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Methods

Analysis of the carbon sequestration costs of afforestation and reforestation agroforestry practices and the use of cost curves to evaluate their potential for implementation of climate change mitigation

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ABSTRACT

Carbon sequestration in forest sinks is an important strategy to remove greenhouse gases and to mitigate climate change; however its implementation has been limited under the Clean Development Mechanism of the Kyoto Protocol which has not created the incentives for widespread implementation. The objective of this paper is to analyze the sequestration costs of agroforestry afforestation and reforestation projects (ARPs) following a partial market equilibrium using average cost curves and economic break even analysis to identify the supply costs. The modelling done in this work contrasts the voluntary and clean development mechanism transaction costs. Data is based on the voluntary project, Scolel Té, being implemented in Mexico. Cost curves are developed for seven different sequestration options considering transaction and implementation costs; information from agricultural production in Chiapas Mexico is used to integrate opportunity costs of two agroforestry practices suggesting that sequestration costs may follow a "U" shape, with an initial reduction due to economies of scale and a subsequent increase caused by high opportunity costs. The widespread implementation of agroforestry options not requiring complete land conversion (e.g. living fences and coffee under shade) might be cost effective strategies not generating high opportunity costs. Results also suggest that payments in the early years of the project and lower transaction costs favour the development of ARPs in the voluntary market especially in marginal rural areas with high discount rates.

1. Introduction

The use of carbon sequestration projects to mitigate climate change is limited to a small fraction of their potential biological capacity due to technical, political and socioeconomic factors such as difficulties of establishing measurement methodologies, non-permanence of carbon in forests, high land opportunity costs, and the transactions costs generated by a weak and complex climate agreement in the Land Use Land Use Change and Forestry (LULUCF) sector (Dixon et al., 1993; Bass et al., 2000; Richards and Andersson, 2001; Van Kooten et al., 2007; Schlamadinger et al., 2007). Moreover the use of different methods, concepts and terms when costing carbon sequestration activities has complicated comparison of estimates from different projects and studies (Richards and Stokes, 2004). These shortcomings have prevented generation of the appropriate incentives to implement extensive afforestation/reforestation projects (ARPs). However projects being developed in the Clean Development Mechanism (CDM) and voluntary markets indicate that the information, knowledge and capacities required to implement the projects can be developed, though large initial costs need to be covered. Hence after a political decision is taken to develop these activities as part of a strategy to mitigate climate change, a challenge remains: the supply costs of carbon sequestration activities need to be understood and analyzed within their socioeconomic context, in order to generate appropriate policies and incentives to implement these activities extensively enough to cause significant reduction in greenhouse gases.

The objective of this article is to analyze the carbon sequestration costs of agroforestry ARPs to contribute to the understanding of the factors determining supply costs and potential implementation under market-based mechanisms. This information is necessary to help identify the carbon prices required to encourage uptake of agroforestry ARPs as part of a strategy to mitigate climate change using incentive based mechanisms. This paper builds on work done in the costing of carbon sequestration (Richards and Stokes, 2004) and the use of cost curves to identify potential implementation limits (De Jong et al., 2004, 2000; Cacho and Lipper, 2007). We follow a partial market equilibrium analysis to calculate the average net present value

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(ANPV) of a project as function of carbon price and project area to derive cost curves at constant ANPV (*iso*-NPV). Break even analysis is used to identify the minimum output that a project should deliver in terms of hectares planted under a certain carbon sequestration practice considering implementation and transaction costs. This model is used to analyze the effect of discounting in marginal areas under the CDM and voluntary market schemes and the implications for ARP adoption. We also present a sensitivity analysis of individual variables in the cost; and finally we consider opportunity costs of agricultural activities in Chiapas, Mexico to estimate the total sequestration cost expected when adopting two agroforestry practices over an area of 1,000,000 ha.

Information used for the modelling is based on the Scolel Té project developed in Chiapas since the mid 1990s. A visit was made to Mexico in the summer of 2007 to verify the information used in the modelling and interview project coordinators and a group of participating landowners. This article is structured as follows: Firstly relevant background information is presented; secondly, the theoretical framework for the construction of the *iso*-NPV cost curves is explained followed by the data used and assumptions for the modelling; thirdly the results of the modelling, sensitivity analysis and the case study of Chiapas are presented and discussed; and finally the conclusions are presented.

2. Background

2.1. Valuation of forest carbon services

Following the principles for sustainable development suggested by Daly (1990),[1] knowledge on the assimilation of greenhouse gases (GHG) into carbon sinks is critical to set the level by which carbon emissions should be reduced. Hence both strategies of reduction of emissions and carbon removals are complementary activities to achieve the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC). Lack of compensation for forest services, including carbon sequestration and storage, causes an underinvestment in this sector that reduces the provision of these services (Landell-Mills and Porras, 2002). In order to address this market failure, efforts to realise the economic value and create incentives for carbon sequestration in biomass via ARPs have emerged in the CDM and voluntary carbon markets. Market-based mechanisms are used, aiming for an efficient allocation of limited resources by setting the carbon price through the equilibrium between demand and supply. The use of market mechanisms could create a win–win situation where buyers and sellers obtain the consumers' and producers' surpluses respectively, thus generating incentives for participation among both groups of actors.

ARPs are being developed in both the compliance (Kyoto Protocol obligations) and voluntary carbon markets, but participation is marginal despite the potential for huge implementation.[2] Currently, there are 39 ARPs in the CDM pipeline from which 6 are registered with no temporal certified emissions reductions issued yet. ARPs may encompass roughly 1% of the projects by number and 0.40% of expected certified emissions reductions (CERs) by 2012[3] (UNFCCC, 2009; UNEP, 2009). The voluntary market is smaller in size accounting for 5% of the compliance market; however it is also dynamic with a growth rate of 200% in volume and 279% in value during the period 2006–2007; the share of forestry projects in the voluntary market in 2006 was 36% (Capoor and Ambrosi, 2008; Hamilton et al., 2007). However, information on the voluntary market is less certain than on the compliance market. According to these statistics the share of forestry projects, combining projects in the voluntary and compliance markets, would account for less than 2% of the expected emissions reductions; but it is expected that carbon offset markets will continue growing (Kollmuss et al., 2008). Changes in the LULUCF regulation are expected, possible and desired for the post-Kyoto commitments to improve participation of this sector in the efforts to mitigate climate change (Schlamadinger et al., 2007). Reforms may include the CDM scheme and a new mechanism to value reduced emissions from deforestation and forest degradation (REDD). In order to generate the appropriate incentives for carbon sequestration it is paramount to identify the supply costs that may allow implementation of these activities.

2.2. Costing carbon sequestration

The costing of ARPs is not a straightforward process. Reported costs typically range from 1 to 8 \$/ton-C,[4] however extreme values in different studies range from 0 to 1778 \$/ton-C (Van Kooten et al., 2007) or even 6070 \$/ton-C (Richards and Stokes, 2004); Richards and Stokes (2004) conclude that estimates were hardly comparable due to an inconsistent use of definitions, assumptions and methods. Analytically they identify the flow summation method, average storage method and levelization/discounting method to model carbon sequestration. In order to favour comparability Richards and Stokes (2004) indicate studies should describe the practices to be implemented and the sequestration pathway on the long term; the baseline without the project, the geographical scope and description of the costs; all information and assumptions related to the methodology should be made explicit. Moreover they recognize that the most important factor in costing, and the most difficult to assess, is the opportunity cost of land.

Another difficulty when comparing cost estimates is that projects incur initial costs that usually are not considered when carbon payments are negotiated. This is explained because many of the pioneer operating projects received research or international grants as seed capital which did not have to be recovered. In other cases, these initial costs were covered by governmental agencies. However if total costs are not considered, similar projects would not be replicated and agencies financing the initial costs of the projects would have subsidized the continued GHG emissions of the carbon buyers, mostly in developed countries. Furthermore if the total sequestration cost is unknown it is difficult to estimate if carbon suppliers are accessing the producer surplus when participating in the markets.

Depending on the activity that generates the costs, they can be classified as implementation, transaction and opportunity costs (Wunder et al., 2008).[5] Methodologically costs can be assessed as simple point estimates, or calculated following a partial or full market equilibrium; in a partial market equilibrium a cost function is derived where the prices of inputs are held constant (Kauppi et al., 2001). Thus cost curves can be generated from this function to show the variations in total sequestration cost (\$), average cost (\$/ton-C, \$/ton-C/year) or marginal costs (\$/ton-C) as function of the area of the project (ha) or the sequestration potential in a region (ton-C). We construct curves using the average cost because it shows the effect of initial costs required to establish the project. In the modelling we consider that a nongovernmental organization (NGO) coordinates several landowners who decide to implement the ARP on their land if they find it attractive. Most of the transaction and coordination costs

[1] The harvest of renewable resources should be equal to the regeneration rates, and the emissions of a pollutant should be equal to the assimilation rates of the ecosystem to avoid the consumption of natural capital (Daly, 1990).

[2] Available area for ARP would be 790 MHa in non-Annex I countries (Zomer et al., 2008). Natural vegetation might be able to sequester 25–30% of expected emissions in 1990–2100 (Beerling and Woodward, 2004).

[3] Temporal lCERs or tCERs for ARPs.

[4] All monetary units are expressed on \$US unless specified; 1 ton-C is equivalent to 3.67 ton-CO_{2e}.

[5] Measures of welfare trade-offs when shifting land use and changing goods/services delivered to society can be included see Alig et al. (1997) and Adams et al. (1999) for an example of these estimations.

are covered by the NGO while the implementation costs are faced by the landowners. This is the model followed by Scolel Té and the coordinating NGO Ambio. This approach has been also suggested to enable landowners to participate in the carbon markets (Black-Solís et al., 2004; Cacho and Lipper, 2007). We aggregate the costs faced by the NGO and the landowners along with local opportunity costs to integrate the supply cost curves.

Cost curves are used to assess carbon sequestration potential and so help in decision making at policy and project levels. De Jong et al. (2000) estimated the potential of carbon sequestration through agroforestry and forest management in Chiapas as function of the incentives, finding a potential of 1 to 38 Mton-C for incentives within \$5–15/ton-C in a study area of 600,000 ha. De Jong et al. (2004) show that the share of fixed cost required to develop an agroforestry sequestration option are reduced to about 7% of hypothetical revenues when the sequestration potential of the project is 55 kton-C with payments of \$13/ton-C. Cacho and Lipper (2007) modelled the interactions between a buyer organization and a group of landowners to identify the characteristics of viable ARPs. They generated cost curves of the project feasibility frontier for ARPs showing the carbon sequestration potential as function of carbon price showing the effect of economies of scale. For carbon prices ranging from \$20 to \$30/ton-C and constant opportunity costs, viable projects would range from 65 to 33 kton-C.[6] In this work we identify the expected carbon sequestration supply costs and potential implementation within a region through the generation of costs curves for different agroforestry activities using break even analysis. The following section describes the rationale used in the construction of the model and data used in this exercise.

3. Methodology and data

3.1. Analytical framework

Break even analysis is commonly used in the private sector to determine the minimum amount of output that a firm should produce and sell in order to cover all the production costs. In order to adapt this approach to ARPs, once the geographical limits of the project, the feasibility studies, the baselines and methodologies for a carbon sequestration option are set, we assume the production unit that a project can deliver is the number of hectares adopting a given sequestration practice. Solving the general break even equation where revenues are equal to total costs, it is possible to obtain the minimum viable area of the project (Eq. (1)):

$$S = \frac{C_F}{p_C \times CS - C_V} \tag{1}$$

where S is the area implementing carbon sequestration practices (ha), C_F are the fixed costs (\$), p_C is the carbon price (\$/ton-C), CS is the carbon sequestered (ton-C/ha) and C_V are the variable costs (\$/ha). All values refer to costs and carbon sequestered over the full length of the project. From Eq. (1) it can be seen that in order to have viable projects the marginal income per ha ($p_C \times CS$) should be bigger than the variable costs, considering homogenous variable costs across landowners (marginal utility>0); otherwise the denominator would be negative, generating economic losses, or zero, not recovering fixed costs. The options with lower sequestration potential could be implemented by increasing the marginal utility at the required levels either by reducing the variable costs, increasing the accuracy of methodologies to claim more carbon sequestered, or by negotiating higher carbon prices. It can also be seen that when the marginal utility increases, or the fixed costs are reduced, the size of the minimum viable project decreases.

However, in order to access the producer surplus, as market mechanisms intend, suppliers in ARPs should not only recover all the costs but also obtain a profit. Then the economic performance of ARPs can be evaluated using the net present value generated by the project which is estimated as the difference of total discounted benefits and costs over its whole duration. Average net present value (ANPV) is obtained per hectare per year (Eq. (2)). ARPs with negative ANPVs would not be implemented, while those with zero or positive values are regarded as viable and if they generate an operative utility may indicate access to the producer surplus.[7]

$$\begin{aligned} ANPV = {} & \frac{1}{T} \times \sum_{t=0}^{T} \rho^t \left\{ p_{C,t} \times CS_t \right\} \\ & - \frac{1}{T} \times \sum_{t=0}^{T} \rho^t \left\{ \frac{(I_{F,t} + T_{F,t})}{S} + I_{V,t} + T_{V,t} + Op_t \right\} \end{aligned} \tag{2}$$

ANPV	Average net present value (\$/ha-year)
t	time (years)
T	duration of the project (years)
ρ	discounting factor, $\rho = (1+\delta)^{-1}$, δ is the discount rate.
$I_{F,t}$	Implementation Fixed Cost in year t (\$/project)
$T_{F,t}$	Transaction Fixed Cost in year t (\$/project)
$I_{V,t}$	Implementation Variable Cost in year t (\$/ha)
$T_{V,t}$	Transaction Variable Cost in year t (\$/ha)
Op	Opportunity Cost in year t (\$/ha)
S	Project Area (ha/project)
$p_{C,t}$	Carbon price paid at time t (\$/ton-C)
CS_t	Carbon sequestrated from $t-1$ to t, (ton-C/ha)

We use a single discount rate representing the marginal conditions of landowners in poor rural areas; however we need to recall that some costs are faced by the landowners and others by the coordinating NGO which may have a lower discount rate. We decided to use a single discount rate and so state the time preference in marginal areas because resources used for the project could have been used to cover other local needs and most of the costs faced by the coordinating NGO occur in the first years of the project and so are less sensitive to changes in the discount rate. For an analysis using two different discount rates for the landowners and the coordinating NGO see Cacho and Lipper (2007).

Once the methodologies for an ARP have been developed, ANPV in Eq. (2) can be analyzed as a function of p_C and S considering all other parameters as constants. For an initial analysis of the behaviour of sequestration costs, opportunity costs are set constant at zero. Then ANPV can be plotted for a sequestration option as function of carbon price and project area (Fig. 1). The ANPV surface indicates that for projects which adopt small areas and negotiate low carbon payments, the ANPV obtained would be negative. Conversely when projects are implemented across larger areas and with high carbon income, projects would have positive and higher ANPVs. In order to identify viable projects according to the break even criterion, ANPV is set equal to zero. Thus after developing the summations, Eq. (2) can be solved to determine p_C, which will be equal to the average sequestration cost, as a function of S (Eq. (3)). S is proposed as the independent variable because we consider that the project is coordinated by an NGO with more opportunities to engage landowners to increase a project's area

[6] When implementing activities with a potential of 89.3 ton-C/ha over an area from 366 to 732 ha (Cacho and Lipper, 2007).

[7] Carbon revenue is considered in the model as the only benefit, additional terms can be included for timber, non timber forest products, increased agricultural yields or benefits from local environmental services if they are part of the project.

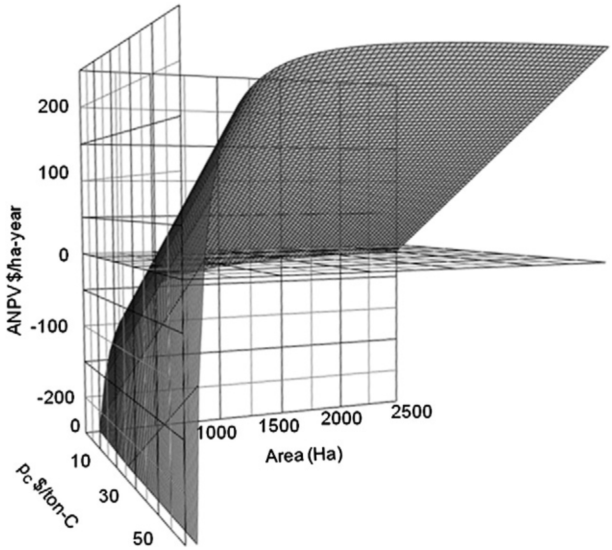

Fig. 1. Expected shape of an ANPV surface as function of p_C and ARP area for a single sequestration option.

than opportunities for negotiating higher carbon prices which may be a function of international markets.

$$p_C = \frac{1}{CS}\left[\frac{(I_F + T_F)}{S} + I_V + T_V + ANPV\right] \tag{3}$$

When ANPV is equal to zero, Eq. (3) is equivalent to Eq. (1), and generates the cost curves in the two dimensional plane generated when Fig. 1 is 'cut' at ANPV = 0 with p_C and S on the axes. As in the project feasibility frontier defined by Cacho and Lipper (2007), the p_C–S relationship shows the pairs of carbon prices and projects areas needed for viable projects assuming that if costs considered are covered, the project would be implemented. Eq. (3) shows the inverse relationship between S and p_C and the changes in costs due to economies of scale associated to the project's area and fixed costs. ANPV can be set at any positive value in Eq. (3) to obtain a desired utility per ha per year to improve landowners' conditions.

From the previous analysis, average sequestration costs would decrease towards the variable cost due to economies of scale when implementing a project across larger areas. However following Moulton and Richards (1990), opportunity costs would increase sequestration cost when incorporating areas with higher economic productivity. Hence in a region total costs may decrease initially due to economies of scale and then would rise again due to increased opportunity costs. The cost path would thus have a "U" shape with the lowest sequestration cost expected at the bottom.

3.2. Scolel Té project data

The Scolel Té project was selected for this modelling because it has been implementing conservation, afforestation and reforestation practices in rural communities in Chiapas and Oaxaca in Mexico for more than 10 years in over 2800 ha in different municipalities implementing different sequestration practices, potential and costs. Scolel Té developed the now internationally used 'Plan Vivo' which is one of the few operative systems in the voluntary market exclusively for LULUCF activities and with a strong focus on rural livelihoods (Kollmuss et al., 2008). Another advantage is that it has generated historical technical and economic data covering all stages of project development from design to operative and monitoring stages. Under the Plan Vivo system, before a landowner commits his land to the project, potential for leakage is assessed and it is assured that the project's implementation will not reduce capacity to produce agricultural products required in the household. This often limits project implementation up to 25% of landowners' eligible land (Esquivel and Quechulpa, personal communication). This potential is influenced by land available and opportunity costs across landowners and communities. During fieldwork 64 files of Scolel Té's participants comprising four communities were reviewed from which 36 interviews were carried out. We consider this is a representative sample since landowners interviewed have committed 97 ha of land to the project representing about 12% of the area committed to agroforestry systems.

3.3. Technical and implementation costs

Information on Scolel Té's costs is based on data published in De Jong et al. (2004). Scolel Té's specifications use the information generated by the project and the model CO2Fix to estimate carbon sequestration in stocks of biomass above and below ground, soil and products over a period of 100 years with rotation cycles of 25 years (De Jong et al., 2004; ECCM, 2001). Cost curves are constructed for seven sequestration options (Table 1). Sequestration options considered include practices on agricultural land in tropical and sub-tropical environments, for which *Swietenia marcophylla* and *Cedrela odorata* are used in the former; and *Pinus oocarpa*, *Quercus sp*. or *Cupressus benthamii* in the latter. Additional to the Scolel Té options, one curve is prepared considering the highest sequestration rate reported for reforestation in Mexico (Masera et al., 2000) to identify cost reduction due to a higher sequestration potential. The inclusion of these practices allows us to compare the economic variation among different sequestration options over different vegetation types and habitats.

Agroforestry activities considered are tree planting in fallows or living fences, and tree planting combined with coffee production. Tree densities are 130 trees/ha for living fences, 180 trees/ha for coffee under shade and 625 trees/ha for improved fallow systems. The cost of production of each plant is \$0.19/plant and materials for protecting the plants account for \$0.08/plant. The main factor affecting the implementation costs is labour. The default wage value used to estimate variable costs is \$6 per day (De Jong et al., 2004). Labour requirements used vary from 30 to 130 man-days for the establishment and maintenance requirements in years 1, 2, 3, 4 and 8.

3.4. Transaction costs

The initial implementation costs for Scolel Té were \$850,000 for an area of 2,700,000 ha; the cost of developing a new agroforestry sequestration option is \$45,400 (De Jong et al., 2004). These figures include development of the feasibility study, carbon inventories, the implementation scheme, the establishment of sampling points and definition of regional baselines. Most of the costs were fixed independent of scale. Scolel Té bore these costs because it was a pioneer project that had to develop its own methodology. It involved participation in policy discussion and establishment of conventions and terminology that are now widely used. It is expected that for new

Table 1
Sequestration options analyzed.

Sequestration option		Ton-C/ha
1	Reforestation Tropical	150[a]
2	Improved fallow tropical (high)	128[b]
3	Improved fallow tropical (low)	96[c]
4	Living fence tropical	54.1[b]
5	Improved fallow sub tropical	45.7[d]
6	Improved coffee (under shade)	39[d]
7	Living fence, sub-tropical	27.9[d]

[a] Masera et al. (2000).
[b] De Jong et al. (2004).
[c] Esquivel and Quechulpa, personal communication.
[d] ECCM (2001).

projects the cost could be reduced by up to 50% of these values; however, these costs are used in this work to set a higher limit in the modelling. Costs of initial training for local technicians and participants are $50 per ha, and monitoring costs are $20 per hectare per year in the first three years. Operating costs for the coordinating NGO are approximately $4/ton-C. These costs are regarded as the transaction costs associated to the voluntary market.

In addition to the costs described above needed to establish the project, CDM transaction costs used in the model range from $43,000 to $210,000 for fixed transaction costs (Project Design Document, validation and registration). The lower limit is for small CDM projects and the upper limit for full scale projects. CDM variable costs range from $3000 to $15,000 per year for verification and certification and 2%–17% of the temporal CERs value for credit issuance and sale (all values from Bauer et al., 2005).

3.5. Opportunity costs

Opportunity costs of agricultural production in Chiapas are estimated for maize, cocoa, bean and coffee crops. Statistics from 2004 show on a per municipality basis the harvested area, price paid to producer, production costs and production yields for each crop (SAGRAPA, 2008) (Table 2). Following Moulton and Richards (1990) harvested areas are sorted by increasing productivity, first by its net income value (production value minus costs) and then by its production value since most of agricultural practices are for subsistence and this may better reflect the opportunity cost. The opportunity costs assuming constant crops prices and production costs for the period of 30 years are included. For improved fallow systems full positive opportunity costs are added to the transaction and implementation costs; for living fence systems only 10% of estimated opportunity costs are added. This is a pessimistic scenario for living fences since usually agricultural production may be unaffected and the use of trees may even reduce some costs in the construction of conventional fences.

3.6. General considerations

The modelling uses the average storage method, dividing present costs over average carbon stored per year; without harvest this may provide the same results as the flow summation method (Richards and Stokes, 2004). The economic modelling horizon is 30 years, which is the duration of a single non-renewable period for ARP under CDM rules. It is considered that initial studies and implementation activities are realised in the first year. CDM carbon credits are generated and paid each year, following a linear sequestration rate for the period of 30 years. For voluntary projects, payments are distributed in years 1, 2, 3, 4 and 8, paying 20% of the total carbon sequestration payment each year. The discount rate used to assess the effect of time distribution of costs and benefits in marginal areas is 10% and the reference carbon price is $13/ton-C (De Jong et al., 2000, 2004).

Sequestration options are designed in such a way that after the first rotation period landowners' may have an income from timber exploitation ranging from $5000 to $14,000 per ha. However access to this income is uncertain given the difficulties of obtaining permits for timber exploitation and, for communities inside protected areas this may not be permitted at all (Esquivel and Quechulpa, personal communication). Moreover given local marginal conditions the present value of timber may be low ($507–$1421 discounting by 10%). Hence we assume no harvest will occur. The main risk for project performance arises from the fact that sequestration activities consider a horizon of 100 years and *ex-ante* payments occur in the first eight years of the project adopting the voluntary scheme. Nevertheless parallel work undertaken by Ambio with participating communities in the management of natural resources increases the probabilities of ensuring long term climate benefits. We should remember that most of the work required to implement these activities is done in the first years of the project. In the context of rural poverty it may be difficult to get resources to finance the project in the early stages while the credits are generated; and asking landowners to temporarily internalise the costs is arguable on equity grounds.

In order to prepare the curves the roll-up of expected costs and benefits for each year was prepared for the duration of the project. Then the coefficients of Eq. (3) were obtained for each sequestration option in order to create the curves as a function of the project's area. In the sensitivity analysis, single values in the roll-up were changed to investigate the effect in control variables to estimate average elasticities (Table 3). The change in CDM costs considered the reduction to the expected lower limit costs; this implies reduction by 80% of initial costs, yearly costs and the percentage charged in certification sales from 15% to 3%. When the estimated total variable cost (TVC) in $/ton-C is higher than the reference carbon price the project is set at 5000 ha to perform the sensitivity analysis. This area value was chosen for practical reasons of project management.

Table 2
Data on agricultural productivity used for the assessment of opportunity costs in 2004 (SAGRAPA, 2008).

Product	Harvested area (Ha)	Production yield ton/ha-year	Price paid to producer $/ton	Production cost reported $/ha
Maize	801,222	0.37–3.65	110.2–166.2	528.4; used 192.8
Coffee	251,606	1.4 –3.92	164.4–413.2	209.4–1168.1; used 339.8
Bean	127,378	0.28–0.91	459.1–826.4	562.0; used 367.3
Cocoa	20,281	0.06–0.80	1377.4–2020.2	881.5

4. Results and discussion

4.1. Implementation and transaction costs curves

After obtaining the coefficients for Eq. (2) without discounting, cost curves are constructed for the seven sequestration options under the voluntary scheme considering transaction and implementation costs (Fig. 2); option 3 is plotted at break even and at ANPV = $50/ha-year to show what the curve would look like when Fig. 1 is cut at that level for this specific sequestration option to offer a yearly profit to landowners; inclusion of this intended rent increases the required price by $15.6/ton-C at any project size, so the viability curve is displaced upwards. Table 4 shows a summary of the results for each sequestration option. In general, costs reduce rapidly as area increases from 1500 to 3000 ha, and thereafter converge to TVC. In order to generate a project of 1500 to 3000 ha, the local NGO would have to work over a region of at least 10,000 to 20,000 ha coordinating between 769 and 1538 landowners,[8] according to the average implementation of eligible area observed during fieldwork (15%).

Only sequestration options 1, 2 and 4 in the voluntary scheme, break even at 3263, 11,720 and 11,548 ha respectively with the carbon price of $13/ton-C (Table 4). The project's potential range is from 0.139 to 1.500 Mton-C; in all cases carbon sequestered is higher than 16 kton-CO_2/year, and would result in full scale CDM projects. Undiscounted TVC ranges from $11.17 to $22.08/ton-C and total transaction and implementation cost from $12.36 to $29.02/ton-C for a total area of 5000 ha. Landowners' direct costs vary from $5.53 to $13.46/ton-C, this is 35% to 58% of the costs in the voluntary scheme and 26.6% to 48.7% under CDM; thus in most of the cases the majority of the resources would be spent in the initial studies and transaction costs. Reducing transaction costs favours the transfer of benefits to landowners; however these costs are required to verify project

[8] Land allotment per landowner in the ejidos property system, is in average around 13 ha in Chiapas. Soto-Pinto et al. (2001).

Table 3
Sensitivity analysis of ARP economic performance.

Change evaluated		Change in variable	Control variable		
			Total cost @ 5000 ha	Landowner income	TVC ($/ton-C)
1	Initial and developing costs	−50%	−5% (0.10)		
2	CDM (lower limit values)	−80%	−13% (0.15)		−9% (0.11)
5	Wage ($16.62/day)[a]	177%	86% (0.49)	146% (0.82)	96% (0.54)
6	Plant cost increase (high)	421%	31% (0.07)	52% (0.12)	35% (0.08)
8	Discount rate 2%	2%	−3% (−1.50)	−3% (−1.50)	−3% (−1.50)
9	Discount rate 10%	10%	−11% (−1.10)	−10% (−1.00)	−12% (−1.20)
11	Maintenance labour (reduction)	−39%	−24% (0.62)	−32% (0.82)	−21% (0.54)

All changes in Total Cost, Landowner Income/cost and TVC refer to the voluntary scheme baseline; the exception is the change in CDM (Lower Limit Values).
[a] Considering minimum wage to cross patrimony poverty line (SEDESOL, 2002); an average household occupancy in Chiapas of 4.48 persons (INEGI, 2005) and inflation, exchange rate and minimum wages published $US 1 = $10.89 MXP(CEFP, 2007; Banxico, 2007).

implementation and demonstrate the benefits. Although costs should be reduced when possible, the implication is that higher valuation expressed as higher carbon prices is needed.

Options with higher sequestration rates generally result in lower costs per ton-C than those with lower sequestration potential because there are more tonnes of carbon sequestered. However this effect is reduced in larger projects when fixed costs are considered. The difference between Options 7 and 1 at projects of 500 ha, is $56.7/ton-C, while at 10,000 ha it is $7.10/ton-C. Despite the fact that Option 7 sequesters only 18% of Option 1, TVC for Option 7 is only 40% higher and the TVC difference between both options is small: $4.49/ton-C ($1.22/ton-CO_2). Moreover options with lower sequestration rates and lower variable cost (Living Fences and Improved Coffee, under shade, Options 4, 6 and 7), might have lower costs than some options with higher sequestration potential when implemented across large areas as the effect of fixed costs diminishes. These results suggest that if the target is an efficient use of resources, those options with lower carbon potential may perform almost as well, and sometimes better, than options with higher carbon sequestration potential and full land use conversion.

4.2. Impact of CDM adoption

CDM fixed costs are 77% costlier than those incurred in the voluntary market (Project Design Document, Validation, Contract Negotiation, Register and yearly fees for Monitoring and Verification without discounting); this share will be larger for full scale projects with a smaller scope and smaller initial costs than Scolel Té. For projects working in the areas proposed in Table 4, CDM transaction costs range from 16.9% to 23.9% of total costs; and are 20.3% to 31.4% costlier. However when considering marginal conditions, discounting reduces the value of carbon revenues more in the CDM scheme than in the voluntary scheme and higher nominal carbon prices are required to break even under the CDM scheme. For example, for Option 3, discounting at 10% in a project of 5000 ha, present transaction and implementation costs account for $15.17/ton-C in the voluntary market, and $14.88/ton-C in the CDM. However given the time distribution of carbon payments, in order to obtain those discounted values, initial nominal prices should be $19.3/ton-C for the voluntary scheme and $43.1/ton-C under CDM. The price required for the voluntary scheme would be 45% that of the CDM scheme; discounting at 20% the value would be 30%. We consider that adoption of the voluntary scheme, concentrating the payments in the first years after the implementation of the activities would allow landowners in marginal areas to join the project and reduce overall costs due to economies of scale.

4.3. Sensitivity analysis

From inspection of Eq. (1), three strategies to enable the viability of smaller projects were identified: negotiation of higher carbon prices; preparation of better methodologies for claiming for more carbon; and reduction of fixed and variable costs. Table 3 presents the results from the sensitivity analysis when changing particular elements in the cost function. Changes in the variables refer to baseline of Option 3 values without discounting. The factor that exerts

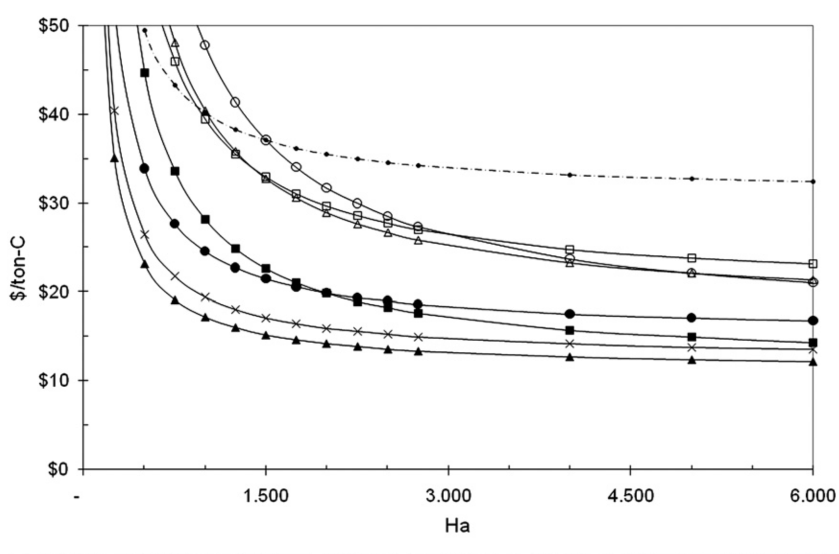

Fig. 2. Sequestration cost curves considering initial transaction and implementation costs. *Note*: The code [number and letters, e.g. (1) 150RT] refers to the sequestration potential and activities listed in Table 1.

Table 4
General results for economic performance, baseline for seven sequestration options.

Sequestration option	1		2		3		4		5		6		7	
	Vol	CDM	Vol	CDM	Vol	CDM	Vol	CDM	Vol	CDM	Vol	CDM	Vol	CDM
Area (ha)[a]	3263		11,720		5000		11,548		5000		5000		5000	
Total variable cost ($/ton-C)	11.17	13.38	12.40	14.61	15.20	17.41	11.57	13.78	19.87	22.08	17.45	19.66	15.66	17.87
Total costs ($x1000)	6363	8105	19,502	23,477	8193	9914	8121	10,162	5435	6600	4298	5389	3080	4048
% Landowner cost	49.5	38.9	58.0	48.2	58.9	48.7	42.6	34.0	56.6	46.6	48.2	38.5	35.0	26.6
% Coordination cost	50.5	39.6	42.0	34.9	41.1	33.9	57.4	45.9	43.4	35.7	51.8	41.3	65.0	49.5
% CDM Transaction cost	NA	21.5	NA	16.9	NA	17.4	NA	20.1	NA	17.7	NA	20.2	NA	23.9
p_c(@5000 ha)	12.3	15.4	13.8	17.0	17.0	20.6	14.8	19.5	23.7	28.8	22.0	27.6	22.0	29.0

Vol: Voluntary Market Scheme; CDM: Clean Development Mechanism Scheme.
[a] CDM variable costs were higher than the reference price in all cases. The area is set equal for projects in the voluntary and CDM schemes to facilitate comparison.

the biggest influence over total cost is discounting (ε, −0.90 to −1.50), followed by labour related features – wage and days worked – (ε, 0.48 to 0.62) and CDM scheme adoption (ε, 0.15). ARP may contribute to alleviate poverty if projects consider all the activities implemented and offer an equivalent wage sufficient to cross the poverty line; the elasticity between wage and total costs indicates benefits for landowners would be in a ratio of 2:1. As mentioned above, another feature to improve landowners' conditions is inclusion of an intended rent (positive ANPV). The average elasticity between plant costs and the total costs and TVC is small (ε, 0.07–0.08), and the effect is slightly higher for landowner costs (ε, 0.12). The investment in better baselines to claim more carbon can also be considered especially in large projects for which the impact on total costs would be low (ε, 0.10 for initial costs).

4.4. Opportunity costs and potential for implementation

Fig. 3A and B shows the sequestration costs with the expected 'U' shape including implementation, transaction and opportunity costs of agricultural practices from four crops over an area of 1,000,000 ha in

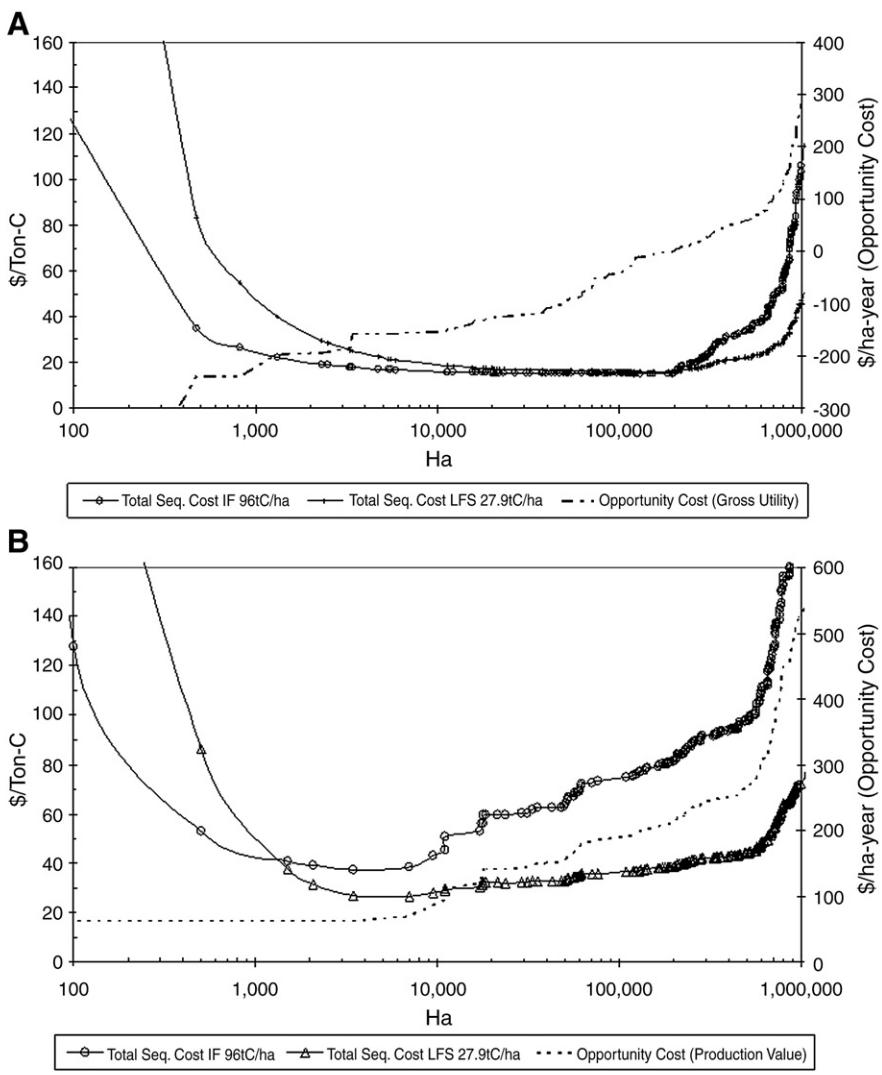

Fig. 3. A. Total sequestration costs for two sequestration options in Chiapas, Mexico. Opportunity costs as agricultural gross utility. B. Total sequestration costs for two sequestration options in Chiapas, Mexico. Opportunity costs as agricultural production value.

Chiapas, Mexico. Sequestration practices modelled are option 3, improved fallow in tropical system (96 ton-C/ha) and option 7 living fence in a sub tropical environment (27.9 ton-C/ha). Opportunity costs are often regarded as net income (benefits − costs) as depicted in Fig. 3A. Using this criterion, there may be around 200,000 ha devoted to agriculture with net economic losses in the study area, not generating opportunity costs implying landowners might be indifferent to the adoption of living fences or improved fallows. However since activities in this region correspond mainly to subsistence agriculture – especially maize – landowners may not be indifferent to the loss of agricultural output; thus we consider that in marginal conditions total production value of agricultural products gives a better idea of the opportunity costs than net income (Fig. 3 B).

Fig. 3 B shows that implementation of living fences results in lower costs than the improved fallow option when implemented over areas larger than 1500 ha, With a price of $40/ton-C project potential for the improved fallow option would be 0.67 Mton-C (7048 ha), which could generate a lost agricultural output of 2964 tons per year. For the living fence system the potential at the same carbon price would be 6.45 Mton-C (231,315 ha) and 23,864 tons per year of agricultural products would be lost considering a reduction of 10% in agricultural production. Even if the area of the Scolel Té project may not correspond entirely to the area where the opportunity costs are estimated, conditions may be similar in both. Most of the area with low opportunity costs was used for maize and bean, while the areas with higher opportunity costs were mainly used to grow for coffee and cocoa. From this analysis, total sequestration costs would get to the lower levels expected when projects target low opportunity cost land and cover an area of 3000 ha. Leakage can be controlled by continuing with the evaluation of landowners' proposals especially if living fences are implemented and agricultural practices are enhanced. However the demand for carbon credits at levels between $20 and $40/ton-C should be generated to cover all costs. The emergence of higher opportunity costs of agricultural land due to food scarcity and bio-fuels demand might change these figures.

Implementation of living fences may be an important strategy to mitigate climate change at a national level. The agricultural area sown in 2007 in Mexico was 15.6 million ha (cyclic crops) (SAGRAPA, 2008); if living fences could be widely implemented at a conservative rate of 20 ton-C/ha, sequestration potential would be 312 Mton-C. In order to implement such a programme other implications should be considered including the generation of national baselines; the impact on water requirements and food production; and the development of the appropriate institutions and mechanisms.

5. Conclusions

The aim of this work is to analyze sequestration supply costs in order to contribute to the understanding and identification of carbon prices and characteristics of the market required to implement these activities. We use the expertise developed in this area and the consolidated data and experience built up for more than ten years of the Scolel Té project in combination with economic break even analysis to integrate a framework to identify total sequestration costs. Our results suggest that since total sequestration costs are affected by both economies of scale and opportunity costs, as it has been discussed separately in the literature (e.g. Cacho and Lipper, 2007 and Moulton and Richards 1990), policy and project design should include all the costs incurred in order to evaluate its potential; likewise projects and policies should aim to negotiate financing and offer payments levels to landowners sufficient to ensure minimum levels of adoption to facilitate implementation of projects within the region of lower sequestration costs; this is critical if carbon sequestration is to be considered a viable land use option at a landscape scale. The recovery of initial fixed costs might allow the replication of projects. This approach is flexible and can be adapted to different regions and carbon sequestration options to provide what we consider is a clear idea of the levels of valuation of carbon services required to develop ARPs.

In order to create incentives for the implementation of ARPs, demand for these projects should be enhanced. Assuming that reduction in costs may represent lower incomes for landowners in marginal areas, the main strategies to enhance ARP implementation should aim for negotiation of higher carbon payments, investment in high quality baselines to enable landowners to participate and reduce transaction costs. We consider that up-front carbon payments to landowners and lower transaction costs in the voluntary market generate more plausible conditions for the development of ARP in marginal rural areas than the current CDM scheme. Agroforestry practices which do not require full land use conversion (e.g. living fences) can be particularly useful and should play a larger role in the efforts to mitigate climate change.

The spirit of market-based mechanisms for climate change mitigation is to use resources efficiently, taking advantage of the lower costs prevailing in less developed areas. However, if financing does not allow recovery of all costs, then markets will fail to generate incentives for producers. As a result, projects will not be adopted widely, and in the case of ARPs, landowners will be asked to finance and subsidize the mitigation of a problem for which they may have had little historical responsibility. Moreover, targeting financing only in terms of costs may resemble more an employment relationship than trading between similar actors.

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References

Adams, D.M., Alig, R.J., McCarl, B.A., Callaway, J.M., Winnett, S.M., 1999. Minimum cost strategies for sequestering carbon in forests. Land Economics 75, 360–374.
Alig, R., Adams, D., McCarl, B., Callaway, J.M., Winnett, S., 1997. Assessing effects of mitigation strategies for global climate change with an intertemporal model of the U.S. forest and agricultural sectors. Environmental and Resource Economics 9, 259–274.
Banxico, 2007. Series históricas de Salarios Mínimos diarios. Banco de México, México. http://www.banxico.org.mx/polmoneinflacion/estadisticas/laboral/laboral.html.
Bass, S., Dubois, O., Moura Costa, P., Pinard, M., Tipper, R., Wilson, C., 2000. Rural livelihoods and carbon management. : IIED Natural Resource Issues Paper, vol. 1. International Institute for Environment and Development, London.
Bauer, M., et al., 2005. Metodologías para la implementación de los mecanismos flexibles de Kyoto— Mecanismo de Desarrollo Limpio MDL. Programa Synergy de la Comunidad Europea. Mexico.
Beerling, D.J., Woodward, F.I., 2004. Vegetation and terrestrial carbon cycle: modeling the first 400 million years. Cambridge University Press, United Kingdom.
Black-Solís, J., Locatelli, B., Pedroni, L., 2004. Diseño de Proyectos de Venta de Carbono Atractivos para Pequeñas Plantaciones Forestales. VI Semana Científica del CATIE. Centro Agronómico Tropical de Investigación y Enseñanza, Costa Rica.
Cacho, O., Lipper, L., 2007. Abatement and Transaction Costs of Carbon-Sink Projects Involving Smallholders. Nota di Lavoro 27.2007. Fondazione Eni Enrico Mattei. Italy.
Capoor, K., Ambrosi, P., 2008. State and Trends of the Carbon Market 2007. World Bank Institute. Available at http://wbcarbonfinance.org/docs/State_Trends_FINAL.pdf.
CEFP, 2007. Información Histórica de Inflación, Tipo de Cambio y Salario Diario para Agricultura Silvicultura y Ganadería. Centro de Estudios de las Finanzas Públicas de la H. Cámara de Diputados, México. http://www3.diputados.gob.mx/camara/content/view/full/4987.

Daly, H., 1990. Commentary: Toward some operational principles of sustainable development. Ecological Economics 2, 1–6.
De Jong, B.H.J., Ochoa Gaona, S., Quechulpa Montalvo, S., Esquivel Bazán, E., Pérez Hernández, N., 2004. Economics of agroforestry carbon sequestration: a case study from southern Mexico. In: Alavalapati, J.R.R., Mercer, D.E. (Eds.), Valuing Agroforestry Systems. Kluwer Academic Publishers, The Netherlands, pp. 123–138.
De Jong, B.H.J., Tipper, R., Montoya-Gomez, G., 2000. An economic analysis of the potential for carbon sequestration by forests: evidence from southern Mexico. Ecological Economics 33 (2), 313–327.
Dixon, et al., 1993. Forest sector carbon offset projects: near-term opportunities to mitigate greenhouse gas emissions. Water, Air and Soil Pollution 70, 561–577.
ECCM, 2001. Especificaciones Tecnicas del Proyecto Scolelt Té. AF-CERVI-SUBT1, FOR-ACME-SUBT1, AF-CAFE-TROP. Edinburgh Centre for Carbon Management. Chiapas, Mexico.
Esquivel, E., Quechulpa, S., personal communication. Ambio, Chiapas. Mexico.
Hamilton, K., Bayon, R., Turner, G., Higgins, D., 2007. State of the Voluntary Carbon Markets 2007: Picking Up Steam. EcoSystem Marketplace and New Carbon Finance. Available at http://ecosystemmarketplace.com/documents/acrobat/StateoftheVoluntaryCarbonMarket17July.pdf.
INEGI, 2005. II Conteo de Población y Vivienda 2005. Instituto Nacional de Estadística, Geografía e Informática, México. www.inegi.gob.mx.
Kauppi, P., Sedjo, R., Apps, M., Cerri, C., Fujimori, T., Janzen, T., 2001. Technical and economic potential options to enhance, maintain and manage biological carbon reservoirs and geo-engineering. In: Davidson, O., Metz, B., Swart, R. (Eds.), Climate Change 2001: Mitigation. Cambridge University Press, Cambridge, United Kingdom, pp. 301–344.
Kollmuss, A, Zink, H., Polycarp, C., 2008. Making Sense of the Voluntary Carbon Market: A Comparison of Carbon Offset Standards. WWF Germany and Stockholm Environment Institute and Tricorona.
Landell-Mills, N., Porras, I.T., 2002. Silver Bullet or Fool's Gold: A Global Review of Markets for Forest Environmental Services and their Impact in the Poor. International Institute for Environment and Development, London.
Masera, O., De Jong, B.H.J., Ricalde, I., Ordóñez, A., 2000. Consolidación de la Oficina Mexicana para la Mitigación de Gases de Efecto Invernadero. Reporte Final. INE-UNAM, México.
Moulton, R.J., Richards, K.R., 1990. Costs of sequestering carbon through tree planting and forest management in the United States. USDA-Forest Service. Gen. Tech. Rep. WO-58.
Richards, K., Andersson, K., 2001. The leaky sink: persistent obstacles to a forest carbon sequestration program based on individual projects. Climate Policy 1, 41–54.
Richards, K.R., Stokes, C., 2004. A review of forest carbon sequestration cost studies: a dozen years of research. Climatic Change 63 (1/2), 1–48.
SAGRAPA, 2008. Servicio de Información Agroalimentaria y Pesquera. Secretaría de Agricultura, Ganadería Desarrollo Rural, Pesca y Alimentación, Mexico. http://www.siap.gob.mx/.
Schlamadinger, B., Johns, T., Ciccarese, L., Braun, M., Sato, A., Senyaz, A., Stephens, P., Takahashi, M., Zhang, X., 2007. Options for including land use in a climate agreement post-2012: improving the Kyoto Protocol approach. Environmental Science & Policy 10, 295–305.
SEDESOL, 2002. Medición de la Pobreza. Variantes Metodológicas y Estimación Preliminar. Serie: documentos de investigación. Comité Técnico para la Medición de la Pobreza. Secretaría de Desarrollo Social, México, D.F.
Soto-Pinto, L., Jimenez-Ferrer, G., Vargas Guillen, A., de Jong, B., Esquivel-Bazan, E., 2001. Experiencia agroforestal para la captura de carbono en comunidades indígenas de Mexico. Paper presented at the International Workshop on Carbon Sequestration, Venezuela, pp. 16–17.
UNEP, 2009. United Nations Environment Programme, Risoe Centre. CDM/JI Pipeline Analysis and Data Base. http://cdmpipeline.org/cdm-projects-type.htm.
UNFCCC, 2009. Clean Development Mechanism Statistics. CDM website. http://cdm.unfccc.int/Projects/projsearch.html.
Van Kooten, G.C., Wang, Y., Laaksonen-Craig, S., 2007. Carbon sequestration in forest ecosystems as a strategy for mitigating climate change. Selected Paper prepared for presentation at the American Agricultural Economics Association Annual Meeting. United States.
Wunder, S., Engel, S., Pagiola, S., 2008. Taking stock: a comparative analysis of payments for environmental services programs in developed and developing countries. Ecological Economics 65 (4), 834–852.
Zomer, R.J., Trabucco, A., Bossio, D.A., Verchot, L.V., 2008. Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agriculture, Ecosystem & Environment 126, 67–80.