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Department of Economics

WORKING PAPER
08/2014

Economic incentives for carbon sequestration: A review of the literature

[a]Aklilu Abenezer, [b]Gren Ing-Marie

Economics

[a]Department of Economics, Swedish University of Agricultural Sciences, Uppsala
e-mail: abenezer.zeleke@slu.se

[b]Department of Economics, Swedish University of Agricultural Sciences, Uppsala
e-mail: ing-marie.gren@slu.se

Sveriges lantbruksuniversitet, Institutionen för ekonomi
Swedish University of Agricultural Sciences, Department of Economics

ISSN 1401-4068
ISRN SLU-EKON-WPS-1408-SE

Working Paper Series 2014:08
Uppsala 2014

Corresponding author:
Ing-marie.gren@slu.se

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Economic incentives for carbon sequestration: A review of the literature

Abstract. The main purpose of this study is to review studies in economics on policies for carbon sequestration. Specific design problems are associated with heterogeneous land holders, additionality and permanence in carbon projects, and the risk of leakage. It was found that a large part of the literature, which started in the late 1980s, has been focused on the calculation of costs for carbon sequestration, mainly in forests, and on calculations of cost savings from its introduction in climate programs. Results from the literature point to cost savings of up to 40%. The small body of literature on transaction costs, mainly attributed to monitoring and verification, indicates that these costs are modest. The literature on policy design is much more scant, and the main part suggests discounting of the carbon sink value to account for the uncertainty. Assessment of equilibrium prices in the many existing voluntary and regulatory carbon sink markets shows a lower price of carbon sink compared with certain abatement of fossil fuels. This can be explained by risk discounting. A few studies suggest contract design for self-enforcement of efficient carbon projects. This has not yet been implemented in carbon sink offsets in practice, the carbon trade of which corresponds to approximately 0.3% of all carbon trade.

Key words: economic incentives, carbon sequestration, policy design, survey

JEL codes: Q52, Q54, Q58

Department of Economics
Swedish University of Agricultural Sciences (SLU)
P.O. Box 7013, SE-750 07 Uppsala, Sweden
Ph. +46 18 6710 00, Fax+ 46 18 67 35 02
www.slu.se
www.slu.se/economics

Institutionen för ekonomi
Sveriges lantbruksuniversitet
Box 7013, 750 07 Uppsala
Tel. 018-67 10 00, fax 018 67 35 02
www.slu.se
www.slu.se/ekonomi

1. Introduction

The damaging impacts of anthropogenic emissions of greenhouse gases (GHG) have been demonstrated in a number of studies (e.g. IPCC, 2001). The recognition of the need to stabilize the carbon content in the atmosphere emission reductions have been manifested in a number of international and national agreements and policies, such as the Kyoto Protocol and the EU climate policy. The main focus of these agreements and policies has been on reducing GHG emissions. However, the carbon content in the atmosphere can be reduced also by carbon sink enhancement. The global net carbon uptake by terrestrial vegetation, mainly forests, corresponds to 2-3 GtC/per year, which corresponds to 30-50% of the emissions from fossil fuels in 2001 (Figure A1 in appendix). However, carbon is stored in soil, which implies that conversion of forests into agriculture releases carbon. The global release from forest conversion amounts to approximately 1.5 GtC, which corresponds to 30% of the GHG emissions from fossil fuel combustion in 2001 (Figure A1 in appendix).

Thus, the potential reduction in carbon content from avoided deforestation, and increased forest plantation and improved management can be of significant importance for climate policy. The Kyoto Protocol allows for carbon sequestration by afforestation and reforestation under the Clean Development Mechanism (CDM) within the LULUCF (Land Use, Land Use Change, and Forestry) activities, but this is limited to a small fraction of emissions in 1990. More recently, carbon sequestration is introduced under different national regulations of GHG and voluntary systems (Peter-Stanley, 2012; Kerr, 2013). A majority of these carbon sink offset projects has been incorporated in different voluntary systems, in particular under the Reducing Emissions from Deforestation and forest Degradation (REDD) program, which, in 2008, was created by the United Nations in order to enhance the use of carbon sinks (UNFCCC, 2008). Despite these efforts total carbon sequestration accounts for only 0.3% of the total volume of carbon trade (Peter-Stanley, 2012).

The potential of carbon sequestration in meeting climate targets depends not only on the size of carbon sink enhancement but also on the costs compared with those of fossil fuel reductions. There is a large body of literature on the calculation of costs of carbon sequestration (see reviews by Sedjo et al., 1995; Richards and Stokes, 2004; van Kooten et al., 2004; 2009; Manley et al., 2005; Phan et al., 2014). Other studies point at considerable cost savings from the inclusion of carbon sink into carbon abatement programs (e.g. Tavoni et al., 2007; Anger and Sathaye, 2008; Bosetti et al., 2011; Michetti and Rosa, 2012; Gren and Elofsson, 2014). However, whether or not these cost savings can be materialized depends on the policy design. Policies targeting carbon sequestration have to deal with specific design problems; additionality, permanence, and leakage. Additionality refers to the difficulty of assessing whether the project would be implemented without the policy in question. Permanence in carbon sequestration during the project period can be hampered by natural causes, such as variation in temperature and precipitation, storms and fires, but also from intentional violation of the rules of the project by, for example, harvesting before the project period expires. Leakage can occur when, for example, land conservation in one region results in forest land conversion in other regions.

Compared with the large body of literature on calculations of cost savings from introduction of carbon sequestration, the literature on efficient policy design is more scant. Capon et al. (2010) presents a thorough discussion on the different design problems for market based instruments on carbon sequestration, and lists a few studies. Fortmann et al. (2014) discuss contract design problems under the REDD system and present suggested solutions to these problem by a few studies. The main purpose of this study is to add to this literature by investigating how the literature in economics contributes to solving the specific problems associated with policy design for carbon sequestration, and how these problems have been solved in practice by existing regulatory and voluntary systems. We then focus on studies directed towards improved carbon sequestration. There are also a number of studies investigating side effects on carbon sequestration or leaching from soil of forestry and agricultural policies, such as subsidies for bioenergy or taxes on emissions of carbon dioxide (e.g. van Kooten et al., 1995), which are not included in this study.

The study is organized as follows. We start by surveying the reviews of studies estimating costs of carbon sequestration, and present studies on cost savings from carbon sequestration introduction. Section 3 contains a presentation of studies addressing one or several of different types of design problems. Solutions to these design problems are to some extent met by increased monitoring of carbon stocks, which results in transaction costs. Studies on transaction costs are presented in Section 4 makes and carbon sink markets in are reported in Section 5. The study ends with a brief summary and concluding remarks.

2. Carbon sequestration costs and cost savings

The estimation of costs of carbon sequestration is a necessary input for determining its potential in relation to other climate change mitigation measures. Starting with Sedjo and Solomon (1989) there is now a large body of literature on the estimation of such cost. The rapid development of this literature has resulted in six reviews on calculations of carbon sequestration costs (Sedjo et al. 1995; Richards and Stokes, 2004; van Kooten et al. 2004; Manley et al., 2005; van Kooten et al. 2009; Phan et al. 2014). Except for Manley et al. (2005) all surveys are relatively broad with respect to coverage of forest activities and regions. In the following, we make a brief survey of these reviews.

Sedjo et al. (1995) carry out a review of a handful studies which consider conversion of land into forests, long-rotation periods, forest management, long-lived wood products, biomass for energy production, and urban forestry. They find that most studies focus on forest plantation and reforestation, and face difficulties when accounting for the dynamics in forest sequestration. The cost estimates vary within and between forests in tropical, temperate and boreal zones. The unit cost ranges from 1 USD/tonC to 90 USD/tonC (in 1995 prices).

Richards and Stokes (2004) make a comprehensive and thorough review of 36 studies on carbon sequestration in forests (plantation, management, and agroforestry) at different geographical scales (global, regional, national, and subnational). They observe a difficulty in comparing results of the studies because of different definitions and measurements of 'a ton carbon'. The definitions differ with respect to the development of sequestration over time, and the methods for estimating the most important cost component, opportunity cost of land, differ (bottom up engineering approaches, sector optimization models accounting for price responses, and econometric approaches based on revealed behavior). The studies also differ with respect to treatment of carbon content in harvests and the use of the harvest products; as building material implying long term carbon sink enhancement or for bioenergy which can be burned and release carbon short after harvesting. When adjusting for these variations they find that the cost per ton carbon sequestration varies between 10 and 150 dollars per ton carbon. These estimates do not include secondary benefits of conversion of agricultural land, such as water purification, which will reduce the cost. On the other hand, costs are increased if leakage effects occur, i.e. that the production on the land converted is replaced by production elsewhere creating carbon sources.

While Sedjo et al. (1995) and Richards and Stoke (2004) compare studies and point out sources for differences in results, van Kooten et al. (2004; 2009) and Manley et al. (2005) carry out meta regression analyses to detect the main impacts. Van Kooten et al. (2004) include 55 studies, and investigate the impact of forest activity(tree planting and agroforestry), use of forest product (wood and bioenergy), type of cost estimate as average or marginal cost, method for calculating opportunity cost of land, and whether the study is subject to independent review or not. They obtain a baseline estimate that varies between approximately 13 and 71 USD/ton CO_2. All factors but post harvesting increase the costs. Peer review studies and marginal cost estimates increase these costs by a factor of 10 or more. When harvest products are taken into account and used for bioenergy or wood products, the cost may decrease by 75%. Van Kooten et al. (2009) is a follow up meta-analysis where the number of studies have been increased to 68, and the results are used to predict carbon sequestration costs in different countries and for different forest sink activities. The explanatory variables include dummies for forest activities (planting of forests, forest conservation, management and agroforestry), geographic scope, cost estimation method, carbon pools (in products, biomass, and soil), type of cost, and age of the study. The marginal cost ranges from near zero to over 200 USD/t CO_2 (in 2005 prices). Locations in tropical regions are found in the lower range, and the higher range costs are found for activities in Europe. Tree plantation and use of harvested biomass for energy seem to be the least costly forest project.

Manley et al. (2005) provide survey studies on costs of carbon enhancement in the agricultural sector, more precisely of no-till cultivation. No-till seems to be the only method creating carbon benefits but the production costs increase because of the need of more chemical inputs and lower yield. They include 56 studies and compare carbon accumulation under two tillage practices; conventional and no-till practice. Two meta-analyses are needed, one for each of these practices, since there are insufficient number of studies on cost of no-tillage. In the meta-analysis of carbon sequestration by the two methods little difference was found between the two methods. This, in turn, implies relatively high carbon sequestration costs unless other benefits accrue to the land owner, which consist of mitigation of soil erosion. By comparing net returns with and without tillage, they arrive at a cost of switching to no tillage which ranges between 1 and 147 USD/ha. Combined with results from the meta-analysis of carbon storage, the estimated cost ranges between 2 and 347 USD/ton C, but can also be infinite when there is no change in carbon accumulation from switching to no tillage.

Phan et al. (2014) make a meta-analysis on 32 studies on avoidance of deforestation in developing countries. The studies estimate net cost of forest conservation, expressed in dollar per ton carbon. This should reflect the opportunity cost of land, which, in turn, is determined by a number of different factors such as profits from alternative use (in agriculture), discount rate, side benefits, and land owners' preferences. The results show that the unit carbon sequestration costs depends significantly on carbon accounting method, location of carbon project, time horizon, carbon storage capacity, allocation of land area, deforestation rate, and share of agriculture of GDP. They found that the avoidance cost ranges between US 0.4/t C and US 171/ton C with an average of 10.3.

In sum, we found that the unit cost of carbon sequestration in the reported studies range between 0 and 443 USD/ton C as measured in 2011 prices (Table 1).

Table 1: List of survey studies, sink activities, and marginal sink enhancement cost, in 2011 prices

Survey study	***Carbon sink activity and geographical scale***	***Marginal cost range, US/ton C***
Sedjo et al., (1995)	Forest plantation and management, global	1.5 – 133
Richards and Stokes (2004)	Forest plantation and management, global	13 – 188
Van Kooten et al. (2004)	Forest plantation and agroforestry, global	4.5 – 24
Manley et al. (2005)	No-till cultivation in agriculture, global	1.5 – 443
Van Kooten et al. (2009)	Forest plantation, forest management, and agroforestry, global	0 – 60
Phan et al. (2014)	Avoidance of deforestation, developing countries	0.4 – 171

Closely related to the studies on unit carbon sink costs are those that calculate gains from introducing carbon sink options into a climate policy, such as a hypothetical carbon trading market (e.g. Jung, 2005; Tavoni et al., 2007; Anger and Sathaye, 2008; Bosetti et al., 2011; Michetti and Rosa, 2012; Gren and Elofsson, 2014). In a trading market, the equilibrium carbon prices are determined where marginal costs are equal for all abatement, including reductions in emissions from fossil fuels and creation of carbon sinks, and the latter is of interest only if its marginal cost is low enough.

The early study estimates global equilibrium carbon prices on a hypothetical market where cost estimates are based on marginal abatement cost (MAC) approach for the energy and carbon enhancement sectors (Jung, 2005). Carbon forestry options are improved forest management, afforestation and reforestation, avoided deforestation, and agroforestry. The equilibrium carbon price can decrease by approximately 80% when all carbon option are included but by only 10% when only agroforestry is considered. Annex B countries make the largest gains from LULUCF inclusions and Non-Annex B countries the largest losses, in particular China which makes gains from CDM projects in renewable energy.

Tavoni et al. (2007) calculate potential cost savings from forest management, afforestation and avoidance of deforestation for meeting the target of 550 ppmv in 2100. This is made by combining a global climate-energy economy model with a global forestry land use model. The former includes endogenous technological development in the energy sector, and the combination with the forest model allows for prediction of forest carbon policies on technological development. This feature relates to the argument against forest carbon put forward by, among others, European Commission (Commission of the European Communities, 2008) that introduction of low cost carbon sink measures would provide an impediment to technological development in the energy sectors. They find that introduction of carbon sink reduces equilibrium prices by approximately 50% and the total costs by 40%. With respect to technological development they show a delay in investment in new cleaning technologies because of the lower costs of carbon forests. Bosetti et al. (2011) builds on Tavoni et al. (2007) but consider only emission reduction from avoided deforestation in a global climate-energy economy model. The results show that the inclusion of deforestation avoidance could reduce total abatement costs for achieving 535 ppm target in 2100 by approximately 25%. Unlike Tavoni et al. (2007) they found a modest impact on technological development in the energy sector. However, the results are dependent of credit banking policy, if restricted the gains from carbon sinks from avoided deforestation are smaller.

Reduced deforestation is also included by Anger and Sathaye (2008) who calculate associated cost savings at the global scale for achieving the Kyoto target of 5.2% emission reduction in 2020. Similar to Tavoni et al (2007) and Bosetti et al. (2011) they link a numerical equilibrium model of the global carbon market with a dynamic partial equilibrium model of the forestry sector. Unique features of the modelling are the consideration of transaction costs and risk of carbon sink investment in host countries. The calculation of country specific risk is based on the risk premium of governmental bonds in relation to that of US government, which is considered to be risk free. Transaction costs and risk enter the model as a risk discount on the cost of avoided deforestation. The results indicate a decrease in equilibrating carbon permit price of approximately 40% and total abatement cost by 35% - even when accounting for conventional abatement options of developing countries under the CDM.

Michetti and Rosa (2011) calculate cost savings from afforestation and forest management in cost effective emission reductions by 20% and 30% in the EU. They do this by introducing forest carbon supply curves into a global computable general equilibrium (CGE) model. They show that the total abatement costs for EU27 are reduced by 26% and 29% for obtaining the 20% and 30% reduction target, respectively. The reductions in equilibrium carbon allowance prices are in the same order of magnitude. They also show that the introduction of the carbon sequestration options reduce the leakage effect because of the lower abatement costs within EU. The increases in emissions outside EU caused by re-allocation of production are approximately 25% lower. However, they did not consider leakage effects associated with deforestation because of higher food prices and change forest practices from higher prices of timber.

Gren and Elofsson (2014) also calculate cost saving for reaching the EU 2020 climate policy from introduction of afforestation and forest management. They construct a model for all EU countries with abatement costs for different fossil fuels, and account for uncertainty in forest sequestration with probabilistic constraints on emission reductions in a chance constrained framework. It is shown that the inclusion of carbon sequestration could reduce overall abatement cost of achieving the EU 2020 climate policy by 40% for a risk neutral social planner. However, there are no savings for high reliability levels, 99% confidence level, because of the high risk discount on carbon sequestration. The risk discount is discussed more in the next Section 4 on policy design.

A summary of the reported studies on calculation of cost savings from introducing carbon sink enhancement into a climate abatement program shows that the equilibrating price can be reduced by 80% and savings can be up to 40% (Table 2).

Table 2: Calculated costs savings from introducing carbon sequestration into a GHG reduction program

Study	*Region and target*	*Options*	*Cost savings from introducing carbon sequestration*
Jung (2005)	Global	All LULUCF potential	Carbon price decrease by 80%
Tavoni et al (2007)	Global, 550 ppmv target in 2100	Forest management, afforestation, and avoidance of deforestation	Total cost decrease by 40%, and carbon price decrease by 50%
Anger and Sathaye, (2008)	Global, 5.2% emission reduction in 2020	Reduced deforestation	Total cost savings by 40%, and carbon price decrease by 35%
Bosetti et al. (2011)	Global, 535 ppm target in 2100	Reduced deforestation	Total cost decrease by 25%
Michetti and Rosa (2012)	EU27, 20% and 30% emission reduction by 2020	Forest management, afforestation	Total cost and carbon price decrease by 25%-29%
Gren and Elofsson (2014)	EU27, 20% reduction by 2020	Forest management and afforestation	Total cost decrease by 0-40% depending on risk aversion

3. Design of policies

Whether or not the gains from introducing carbon sinks into a climate policy reported in Section 2 can be materialized depends on the policy design. It can be argued that the policy design for mitigating emissions from combustions of fossil fuel is relatively easy since the effect on the content of carbon in the atmosphere is the same irrespective of location of the emission sources. This is not the case with carbon sequestration. The impact of carbon sequestration is site specific and depends on several factors such as soil quality, tree species, and local climate. A cost effective policy design then requires that policies, such as subsidies for afforestation, should be adjusted according to the site specific sink enhancement.

Other complicating factors are associated with different types of uncertainty in carbon sequestration. One is the variability in climate which affects biomass growth and thereby carbon sequestration in above and below ground living biomass. Another is the uncertainty created by the difficulty of measuring, monitoring and verifying carbon sequestration. A third uncertainty factor is related to permanence in a created sink, which can be turned into a source from e.g. deforestation after a period of time. Permanence is hampered by risk of natural conditions, such as fires, or intentional by, for example, harvesting of planted trees before expiration of the project. These uncertainty factors in combination with asymmetric information on forest management makes it difficult to ensure additionality by carbon sink project because of the need to measure and establish a baseline and to monitor and verify the increase in carbon sink created by the project and which would not have occurred without the project.

The literature on policy design for carbon sink has met these challenges in three main ways. One is to take uncertainty and heterogeneity among land holders as given and compare the costs of policies with different points of applications, such as area of afforested land, with a first-best design on carbon sink enhancement. In the second approach attempts are made to reduce the problems with uncertainty and asymmetric information by a clever policy contract design. The third approach makes no attempt to find optimal solutions or policy design but instead simulates the effects on carbon pools from exogenously given policies.

3.1 Heterogeneity in space and time

There is a relatively early and large body of literature on the role of heterogeneity which compares total abatement costs under a system with per ton carbon based payment with other payment bases such as area of land or forest practice (Parks and Hardie, 1995; Pautsch et al., 2001; Antle et al., 2003; Fuss et al., 2013; Kim and Langpap, 2014; Haim, 2014). Given that the ultimate purpose is to increase carbon sink, cost effective contracts are obtained only on a per ton carbon basis when sequestration differs among sites. The efficiency losses of per ha based contracts depend on the variability in carbon sequestration per ha among the different sites. These losses can then be compared with the transaction costs of differentiated contracts which need more monitoring and supervision of compliance.

Parks and Hardie (1995) estimate supply functions for forests planted on marginal agricultural land, crop land and pasture land, in the US and simulate and compare costs of a per ha and per ton carbon based policy. A given budget is assumed and the simulations show relatively small differences in total carbon sequestration between the policies, but a larger difference between whether the plantation is on pasture or cropland. Carbon sequestration is at least doubled for establishments on pasture. Different policies with respect to point of application are also compared by Pautsch et al. (2001), but focused on conservation tillage practices which increase the carbon sequestration in the soil in the US. More precisely, they compare per acre and per ton based subsidies payments to all or only new adopters. They estimate a tillage adoption model, which is used for simulating costs under the different policies. Results show, as expected, that a per ton carbon policy is less costly than a single subsidy. However, the difference is relatively small compared with who receives the subsidy; the cost can be almost three times as large under both per ha and per carbon ton subsidy when all adopters receive payments instead of only new adopters.

Antle et al (2003) also calculate efficiency losses of a per ha based system for carbon uptake in cropland soils in the US. They develop a theoretical model where costs are determined by on-farm opportunity cost of land and carbon measurement costs. The numerical application of this model requires an integrated assessment of an econometric analysis of opportunity cost of land and a crop ecosystem model of carbon sequestration. They find that the per ha based contract can be five times more costly than the per ton carbon contract. The measurement costs associated with the latter depends on sampling strategies, but are at least one order of magnitude lower than the efficiency losses for 5% sampling error. The conclusion is thus that it pays for the buyer of carbon sequestration to base payments on per ton carbon sequestration instead of per ha.

Kim and Langpap (2014) calculate and compare costs of different carbon sink policies for improved forest management practices in forests held by nonindustrial private forest owners in the US. They simulate effects of different payments by developing an econometric model of the determinants of farmers' intermediate choice of forest practices (thinning, fertilization, fire hazard reduction). The probability of adoption of a certain forest practice is estimated as a function of different site and socio-economic characteristics. These estimates are used to simulate effects on carbon sequestration from per ton carbon and practice based incentive schemes. They find that the practice based payments for fertilization gives relatively high sequestration. Not surprisingly, they show that the per ton carbon based incentive system gives the largest amount of carbon sequestration. A comparison with other studies shows that their marginal cost of carbon sequestration by intermediate forest practices is relatively large compared with afforestation and reforestation.

Two studies address the question when carbon sequestration should be implemented, early or late in a program period (Fuss et al., 2013; Haim et al., 2014). Fuss et al. (2013) apply a portfolio perspective where the uncertainty in carbon sink is modelled as a positive function of atmospheric GHG and account for possible climate feed-back effects. They construct a global model with a planner minimizing expected abatement costs for achieving a certain cumulative emission target at the latest in the end of the planning period. Abatement measures included are sink enhancements and reductions in emissions. They show that abatement of emissions is always carried out while sink enhancement takes place in later period because of the positive correlation with cumulative emissions which reduces the need for emission reductions, and the constrained availability of carbon sink options.

Haim et al. (2014) develop a theoretical model with two abatement methods; reductions in fossil fuel and creation of carbon sinks, and with uncertainty in climate damage. Due to the potential of carbon sink in reducing the carbon content in the atmosphere, it has a relative advantage over emission reductions since the latter cannot be reduced more than the emissions in a specific year. The authors show that the choice of strategy depends on the changes in the marginal abatement and sequestration costs. When the rate of increase is relatively high in marginal abatement cost (which implies much sequestration capacity), more abatement is carried out in the first period in order to avoid the risk of bad climate outcome in the last period. When instead the marginal sequestration cost shows higher rate of increase (low capacity), it is better to abate less and wait until the second period when state of the climate is revealed and then choose the optimal abatement/sequestration strategy.

3.2 Uncertainty, additionality and permanence

Most of the studies on endogenous policy design have been investigating how to discount for uncertainty in general (Kurkalova, 2005; Benitz et al., 2007; Kim et al., 2008; Kim and McCarl, 2009; Gren et al. 2012; Munnich et al., 2013). A few studies use mechanism design for developing self-enforcing and efficient contracts for carbon sequestration (MacKenzey et al. 2012; Mason and Plantinga 2013; Cordero-Salas et al., 2013). The problem of additionality is then treated in an asymmetric information framework (Cordero-Salas et al., 2013; Mason and Plantinga 2013) and permanence as a moral hazard problem (MacKenzey et al. (2012).

When discounting for uncertainty it is assumed that the social planner holds risk aversion against risky emission reduction and carbon sink outcomes. The value of an uncertainty project, say plantation of trees, is then lower than if the same average emission reduction could be obtained by certainty from fossil fuel reductions. This implies that carbon reductions from enhanced carbon sink and emission reductions from decreases in fossil fuel cannot be exchanged on a one to one basis. Instead, in a trading or offsetting system the discounting implies less value of carbon sink, which implies more average carbon sink enhancement compared with certain emission reduction, the magnitude of which depends on the level of risk aversion and risk in carbon sink.

Kurjalova (2005) develops a conceptual portfolio model for the determination of uncertainty discount, which rests on buyers' maximization of total net benefits from carbon sequestration in a mean variance framework, under a probabilistic constraint on the budget available for purchases. The risk discount is determined by the variance in carbon sequestration, and risk attitudes. An empirical demonstration on a study region in US gives an uncertainty discount of approximately 5% of the expected carbon price.

Another approach is suggested by Benitz et al. (2007) who do not compare forest sink projects with certain emission reductions from fossil fuel decreases but instead calculated relative risk in carbon sink projects among host countries. This is made by calculating the potential and net benefits (including timber and carbon sales) of afforestation on the global scale. Net benefits are then assumed to be risky in proportion to recorded country risks. Optimal allocation of afforestation is obtained in a CAPM (capital asset pricing model), which includes expected profit and risk in excess of the average market risk. Consideration of country risk generates an average risk discount of approximately 100%, i.e. a doubling of the marginal cost of afforestation.

Kim et al (2008) investigate the impact of impermanence in carbon sequestration on carbon prices by comparing prices under risk free conditions with those under risky permanence conditions. They calculate the discount by equalizing the perceived use values of carbon offsets from a perfect offset without any uncertainty with that of forest carbon sequestration under risk. This is made by calculating the cost of a perfect offset defined as the discounted purchasing costs of current and future offsets where the time period is determined by the contract length. The effective price is then defined as the discounted outlays divided by total amount of offsets. The effective price for the impermanent project is calculated in a similar way but adds future costs in terms of buyback of offsets in case of impermanence before the contract expires, maintenance costs of carbon sequestration, and variation in carbon sequestration over time. They then determine the constant permanence discount where the effective perfect price equals the imperfect effective price. The level of the constant permanence discount is then increasing in buyback, maintenance costs, and growth rate in carbon prices.

Another discounting is suggested by Kim and McCarl (2009) where carbon sequestration is expressed in terms of average, confidence interval, and standard deviation. The main empirical questions are then concerned with the sizes of the values of these parameters. They recognize that such data can be obtained from field measurement, biophysical data, or by proxies such as crop yield.

In an application to the East Texas region in the US, the authors use crop yields as proxies, and show that the discount is about 15%-20% of the carbon price.

Gren et al., (2012) and Munnich et al. (2013) calculate the optimal discounting of stochastic forest carbon sink in the EU 2020 climate policy. The policy includes the emission trading system and national allocation plans. Both studies include emission reductions from fossil fuel and apply a chance constrained decision framework where policy makers holds risk aversion against non-attainment of emission reduction targets, which are modelled with probabilistic targets in a chance constrained framework. Similar to Kim and McCarl (2009) the risk discount is determined by the desired confidence level and the standard deviation in carbon sink. In this setting, Gren et al. (2012) show that the discounting of carbon forest on the ETS market is relatively low, approximately 5%. This relatively low level is due to low supply of carbon credits on the market because of the main use of the credits for reducing the relatively high cost of fulfilling the national allocation plans. Munnich et al. (2013) provide, to the best of our knowledge, the only study that investigates the implication of carbon credits for equity considerations. Equity is modelled as a Gini index with different bases, such as cost burden capita and in relation to GDP. They show that the introduction of carbon sinks aggravates equity as measured by Gini index. The reason is that countries with relatively high costs are rich, and they make the largest gains from an introduction of a low cost carbon sink option.

The literature on optimal design of contracts for the creation of incentives for problems associated with additionality and non-permanence is relatively small and recent (MacKenzey et al., 2012; Mason and Plantinga, 2103; Cordero-Salas et al., 2013). Two of them address the additionality problem in an asymmetric information framework where the seller of the project is assumed to have private information on her/his management costs and, hence, the deviations in carbon sink from the baseline at a given offset price (Cordero-Salas et al., 2013; Mason and Plantinga ,2013). The creation of incentive compatible contracts could then, in principle, solve the problem and reveal additional carbon sink. The problem when a principal has less precise information than the agent is that an agent with relatively low management costs could pretend to have higher costs and make more gains from compensation payments. This will cause higher budget costs for the principal, such as governmental expenses for afforestation.

Cordero-Salas et al. (2013) develop a model where the buyer of forest carbon offset offers a two-part tariff contract with a base payment and payments depending on risk of conversion of the forest, and where the parties can renege on or adhere to the contract after its acceptance. An assumption is that the representative seller's type can switch among periods, depending on changing opportunity cost of the forest land. Net social surplus of the contract is determined by the seller's and buyer's surplus minus the carbon mitigation alternative for the buyer. In a first best setting, the buyer will not provide any base payment since it is not related to performance. Under asymmetric information, a certain base payment corresponding to the information rent is needed for ensuring first-best forest conservation of the low cost type. Mason and Plantinga (2013) also use standard mechanism design to identify the optimal contract that ensures acceptance but also creates costs in terms of information rent to the low cost type in order to make him/her to participate and deliver the first-best land use. They apply their model to private land owners in the US, and compare the outcome under optimal contracts with those under a unit subsidy system. The results indicate that the total cost of the optimal contract system would be half of the costs of a unit subsidy for a given increase in forest area.

MacKenzey et al. (2012) investigate the implications for optimal contract design under conditions of non-permanence in forest carbon. With upfront investment and subsequent payments for outputs, there is a risk of opportunistic behavior by the agent in terms of breaking the contract and keep the upfront investment. There also exists a moral hazard problem where the agent may not take due care to prevent fires which release carbon. The agent's incentives to break the contract depend on the opportunity cost of compliance, which is uncertain. The relative weak enforcement institutions in many developing countries with carbon sequestration then makes it difficult for a buyer to trust enforcement of the contract which creates incentives for the agent to break the contract and violate the condition in the contract. They develop a model with imperfect enforcement, and show that an optimal choice of a payment scheme with upfront investment by the principal and a unit price paid by delivery of the carbon sink can ensure permanence. They investigate the properties of the optimal contract under three alternative liability regimes where either the principal or the agent or nobody is responsible for the carbon sink reversal. It is shown that a switch from a practice of buyers' liability to sellers' would improve enforcement of the contract and hence increase investment and carbon sink. Investment may also be higher under no liability compared with buyers' liability, since the buyer does not have to pay any penalty for carbon releases. On the other hand carbon sink may be lower since nobody is held responsible for its realization and associated creation of incentives.

3.3 Simulation of policies

The third type of studies do not investigate properties of efficient policy design, but instead simulate effects on forest management and carbon sink of the introduction of an exogenous policy, such as a subsidy on carbon sink or a tax on forest degradation (Olschewski et al. 2005; Lubowski et al., 2006; Daigneault et al. 2010; Yu et al. 2014). Olschewski et al. (2005) address the issue on the impact of project length on the marginal abatement costs and compares supply and demand for temporary and long term CER (Certified Emission Reduction) under the CDM system. The study is applied to CDM projects in north-western Patagonia. The supply is determined by the provision cost, and the demand by the costs of alternative methods for carbon abatement mainly in terms of fossil fuel reductions. Temporary CER are attractive for sellers since they give flexibility on land use. Long term CER are more attractive to buyers who look for safe and long term solutions. They find that supply prices are well within the range of marginal abatement costs for the potential buyers which create opportunities for transactions.

Lubowski et al. (2006) simulate the effects on carbon storage from a combination of policies promoting carbon sequestration in the US; subsidies on afforestation and mitigation taxes on deforestation. These simulations are made by means of a constructed land use model with probabilities of shifting land use which depend on expected return. This model is combined with a model on carbon storage model which includes litter, biomass, soils, emission at harvesting in forest and agricultural soils. The results show that carbon pools are increasing at a declining rate for higher levels of the taxes/subsidies. For high levels the carbon pools can show a scalloped pattern where they increase under tree growth phases, decrease in the harvesting phase, and then increase again as trees are planted. They also note that forest-based carbon sequestration merits consideration in a cost effective portfolio of domestic US climate change strategies.

Daigneault et al. (2010) investigate whether carbon credits would improve forest management in fire prone regions. To this end, the authors develop a stochastic dynamic profit maximization model to simulate the effects of changing carbon prices on optimal forest management practices for stands facing wildfire risk. The risk of wildfire is endogenous and depends on forest management practice, where thinning mitigates the risk, and at the same time can increase growth rates and mitigate loss of timber and carbon stocks in case of fire. Results from an empirical application to *Douglas-Fir* stands in the US indicate that thinning and shortening rotations are cost effective strategies to mitigate wildfire risk. Carbon prices cause landowners to delay both their thinning treatments and the final rotation age. Thinning and extending timber rotations are thus a viable climate change mitigation option even when stands are susceptible to risks of fire.

The purpose of the study by Yu et al. (2014) is to find the subsidy levels that induce farmers to plant forest on impediment agriculture land in China. They construct a model of optimal rotation for a typical farmer with timber and carbon sequestration as outputs. They then investigate, for given timber prices, how the optimal rotation length will be affected by different levels of a subsidy on carbon sequestration. They find that the subsidy needs to be above 41 USD/year/ha, in order to promote plantation of tree and harvest them after a contract period of 40 years.

4. Transaction costs

Because of the need to monitor and verify carbon sink enhancement the transaction costs of a system including this option can be large. Transaction costs are defined generally as 'costs of running the economic system' that arise from the implementation and enforcement of environmental policies, but to different degrees depending on, among others, type of policy, environmental problem to be addressed, and point of application (e.g Coase, 1960; Arrow, 1969; Dahlman 1977). In spite of the early awareness of the importance of transaction costs, the concept is still vague and different definitions abound. A narrow definition considers only administration costs associated with market transactions, usually borne by public authorities (e.g. Stiglitz, 1986). More recent literature includes private stakeholders and expands on the components of transaction. There is an emerging agreement to distinguish between timing, incumbent, and type of transaction activity (e.g. McCann et al. 2005; Coggan et al. 2010). Although there is large empirical literature on the calculations of transaction costs, the application on environmental policies is scant (McCann et al. 2005). A majority of these empirical studies are carried out for costs for public or private participants. This is most often made for agro-environmental compensation schemes which focus on the administration costs of public participants (see Nilsson 2009 for a review).

In the context of carbon sink, five classes of transaction costs emerge; search and negotiation of contract between buyer and sellers, approval of contract, monitoring and enforcement of contracts. A more detailed representation of these classes of transaction costs is given in Table 3.

Table 3: Classification of transaction costs for LUCF projects for carbon sequestration

Cost	***Buyer***	***Seller***
Search and negotiation	Find sites and contact potential participants • Establish baseline for region • Estimate project offsets • Design individual farm plans • Draft contracts • Provide training	• Attend information sessions • Undertake training • Design farm plan
Approval	• Validate the project proposal • Submit to relevant authority	• Obtain documentation required for participation
Project management	• Establish and run local office • Establish permanent sampling plots • Maintain database and administer payments to landholders • Arrange sale of carbon offsets	• Purchase equipment for measuring trees and sampling soil • Attend project meetings
Monitoring	• Monitor activities against contracts • Maintain carbon inventory • Verify and certify carbon offsets	• Measure carbon stocks • Deliver annual report to project office
Enforcement and insurance	• Maintain buffer of C • Purchase liability insurance • Settle disputes	• Protect plot from poachers and fire • Purchase insurance • Cover legal cost of disputes

Source: Cacho et al. (2013) Table 1

The most investigated item is that of monitoring cost (Cacho et al. 2004; Mooney et al., 2004; Waggoner 2009; Kile, 2009; Macauley and Sedjo, 2011). A few studies cover several transaction cost items (Milne 1999; Galik et al. 2012; Cacho et al., 2014). Mooney et al. (2004) estimate costs for measuring and monitoring carbon in soil, and the magnitude of the transaction cost depends on heterogeneity in carbon soil among farmers, the price of the carbon credit, the desired precision in measurement, and measurement error. An empirical demonstration to farmers' in Montana indicates relatively low monitoring and measurement costs, approximately 3% of the value of a carbon credit. In a review of US Service Forest Inventory and Analysis Waggoner (2009) finds that the annual monitoring costs amounted to approximately USD

24/km^2. Based on similar US data, Kile (2009) estimates a transaction cost that is below 10% of the carbon price without the sequestration offset. Macauely and Sedjo (2011) reports that the costs for improved monitoring ranges between USD 25 and 437/km^2 per year depending on desired precision and monitoring technology.

Cacho et al. (2004) provide an involved study and identify three methods for measuring and monitoring biomass and soil sequestration: computer modelling, remote sensing, and field/site experiments. They define four carbon pools; above and below ground biomass, soil, and necromass, and recognize that it is relatively easy to measure carbon in above ground biomass. There are well developed methods and routines for measuring stands in terms of height and diameter, which can easily be transformed into biomass with allometric methods. The cost depends on desired precision and associated sampling, but an average ranges between USD 11 and 18 per hectare has been recorded. Below ground living biomass, which consists mainly of roots, is more difficult. A common practice is to assume a constant relation, 10%-15%, to the above ground biomass. The measurement of soil carbon requires samples and laboratory procedures, which can be quite costly but can be reduced when combined with modelling. They develop a simple dynamic optimisation problem with harvesting and monitoring costs of different measurement methods for a forest stand in Sumatra. It is assumed that the offset unit is based on reliable minimum estimate (RME), which is expressed in terms of an average above ground biomass adjusted for reliability (95% confidence interval), number of samples, and standard deviation. The monitoring cost depends, in turn, on number of samples, a fixed cost component, and the area under consideration. The optimisation over carbon sinks and number of samples shows that the offered offset unit for sale at a given price is quite sensitive to the monitoring cost.

Extended scope of transaction costs are calculated by Milne (1999) who classifies transaction cost items in a similar way as in Table 3, and makes a brief review of studies estimating transaction costs for forest projects. The review indicates that transaction costs, mainly for certification, ranges between USD 0.5/ha and 80/ha. More importantly, transaction costs are calculated for 11 different case studies on AIJ (Activities Implemented Jointly) forest projects located in Latin America, Asia, and the Russian Federation. Data were obtained from desk studies of the AIJ reports, which give information on expected transaction costs (search, design, negotiation, pre-validation, administration, monitoring and verification). She finds that the expected transaction cost ranges between 6% and 45% of total cost.

Both transaction costs and carbon sequestration costs are calculated by Galik et al. (2012), which they estimate for improved forest management in the US. The sink enhancing forest activities are afforestation, extended forest rotation, and improved productivity, and the transaction cost items include registration, monitoring, and verification. Response surface regression analysis is applied and they find that the median transaction cost is generally less than 25% of total cost, but varies for different project sizes, forest activities, and type of transaction cost. It is relatively large for small projects, afforestation activity, and for establishment of the project base line.

Cacho et al. (2013) note that the presence of transaction costs can be prohibitively high for small land holders. They therefor suggest a pooling of small sellers into one carbon project, with which a buyer can negotiate and purchase carbon credits. A model is developed where the buyer purchases carbon offsets at one price and sell it at a higher price from farmers for a given period of time. Each party will accept the contract only if the benefits minus production and transaction costs are positive. The transaction cost includes all items listed in Table 3 and is increasing in the number of contracts for the buyer. A project feasibility frontier is derived which shows the minimum number of contracts necessary for a purchase to take place at given carbon prices. They then show how this frontier is affected by type of offset payment, purchase or rental, where purchases imply that credits must be redeemed at harvest earlier than stated in the contract, which is not the case for rental offsets. Applications are made on two case studies; small land holders in Indonesia and large land holders in Australia. They differ in opportunity cost of land, being higher in Australia, and transaction cost being largest in Indonesia mainly because of relatively difficulty of monitoring and verification in remote areas. They account for correlations between different transaction cost types. For example, large investment in establishment of baseline carbon and farm plans may reduce enforcement and monitoring costs during the contract period. It is shown that rental contract results in larger minimum project size because initial revenues are small and more contracts are needed for covering fixed costs.

5. Carbon sink policies in practice

Forestry in carbon markets is a relatively new phenomenon, the trading volume of which increased from 2.1 $MtCO_2e$ in 2005 to 14 $MtCO_2e$ in 2011 (Peters-Stanley et al., 2012). It has been introduced within regulatory system with governmental responsibility and as voluntary agreements. Some of these systems in practice have been subject to assessment with respect to their financial viability and land holders' motives to participate. In the following, we give a brief presentation of existing systems and survey assessment studies.

5.1 Carbon exchange systems

Currently, several offset and carbon market systems exist and they treat LULUCF and carbon sequestration in different ways. EU ETS is the largest market, and other markets are found in the New South Wales Greenhouse Gas Abatement system in Australia (GGAS), California cap-and-trade system, Quebec, Kazakhstan, New Zealand, Regional Greenhouse Gas Initiative in the US (RGGI), Québec, and Tokyo, Saitma and Kyoto in Japan (see World Bank 2013 for an overview). In addition, there exist a number of different voluntary (non-governmental) mechanisms, mainly through OTC (over the counter trading). A few of the regulatory systems allow for carbon sequestration; New Zealand, California cap-and-trade system, RGGI, and

Australia. The largest carbon market, EU ETS which accounts for 77% of the carbon trade, does not allow for carbon sequestration at all (Table 4).

Table 4: Volume and value of carbon and forest carbon markets in 2011

	Total: ***Volume, MtCO$_2$e***	***Value USD million***	***Forest:*** ***Volume MtCO$_2$e***	***Value USD million***
EU ETS	7853	147848	0	0
CDM	2113	26570	5.9	23
Others, NZ, GGAS, RGGI	228	1033	1.5	29
Regulatory, total	10094	175451	7.4	52
Voluntary OTC (over the counter)	93	572	16.7	172
CCX and others within an abatement system	2	17	1.6	13
Voluntary, total	95	589	18.3	185
Total	10199	176040	25.7	237

Sources: Peter-Stanley et al. (2012), Ascui and Neeff (2013)

In total, forestry carbon accounts for 0.3% of total trade carbon volume and for 0.1% of the value. A vast majority, 71%, of this forest carbon is exchanged by voluntary systems, in particular OTC which accounts for 65% of total forest carbon exchange. Most of these voluntary exchanges invest in REDD projects (Peter-Stanley, 2012). The second largest forest carbon actor, CDM of the Kyoto Protocol allows only for afforestation and reforestation in developing countries as legible credits for certified emission reductions, corresponding to 1% of the carbon emissions in the base year. Due to the dominance of these two project types and the restriction on carbon sink in the European climate policy, a vast majority of the buyers but a minority of project locations are found in Europe (Figure 1).

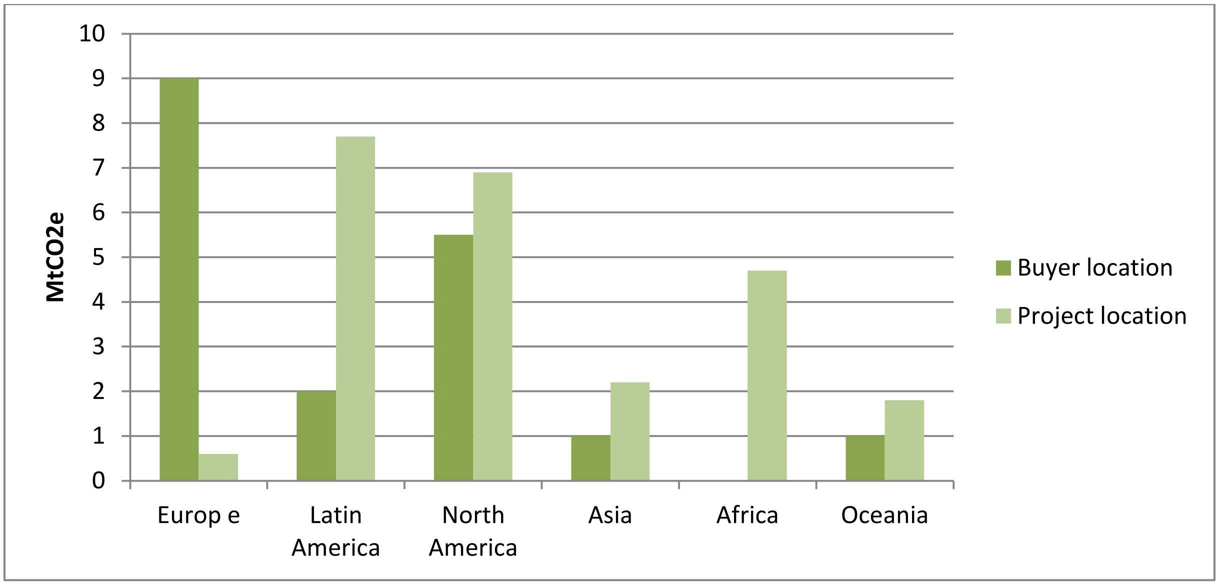


Figure 1: Allocation of carbon sink trades in 2011 among buyers and sellers, $MtCO_2e$
Source: Peters-Stanley (2012), Figures 21 and 40

The specific policy design problems for carbon sequestration have been met in different ways in the systems. Within the CDM system, permanence is dealt with by distinguishing between two types of certified emission reduction (CER); temporary and permanent. The temporary credits expire every 5 years, and then have to be renewed.

New Zealand was the first country to include carbon sink into a carbon market system. It was established in 2008 and did in the beginning contain only forest, where all forest owners had to participate. One reason could be the unique role of agriculture and forestry sectors which account for 48% of the total GHG emissions (Jiang et al., 2009). Two years later, all GHG emitting sectors were included. In this way, the problem of leakage could be avoided. The New Zealand Unit is comparable with the Kyoto Units and can thus be sold or bought, not only on the New Zealand market, but also in the international market. The system contains two parts for forest owners: NZ ETS forestry for short rotation timber plantations and Permanent Forest Sink Initiative for ensuring long term carbon conservation (Belton, 2012). The PFSI was designed to meet the permanence problem by setting minimum sustainable timber harvest under 99 years, liability in case of carbon release, and permission to withdraw after 50 years subject to replacement of carbon stock. The land owner is responsible for carbon releases during the contract period, and insurance systems have developed to meet unintentional releases. Measurement of carbon pool is carried out every 5 year.

Streck et al. (2009) describe how the regulatory systems New South Wales Greenhouse Gas Abatement system in Australia (GGAS) and the Regional Greenhouse Gas Initiative in US (RGGI), and the voluntary Chicago Climate Exchange (CCX) deal with the monitoring, verification, and permanence problems in their inclusions of forestry carbon offset. GGAS includes only A/R, and an eligible project must be accredited under GGAS. Participants must demonstrate that the carbon sequestration offsets can be maintained for 100 years. Uncertainty is addressed by the requirement that the probability of exceeding the specified carbon offset must in any period be at least 70%. The RGGI constitutes a cooperation among ten states in the US for the purpose of running a cap-and-trade system, which is the first system of its kind in the US. Both agriculture and forest sequestration in the US are allowed as offsets in the system. The amount of allowable offsets depends on the carbon allowance price, and reaches a maximum of 10% of total carbon at a high allowance price. Permanence is required by the conservations of land for carbon sequestration in perpetuity. An uncertainty discount is introduced by the deduction of the total carbon offset in the project by 10%, which could be waived if the owner retains an insurance against carbon releases.

The voluntary CCX is a US program with members accepting legally binding commitments to reduce their GHG emissions, which can be traded among the members. Offsets projects include carbon sequestration projects within and outside the US. The scope of eligible sequestration project is relatively large by including forest management, A/R, avoidance of deforestation, and urban trees. The projects must be verified by a CCX approved verifier, and permanence is required by long-term commitments. Similar to RGGI an uncertainty discount is introduced which corresponds to 20% of the forest offsets. These are saved in a buffer pool, and returned to the owner of the project at the end of the contract period.

The Verified Carbon Standard (VCS), which is used by many voluntary project based exchanges, was set up in 2005 by non-governmental organizations including the Climate Group, the International Emission Trading Association, The World Economic Forum, and the Business Council for Sustainable Development (Ascui and Neeff, 2013). It is the major standard in the voluntary markets and accounts for 58% of the transaction volume in 2011. The land management segment includes almost all types of projects; A/R, REDD, forest management, avoided conversion of grass and shrub lands, and wetland restoration and conservation. Permanence is ensured through a buffer requirement where the project receives a percentage of the total carbon offsets and gives the rest to a central administrator of the buffer pool. The project can claim back the offsets in the pool if there is no carbon reversal.

In addition to the VCF other standards operate on the voluntary markets with the Gold Standard (GS) and Climate Action Reserve (CAR) being the largest in terms of market share (12% each) of the trade volume (Ascui and Neeff, 2013). The Gold Standard was set up in 2003 by environmental non-governmental organizations and led by WWF. This standard includes a large number of sustainability requirements in addition to carbon emission reduction, and forestry carbon offsets where included from 2013. The purpose of CAR is to establish necessary infrastructure for carbon offsetting schemes in the North American carbon markets.

5.2 Assessments of carbon sink systems

Studies evaluating existing systems with carbon sink offsets have focused on two aspects; *i)* financial viability of carbon offset projects (Jindal et al., 2008; Manley and Maclaren, 2012; Kerchner and Keaton, 2014), and *ii)* land holders' motives to participate in such programs

(Fletcher et al., 2009; Gong et al., 2010; Dickenson et al., 2012; Miller et al., 2012). A more unusual topic has been provided by Conte and Kotchen (2010) who analyze the determinants of equilibrating prices of carbon offsets in voluntary markets.

Jindal et al. (2008) survey 23 voluntary and governmental carbon offset projects implemented in three Eastern African countries (Tanzania, Kenya, Uganda). These projects differ with respect to project size, benefit sharing with the community, potential carbon sequestration and method (forest conservation, management, or A/R). Most projects are non-Kyoto compliant and represent voluntary emission reductions. They find that seemingly promising projects with respect to carbon sequestration and income provision to the local communities are constrained by insecure land tenure. The local communities face the risk of loosing access to forests, which hampers the incentives to implement offset projects. The authors also point to the high transaction costs associated with smallholder projects.

Two studies evaluate effects on forest management and carbon sequestration in regulatory carbon sequestration programs (Manley and Maclaren, 2012; Kerchner and Keaton, 2014). Manley and Maclaren (2012) evaluate the effect on forest management of the New Zealand emission trading system, according to which forest owners receive units for increases in carbon stocks of their plantations. Effects on choice of species, rotation lengths, and new plantations are included and the results show that profits can increase also when considering the surrender of units when harvesting. However, they emphasize the importance of carbon price risk and suggest a hedging policy where part of the received units is traded for a valuable crop and the other part is sold when carbon units are surrendered. Kerchner and Keaton (2014) investigate the financial viability of 25 family landowner projects in the California's Air Resource Board. Key factors were property characteristics, silviculture treatment, and protocol and legislative requirements. They found that carbon stocking and size of the property were the main determinants of return for the forest owners. Other findings were the importance of transaction costs in terms of long term monitoring costs, and uncertainty associated with carbon policies.

In the second class of evaluation, land owners are interviewed or respond to questionnaires on their motives for participating in regulatory programs (Fletcher et al., 2009; Gong et al., 2010; Dickinson et al., 2012; Miller et al., 2012). Except for Gong et al. (2010) all studies are carried out with land owners and carbon markets in the US. A relatively early study interviewed family forest owners' in Massachusetts on their attitudes to four main attributes; compensation payment, contract length, requirement of management plan, and enforcement of withdrawal penalties (Fletcher et al., 2009). Not surprisingly, it was found that level of payments, lack of management plans and enforcement penalties had a positive effect on the willingness to participate. Similar attributes were included in a questionnaire survey by Dickinson et al. (2012) in the same state, but with a much larger sample of forest owners. The results confirmed those of Fletcher et al. (2009) and did reveal a relatively low participation interest. Miller et al. (2012) carried out a survey to family forest owners in the Lake States region of the US (Michigan, Minnesota, and Wisconsin) in order to estimate the explanatory power of different variables for the probability of participation in a carbon market. The explanatory variables included payment, contract length, parcel site, previous harvesting, and socio-economic variables such as income, gender, and education. They found that the single most important explanatory variable was payment, higher payment generates higher probability. Contract length was also significant with a negative sign, i.e. shorter period increased the participation probability. .

Gong et al. (2010) provides a rare study on participation motives outside the US. They investigate why so few areas remain un-forested under a CDM project in China, the first of its kind. They note that in addition to the uncertainty associated with carbon sequestration as such, farmers face risks with vaguely defined property rights, uncertain governmental policies and carbon market prices. Cooperation among small holders may then be an alternative to individual contracts because of the possibility of sharing risk and transaction costs. In interviews and surveys to different groups of smallholders they found that the groups with collective action reduced transaction cost considerably.

The determinants of prices in actual carbon markets were analyzed by Conte and Kotchen (2010). They carry out an econometric analysis with a hedonic model of carbon offset prices on the voluntary markets. Based on project data at the Carbon Catalog (CC) they were able to regress prices of offsets on different attributes; type of offset (wind, solar, forestry carbon, etc), developed, developing, and least developed country, CDM, GS or VCS verification. They found that a forestry carbon project reduces the carbon price, and that developing countries increases it. The lower forestry carbon price could be explained by the uncertainty and/or permanence discount attributed to these projects. Another result is that VCS verification reduces price and the CDM and GS increases it. This can be explained by the fact that certification of the two latter qualifies for emission reductions under the Kyoto Protocol. A further analysis of the determination of only the forestry carbon prices, which amount to 40% of all included projects, shows that forestry projects in developing and least developed countries are subject to substantial price reductions, up to 70%, which may reflect the particular uncertainty associated with week enforcement institutions in these countries.

6. Conclusions

The purpose of this study has been to review the literature in economic on incentives for promoting carbon sequestration. The most early and largest part of this literature calculated costs for carbon sink enhancement, which are reported in several survey studies. The summary of these surveys made in this paper pointed at marginal carbon sequestration costs that range between 0 and 443 USD/ton C (in 2011 prices). The low costs are attributed to the side benefits obtained by the land holders, and include most often forest plantation, while improved forest management is a more costly option. However, whether or not carbon sequestration is of interest for inclusion into a climate policy depends on the marginal costs in relation to those of other abatement measures, such as reductions in fossil fuels. The findings of the survey in this study show large variations in cost savings from including carbon sequestration for reaching given carbon reduction target; they can range between 0 and 40% depending on target reduction and spatial scale.

However, the materialization of cost savings depends on policy design. The specific difficulties associated with the policy design for carbon sequestration are associated with the site specific sequestration conditions, uncertainty in sequestration, additionality, permanence, and leakage. The literature on policy design is relatively small compared with that on calculations of costs of carbon sequestration and cost savings from its inclusion into a carbon program, but more diverse in scope. It can be classified into three categories; *i)* comparison of first and second best policies for heterogeneous land holders, *ii)* treatment of uncertainty in carbon sequestration by discounting, and *iii)* contract design for attaining first best solutions.

The major part of the literature is found in the first category where the approach has been to calculate and compare total costs of reaching carbon target in a first best setting where the policy is differentiated with respect to carbon sequestration with a second best policy based on per ha compensation. Large differences would justify transaction costs from improved monitoring and measurement. Most studies arrive at relatively small differences in costs, i.e. efficiency losses, of a second best policy. The main approach in the second category has been to calculate a discount on carbon sequestration based on its uncertainty in relation to a certain emission reduction. The calculated discounts range between 5% and 30% of the value of a certain reduction. We found the smallest body of literature in the third category. Here, the problem of additionality is modelled in an asymmetric information framework where the land holders are incentivized to reveal information on carbon sequestration in the projected land area. The problem of permanence is modelled in a moral hazard framework where the land holders are given incentives to manage land in order to mitigate risk of carbon release.

Despite the important role of monitoring and verification for the implementation and enforcement of carbon sequestration projects, there are relatively few studies calculating associated transaction costs. The results of these studies indicate that the monitoring and verification costs are modest. When other types of transaction costs are considered, such as search for projects and negotiations, the transaction cost can correspond to 25% of total cost. The relatively low transaction costs can then motivate a first best policy design based on ton carbon sequestration although the efficiency losses of a second best policy were found to be modest.

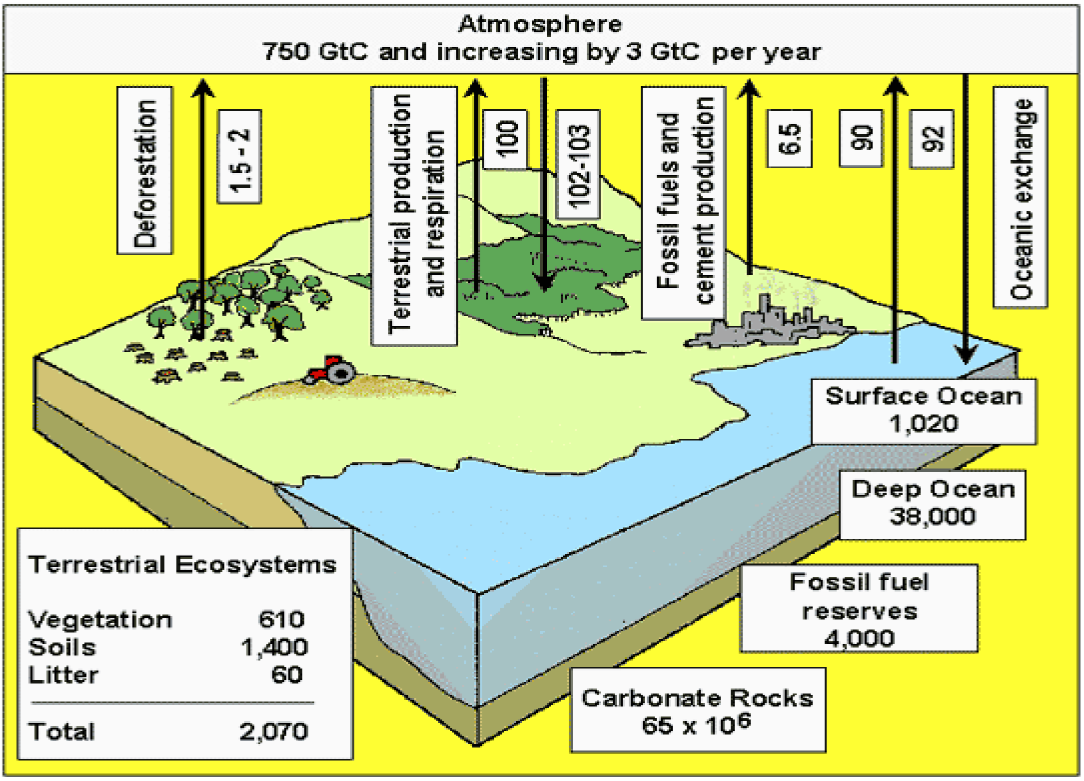
It is interesting to note the rapid increase in trade with carbon sequestration in practice; it has increased by six-fold since 2005. However, it accounts for only 0.3% of all carbon trade, which is due to the illegibility of carbon sink in the largest market in the world, the EU emission trading system. The main part of the carbon sequestration trade, 66%, is voluntary, usually on a project by project base. The CDM under the Kyoto protocol is the largest regulatory system, which accounts for 23% of the total carbon sequestration trade. Common for both regulatory and voluntary systems is the use of authorized bodies for monitoring and verification of carbon sequestration.

When comparing the solutions to the specific policy design problems suggested in the economics literature with those implemented in practice we find both similarities and differences. Common in both the literature and practice is the uncertainty discounting. Market prices of carbon sequestration are lower than for corresponding carbon reductions from measures reducing fossil fuel emissions. Another similarity is the lack of approaches to mitigate the leakage problem, which seems to have been tackled only in the New Zealand system which requires the participation of all forest owners. A difference is the lack of sophisticated contracts based on mechanism design for addressing the problems of additionality and permanence in practice. Instead, these problems have been met in practice by the creation of offset buffers where a part of the carbon sequestration in a project is saved and surrendered at the end of the project period in case of no release.

However, studies evaluating carbon trade in practice note that weak enforcement of projects in several developing countries is a serious impediment to the implementation of the full potential of carbon sequestration. Design of contracts creating incentives for self-enforcement can then be of more practical relevance in the future, in particular since many of the low cost options for carbon offsets are found in the developing countries. On the other hand, carbon projects are relatively rare in developed countries, in particular in Europe, with stronger enforcement capabilities. Insights from the economics literature and lessons learned from carbon sink projects in practice could contribute to an exploitation of the low cost potential of carbon sink enhancement in the climate policy in these regions.

Appendix

Figure 1: A simplified diagram indicating carbon pools and CO_2fluxes between the earth and the atmosphere



Source: *Edinburgh Centre for Carbon Management* (http://www.eccm.uk.com/climate.htm)

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Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Economics
Swedish University of Agricultural Sciences (SLU)
P.O. Box 7013, SE-750 07 Uppsala, Sweden
Ph. +46 18 6710 00, Fax+ 46 18 67 35 02
www.slu.se
www.slu.se/economics

Institutionen för ekonomi
Sveriges lantbruksuniversitet
Box 7013, 750 07 Uppsala
Tel. 018-67 10 00, fax 018 67 35 02
www.slu.se
www.slu.se/ekonomi