS technology (Mugera and Langemeier, 2011; Nicholson, 2005). This research analyzes VRS technical efficiencies scores. The VRS technical efficiency scores are subsequently regressed on household demographic and farm operation characteristics, credit opportunities and the adoption of CAPs.

The inputs used to estimate technical efficiency are field-level observations on labor (in labor/day), fertilizer (in kg), planted field area (in ha), and seed (in kg), distinguished according to the management practice used on the field; e.g. CAPs or conventional practices. Labor used on farms managed using CAPs and conventional practices was calculated by multiplying the reported rate of labor used per hectare (in labor/day/hectare) by the area of each field. On the output side, maize production was the only crop on which data was collected (in kg). The distribution of these variables according to CAPs and conventional agriculture practices used, and the distributions of the technical efficiency scores are compared using the Kolmogorov-Smirnov (K-S) statistic (Smirnov, 1939). Failure to reject the null hypothesis of the K-S test

implies that the distribution of inputs, maize outputs and technical efficiency scores are similar between CAPs and conventionally managed fields. The hypotheses for the K-S tests are:

H0: Distributions of inputs, maize output and technical efficiency scores for CAPs field= distributions of inputs, maize output and technical efficiency for conventional fields.

H1: The distributions of inputs, maize output and technical efficiency scores differ across CAPs and conventionally managed fields.

2.3.2. Empirical model comparing the efficiency scores of CAPs/non-CAPs adopters

The empirical model compares the effect of CAPs adoption on maize production technical efficiency scores, holding household and farm operation characteristics constant. Technical efficiency scores range between 1 (the most efficient fields) to 0 (the least efficient fields). Because of the bounded range of efficiency scores and the potential piling up of scores at 1, past studies typically analyze DEA technical efficiency scores using censored regression approaches (Chavas and Aliber, 1993; Idris et al., 2013; Mugera and Featherstone, 2008; Zheng et al., 1998). Several previous studies have alternatively used least squares regression to analyze technical efficiency increase (McDonald, 2009; Stanton, 2002; Sufian and Habibullah, 2010).

One argument for not using Tobit or similar censored regression approaches is that although technical efficiency scores range between 0 and 1, there is no clear evidence these bounds are generated by a censoring mechanism. The calculation of DEA technical efficiency scores is probably best described as a normalization, where maximum efficiencies are standardized to 1 and the other scores remain inside the unit interval. The efficiency scores

resulting from this normalization are proportional data and may be suitably analyzed using Ordinary Least-Squares (OLS) for instance (McDonald, 2009).

Another reason for not considering censored regression methods relates to the normality and homoscedasticity error distribution assumptions typically required by the censored regression approaches (Hurd, 1979; Newey, 1987). Violation of homoscedasticity and normality assumptions may result in biased and inconsistent estimates from censored regression models (Amemiya, 1973; McDonald and Nguyen, 2012). Skeels and Vella (1999) suggests using conditional moment tests to validate the normality and homoscedasticity assumptions maintained by Tobit or other parametric censored regression methods. These procedures are applied in this research to test these assumptions.

The linear model proposed to compare technical efficiency scores on fields managed with CAPs and conventional methods by least squares is;

$$eff_{ij} = X_i\delta_1 + CA_{ij} \cdot \delta_2 + v_{ij}\ , \qquad (2.3)$$

$i = 1, \dots n$ households

$j = 1, \dots k$ fields

where eff_{ij} are the VRS technical efficiency scores θ_{ij}^{-1}; v_{ij} is an error term with an expected mean of zero and constant variance σ^2; and CA_{ij} is a binary variable indicating the use of CAPs on a particular field of a household. The *CA* variable equals one in fields where minimum or zero tillage and crop rotation were practiced and at least 25% of the field was covered with crop residues. The covariates included in X_i are farmer and farm household characteristics including age, education, and gender of the primary decision maker, household size, the percentage of

household income from off-farm sources, previous agricultural loan, maize marketing, and an index measuring the degree to which the households were engaged in livestock production. The δ_1 coefficients are the conditional average effect of the X_i covariates because these variables are indexed by household. The δ_2 coefficient measures the average effect of CAPs on field-level technical efficiency, holding household and operator attributes constant.

2.3.3. Potential endogeneity of CAPs adoption

Previous research suggests that adoption of farming practices may be influenced by farmer efficiency (Kumbhakar et al., 2009; Lansink et al., 2002; Wang and Yu, 2011). This assumption has implications for how the CAPs indicator variable enters the regression analysis and the choice of regression procedure used to compare technical efficiency scores. If the hypothesis that CAPs adoption is influenced by technical efficiency is true, then CAPs adoption is endogenous, implying that the *CA* indicator variable is correlated with the error term of the technical efficiency equation, e.g. $cov(CA_{ij}, v_{ij}) \neq 0$. A common approach to address endogeneity is to estimate the linear model using two-stage least squares (2SLS) (Wooldridge, 2010). In the first stage, the predicted values of the variable hypothesized to be endogenous (CA_{ij}) are estimated using instruments that are correlated with CAPs but uncorrelated with v_{ij}. The predicted values from the first stage ($\widehat{CA}_{ij}$) subsequently enter the technical efficiency equation, estimated in the second stage. The 2SLS regression stages are;

$$CA_{ij} = \beta_1 Z_i + \beta_2 X_i + \varepsilon_{ij} \qquad \text{(stage 1)} \qquad (2.4)$$

$$eff_{ij} = X_i \delta_1 + CA_{ij} \cdot \delta_2 + v_{ij} \qquad \text{(stage 2)} \qquad (2.5)$$

where Z includes a dummy variable indicating that a member of the household received agricultural training from government extension service, the square of household head age, a construction materials index, and an index measuring household asset ownership. The last two instruments measure proxy the overall wealth of households (McNair, 2013). The first stage also includes covariates used on the second stage to estimate efficiency, X_i. Staiger and Stock (1997) use the F-statistic of the first stage of the 2SLS to test the relevance and appropriateness of the instruments. If the F-statistic is greater than 10, the null hypothesis that the instruments are weak is rejected. Suitability of the instruments is also evaluated by testing overidentification restrictions (Wooldridge, 2009) and investigating the correlation of instrumental variables and the errors of the technical efficiency scores .

2.3.4. Testing exogeneity of CAPs adoption

Hausman's endogeneity test was used to determine if adoption of CAPs (CA_{ij}) was exogenous (Hausman, 1978). A nonparametric bootstrap procedure based on resampling the error terms with replacement of the OLS (equation 2.3) and the 2SLS model (equations 2.4 and 2.5) was applied to improve the asymptotic performance of the Hausman exogeneity test (Cameron and Trivedi, 2009). The Hausman test is based on the difference between vectors of the 2SLS (equations 2.4 and 2.5) and OLS (equation 2.3) coefficients, ($\hat{\delta}_{2SLS} - \hat{\delta}_{OLS}$). If the difference between the coefficient vectors is not statistically significant, it means that the adoption of CAPs is exogenous, and differences in the coefficients estimated by 2SLS and OLS are attributable to sampling error (Hausman, 1978; Wooldridge, 2010). The null hypothesis of this test is that CA_{ij} is exogenous. If the null hypothesis is rejected, the 2SLS regression approach is appropriate.

2.3.5. Sensitivity analysis

A quantile regression is estimated as a sensitivity analysis. Quantile regression is generally robust to outliers because estimates are centered on specific points of the error distribution (e.g. the median, upper, or lower quantiles) (Koenker and Hallock, 2001; Wooldridge, 2010). Changes in extreme values of covariates and technical efficiency scores may affect least squares estimates because they are conditional population means. The quantile regression method is also free from distributional assumptions, and estimates are robust to heteroskedasticity (Chidmi et al., 2011). A quantile regression is estimated for the 25th, 50th, and the 75th quantiles of technical efficiency scores.

2.4. Independent variables included in the technical efficiency score regression

The null hypothesis is that use of CAPs is uncorrelated with the technical efficiency scores of maize production. A significant and positive ceteris paribus correlation between CAPs adoption and technical efficiency scores would suggest that using CAPs improves field-level input use efficiency.

It is hypothesized that differences in the communities surveyed could explain some variation in the efficiency scores. The districts surveyed have different levels of CAPs adoption. For instance, according to this survey, CAPs adoption estimated by the household survey was 40%, 34% and 28% in Barue, Angonia and Tsangano, respectively. Governo da Província de Manica (2011) reports on the agricultural potential of the Barue district suggest that the agro-climatic conditions of this region are suitable to sustain higher production levels of important food crops. Grabowski (2011) concludes that farming in Angonia is relatively diversified, with cash crops such as tobacco and potatoes cultivated in addition to maize. Anecdotally, CAPs

farmers in Angonia may use fertilizer obtained for producing maize using CAPs on cash crops. There is also a difference between input supply networks in these three districts. Farmers in Barue who adopt CAPs usually receive free inputs, like fertilizer and improved seeds, to use in CAPs fields from government extension services. Inputs received by farmers in Tsangano and Angonia districts from NGOs are repaid in agricultural produce after harvest. Two regional dummy variables are included in the regressions; the variables *barue* and *angonia* indicate whether the surveyed household is located in the Barue or Angonia districts, respectively. The Tsangano district where CAPs adoption is lower than the other two districts is chosen as the reference group. The null hypothesis is that technical efficiency of households in Barue and Angonia are not different from households in Tsangano.

Managerial ability may cause differences between farmer agricultural production performance (Hansson, 2008; Kalaitzandonakes and Dunn, 1995; Wilson et al., 2001). Managerial ability is difficult to measure (Rougoor et al., 1998), and personal characteristics such as age, and education are typically used to proxy managerial ability. A binary variable indicating that the household head had more than 5 years schooling (*5yrschling*) represented educational attainment. Previous research suggests that education is positively correlated with managerial ability (Fane, 1975). Welch (1970) found also that there is a positive correlation between education and better allocation of inputs among alternative uses may ultimately increase farming efficiency (Kalaitzandonakes and Dunn, 1995).

The effect of household head age (*hhage*) on technical efficiency is expected to be positive. Older farmers typically have more farming experience, and are therefore hypothesized to use resources more efficiently. In previous studies, Al-Hassan (2008) found a positive

correlation between technical efficiency and farmer age, but negative relationships between age and production efficiency have also been reported (Amudavi et al., 2009; Seyoum et al., 1998).

Family labor is an important resource among smallholder farmers. Households occasionally hire in labor, but family members are typically the primary source of farm labor (Takane, 2008). Assuming that family labor is free, larger families may have immediate access to more labor (Bagamba et al., 2009). Furthermore, employing family labor also saves on expenses that could be spent to purchase other inputs (Scully, 1962). It is expected that technical efficiency scores will be positively correlated with the household size (*familysize*).

The association between livestock ownership and the technical efficiency of maize production is examined by including an animal ownership index (McNair, 2013). The expected relationship of *animalindex* with technical efficiency is positive. Livestock is a source of additional income that could be invested in field crop inputs. Animals may also facilitate cultivation and reduce human labor requirements. Manure from livestock can be used to fertilize fields. The index ranges between 0 and 100. Higher index scores indicate that farmers are more intensively engaged in raising livestock.

A dummy variable indicating if the household received agricultural loans (*loan*) is included in the regressions to investigate the role of access to financial capital on technical efficiency. Throughout the survey regions farmers receive cash loans for various agricultural purposes. It is hypothesized that loans will be positively correlated with technical efficiency scores because they provide additional cash needed to purchase agricultural inputs (Freeman et al., 1998). It is also hypothesized that households with access to loans invest more in inputs, thereby potentially increasing maize productivity.

Household head gender (*malehh*) is hypothesized to explain differences in maize production efficiency. Female headed households are expected to have, on average, lower efficiency scores due to difficulties in obtaining farming inputs. Women in rural Mozambique have fewer access opportunities to productive assets such as land, credit from commercial financing institutions, limited participation in leadership and decision making roles in farmers groups, and usually do not receive timely agricultural market information (Gawaya, 2008). The null hypothesis is that technical efficiency scores are not different across farmers of both groups.

Working off-farm may reduce income risk typically associated with agricultural production (Barrett et al., 2001). Off-farm income also supplements income from farming. A variable measuring the percentage of household income earned from off-farm work (*off-farmprct*) is expected to be positively correlated with technical efficiency.

Access to maize markets may increase household income (Rios et al., 2008). It is hypothesized that farmers participating in maize markets will have higher technical efficiency scores. The market access variable is included as a binary variable (*marketpart*) indicating if the household sold maize in 2011. Presumably, households selling maize are able to do so because they have met their own consumption needs with surplus remaining. The description of the variables used in the regressions and their means is presented in Table 2-1.

Table 2-1. Summary of data used in regression analyses

Variable	Description	Units	Mean	Standard Dev.	Min	Max
CA	Field managed using CAPs	1= yes	0.32		0	1
hhage	Age of HH	years	45.60	13.03	21	82
5yrschling	HH with more than 5 years of schooling	1= yes	0.93		0	1
familysize	Size of HH	Number	6.32	3.00	1	25
loan	Agricultural loan	1= yes	0.13		0	1
animalindex	Animal index	Number	30.50	19.14	0	87.2
malehh	Male HH	1= yes	0.85		0	1
off-farmprct	% Income from off-farm work	percent	19.68	25.46	0	80
marketpart	Selling maize produce in the market	1= yes	0.66		0	1
barue	HH located in Barue	1= yes	0.33		0	1
angonia	HH located in Angonia	1= yes	0.10		0	1
n=488						

Notes: HH stands for household.

2.5. Results and discussion

The Kolmogorov-Smirnov test comparing the empirical distributions of field level input use and maize output suggests that the distributions of observed fertilizer and seed use differ among CAPs and conventionally managed fields. On average, farmers use more fertilizer and less seed in fields managed using CAPs than fields managed using conventional practices (Table 2-2). Higher fertilizer use in fields with adopted CAPs is possibly explained by fertilizer discounts that adopters of CAPs receive from organizations promoting the technology (Grabowski, 2011). In Angonia and Tsangano districts, fertilizer and seeds are available to farmers on credit provided by NGOs. These inputs are provided on contract at the beginning of the farming season and have to be repaid after harvest. In Barue, farmers who adopt CAPs are eligible to receive free fertilizer from government agencies.

Table 2-2. Descriptive statistics of variables used to estimate technical efficiency

Variable	CAPs Fields (n=172)	Conventional Fields (n=415)	Kolmogorov-Smirnov D-statistic
Labor (labor/day)	0.52 (0.67)	0.40 (0.53)	0.118
Fertilizer (kg)	33.733(65.05)	17.26 (90.48)	0.399 †
Maize seed (kg)	17.62 (19.06)	29.26 (45.45)	0.248 †
Land (hectares)	0.69 (0.89)	0.65 (0.60)	0.070
Maize production (kg)	589.89 (435.62)	629.57 (576.38)	0.089
VRS technical efficiency scores	0.51 (0.30)	0.26 (0.22)	0.436 †

Notes: Significance level: † $p<0.05$. Standard deviation is in parenthesis. VRS represents variable returns to scale.

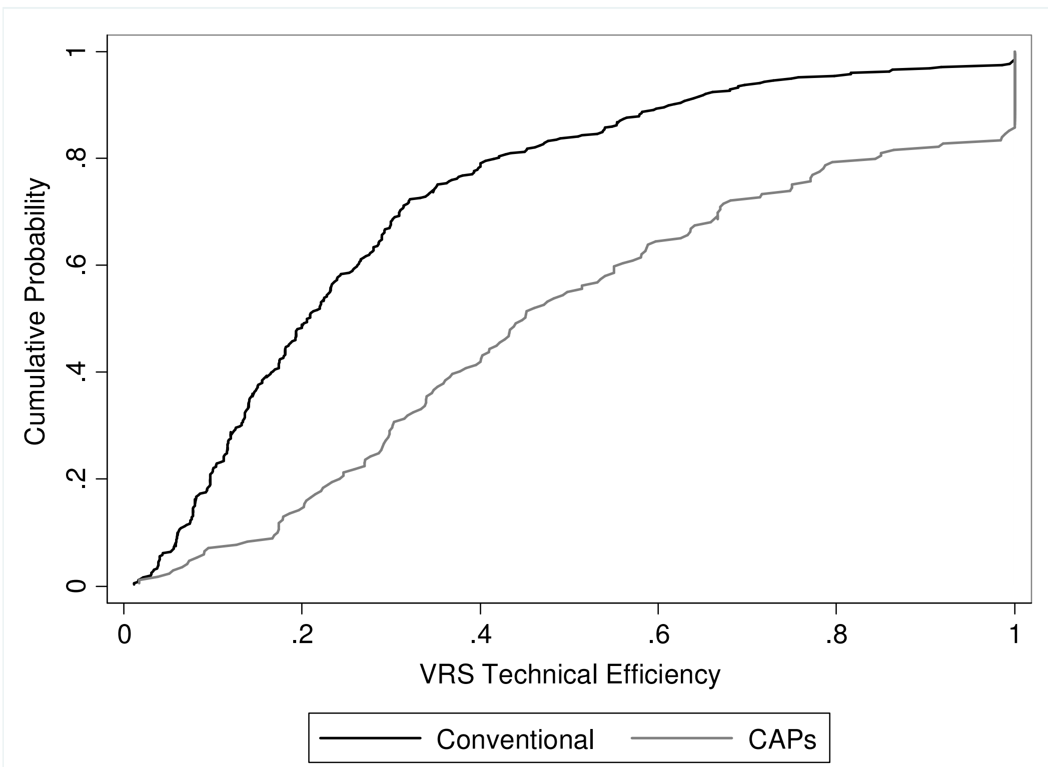

Figure 2-2. Cumulative distributions of variable returns to scale (VRS) technical efficiency scores of fields managed using conventional and conservation practices.

The distribution of technical efficiency scores are summarized in Figure 2-2. Overall technical efficiency scores are relatively low for most fields regardless of the farming practices used. The efficiency results suggest that the majority of the surveyed fields operated at efficiency

levels below 0.5. The Kolmogorov-Smirnov test suggests that the empirical distribution of field-level technical efficiency scores were different for CAPs and conventionally managed practice fields. The average VRS technical efficiency score was higher on fields managed with CAPs (0.51) than fields managed using conventional practices (0.26). Low technical efficiency scores were previously documented in Mozambique by Uaiene (2008). Uaiene's assessment of 2002 and 2005 cropping seasons estimated the average technical efficiency scores to range between 0.40 and 0.60. The field-level efficiency scores estimated for farms using conventional practices in this study are comparable to results obtained by Mugera and Ojede (2013) who estimated technical efficiency scores for Mozambique farmers from 1966 to 2001 ranging between 0.26 and 0.34.

2.5.1. Model specification tests

The Vella and Skeels tests for normality and homoscedasticity tests were rejected, suggesting that using a Tobit regression to analyze the *ceteris paribus* effects of household and farm characteristics on technical efficiency scores may result in inconsistent parameter estimates (Greene, 2003). The result supports the use of the least squares regression to analyze technical efficiency scores.

The F-statistics for the first stage of the 2SLS regression exceeded 10, suggesting that according Staiger and Stock (1997) criteria the instruments used in the first stage of the 2SLS were not weak. A test of overidentification was not significant, supporting the assumption that the valid instruments were used. The Hausman test of CAPs adoption exogeneity statistic was 5.48 (p=0.02), resulting in the rejection of the hypothesis that CAPs adoption was exogenous.

Adoption of CAPs was correlated with the error terms in the technical efficiency equation. This result justifies the use of the 2SLS approach.

2.5.2. Two-stage Least Squares regression results

The estimates of the OLS and 2SLS regressions have mostly similar signs and the magnitudes of the estimates do not differ greatly (Table 2-3). As the CAPs adoption was found to be endogenous, the results from the 2SLS regression are interpreted. First, it was hypothesized that the technical efficiency scores of fields managed with CAPs and conventional practices did not differ. The coefficient on CAPs adoption was 0.369 and significantly different from 0 (p<0.01). All else equal, the technical efficiency scores of fields managed using CAPs were 36% higher than maize fields managed using conventional practices.

Agricultural loans were positively and significantly associated with field-level technical efficiency scores. The estimated coefficient suggests that the technical efficiency scores of farmers who obtained agricultural loans were, on average, 6% higher than the scores of other farmers. Farmers with access to credit may be able to more easily obtain inputs such as fertilizer, and herbicide or pay for cost of operating the farm. In case of Angonia and Tsangano some loans were given directly as agricultural inputs. Thus there was some concern that multicollinearity between these variables could inflate the variances of the least-squares estimates (Wooldridge, 2009). Multicollinearity was measured using variance inflation factors (VIFs) (Freund et al., 2006). The VIFs ranged between 2.12 to 1.05 with mean of 1.32, suggesting that there were not significant correlations between the variables used in the regression.

The coefficient on selling maize was significant and positively correlated with field-level technical efficiency scores. Holding other factors constant, farmers who sold surplus maize is 7%

higher than other farmers. The positive correlation between participation in maize markets and field level efficiency is a result of household income gains from selling maize which may in turn increase their ability to purchase productive inputs. Also, households with the objective of producing surplus maize for market may face a different set of incentives in their input and managerial decisions to increase productivity. The prospects of increased household income establish an incentive to invest and experiment with relatively new farming practices that may improve resource use efficiency such as CAPs.

The significant coefficient of the regional dummy variables, suggests that farm households located in the *barue* district have 10% higher technical efficiency scores than farms in the reference Tsangano district. Uaiene (2008) argues that due to their proximity to Zimbabwe, farmers in Manica typically use more inputs such as improved open pollinated seeds, irrigation, fertilizer, pesticides than farmers in other parts of Mozambique. Higher technical efficiency scores among farmers in Barue is probably due to a combination of higher use of inputs fertilizer, pesticide, irrigation and the agro-climatic conditions of this region. The fact that farmers in Barue receive free inputs also appears to influence the allocation of inputs. The coefficient on *angonia* was negative but not significant.

Table 2-3. Two-Stage Least Squares regression for VRS technical efficiency

	IV regression (*First stage*)	IV regression (*Second stage*)	OLS
CA		0.369***	0.170***
		(0.0831)	(0.0385)
hhage	0.028**	-0.0002	0.000
	(0.0115)	(0.0008)	(0.0009)
5yrschling	0.006	-0.070	-0.049
	(0.0858)	(0.0554)	(0.0620)
familysize	-0.025***	0.003	0.002
	(0.0063)	(0.0043)	(0.0052)
loan	-0.257***	0.062*	0.051
	(0.0540)	(0.0340)	(0.0358)
animalindex	-0.003**	0.0006	0.001
	(0.0014)	(0.0007)	(0.0008)
malehh	-0.010	-0.044	-0.022
	(0.0564)	(0.0345)	(0.0374)
off-farmprct	-0.002***	0.000	-0.0001
	(0.0008)	(0.0005)	(0.0004)
marketpart	0.123***	0.070**	0.055**
	(0.043)	(0.0261)	(0.0243)
barue	0.165***	0.107***	0.149***
	(0.0565)	(0.0341)	(0.0377)
angonia	0.151*	-0.064	-0.034
	(0.0797)	(0.0446)	(0.0342)
hhage2	-0.0003**		
	(0.0001)		
trainbygov	0.285***		
	(0.0596)		
wellbeingindex	-0.001		
	(0.0015)		
assetindex	0.006***		
	(0.0021)		
constant	-0.436*	0.226***	0.259***
	(0.2333)	(0.0743)	(0.0782)
n	488	488	488
Adj. R^2	0.162	0.217	0.286
Hausman test[1]		5.48 (p= 0.02)	
Overidentification test[2]		6.45 (p = 0.09)	
F of first stage[3]		11.66	

Notes: Robust Standard errors in parentheses. Significance categories: * $p < .1$, ** $p < .05$, *** $p < .01$.

[1] Hausman tests exogeneity (Wooldridge, 2010). [2] Overidentification tests suitability of instruments (Wooldridge, 2009). [3] F statistic of first stage of 2SLS tests weak instruments (Staiger and Stock, 1997).

2.5.3. Quantile regression results

The results from the 25th, 50th and 75th quantile regressions are presented in Table 2-4. Conservation agriculture practices adoption was significant in each quantile regression estimated. The technical efficiency scores on fields managed using CAPs were 25% to 50% higher than fields managed using conventional practices depending on the location of the technical efficiency score distribution analyzed. The magnitude of the coefficients increased from the 25th, to 50th, to the 75th quantiles.

The sign on *loans* was positive in all quantiles regressions. Access to loans was significant in the 50th quantile. But there was no effect of *loans* on technical efficiency on the 25th and the 75th quantiles. The coefficient of loans in the median regression suggested that farms located near the median of the technical efficiency scores distribution and had access to loans increased their technical efficiency scores by 9.8%.

The ability to sell surplus maize, *marketpart*, was positively correlated with field-level technical efficiency. This variable was only significant at the 75th quantile of the efficiency scores distribution. The estimated coefficient suggests that farms in the highest quantile analyzed had technical efficiency gains of 9%.

The regional dummy variable *barue* was positive in the 25th, 50th and 75th quantiles of technical efficiency scores. The coefficients on the *barue* variable increased progressively from the 25th to the 75th quantile, suggeting that the effect of this regional dummy variable was higher for farmers with relatively higher technical efficiency scores. All the significant coefficients in the quantiles regression, *barue*, *loans*, *marketpart*, and *CA* had the same sign as their corresponding 2SLS coefficients.

Table 2-4. Quantile regression analyzing VRS technical efficiency scores

	Quantile (25th)	Quantile (50th)	Quantile (75th)
CA	0.2502†	0.3927†	0.5053†
hhage	0.0007	-0.0002	-0.0008
5yrschling	-0.0143	-0.0277	-0.1711
familysize	-0.0002	-0.0026	0.0044
loan	0.0390	0.0983†	0.0396
animalindex	0.0003	0.0007	0.0005
malehh	-0.0309	-0.0360	0.0116
off-farmprct	-0.0003	0.0001	0.0007
marketpart	0.0075	0.0451	0.0975†
barue	0.0892†	0.1395†	0.1736†
angonia	-0.0468	-0.0521	-0.0670
constant	0.0782	0.1626	0.3398†
n	494		

Note: Significance level: † is p<0.05.

2.6. Conclusions

Poverty is a major development concern in Mozambique. Growth in agriculture, which is the principal activity for the majority of people in the country, is the focus of many poverty reducing policies. Conservation agriculture is a sustainable farming system because it reduces soil degradation and conserves moisture in dry, arid growing conditions. The chapter evaluated if CAPs also increase resource use efficiency, and thus could contribute to agricultural growth with less environmental impact.

Estimation of technical efficiency found that most of the surveyed maize farmers were relatively inefficient with respect to input use, and that the estimated technical efficiency scores were also comparable to previous estimates of technical efficiency of Mozambican farmers. Although fields managed with CAPs appeared to be relatively more efficient, efficiency scores for most fields were below 50%. A comparison of distributions of technical efficiency scores of CAPs adopters and conventional farmers found that distribution was unequal for these two groups.

The technical efficiency scores of CAPs and conventional farms were compared using 2SLS and quantile regressions. These analyses confirmed differences in efficiency between farms using CAPs and those using conventional practices. CAPs adoption was positively correlated with technical efficiency.

An important finding of this study was that supporting services such as credit access and access to markets play an important role in how farms allocate resources. Both of these variables are expected to be positively correlated with farmer ability to invest in inputs. As access and use of improved inputs continue to be low in Mozambique's agriculture, this finding suggests that efforts to increase agricultural production in Mozambique should continue focusing on support services such as credit access, markets and infrastructure that would promote increased use of improved inputs.

This thesis used regional dummies to control for differences among farmers in these regions. However, these variables have limited application in control of characteristics of groups of farmers with the same region. For instance, some CAPs adopters in Barue district receive free inputs, CAPs adopters in Tsangano and Angonia received inputs on loan, while other farmers bought inputs. These input supply arrangement may affect farmers input use decision, but this analysis does not distinguish between these groups in estimating technical efficiency.

For future policy, this study suggests that promoting adoption of CAPs to smallholders farmers in Mozambique may improve resource their use efficiency. Smallholder farmers are usually resource poor, thus an increase in efficiency of their resource use may significantly decrease resource waste. Promotion of CAPs however should not be undertaken alone other aspects such as increased accessibility to agricultural markets and cash also need to be addressed to improve agricultural production in Mozambique.

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Chapter 3 - Soil Carbon Sequestration, Carbon Markets, and Smallholder Adoption of Conservation Agriculture in Mozambique

Abstract

Payments for Environmental Services (PES) are relatively new approaches to environmental conservation whereby environmental service providers are rewarded for adopting specific sustainable natural resources practices. Smallholder farmer adoption of conservation agriculture practices (CAPs) such as minimum tillage, crop rotation and crop residue management may provide opportunities to increase household income or cover the costs of adoption if the carbon sequestration benefits of CA are quantifiable, adoption rates are accelerated and maintained, and carbon exchange markets are transparent and viable. This research provides an *ex ante* analysis of a PES market for carbon offsets generated by the adoption of CA by smallholder farmers in the Tete and Manica provinces of Mozambique. Conservation agriculture adoption is predicted to 2032 based on adoption rates obtained from a household survey conducted in 2011. Carbon sequestration simulations until 2032 for conventional and conservation agriculture practices are calibrated using local meteorological and soil data, and information about fertilizer use from extension personnel and survey respondents. Prices of carbon are forecasted assuming optimistic, pessimistic, and status quo trends, also terminating in 2032. Aggregated present values of returns to the community of producers partially and fully adopting CA, given the potential for market exchange of carbon, are compared. Full adoption of CA over the simulated 20 year period generated returns two fold higher than those from an adopt-then-abandon scenario, and returns four fold higher than late adoption of CA.

3.1. Literature review

Role of agriculture in greenhouse gas emissions

Human activities including agriculture affect climate change by increasing greenhouse gas (GHG) concentration in the atmosphere (IPCC 1995). Naturally occurring and anthropogenic GHG can change the amount of radiation received by the earth, its redistribution and loss which in turn influences the energy balance of the earth (Alves et al., 1996). The contribution of agricultural cultivation to atmospheric GHG is considerable. Agriculture accounts for about 25% of the CO_2, 50% of the CH_4 and 70% of the N_2O anthropogenic gas emissions (Hutchinson et al., 2007). Agriculture is also a significant source of CO, NO, NO_x and NH_4. But improving certain agricultural practices such as reducing tillage, adopting agroforestry, and more efficient use of fertilizers could significantly curb current GHG emissions (Smith et al., 2008). Agriculture can reduce emissions by creating or expanding C sinks in soil organic matter and above ground biomass, burning less fossil fuel and hence decreasing emissions during farming operations, or by providing products like biofuels that can substitute products with higher GHG emissions (McCarl and Schneider, 2000; Pretty et al., 2002; Smith et al., 2008).

This study evaluates the extent to which CAPs can mitigate GHG emissions through C sequestration as practiced by smallholder farmers in Mozambique. CAPs such as zero or reduced tillage, crop rotation and crop residue management could decrease GHG emissions from agriculture (Dumanski et al., 2006). Avoiding ploughing decreases microbial action (Beare et al., 1994) and soil organic matter oxidation which in turn decreases CO_2 emissions (Logan et al., 1991). Crop residues undergo reduced decomposition on untilled land due to reduced soil-residue contact and lower soil temperature (Reicosky et al., 1999). Including leguminous plants in crop rotations may affect fossil fuel use in farming because legumes decrease inorganic

fertilizer requirements (Zentner et al., 2004). Practicing crop rotations may also decrease fossil fuel use by promoting the biological control of pests and diseases which may reduce pesticide use (Pretty et al., 2002).

Studies on conservation agriculture practices, greenhouse gas emissions control and carbon sequestration

Several previous works evaluated GHG emissions and C sequestration of farmers using CAPS. Bayer et al. (2006) found that untilled tropical and subtropical soils stored more C than similar tilled soils. Campos et al. (2011) concluded that combining no-till and crop rotation in farming increases C sequestration. Naab et al. (2008) found that combining no-till and crop residue retention results in higher C stocks. Six et al. (2004) concluded that N_2O emissions of farms using no-till initially increase but in the long term (more than 20 years), use of CAPs resulted in N_2O emission levels equal to conventional tillage farming. Estimates of C sequestration for farmers using no-till and mulching show that it varies widely from 50-150 kg C ha^{-1} yr^{-1} in dry zones, to 1000-1500 kg C ha^{-1} yr^{-1} in humid climate (Lal, 2011; Lal, 2004).

Environmental damage due to GHG emitted from agricultural activities is an externality. The damage happens concomitantly with agricultural production, but the environmental costs are not paid by producers and not included in the prices paid by consumers (Pretty et al., 2000). Other types of externalities from agricultural activities may benefit the environment. Sequestration of C by farmers using CAPs, for example, is a positive externality from these farming practices (Akpalu and Ekbom, 2010). It is difficult to limit the production of externalities in agriculture because the private farmer costs of production of goods do not account for external costs and differ from the social costs of production. As a result, farmers tend

to over produce the goods and increase the externality associated with them (Pearce and Tinch, 1998).

The control of externalities is difficult because markets for them are generally nonexistent. Consequently, providers of environmentally beneficial externalities such as C sequestration are not paid for providing these services, leading to under-investment in environmental service provision (Landell-Mills and Porras, 2002). Absence of markets for externalities prevents mutually beneficial transactions of environmental services to take place and results in social welfare losses (Dahlman, 1979; Landell-Mills and Porras, 2002).

Payments for environmental services

Payments for environmental services (PES) are a potential market-based solution to moderate externalities and promote environmental conservation. Payments for environmental services are designed as voluntary schemes where users of an environmental service pay the providers for the service itself or for adoption of a land use that will provide it (DAI 2008; Wunder, 2005). The payments received by service providers under the PES are financial incentives to increase production of environmental services or adoption of farming practices that promote resource conservation (Engel et al., 2008). In the case of C emissions, the mechanism that allows countries to trade C emission rights was created by the Kyoto protocol of the United Nations. Under this mechanism stakeholders that emit CO_2 above the agreed limit in developed countries can counter balance their emissions by paying environmental services provided by agents implementing activities that biologically reduce or absorb C in developing countries (Breidenich et al., 1998; Ringius, 2002).

Payments for environmental services are generally considered efficient in promoting environmental conservation. Perpetuation of the schemes is motivated by the interests of service providers and users. PES programs are likely to achieve efficient outcomes, providing only environmental services whose benefits are higher than their costs (Whittington and Pagiola, 2012). Wunder et al. (2010) note that the efficiency of PES programs sometimes may be reduced because political or social goals are given priority to environmental service provision efficiency goals during the selection of program participants. Wunder (2007) pointed out that, for a PES program to be efficient, it must avoid selecting participants who would provide the environmental service even without the payments, and select individuals who are more likely to increase the service provision with the payments. Sierra and Russman (2006) suggested measuring PES efficiency by seeing whether the payments would induce permanent land use change, and if the payments for land use change on one site would not shift degradation pressure to other ecological systems.

Previous studies suggest that successful implementation of PES schemes depends on existence of well-defined property rights over resources used to supply the environmental service, scientific knowledge about the environmental service, and institutional support (Crook and Clapp, 1998; Jack et al., 2008). In the developing country context, informal property rights are very common and private property rights often do not exist (Feder and Feeny, 1991; Jacoby and Minten, 2007). In these cases a common property right can be used to implement PES (Corbera et al., 2007). Examples of this type of PES are the carbon sequestration projects contracts established in land owned by entire communities in Mozambique (International Institute for Environment and Development, 2012). Nevertheless, some form of property recognition is crucial to allow service providers the flexibility to change land use and establish

long-term PES contracts such as C sequestration (Tschakert, 2007). Institutional support is needed because many PES schemes are implemented in collaboration with NGOs and government institutions. These institutions are necessary for verification, monitoring and other activities supporting the PES program process (Jack et al., 2008; Perez et al., 2007).

Pagiola et al. (2005) identify the financial hindrances discouraging farmer participation in PES programs. Adoption of an alternative land-use may require initial investments that resource poor farmers may be unable to provide. Investment costs make participation in some PES programs more difficult because the opportunity costs of land might be higher than returns in the initial years of the program, causing farmers to forgo part of their income (Pagiola et al., 2005). Perez et al. (2007) propose adjusting the timing of C payments with the beginning of the program to cover costs of transitioning to new land uses or practices. The importance of adjusting payment timing or another incentive mechanism might be even greater on more productive land where opportunity costs are higher. For instance, the marginal cost of sequestering C through tree planting in fallow land in the Manupali watershed in the Philippines were calculated to be US$ 3.3 per ton of C. In land planted with maize the opportunity cost of C sequestration was US$ 25 but it was lower than opportunity costs of sequestration in more productive land planted with vegetable crops, US$ 61.1 (Shively et al., 2004).

Payments for environmental services programs use market mechanisms to promote environmental conservation goals (Pagiola et al., 2007; Wunder, 2005) but they may also stabilize the incomes of service providers engaged in activities with high income fluctuations such as agriculture (Pagiola et al., 2005). Payments for environmental services may also increase rural incomes in developing countries (Landell-Mills and Porras, 2002; Smith and Scherr, 2002). The empirical evidence finds positive and negative impacts of PES programs on farmer income.

Tschakert (2004) simulated the impact of C sequestration through the adoption of various farming practices such as manure use, grazing, and crop rotations on smallholder farmer income in Senegal. The 25 years simulation found net benefits varying from US$ -1400 to US$ 9600 t^{-1} C depending on the land use system adopted and initial farmer resource endowments. Antle et al. (2007) studied C sequestration through terracing and agro-forestry systems and found that C sequestration can potentially increase farmer income by 15%. But sequestering a metric tonne of C in these systems costs US$ 25 and US$ 150. Thus, a minimum price of US$ 50 per tonne of C would be necessary to significantly increase farmer income in this case.

Payments for environmental services programs in Mozambique

Jindal et al. (2012) evaluated a forestry based PES program implemented in the Chicale *regulado,* Nhambita region of Mozambique. This program established seven year contracts with participating households to adopt agro-forestry systems such as intercropping with nitrogen fixing tree acacia (*Faidherbia albida*), planting native hardwood panga panga (*Millettia stuhlmannii*) on cropping plot boundaries, and planting fruit trees. In return, these households received revenues from the sale of C offsets to international buyers at a price of US$ 4.5 t^{-1} CO_2. In 2007-2008, each participating household received about US$ 80 from C payments. The study used household survey data to investigate the income effects of the PES program and concluded that after seven years the nominal value of cash income of households with agro-forestry contracts increased by 48%. Households without agro-forestry contracts also experienced positive changes in income during the same period but the nominal income change of this group was not different from zero.

Hegde and Bull (2011) used survey data to analyze the impacts of agro-forestry based PES in Chicale *regulado.* Using total expenses on items such as grains, vegetables, and meat to proxy consumption and household income, Hegde and Bull (2011) concluded the PES program evaluated had positive impact on the income of participating households and their expenditure food items including food-grains, vegetables and meat. Similar impacts were not identified on a subsample of the poorest and the female headed participating households.

Palmer and Silber (2012) conducted a benefit-cost analysis on a C sequestration PES program of Nhambita. Participants enrolled in this program by adopting land-use systems such as boundary or homestead tree planting, growing cash crop like cashew (*Anacardium occidentale*) and mango (*Mangifera indica*) orchards, inter-planting trees with crops, or planting woodlots. The analysis compared the benefits such as revenues from C offsets sold at the price of US$ 6.72 t^{-1} CO_2, the sale of cash crops, timber harvest, and crop yields gains, to the cost of establishing agro-forestry land-use systems included in the PES program. The project was simulated for 100 years. This analysis found that farmers who adopted cash crops have the highest income gains in the long-run. Growing cash crops resulted in negative annual net benefits in the first 6 years but after the first harvest of fruits, which was assumed to happen in the seventh year, the annual net benefits adopting this land use system became positive. Payments for C only occurred during the first 7 years, which is the period of establishment of the cash crops. The authors concluded that C payments could provide farmers with financial means for long-run investments such as cash crops.

Empirical evidence of GHG reduction potential for no-till agriculture in Mozambique is limited. This study simulates 20 years of C sequestration for farmers adopting CAPs. The total amount of C sequestered is simulated using estimates of area managed using CAPs during the

relevant period. Combinations of the amount of sequestered C, CAPs adopters, and the costs of adoption of CAPs are used to estimate community benefits from a 20 year PES scheme.

3.2. Conceptual framework for diffusion of agricultural practices

Diffusion of agricultural technologies is often a long process and complex process than many characterize by an S-shaped curve with increasing initial adoption of the technology followed by slower adoption rate later (Geroski, 2000). This paper uses the S-shaped curve to characterize the adoption of CA which consequently will also determine the enrolment into the C sequestration PES program. As a simplification it is assumed that enrolment into the PES progresses at the same rate as the adoption of CA. In other words every new land that is farmed using CA practices will also be enrolled into the PES.

A popular conceptual explanation for the S-shaped path of diffusion is that diffusion of technology is learning process (Geroski, 2000; Hiebert, 1974). At the beginning of technology diffusion farmers have basic knowledge about the technology, but lack perfect knowledge about all of its aspects, learning is relevant in revealing those unknown parameters of the technology as farmers acquire such information by experimenting with the technology (Bardhan and Udry, 1999; Hiebert, 1974; Welch, 1970). For instance, CA practices are relatively new in Mozambique (Kassam et al., 2009), and it is reasonable to think that the amount of inputs, yields, and profitability. for this technology are not well known by the farmers. The theory on adoption as a learning process predicts that each farmer who adopts CA practices generates knowledge about the parameters involved in this technology (Bardhan and Udry, 1999) and as more of such knowledge is acquired more area will be dedicated to farming using CA technology (Foster and

Rosenzweig, 1995; Krishnan and Patnam, 2014). Bardhan and Udry (1999) formalized the theory of adoption by learning.

Assuming that a farmer has the alternatives of using the conventional technology with a known return q_a or a conservation technology with expected return from agricultural production yields and PES $E(q_s)$. The value of future profits from period *t* until *T* will be:

$$V_t(I_{t-1}) = \max_{\iota_s \epsilon \{0,1\}} E_t \sum_{s=t}^{T} \delta^{s-t}[(1-\iota_s)q_a + \iota_s q_s(I_{s-1})], \tag{3.1}$$

where $I_s = \sum_{t=0}^{s} \iota_t$, ι_t is a binary variable that is equal to 1 when farmer adopts CA and 0 otherwise and δ is the discount factor. For time *t* the value of future stream of profits is:

$$V_t(I_{t-1}) = max_{\iota_t}(1-\iota_t)q_a + \iota_t E_t q_t(I_{t-1}) + \delta V_{t+1}(I_t), \tag{3.2}$$

The farmer has incentive to try CA technology because of expected future gains in profit which are revealed by such trials. And, the decision to bring additional land into CA farming will happen whenever the incurred loss of current expected profits is less than the (discounted) future profitability that results from own trials with the technology. For instance, the adoption in period 0 can be represented as:

$$q_a - Eq(0) \leq \delta(V_{\mathrm{I}}(1) - V_{\mathrm{I}}(0)) \tag{3.3}$$

$$V_{\mathrm{I}}(1) - V_{\mathrm{I}}(0) = E_0 \sum_{s=1}^{T} \delta^s (q(s) - q(s-1)) \tag{3.4}$$

When interaction between farmers is taken into consideration, a farmer's decision to adopt CAPs will also be influenced by the parameters revealed in the trials of other farmers in the same community. The future value of the profits of a particular farmer will depend upon his expectation of other farmer profits. More trials in one farmer fields, increases his as well as his neighbors' expected profits, it also increases the probability of dissemination of the technology to other farmers in the community.

3.3. Methods

Figure 3-1 summarizes the steps used to link agricultural practices with soil C dynamics and estimate benefits of PES program for C sequestration. Estimating the benefits of PES for C sequestration requires annual estimates of C sequestration per hectare, the area farmed using CAPs and with potential to sequester C, and C prices. Each component used in the calculation of the PES program benefits is considered for a period of 20 years.

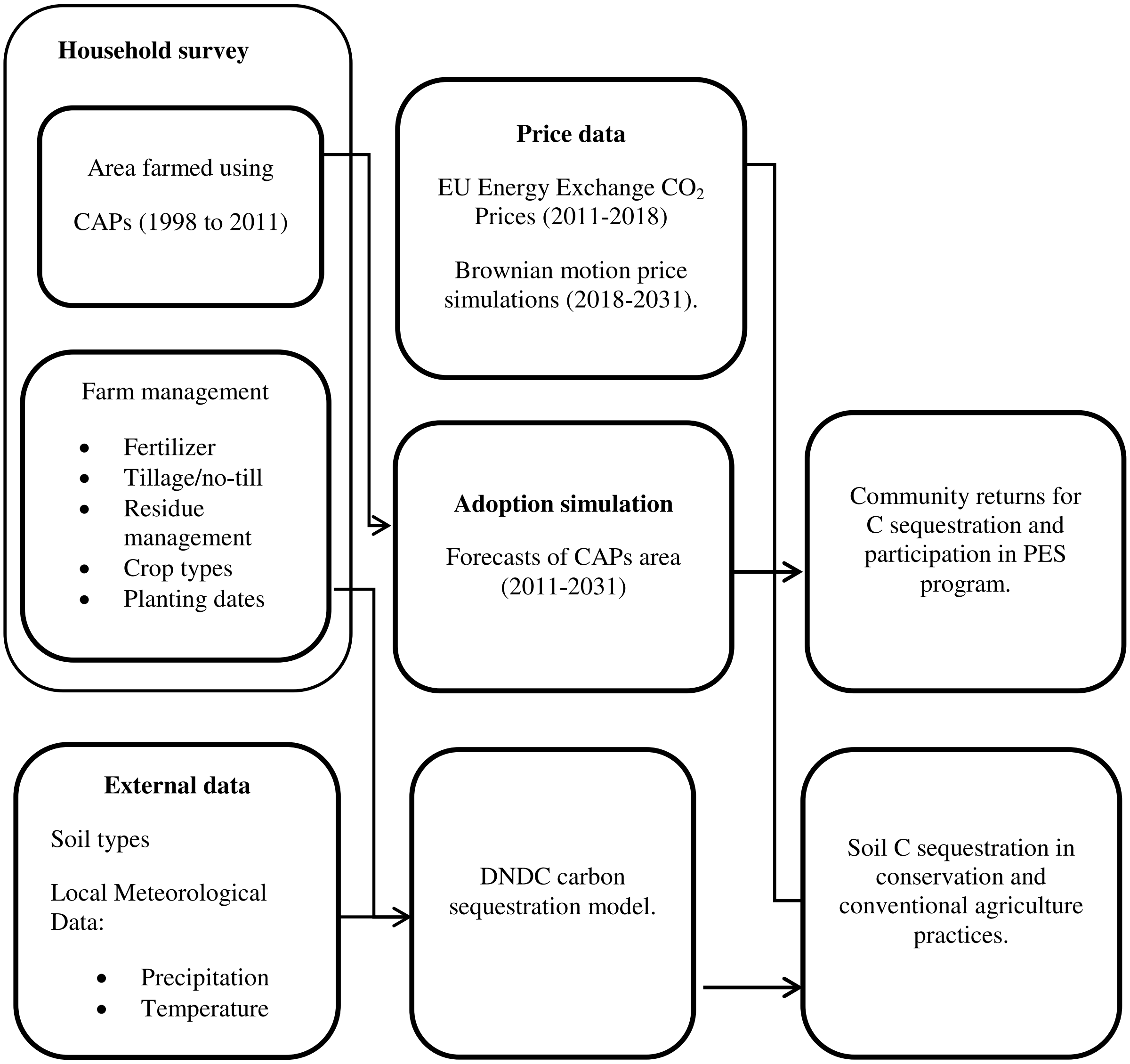

Figure 3-1. Summary of the simulation approach to estimate benefits of payments for environmental services program

3.3.1. Simulations of soil organic carbon

Understanding what happens to SOC is important in investigating greenhouse reductions. The status of C in soil depends on gains by addition of organic matter on the one hand, and loss by emissions, leaching, and erosion, on the other hand (Izaurralde et al., 2007). The final destination of organic matter added to soils depends on the action of microbes and other chemical, physical processes (Li et al., 2012).

The Denitrification-Decomposition (DNDC) model is applied to assess soil C (Li et al., 2003). The DNDC model integrates crop, climate, soil, agronomic parameters in a process oriented simulation of the biogeochemical cycles of soil C and N (Li et al., 1992; Li et al., 1994). The biogeochemistry of C and N is incorporated into the DNDC through six sub-models: soil climate, crop growth, decomposition, nitrification, denitrification and fermentation (Farahbakhshazad et al., 2008; Hsieh et al., 2005; Li, 2000).

The soil climate sub-model estimates the temperature, moisture, and redox potential of the soil profile layers. The plant growth sub-module calculates the accumulation of biomass by plant parts such as stalks, roots and grain, the contribution of plant material to dissolved organic carbon (DOC), and its influence on soil moisture, redox potential, and pH. In the DNDC model soil organic material exists in four pools: plant residue or litter, microbial biomass, active humus or humads, and passive humus. These forms of organic matter are used by the decomposition sub-module to generate profiles of concentrations of DOC, NH_4^+, and NO_3^- in the soil. The outputs from the three sub-modules: soil climate, plant growth and decomposition are used by fermentation, nitrification and denitrification sub-modules to estimate the soil generating capacity of greenhouse gases like NO, N_2 and N_2O, and free ions such as NO_3^- (Hsieh et al., 2005; Li, 2000). The DNDC model is summarized in Figure 3-2.

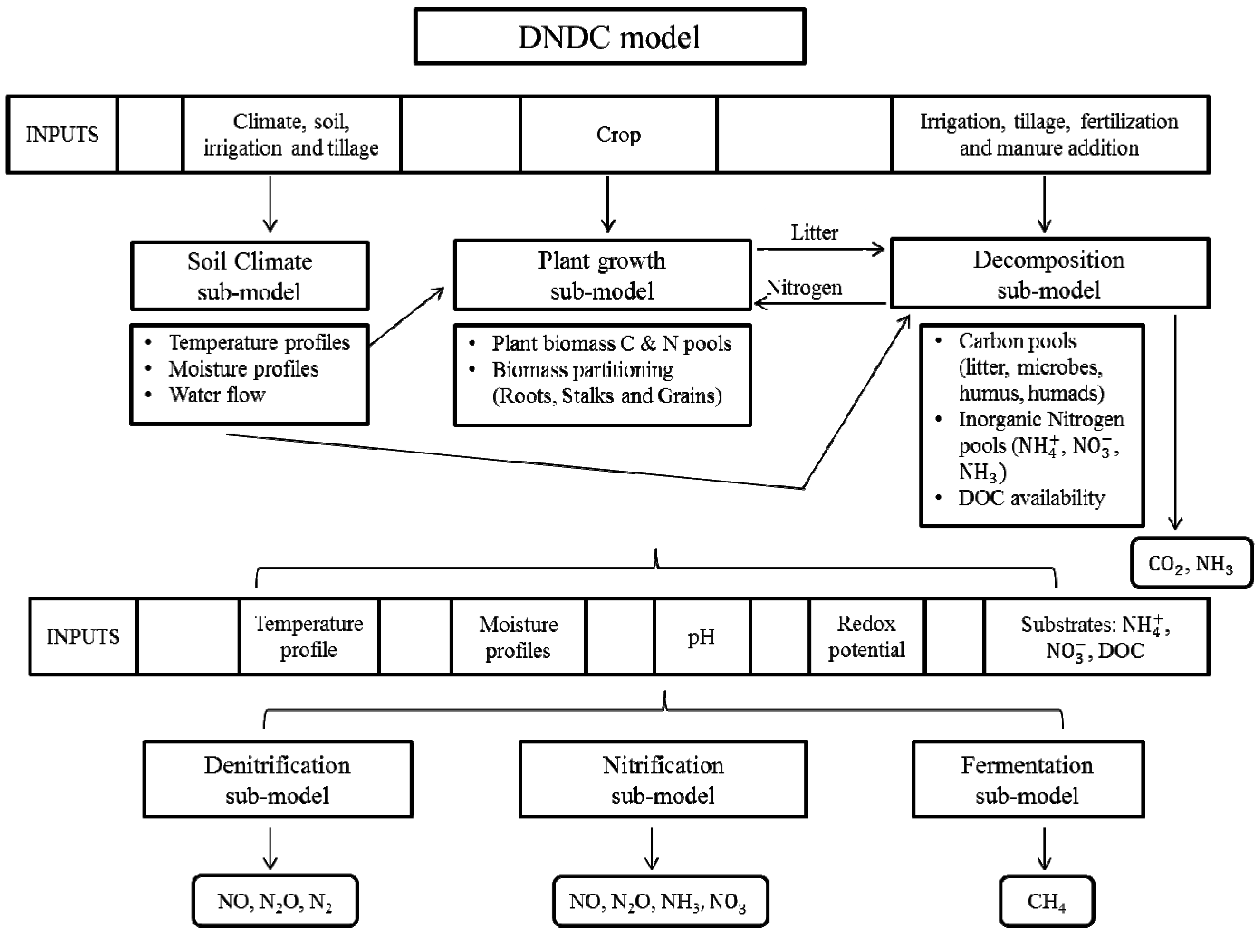

Figure 3-2. Summarized representation of denitrification-decomposition (DN-DC) model

Notes: Summary after Li, et al. (1992) and Li (2000) work. Temperature, moisture, pH, redox potential and substrates are calculated through the soil climate, plant growth and decomposition sub-models and these are used in calculations for denitrification, nitrification and fermentation sub-models.

3.3.2. Soil organic carbon simulation scenarios

Conservation farming systems (CA) are represented by the combination of no-till, crop rotation and crop residue retention on the field. These data were obtained from a survey of field management practices of farmers in the Manica and Tete provinces of Mozamique. In the case of maize, about 25% crop residue was left on the surface of soils, while 15% of residue from beans was incorporated into the soils as green manure. In contrast, for crops produced using

conventional farming methods (CF) the fields were ploughed for field preparation at a depth of 10 cm (in case of maize crop), and at 5 cm depth before planting beans. The residues from each of these crops was removed under the convetional management system. Similar to the residue management and tillage practices decribed, irrigation, fertilization modeled to represent conventional or conservation agricultural systems in DNDC.

Evaluation of C dynamics was simulated in four scenarios with duration of 20 years each, from 2013 to 2032. The first scenario included fields managed using CAPs throughout the entire simulation period (CA-CA). The second scenario was for fields managed using conventional methods throughout the 20 year period (CF-CF). The third scenario considered farmers who adopted CAPs for 10 years and then abandoned the practice (CA-CF). The last scenario considered late adopters of CAPs who implement it during the last 10 years of the simulation period (CF-CA).

Li et al. (1994) concluded SOC accumulation may be affected by fertilizer rates. In general, higher fertilizer rates increase SOC although this effect of fertilizer depends on climate, soil texture and initial SOC (Alvarez, 2005; Li et al., 1994). Three levels of inorganic nitrogen fertilizer use were considered and replicated to each conservation and conventional practices simulation. In the first rate fertilizer was a control were no inorganic fertilizer was used to the fields (ZEROFERT). In the next scenario, fertilizer was applied at the rate of 4.83 kg N/ha (EXTENSION), which was the recommended by extension experts in the region. The last fertilizer rate was 25 kg N/ha (DEMO). This is amount of fertilizer applied in CAPs demonstration plots of an organization promoting conservation farming. Combining 4 scenarios of farming practices with 3 scenarios of fertilizer rate there were 12 scenarios of C sequestration

simulated in DNDC. Description of these C sequestration simulation scenarios is summarized in Table 3-1.

Table 3-1. Scenarios considered for carbon sequestration simulations and payments for environmental services program.

Type of Scenario	Scenarios
Farming practices	• CAPs, 20 years (CA-CA) • Conventional, 20 years (CF-CF) • CAPs, 10 years/Conventional, 10 years (CA-CF) • Conventional, 10 years/CAPs, 10 years (CF-CA)
Fertilizer rates	• 0 kg N/ha (ZEROFERT) • 4.83 kg N/ha (EXTENSION) • 25 kg N/ha (DEMO)
Equilibrium adoption plateau	• 20% regional coverage • 60 % regional coverage
Carbon market prices	• Pessimistic • Optimistic • Status quo

Notes: The total period of simulation is 20 years for the scenarios. Conventional agriculture practices are tillage, no crop residue maintained on the fields, while CAPs includes residue incorporation into the soil and zero tillage. There are 12 scenarios for carbon sequestration, and 72 scenarios for PES program.

3.3.3. Conservation agriculture practices adoption simulations

The farmer reported area cultivated using CAPs was available for the period 1998-2011 (Figure 3-3). Predictions of area farmed using CAPs from 2011 to 2032 use estimates previously simulated by Lambert et al. (2013) using methods developed by Griliches (1957). Adoption of an agricultural technology can be described using various functions such as logistic, modified

exponential and cumulative normal (Gershon et al., 1985; Griliches, 1957; Lekvall and Wahlbin, 1973). This study used a logistic function to describe the diffusion of CAPs which is one of the most commonly used functions to describe the S-shaped diffusion path of agricultural innovations (Lekvall and Wahlbin, 1973). Different paths of diffusion result from a series of adjustments from one equilibrium position, characterized by a specific percentage of area cultivated using CAPs, to a new equilibrium position with higher or lower percentage of area cultivated using CAPs (Griliches, 1957). The logistic function characterizing the path of diffusion is:

$$P = \frac{K}{1+exp(-[\alpha_o+\alpha t])} \tag{3.5}$$

where P is the percentage acres farmed using CAPs practices; K is the equilibrium adoption, which in this case varies from 20% to 60% of total area being cultivated using CAPs; α_o is the constant of integration; α growth rate parameter; and t time. Paths of CAPs adoption are presented in Figure 3-4. This same model is also used to forecast the area managed using CAPs and the number of households using CAPs.

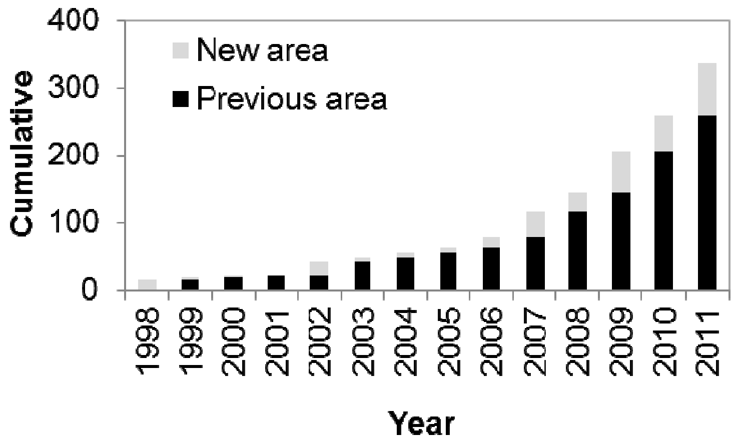

Figure 3-3. Reported hectares managed using CAPs

Source: Lambert et al. 2013

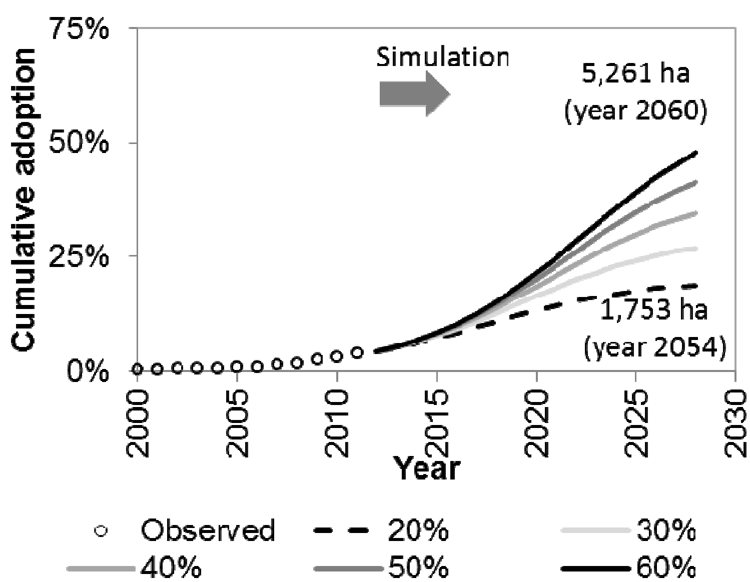

Figure 3-4. Simulated adoption of CAPs

Source: Lambert et al. 2013

3.3.4. *Price forecasts*

Carbon market prices were required to calculate the payments received by CAPs adopters sequestering C. Carbon prices from 2013 to 2019 were obtained from the European Energy Exchange stock market (European Energy Exchange, 2013). The prices for the remaing 13 years of the C simulations, i.e. 2020 to 2032, were forecasted as Brownian motion trends. Brownian motion is a stochastic process B_t that satisfies the following properties (Mörters and Peres, 2010):

- ✓ B_t has a continuous path and $B_t = 0$ when $t = 0$;
- ✓ The increments $B(t_k) - B(t_{k-1})$ are stationary which means that distribution of these increments does not depend on t;
- ✓ The increments of B for each time t are independent, i.e. $B(t_k) - B(t_{k-1})$, $B(t_{k-1}) - B(t_{k-2})$, …, $B(t_2) - B(t_1)$ are uncorrelated; and
- ✓ If t and s are two moments in the Brownian process and $0 < t_{k-1} < t_k$, then the increment from $B(t_k) - B(t_{k-1})$ is normally distributed with mean 0 and variance $t_k - t_{k-1}$.

When these properties are satisfied, the price is simulated by generating a normally distributed random variable $Z \sim (0,1)$ and multiplying it by the standard deviation of the increment:

$$B(t_1) = \sigma Z_1 \qquad (3.6)$$

$$B(t_2) = B(t_2) + \sigma Z_2$$

$$\vdots$$

$$B(t_k) = B(t_{k-1}) + \sum_{i=1}^{k} \sigma Z_i, \quad i=1,\ldots 11.$$

Sensitivity of C payments to future C prices was simulated as Brownian motion to predict growth C prices from 2020 to 2032 considering three trends: decreasing (pessimistic), increasing (optimistic) and unchanged (status-quo), Figure 3-5.

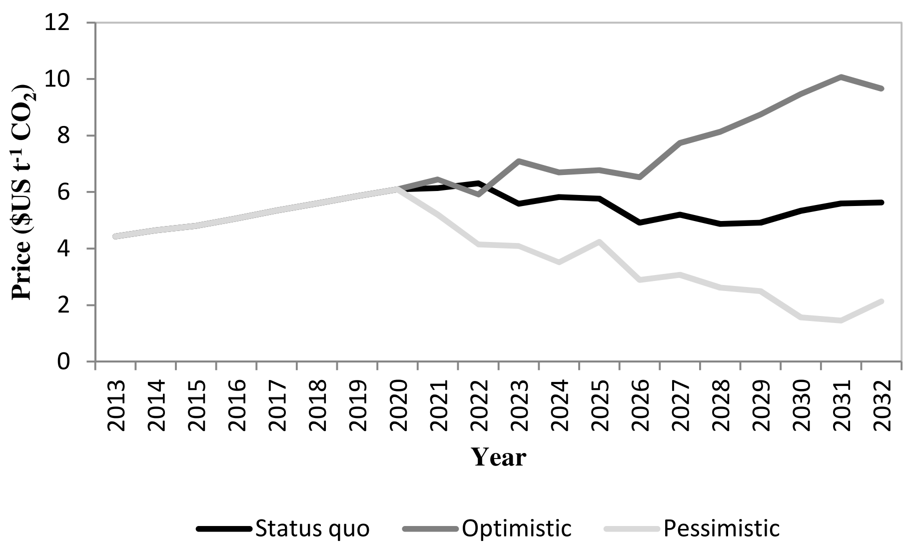

Figure 3-5. Simulated carbon prices

Notes: Carbon prices from 2013 until 2019 obtained from European Energy Exchange, 2013.

3.3.5. Present values and net present values of PES

Benefits of PES payments is measured by the returns received annually by PES participants. The total benefits to participants was estimated by multiplying amount of annual C sequestration in 1 hectare by the total additional area cultivated using CAPs and C market price. Equation 3.7 presents the formula used to calculate the present values of returns from PES.

The future payments are discounted to the present period at a 10% discounted rate (Palmer and Silber, 2012). The present values (PV) of aggregate returns to households according to the year they adopted CAPs is the sum of discounted stream of annual payments.

$$PV_t = \sum_{t=0}^{19} \frac{C_i * CAarea_j * P_t}{(1+r)^t} \qquad (3.7)$$

where PV_t is the aggregate of present values for cohorts of land brought into cultivation using CAPs in year t=0,…,19; $CAarea_j$ is the area managed using CAPs measured in hectares; j indexes the year when the land was converted into cultivation using CAPs; C_i is the annual amount of C sequestered in the soil per hectare, indexed by i, the year when C was sequestered; and P_t is the market price of C in US dollars (US$) per ton. The PV are calculated for combinations conventional and conservation farming practices (CA-CA, CA-CF and CF-CA), fertilizer rates (ZEROFERT, EXTENSION and DEMO), CAPs adoption of equilibrium (20% and 60%) and future C market prices (pessimistic, status quo and optimistic).

The present values are calculated for cohorts of land managed using CAPs, according to the first year of adoption of CAPs. For example, cohort 1 is for the area that started to be managed using CAPs in the first year of simulation, 2013. Area that was first cultivated using CAPs in 2013 is represented as $CAarea_0$ in equation 3.7. The area and year of adoption was obtained from the adoption curves predicted by Lambert et al. (2013).

The second element in the calculation of present values is the amount of C sequestered. The estimates obtained from the C simulations for different scenarios of farming practices are used. The C sequestation estimates used in estimating present values start from index 0 for any cohort (C_0), indicating the first time C is sequestered in a particular cohort of land. For land that starts to be managed using CAPS in 2013, in CA-CA scenario, i.e. cohort 1, for instance, there are 20 C sequestration estimates will be used to estimate PV, C_0, C_1,…, C_{19}. Table 3-2 presents a matrix with the representing how the PV were calculated.

Table 3-2. Matrix demonstrating calculation of community based present values of returns from payments for environmental services program.

T	δ	**C1**	**C2**	**C3**	**.**	**.**	**.**	**C20**
0	$(1+r)^0$	$\frac{P_0 C_0 CAarea_0}{\delta}$	-	-				
1	$(1+r)^1$	$\frac{P_1 C_1 CAarea_0}{\delta}$	$\frac{P_1 C_0 CAarea_1}{\delta}$	-				
2	$(1+r)^2$	$\frac{P_2 C_2 CAarea_0}{\delta}$	$\frac{P_2 C_1 CAarea_1}{\delta}$	$\frac{P_2 C_0 CAarea_2}{\delta}$				
.	.	.	.	.				
.	.	.	.	.	.			
.	.	.	.	.		.		
.	.	.	.	.			.	
19	$(1+r)^{19}$	$\frac{P_{19} C_{19} CAarea_0}{\delta}$	$\frac{P_{19} C_{18} CAarea_1}{\delta}$	$\frac{P_{19} C_{17} CAarea_2}{\delta}$	.	.	.	$\frac{P_{19} C_0 CAarea_{19}}{\delta}$
PV_t		$\sum_{t=0}^{19} \frac{P_t X_t}{\delta}$	$\sum_{t=1}^{19} \frac{P_t X_t}{\delta}$	$\sum_{t=2}^{19} \frac{P_t X_t}{\delta}$	.	.	.	$\sum_{t=19}^{19} \frac{P_t X_{19}}{\delta}$

Notes: X_0, X_1,…X_{19}, is the total C sequestered in year *t* and is equal to the multiplication of area managed using CA ($CAarea$) and the amount of carbon sequestered (C). The area is indexed by the first year when a cohort of land was cultivated using CAPs. Carbon is indexed by year when carbon was sequestered, starting from first year (t=0).

It is assumed that once an area is farmed using CAPs it will countinuously be farmed using CAPs for the maximum period of 20 year in the CA-CA scenario, and 10 years in the CA-CF or CF-CA scenarios of farming practices. The area that starts to be managed using CAPs in the second year of simulations in scenario CA-CA will remain in CAPs for 19 years in the CA-CA scenario. Similarly, in CA-CF and CF-CA scenarios, land that starts to be managed using CAPs in the second year will remain under CAPs mangement for 9 years.

It is also assumed that households only receive payments from the PES scheme if they demonstrate C sequestration in the area farmed using CAPs. Thus, areas managed using CAPs at the beginning of the second year in CA-CA scenario, for instance, will remain under CAPs management for 19 years. This area has the potential to sequester C and farmers may receive

payments for that same period of time. Area that is converted into management using CAPs in the third year in CA-CF fields will be managed using CAPs for 7 years. Farmers managing this area under CAPs may receive payments for maximum of 7 years, as long as they demonstrate C sequestration. Another important aspect about the design of these PES simulations is that households only receive payments for C sequestration by soils. This PES program does not pay CAPs adopters for GHG emission reductions that may result from reduced fuel use in CAPs systems (FAO 2001).

The PVs assumes that transition from conventional tillage to no-till is costless. It does not take into of adopting CAPs such as the purchase of no-till seeder, or jab planter (Derpsch, 2008). Net present values (NPV) were estimated by deducting the cost of adoption from the aggregate returns received by the community. Specifically, NPV was calculated by deducting the total cost of purchasing jab-planters, i.e. the number of households adopting CAPs in year *t* multiplied by the unit price of jab-planter, from the aggregate PV of returns received by the community. It was assumed that every household adopting CAPs purchased a jab planter. Knowledge from field work in the study region suggests that jab-planter costs US$ 70 per unit. NPV values were estimated for different scenarios combinations of farming practices, fertilizer rates, CAPs adoption of equilibrium and future C market prices.

$$NPV = \sum_{t=0}^{19} PV_t - HH_t * P_{planter} \tag{3.8}$$

where HH_t is the number of households adopting CAPs in a particular year and $P_{planter}$ is the price of a jab-planter.

3.4. Data sources

The data used by the DNDC model reflects the conditions of the study area (Zucong et al., 2003). This study models the dynamics of C for soils with agro-ecological conditions of northern Manica and eastern Tete provinces of Mozambique. Plant growth parameters were chosen from maize and bean crops selected from the various crops available in DNDC.

Simulations of SOC in DNDC also required information about farming practices such as the time of planting, harvesting time, irrigation and other practices. Information about farming practices were collected with a household survey conducted in 22 villages of the Manica and Tete provinces of Mozambique. Details about the methodology used in the survey are in chapter 2 of this thesis.

The study area is dominated by oxisols and ultisols (Maria and Yost, 2006) or ferralsols (Panagos et al., 2011). These soils have an acidic pH ranging between 5.8 to 6.0 (Maria and Yost, 2006). Cation exchange capacity can be as high as 7.2 cm kg^{-1} soil (Geurts and Van den Berg, 1998). Details of soils parameters used to initialize the simulations are presented in Table 3-3.

A daily summary of climate parameters was obtained from the National Oceanic and Atmospheric Administration-National Climatic Data Center (1989) database. The National Oceanic and Atmospheric Administration (NOAA) provides records of climate parameters from 9 stations in Mozambique. This study uses the data recorded at the Chimoio station, Manica, identified by the NOAA as the meteorological station MZ000067295, located at -19.117° S, 33.467° E. Finally, information regarding the atmospheric carbon dioxide trends was obtained from data published by Tans and Keeling (2013).

Table 3-3. Climate and soil data used in DNDC simulations

Variables	Value
Yearly maximum average daily temperature (°C)	37.5
Yearly minimum average daily temperature (°C)	9.1
Yearly accumulated precipitation (cm)	148.47
CO_2 in atmosphere (ppm)	390
Annual atmospheric CO_2 increase rate (ppm)	2.07
Soil Texture	Loam soil with 19% Clay
Land use type	Upland crop field
Drainage efficiency	Good drainage
Bulk density (g cm^{-3})	0.00147
pH	5.8
Initial SOC at surface (kg C kg^{-1} soil)	0.03675

Notes: Climate data obtained from The National Oceanic and Atmospheric Administration. Atmospheric CO_2 status parameters were obtained from data published by Tans and Keeling (2013). Soil information obtained from previous literature about predominant soil characteristics in Manica and Tete (Maria and Yost, 2006; Panagos, 2011; Geurts and Van den Berg, 1999).

3.5. Results and discussion

The amount of organic C in soils continuously managed using conventional methods (CF-CF) increases with higher rates of nitrogen fertilizer application (Figure 3-6[a]). Tilled crop land, with fertilizer applied at the rate of 25 kg N ha^{-1} (DEMO), accumulates over 33.6 t of SOC per hectare yearly. In conventionally tilled soils, with 4.83 kg N ha^{-1} fertilizer applied (EXTENSION), SOC content continuously decreases and is lower than SOC in the DEMO scenario. Not using fertilizer (ZEROFERT) in these continuously tilled soils (CF-CF) lowers soil organic matter accumulation further. Paustian et al. (1992) and Syp et al. (2012) also present evidence that SOC increases with higher fertilizer application. The SOC obtained in continuously tilled soils (CF-CF), according to the fertilizer rate, was used as the baseline for analyzing changes in SOC in the other three scenarios; CA-CA, CA-CF, and CF-CA.

Sequestration of C according to the adoption of CAPs and the amount of fertilizer used is summarized in Figure 3-6(b, c, d). First, because the practices are same during the first 10 years of scenarios CF-CF and CF-CA, there is no difference between their simulated SOC profiles.

Examining the CF-CA scenario, shifting from conventional practices after 10 years causes SOC stocks to increase. This increase in SOC following the shift to conventional practices is sensitive to amount of fertilizer used. At the end of 20 years in the CF-CA scenario, and the DEMO fertilizer rate, SOC is 960 kg ha^{-1} $year^{-1}$ more than the CF-CF and the DEMO fertilizer rate scenario, while in the ZEROFERT fertilizer rate it is 560 kg ha^{-1} $year^{-1}$ more than CF-CF and the ZEROFERT fertilizer rate. In the EXTENSION fertilizer rate SOC is about 640 kg ha^{-1} $year^{-1}$ more than its base scenario, CF-CF and the EXTENSION fertilizer rate (figure 3-6[a]).

Second, in the CA-CF scenario, soils accumulate about the same amount of C as in the CA-CA scenario during the initial 10 years. However, in scenario CA-CF, changing from CAPs to conventional practices after 10 years causes C stocks in fields to decrease rapidly. During the study period, the SOC of fields on which CAPs is abandoned after 10 years (CA-CF) remains higher than CAPs of those who never adopt CAPs (CF-CF). Using tillage causes soil C to decrease because tillage destroys soil aggregates that protect organic matter exposing it to degradation by soil biota (Balesdent et al., 2000; Kern and Johnson, 1993).

Third, continuously using CAPs (CA-CA) resulted in increasing soil C accumulation. At the end of 20 years practicing CAPs, annual SOC accumulation was about 1900 kg ha^{-1} for the DEMO, 1100 kg ha^{-1} $year^{-1}$ for the EXTENSION, and 1000 kg ha^{-1} $year^{-1}$ for ZEROFERT fertilizer rate scenarios. West and Post (2002) reported more SOC accumulation in conservation agriculture farming systems compared to conventional systems. These researchers reported C sequestration averaging 48 ± 13 g cm^{-2} $year^{-1}$ in fields farmed using zero tillage and up to 90 ± 59 g cm^{-2} $year^{-1}$ in untilled fields with rotated crops.

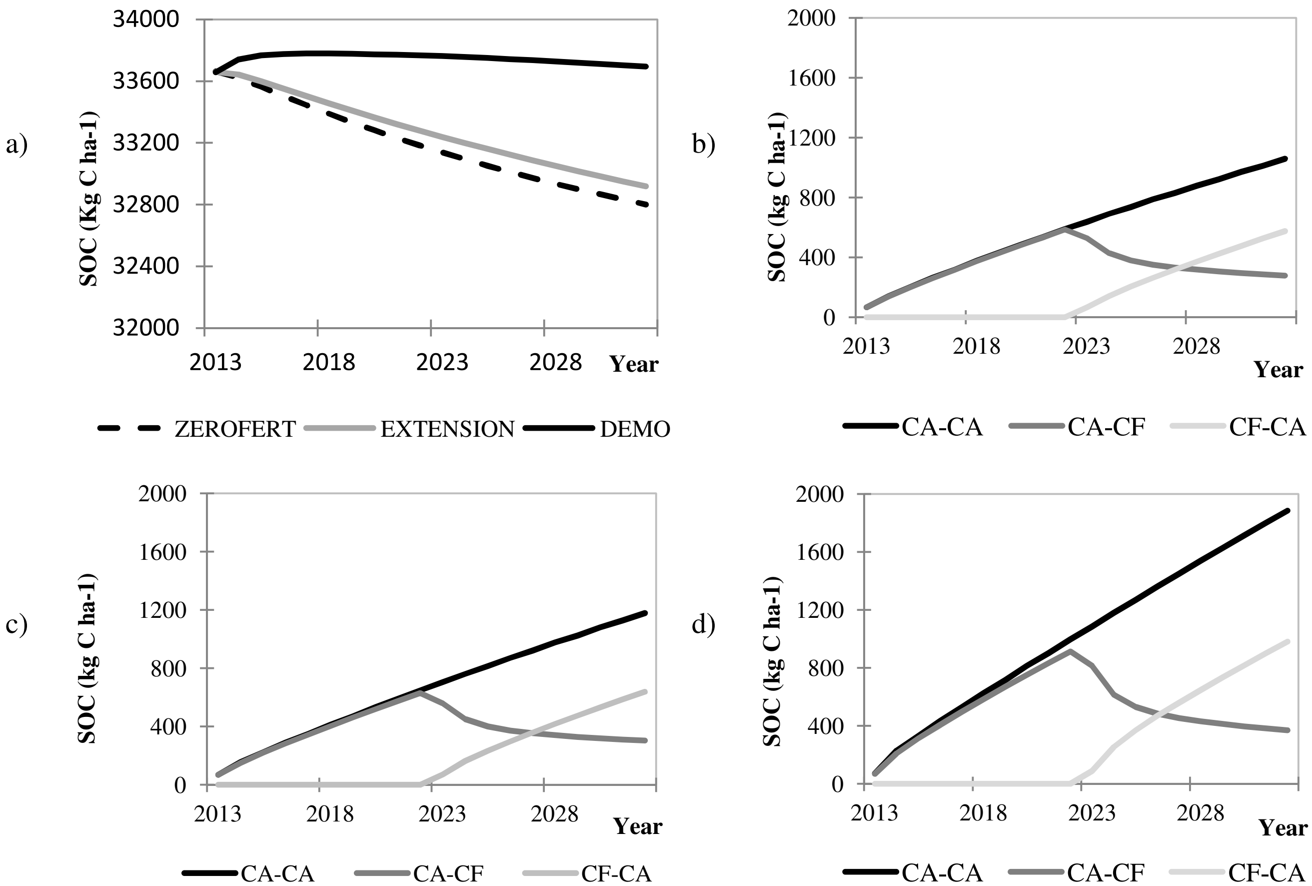

Figure 3-6. Soil organic carbon under continuous conventional farming, b) Carbon sequestration using no fertilizer rate, b) Carbon sequestration using LOW fertilizer rate, d) Carbon sequestration using HIGH fertilizer rate.

Notes: SOC is soil organic carbon. The practices simulated are CAPs (CA) and conventional (CF). Soil organic carbon accumulation is in relation to SOC levels obtained in soils constantly manage using conventional practices (CF-CF), Figure 3-6(a).

Table 3-4 presents the C sequestration estimates aggregated by farming practices, fertilizer rate and CAPs adoption equilibrium. Aggregated C sequestration, including all the fields in the community that were managed using CAPs over the 20 years of simulation, was highest under CA-CA scenario. For CA-CA scenario, aggregate C sequestration ranged from 13876 t C for low CAPs adoption (20% adoption rate) and EXTENSION fertilizer rate scenarios, to 38691 t C under DEMO fertilizer rate and 60% adoption rate scenarios. Aggregate C

sequestration for CA-CF and CF-CA scenarios included all the fields managed using CAPs over 10 years in each case. CA-CF scenario resulted in the lowest aggregate C sequestration estimates among the three conservation farming practices scenarios. Aggregate C sequestration estimates under CF-CA scenarios were intermediate between CA-CF and CA-CA.

Table 3-4. Carbon sequestration (t C) aggregated over 20 years and all conservation agriculture practices adopters

Farming Practices	DEMO Fertilizer Rate		EXTENSION Fertilizer Fate	
	20% Adoption	60% Adoption	20% Adoption	60% Adoption
CA-CA	21438	38691	13876	25227
CA-CF	3938	4748	2754	3321
CF-CA	4422	5739	2860	3716

Income Benefits of PES

The present value of earned returns community members participating in a PES program under the EXTENSION and DEMO fertilizer rates with status quo and optimistic price are presented in Figures 3-7, 3-8 and 3-9. In every scenario simulated, adopting CAPs in the first year of the simulation (2013) and continuously using CAPs for 20 years (CA-CA) resulted in the highest returns from C sequestration payments. Returns from C sequestration progressively decrease for later CAPs adopters. In the EXTENSION fertilizer rate scenario under the status quo price regime, for instance, aggregated community returns for C sequestration on land managed with CAPs for 20 years is US$ 54,580 when CAPs is adopted on 20% of the cultivated land (Figure 3-7[a]). In the same fertilizer rate and price scenario, adopting CAPs in the second year of PES program with CA-CA scenario and managing the fields under conservation practices

for 19 years decreases aggregate returns to CAPs adopters to US$ 9,625. The returns from PES are even lower for later CAPs adopters.

In the scenarios where farmers adopt CAPs and then revert to conventional practices after 10 years (CA-CF), returns earned by the community are lower than the scenarios where farmers use CAPs continuously. For instance, on fields where CAPs is adopted in the first year in the CA-CF scenario with the EXTENSION fertilizer rate, the status-quo price, and 20% CAPs adoption scenario (figure 3-7[c]) returns aggregated over 10 years are nearly half (US$ 26,214) of what is earned over 20 years of practicing CAPs (the CA-CA scenario), with the EXTENSION fertilizer rate and status quo price scenario (US$ 54,581), figure 3-7[a]. In the CA-CF scenario with the EXTENSION fertilizer rate, the status-quo price, but 60% CAPs adoption rate scenario (figure 3-7[d]) returns aggregated over 10 years are also nearly half (US$ 28,266) of what is earned over 20 years of continuously practicing CAPs under the 60% CAPs adoption rate (US$ 58,855), figure 3-7[b].

Returns in CF-CA scenario are lower than both the CA-CA and CA-CF scenarios. Returns earned under CF-CA were almost 2 times lower than returns earned under CA-CA and 1 time lower than returns earned under CA-CF. The 20 years aggregate returns under the EXTENSION fertilizer rate, status quo price and the 20% adoption scenarios decreases from US$ 54,581, to US$ 26,214, and US$ 9,988, under the CA-CA, CA-CF and CF-CA scenarios, respectively, figure 3-7[a, c, e].

Returns to the community are sensitive to the fertilizer rates applied. Using more fertilizer generally increases returns from C payments. This positive relationship between returns and fertilizer rates was expected because increasing fertilizer rates results in higher levels of soil C accumulation. For instance, using CAPs for 20 years under the CA-CA scenario, with the

EXTENSION fertilizer rate, 60% CAPs adoption, and status price scenario (figure 3-7[b]) would result in US$ 58,855 aggregated community returns spread through 20 years, while using CAPs for 20 years under (CA-CA) with 60% adoption and status-quo price, but DEMO fertilization rate would result in US$ 90,580 aggregated community returns, (figure 3-8[b]).

The net present values (NPV) of PES returns earned by CAPs adopters are presented in Table 3-5 according to farming practice, carbon price, CAPs adoption equilibrium rate and fertilizer rates. Net returns depend upon future prices and proportion of land farmed using CAPs. At US$ 70 per jab-planter, aggregate net returns were only positive in some simulations continuous use of CAPs, CA-CA scenario. Under the CA-CA scenario and the optimistic carbon market price, the net returns were positive for every fertilizer rate and CAPs adoption rate combination. While under the status-quo carbon price, EXTENSION fertilizer rate and the 60% adoption rate, negative net returns were evident. Considering a pessimistic carbon market future price, net returns were only positive under the 20% CAPs adoption rate and 25kg N/ha fertilizer rate (DEMO fertilizer rate). The estimated net present value for the pessimistic carbon market price, DEMO fertilizer and 20% adoption rate was US$ 39,811. For rural households in Mozambique with low income, averaging at about US$ 100/adult equivalent (Mather et al., 2008), this PES program could increase CAPs adopters' income.

Table 3-5. Net present values (US$) of carbon payments and total C sequestration aggregated over 20 years.

Farming Practices	Carbon Market Price	DEMO Fertilizer Rate		EXTENSION Fertilizer Rate	
		20% Adoption	60% Adoption	20% Adoption	60% Adoption
CA-CA	Pessimistic	39,811	-51,670	-838	-11,4303
CA-CF		-17,212	-119,363	-34,136	-139,685
CF-CA		-62,405	-173,344	-66,473	-178,322
CA-CA	Status quo	98,383	58,401	36,861	-42,788
CA-CF		-11,786	-112,765	-30,379	-135,121
CF-CA		-48,737	-155,533	-57,632	-166,787
CA-CA	Optimistic	154,280	167,827	72,679	28,068
CA-CF		-11,978	-112,997	-30,512	-135,281
CF-CA		-33,225	-135,183	-47,601	-153,610

Notes: Results obtained using jab planter unit price of US$ 70, and DEMO and EXTENSION fertilizer rates

Table 3-6 presents the average investment per unit of C (in US$ t^{-1} C) in various scenarios. Investment per t of C carbon sequestered varied from US$ 2.48 for the CF-CA with pessimistic price scenario to US$ 15.83 under the CA-CF and status quo price. Investments per t of C under the CA-CA scenario were in general intermediate between the CA-CF and CF-CA scenarios. The late starting PES program (scenario CF-CA) resulted in lowest investment per unit of C sequestered. Total C sequestered under the CF-CA scenario are still lower than the CA-CA scenario.

Table 3-6. Carbon sequestration project payments per unit of carbon sequestered (US$/t C)

Farming Practices	Carbon Market Price	DEMO Fertilizer Rate		EXTENSION Fertilizer Rate	
		20% Adoption	60% Adoption	20% Adoption	60% Adoption
CA-CA	Pessimistic	5.56	4.78	5.66	4.85
CA-CF		14.41	14.36	14.47	14.42
CF-CA		2.62	2.48	2.62	2.48
CA-CA	Status quo	8.29	7.63	8.37	7.69
CA-CF		15.79	15.75	15.83	15.79
CF-CA		5.71	5.58	5.71	5.59
CA-CA	Optimistic	10.90	10.46	10.95	10.50
CA-CF		15.74	15.70	15.78	15.74
CF-CA		9.22	9.13	9.22	9.13

A limitation of the method used in calculating net returns from PES is that it only considers expenditure on jab-planters in the costs of adopting CAPs. Analyzing PES program net benefits was simplified by assuming that changing from conventional to conservation practices didn't involve changes in combination of inputs or the overall use of certain inputs. It is also acknowledged that this study did not account for any gains or losses in agricultural yield to CAPs adopters. Including crop yield changes under CAPs and analyzing any trade-offs between C sequestration and crop yields in future research could broaden the context for interpreting the benefits of adoption these conservation practices.

3.6. Conclusions

Agriculture is one of the major sources of anthropogenic gas emissions and contributes to high atmospheric GHG concentrations. Previous research suggest that conservation farming systems can reduce GHG emissions by turning soils into sinks of C accumulation (Allmaras et al., 2000). Payments to adopters of CAPs may provide incentives for the adoption of sustainable farming practices, and could be a viable means of increasing incomes of the rural poor and abate environmental damage through C sequestration.

This study simulated SOC over a 20 year time horizon for farmers adopting CAPs at different times. One of the main findings of the soil organic matter simulations was that soil C content is higher when higher fertilizer rates are applied. In soils managed using either conventional or conservation methods, using fertilizer at rates recommended by organizations promoting CAPs (25 kg N/ha) resulted in higher C accumulation than, soils fertilized using the farmers usual rate (4.83 kg N/ha) or and not using any fertilizer.

Another important finding from the C sequestration simulations was that practicing CAPs continuously (CA-CA) resulted in higher SOC accumulation than adopting of CAPs then abandoning (CA-CF) or the late adoption or CAPs (CF-CA). At the end of the simulation period, soil organic matter under the continuous CAPs scenario was higher than the other two scenarios and it appears to still be increasing, suggesting that there is still potential to increase soil C further. Under the CA-CF scenario, shifting to conventional farming after practicing CAPs may disturb soil aggregates exposing soil organic matter and causing loss of organic C (Jastrow and Miller, 1998).

Despite SOC gains found on farms that use CAPs, analyzing the net revenues earned from C payments suggests that household incomes may not always increase. After including the

costs associated with jab planters, it was determined that net revenues are negative under some PES scenarios. It was also found that higher net revenues are achieved when future prices of C increase. Fertilizer used indirectly influences revenues received by the community through its influence on soil organic matter. In general higher fertilizer rates result in higher net revenue from PES program.

This study concludes using PES for CAPs adopters could increase the income of farmers. Although not all the PES scenarios resulted in positive net returns, potential for increasing farmer income was found under different C market price trends. The prospects of PES participants achieving positive net returns could be enhanced by using higher fertilizer rates and using CAPs for longer periods. Comparing 10 and 20 years of CAPs used in this study, it was found that field managed using CAPs for 20 years resulted in higher PES net returns. Similarly, fields managed using higher fertilizer rates also resulted in higher net returns than lower fertilizer rates. A design of PES program that subsidizes some of the initial costs of adopting CAPs practices may help decrease the adoption costs, resulting in increased CAPs adoption and higher net returns.

This study also concludes that PES programs for CAPs adopters have the potential to create environmental benefits in terms of SOC build up. Soil organic matter content of fields managed using CAPs was generally higher than conventionally managed fields. Even, considering only PES scenarios that had positive net returns, PES could result in aggregate C sequestration ranging from 13876 t C for CA-CA, EXTENSION fertilizer rate and 20% CAPs adoption rates, to 38691 t C for CA-CA, DEMO fertilizer rate and 60% CAPs adoption rate scenarios.

Despite the potential of implementing a PES program for CAPs adopter, successful implementation of the program may require proper institutional support. National capacity may be built by creating a national designated authority that liaises between local communities and international investors, and ensures transparent assessment of C projects (Jindal et al., 2006). Proper institutional support may also be enhanced by improving coordination between various institutions involved with C sequestration projects such as the ministry of agriculture, ministry for coordination of environmental affairs, research organizations, non-governmental organizations and natural resource management committees (Nhantumbo and Izidine, 2009). Another important factor for the success of PES programs is the existence of an appropriate regulatory environment (Jindal et al., 2006). Well defined rules relevant to C sequestration projects may be conducive to increased foreign investment in the C markets.

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Appendix

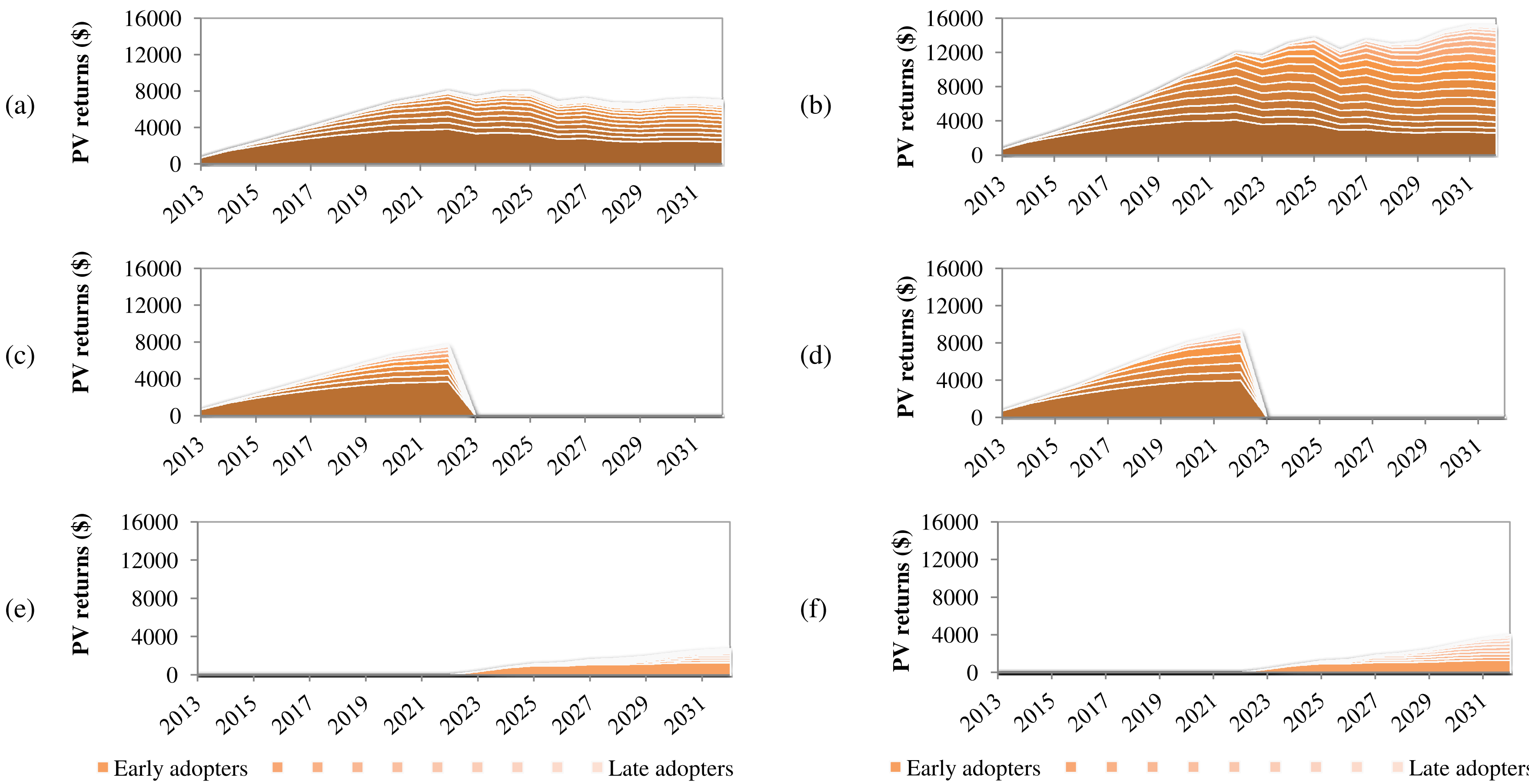

Figure 3-7. Present value of 20 year C sequestration revenues earned by entire community for EXTENSION scenarios, Status quo price (a) CA-CA and 20% adoption, (b) CA-CA and 60% adoption, (c) CA-CF and 20% adoption, (d) CA-CF and 60% adoption, (e) CF-CA and 20% adoption, and (f) CF-CA and 60% adoption.

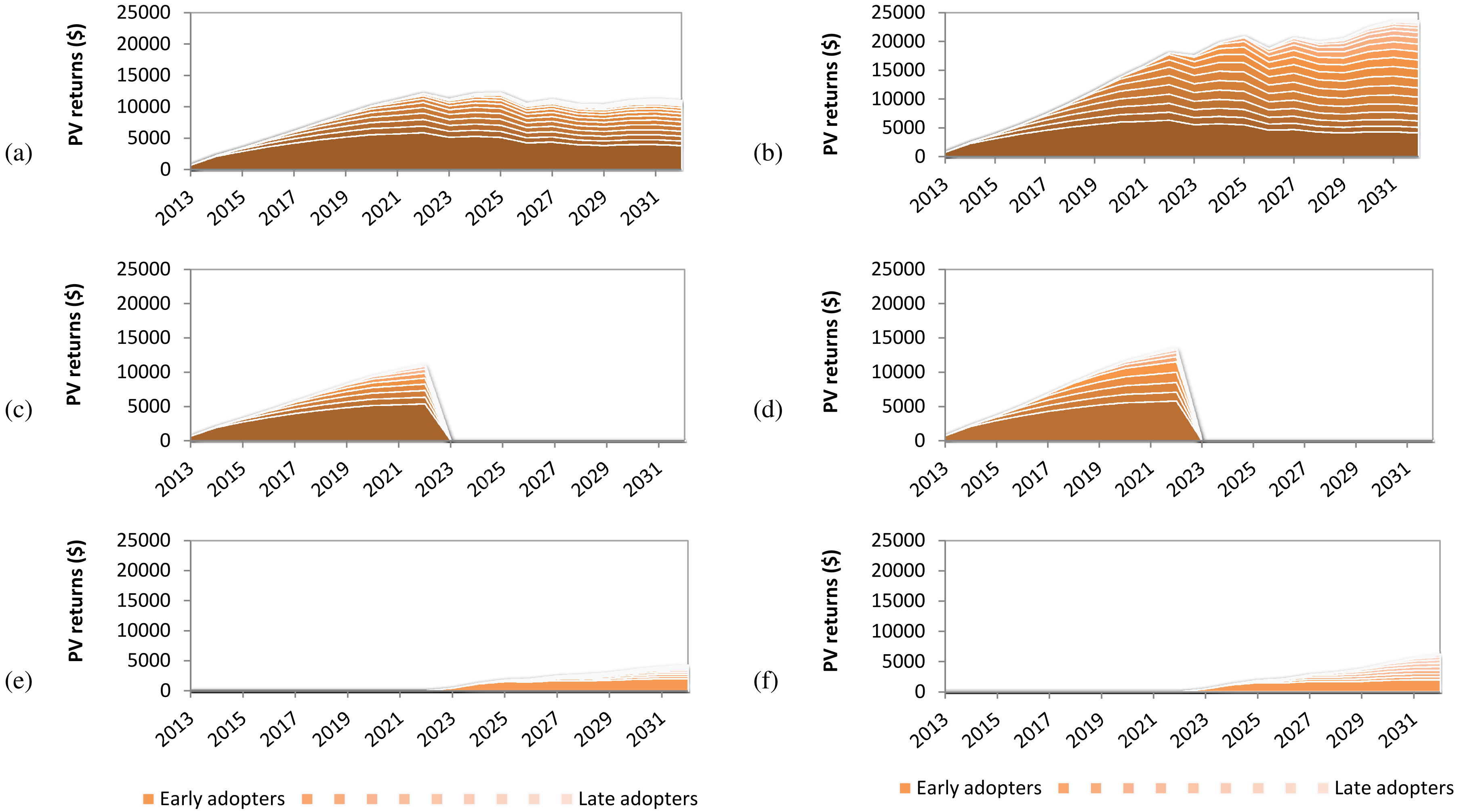

Figure 3-8. Present value of 20 year C sequestration revenues earned by entire community for DEMO scenarios, Status quo price (a) CA-CA and 20% adoption, (b) CA-CA and 60% adoption, (c) CA-CF and 20% adoption, (d) CA-CF and 60% adoption, (e) CF-CA and 20% adoption, and (f) CF-CA and 60% adoption.

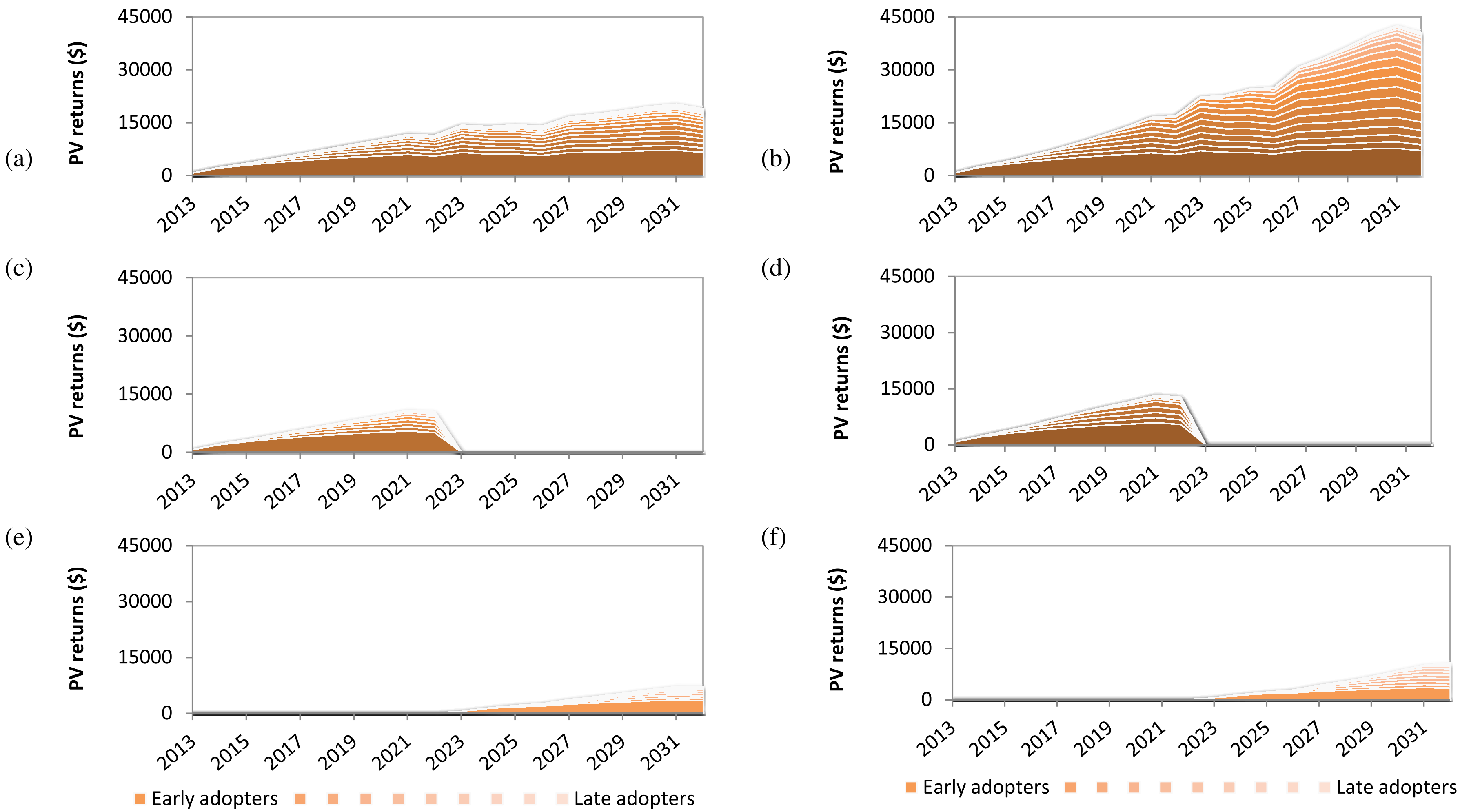

Figure 3-9. Present value of 20 year C sequestration revenues earned by entire community for DEMO scenarios, optimistic price (a) CA-CA and 20% adoption, (b) CA-CA and 60% adoption, (c) CA-CF and 20% adoption, (d) CA-CF and 60% adoption, (e) CF-CA and 20% adoption, and (f) CF-CA and 60% adoption.

Chapter 4 - Summary and Conclusions

This thesis evaluated the effect of CAPs on maize production efficiency, soil organic matter and farmer household incomes. These objectives were accomplished in two studies. Both studies focused on smallholder farmers located in the Tete and Manica provinces of Mozambique.

The first study analyzed the technical efficiency of farmers using CAPs. Technical efficiency scores were estimated using a DEA algorithm, finding that most farmers sampled had low technical efficiency scores. Using 2SLS regression and quantile regressions to compare efficiency of CAPs and conventional farms, it was concluded that adopting CAPs increases technical efficiency farmers. The effect of CAPs is higher for farmers in the higher end of the technical efficiency distribution. Another important conclusion of this study was that both selling maize produce and acquiring agricultural loans are positively correlated with technical efficiency. This study did not identify the causes of low technical efficiency. This may be the pursuit of further research, since little is known about what causes low efficiency among Mozambican farmers.

The second study evaluated the dynamics of organic C in soil managed using CAPs. This study simulated C sequestration in soils managed using different farming practices, including CAPs and different fertilizer rates for 20 years. The findings of this study suggested that adopting CAPs generally resulted in soil C accumulation. Using CAPs continuously resulted in increasing trend in soil C, but adopting then abandoning caused losses in soil C. This study also concluded that higher fertilizer rates increase soil C.

Another objective of this study was to evaluate the income effects of participating in a PES program for CAPs adopters who demonstrate C sequestration. It was found that the returns earned by farmers depend mainly on the future price of carbon. Higher future C prices would

result in higher returns to smallholder who adopted CAPs. The amount of fertilizer also influences returns through its influence on SOC. The study included jab-planter prices of estimate NPV of PES returns, finding that some of the scenarios resulted in negative net returns. It was concluded that there exist a potential to increase farmer incomes by PES but the success of PES in accomplishing this goal depends on the costs of adoption of CAPs that the farmer has to incur.

Vita

Timoteo Eduardo Simone was born in Beira, Mozambique, to Arão Simone Mbulu and Mónica Franzes. He completed his high school from Samora Machel Secondary School of Beira in 2005 and started undergraduate studies in Agricultural Engineering at the Eduardo Mondlane University, Maputo the following year. In August 2007, he started BSc (Honors) Agriculture degree with a full scholarship from the Indian Government. He graduated from CCS Haryana Agricultural University in 2011. Before coming to the University of Tennessee to pursue MS Agricultural and Resource Economics, Timoteo E. Simone worked in monitoring and evaluation of development projects for a non-profit organization in Beira, Mozambique.