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Carbon sequestration versus bioenergy: A case study from South India exploring the relative land-use efficiency of two options for climate change mitigation

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ARTICLE INFO

Article history:
Received 7 October 2005
Accepted 15 October 2009
Available online 20 November 2009

Keywords:
Land use
LULUCF
Carbon sequestration
Bioenergy
Plantation
India
CDM

ABSTRACT

This case study has been carried out as a comparison between two different land-use strategies for climate change mitigation, with possible application within the Clean Development Mechanisms. The benefits of afforestation for carbon sequestration versus for bioenergy production are compared in the context of development planning to meet increasing domestic and agricultural demand for electricity in Hosahalli village, Karnataka, India. One option is to increase the local biomass based electricity generation, requiring an increased biomass plantation area. This option is compared with fossil based electricity generation where the area is instead used for producing wood for non-energy purposes while also sequestering carbon in the soil and standing biomass. The different options have been assessed using the PRO-COMAP model. The ranking of the different options varies depending on the system boundaries and time period. Results indicate that, in the short term (30 years) perspective, the mitigation potential of the long rotation plantation is largest, followed by the short rotation plantation delivering wood for energy. The bioenergy option is however preferred if a long-term view is taken. Short rotation forests delivering wood for short-lived non-energy products have the smallest mitigation potential, unless a large share of the wood products are used for energy purposes (replacing fossil fuels) after having served their initial purpose. If managed in a sustainable manner all of these strategies can contribute to the improvement of the social and environmental situation of the local community.

1. Introduction

The Clean Development Mechanism (CDM) is contained in Article 12 of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The objective of the CDM is to assist non-Annex I countries, which in essence are developing countries, achieve sustainable development and at the same time allow Annex I countries in achieving their obligations under the Kyoto Protocol more cost effectively. CDM projects are up to now (1029 projects registered in April 2008) primarily established within energy industry for renewable and non-renewable sources (53% of all projects), waste handling and

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0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2009.10.008

disposal (21%) and halting fugitive emissions for fuels i.e., solid, oil and gas (8%). Only one afforestation and reforestation project is registered, due to complex methodological and crediting issues [1].

The forestry sector in the developing countries provides low cost mitigation opportunities [2]. Land Use, Land Use Change and Forestry (LUCUCF) activities lead to both emissions and sequestration of carbon. If produced in a sustainable manner, and replacing fossil fuels, biomass use for energy reduces the rate of build-up of atmospheric carbon dioxide (CO_2). Biomass has been suggested a major source of energy in the future and the large-scale expansion of biomass plantations has been envisioned a possible strategy for climate change mitigation [3]. Other land management strategies for climate change mitigation aim at increasing – or reducing losses of – biospheric carbon (C) stocks, such as slowing deforestation (slowing the C loss from plants and soils), or afforestation/reforestation (sequestering atmospheric C in plants and soils by establishment of so-called C sinks).

The forestry sector mitigation projects are, however, more complex than most other CDM projects. Factors like long gestation periods, non-linear rates of C accumulation in vegetation and soil, varying rates of extraction (and varying end uses) of different woody biomass products, and C emission from forest soil, forest floor, forest fire, leads to uncertainties and consequently monitoring/verification challenges [4]. Concerns have also arisen about the risks of leakage (i.e., climate benefits within the project boundary but induced GHG emission increases outside the project boundary) and – in the case of forestry projects aimed at increasing or reduce losses of C stocks – possible non-permanence (i.e., C stock gains are outweighed by losses that occur after project completion: a forested area may for example later be deforested to make place for agricultural activities).

The United Nations Millennium Goals (MDGs) includes LULUCF. If implemented in a sustainable manner LULUCF strategies within CDM could make a valuable contribution towards the realization of the MDGs. Apart from the climate benefit it is possible to conserve soil, rainwater, and biodiversity. On the social side LULUCF projects can lead to local employment generation, capacity development, self-reliance, local control and community participation [5].

2. Study area

The village of Hosahalli is located in Tumkur district, Karnataka state in southern India (13° 26′ 50 N: 77° 26′ 41 E). The village consists of 35 households with a population of 218 (in 2004). Before 1988 the villagers had no access to electricity and limited access to clean drinking water. The farmers relied primarily on rainfall for crop production and there was no flourmill in the village. In 1988, a 20 kW biomass driven power generation system was installed. The system supplied the village with electricity for several services. All the households in Hosahalli were electrified and connected to the bioenergy system. The households used electricity for lightning and were also provided with water through private taps. A flourmill was installed in 1994 with a capacity of 7.5 hp along with 4 irrigation water pumps all connected to the bioenergy system (Table 1). The installation of the power generation system was a result of an initiative from the Center for Sustainable Technology, Indian Institute of Science and the local community was involved in the project at an early stage. The system operated for nearly 16 years before it was closed down [6].

Table 1 – Power demand from different activities in the Hosahalli village [7].

	Load (kW)	Present demand (MWh/year)	Projected demand (MWh/year)
Lighting	4.0	7.1	7.3
Drinking water	2.6	4.6	4.7
Flourmill	5.6	2.8	2.8
Irrigation pumps	18.5	7.5	63.3
Total load	30.7	22.0	78.1[a]
Per capita demand		0.1 MWh/cap/year	0.36 MWh/cap/year

a Assuming an increased plant load factor, from 20% 2003 to 60% 2004.

The bioenergy-based power generation system was based on producer gas from a biomass gasifier using biomass produced on a 4 ha plantation of mixed fast growing tree species situated about 1 km from the village. The forest was planted during two phases: 2.5 ha in 1988 and an additional 1.5 ha in 1991–1992. The plantation contains a mix of species, including: *Eucalyptus* (58%), *Cassia siamea* (22%), *Acacia auriculiformis* (13%) and *Dalbergia sisso* (7%). After harvest, the woody biomass was dried, chopped, sized and finally combusted under controlled air supply inside the gasifier. The producer gas was used to replace diesel in a standard diesel engine running in a dual fuel mode. The system operated on dual fuel mode most of the time (355 days in 2003). On instances when producer gas could not be supplied the system operated on diesel only. The bioenergy system generated 21.6 MWh in 2002 and 22.0 MWh in 2003. Most of the power was generated in dual fuel mode, 80% in 2002 and 85% in 2003, with a diesel substitution rate of 87% and 85%, respectively. On average, roughly 75–85% of the diesel was replaced by the producer gas.

Hosahalli is located in a semi-arid region with a mean annual rainfall of 700 mm and most of the rainfall is concentrated in the monsoon season (July–September). The demand for irrigation water exceeded the supply and the total electricity demand was also higher than the installed power capacity. The different load activities had to be run on separate hours during the day. In order to meet the increasing electricity demand – and also to improve the economic viability of the system – options for increasing the electricity generation was considered, which would lead to increased biomass requirements.

3. Objectives

The aim of the study is to compare the relative attractiveness of two different land-use strategies for climate change mitigation within the context of the bioenergy-based power generation system in Hosahalli and the need to increase the electricity generation. Two options for are evaluated:

- using land for biomass production for the substitution of fossil fuels (bioenergy option).

- using land for C sequestration, via afforestation or reforestation, and meet the increasing power demand by using more fossil fuels in the system (C sink option).

The study also aims to address the question of which land-use strategy can offer the most effective way to meet the different objectives of the project: (i) reliable electricity supply; (ii) reduction of GHG emissions; (iii) cost effectiveness; and (iv) rural development.

4. Methodology

The study is based on data obtained from the biomass gasification project in Hosahalli where data has been collected considering relevant aspects concerning:

- The fossil and biomass based power systems; capacity and loads for the different electricity options and the carbon replacement efficiency of the biomass system.
- The forestry systems; rotation periods, aboveground biomass accumulation rates (tC/ha/year) and soil carbon accumulation rates (tC/ha/year).
- The financial situation; investment costs, opportunity costs of land, annual maintenance, monitoring and management costs, benefit flows and discount rates.

Two fossil based power generation systems are considered; (i) a coal based power plant and (ii) a standard diesel engine generator. Two different plantation systems for the C-sequestration option are evaluated; (i) short rotation plantations (Eucalyptus, Acacia mix) and (ii) long rotation plantations (Timber species mix). The plantation system supporting the fossil fuel substitution option is continuously harvested to supply biomass to the gasification system, but is defined to have the same growth rate and carbon pool characteristics as the short rotation plantation system used for C sequestration.

The carbon pools considered are; Above Ground Biomass (AGB), Below Ground Biomass (BGB) and Soil Organic Carbon (SOC). The amount of BGB is estimated based on the AGB, assuming BGB is equal to about one-fourth of AGB. The growth rates of the different carbon pools are shown in Table 2.

The mitigation potential and the cost effectiveness of the different options were evaluated using the PRO-COMAP model (Project based Comprehensive Mitigation Analysis Process model), which is a tool developed for comprehensive assessment of different forestry based mitigation strategies. The evaluation process includes identification and specification of baseline and mitigation scenarios [8].

5. Analysis and results

5.1. *Energy demand*

Based on the electricity use up to 2003 and an assessment of planned activities in 2004, the annual electricity demand is projected to increase to approximately by 78 MWh by 2004, primarily to meet the irrigation demand from the villagers. The electricity demand is assumed to stay at that level during the remaining modeling period. With a Plant Load Factor (PLF) of 60%, the bioenergy system can meet both the domestic and the agricultural electricity demand. At this load, the irrigation pumps can provide 16 ha of land with water during the dry season. Expanded utilization of the system would also increase the cost effectiveness. The unit cost of electricity declines both for the producer gas system and the diesel system as the load factor increases. An increase in the number of average daily working hours to over 5 h would make the bioenergy system economically favorable in comparison to an identical-capacity diesel alone system [5].

5.2. *Land requirement for biomass production for energy and avoided CO_2 emissions*

If the projected rise in power demand is to be met based on increased biomass based electricity the biomass plantation has to be expanded (Table 3). Approximately 120 tonnes of wood is required to support the generation of 78 MWh/year. An additional 16.2 ha of degraded land bordering the existing plantation would be needed for this expansion. Given an assumed diesel substitution rate of 86%, the avoided C emissions in the bioenergy case is given in Table 4.

Table 2 – Characteristics of the different plantation activities.

Forest activity	Rotation (year)	Growth rate AGB[a] (t of wood/ha/year)	Growth rate BGB[b] (t of wood/ha/year)	Rate of C uptake in soil (tC/ha/year)
1. Bioenergy plantation *Eucalyptus, Acacia mix*	6[c]	6	1.6	0.41
2. Short rotation *Eucalyptus, Acacia mix*	6	6	1.6	0.41
3. Long rotation *Timber species mix*	30	3	0.8	0.36

a From [7].
b Growth rate of BGB is equal to about one-fourth of AGB.
c The bioenergy plantation is continuously harvested in order to supply the gasifier with biomass. 6 years rotation corresponds to the time required for complete plant stock turnover.

Table 3 – Biomass yield- and land requirements for the bioenergy system.

	Electricity demand (MWh/year)	Biomass requirement[a] (t of wood/MWh)	Biomass production (t/ha/year)	Land requirements (ha)
Domestic load	14.8	1.42	6	3.5
Irrigation load	63.3	1.58	6	16.7
Total	78.1			20.2

a Average wood consumption in dual fuel mode (2003).

5.3. *Carbon mitigation potential*

Based on the amount of land needed for the production of biomass for the gasifier in the future demand scenario (20 ha), the mitigation potential of the two alternative land-use strategies can be quantified and compared (Table 5).

5.3.1. *Baseline scenario*

In the baseline scenario no additional plantations are established. The degraded land is used as grazing land with no additional C accumulation in aboveground- or below ground biomass. The amount of soil organic C has been estimated at about 40 tC/ha on the degraded land and no additional C will be sequestered during the period. The opportunity cost of this barren land is judged to be 500 Rs/ha/year (Fig. 1).

5.3.2. *Short rotation bioenergy option*

The bioenergy plantation is continuously harvested to supply biomass to the gasification system. The biomass and soil carbon pool will stabilize at 15 tC/ha above the level of the baseline scenario. The CO_2 emissions reduction from the fossil fuel substitution will however contribute to an accumulating climate benefit over time. The total mitigation potential of the bioenergy scenario will be 43 tC/ha in 2034 and 104 tC/ha in 2100 (Fig. 2).

5.3.3. *Short rotation wood product option*

The short rotation plantation is harvested with 6 years rotation. The wood product stock, 80% of the AGB harvested, consist of poles with a lifetime of 6 years used largely in construction industry. As a result, all of the C in the poles from one harvest will be lost before the next harvest. The C sequestering function of the short rotation forest ceases quite fast and the mitigation potential is therefore limited: stabilizing at roughly 20 tC/ha (Fig. 3). The critical assumption leading to this result is that the C in the produced poles is lost to the atmosphere without providing any fossil fuel substitution benefit. If some of the poles where used for energy purposes (replacing fossil fuels) after having served their initial purpose, the mitigation function would improve. If a large share of the wood products is used for energy purposes in this way, the short rotation sequestration option would in essence be a bioenergy system with initial storage of the biomass fuel in the form of poles.

5.3.4. *Long rotation wood product option*

The long rotation plantation is harvested with 30 years rotation. The wood product stock, 75% of the AGB harvested, consist of sawn wood with a lifetime of 30 years. The C in the sawn wood from one harvest will therefore be lost before the next harvest. Due to the longer rotation period, the C sequestration proceeds much longer than for the short rotation wood product option. In this scenario the maximum amount of C sequestered per ha will be somewhat above 50 tonnes (Fig. 4).

5.3.5. *Comparison of bioenergy and C-sequestration options*

The mitigation potential of the different strategies is presented in Table 6. The mitigation potential represents the

Table 4 – C emissions from electricity generation based on fossil fuel.

		Present		Projected	
		A. coal	B. diesel	A. coal	B. diesel
Fossil fuels	Emission factor (kgC/MWh)[a]	270	240	270	240
	Annual power demand (MWh/year)[b]	22	22	78.1	78.1
	Total annual C emission if generated with fossil fuel (kgC/year)	5940	5280	21,087	18,744
Avoided due to replacement with bioenergy	C emissions in dual mode (kgC/year)[c]	739	739	2624	2624
	C emissions avoided (kgC/year)	5201	4541	18,463	16,120
	C emissions avoided (tC per 30 years)	156	136	554	484

a Approximations based on IPCC default CO_2 emission factors [9].
b From Table 1.
c Assuming that all electricity is generated in dual fuel mode.

Table 5 – The carbon mitigation potential of the two different land-use strategies.

	Biomass for bioenergy		C sequestration via A&R	
	A. coal	B. diesel	Short rotation	Long rotation
Requirements:				
- Power demand	78.1 MWh	78.1 MWh	–	–
- Biomass requirement for fossil fuel substitution	120 t of wood/year	120 t of wood/year	–	–
- Biomass for non-energy wood supply	–	–	120 t of wood/year	60 t of wood/year
- Land requirement	20.2 ha	20.2 ha	20.2 ha	20.2 ha
C dynamics				
1. Biomass C (AGB + BGB)[a]	69 tC/year	69 tC/year	69 tC/year	35 tC/year
2. Soil C[b]	8.2 tC/year	8.2 tC/year	8.2 tC/year	11.1 tC/year
3. Fossil fuel substitution[c]	18.5 tC/year	16.1 tC/year	–	–

a The average carbon ratio in woody biomass is assumed to be 45%.
b Rate of C uptake in soil, 0.41 t/ha/year for the energy- and short rotation plantation and 0.36 t/ha/year for the long rotation plantation and the accumulation time is assumed to be 7 years in all scenarios.
c A. Replacing energy generated in coal power plant. B. Replacing energy generated from standard diesel engine generator.

additionality from the baseline scenario. As can be seen, an evaluation done within a shorter time frame (30 years in Table 6) favors the long rotation wood product option, i.e., C sequestration. This is due to that when harvests are carried out at short rotation intervals (in this case 6 years) the amount of aboveground biomass is relatively low at any given time. A longer time frame on the other hand (100 years in Table 6) favors the bioenergy option. This is in line with the well established understanding of how these forest based mitigation options perform [10]. The relative attractiveness of the different strategies depends strongly on the time periods and system boundaries.

5.4. *Monitoring strategies and costs*

The complexities of most forestry sector mitigation projects make monitoring essential. Forest C is, in a sense, a new commodity that must be measured to acceptable standards for the commodity to exist [11]. In this case the C sequestered and emissions avoided has to be measured, recorded and verified. A key aspect of implementing a forestry project for C mitigation is accurate and precise quantification of project-level C benefits and its verification by independent actors having adequate skills. As has been outlined in the introduction, there are many aspects to consider and this makes

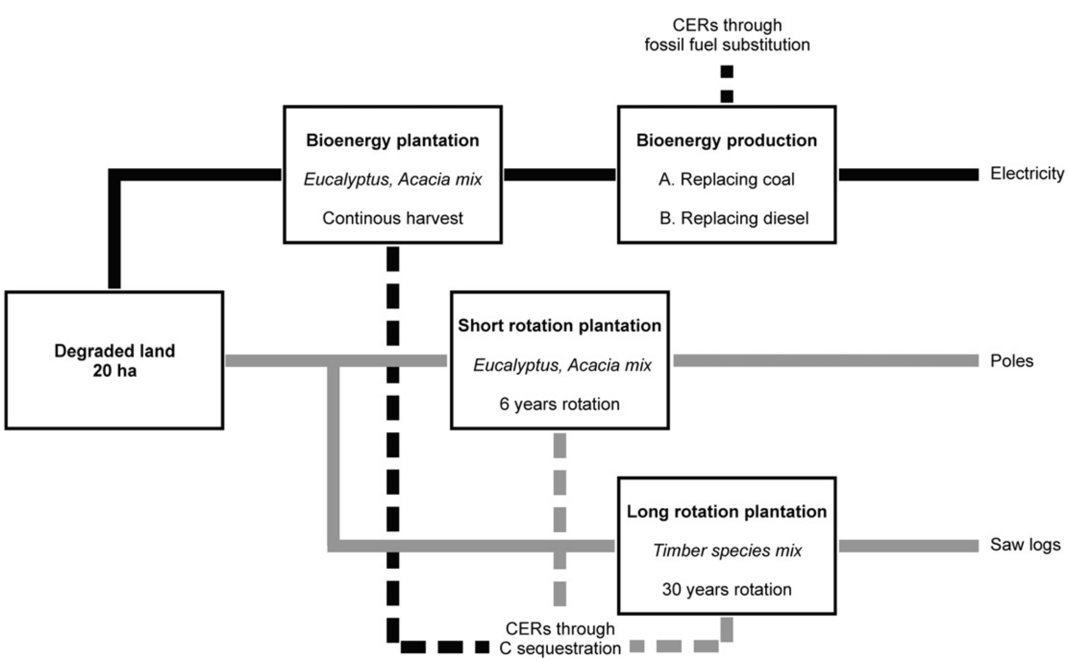

Fig. 1 – Illustration of the different land-use strategies; Bioenergy plantation for bioenergy production and short and long rotation plantation for C sequestration.

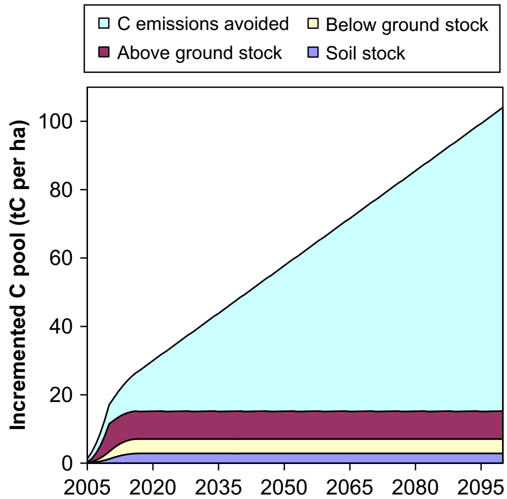

Fig. 2 – Incremented C pool in the bioenergy scenario (tC/ha). The C pools in the bioenergy plantation will stabilize while the fossil fuel substitution will lead to continuous C emission reduction.

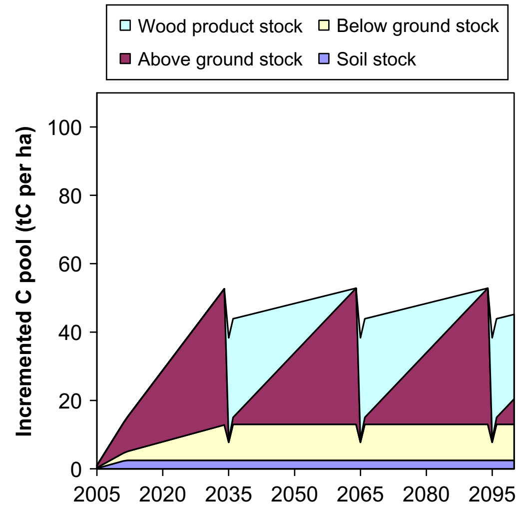

Fig. 4 – Incremented C pool in the long rotation scenario (tC/ha). The total C pool varies over the rotation cycle due to variation in the AGB stock.

monitoring of forestry sector mitigation projects more complex than energy sector mitigation projects.

There are several methods for measuring and monitoring of different carbon pools. There is therefore a need to identify and select methods, which give acceptable accuracy in a cost-effective way. Standard textbook methods are available for measuring and monitoring carbon pools for forestry projects. The Special Report of IPCC on Land Use, Land Use Change and Forestry [12] has discussed different accounting, measurement and monitoring approaches and methods with implications for accuracy, cost and institutional capacity.

A case study of the Western Ghats Forestry and Environment Project showed that less than 10% of the project budget may be adequate for intensive monitoring of carbon stocks and flows, including creation of infrastructure and capacity building activities [4]. There is a direct correlation between cost and accuracy and it varies with the carbon pool. The methods and frequency of monitoring must be set on a level that meets the demand for certainty and cost effectiveness. Carbon-monitoring costs can be classified into three types [13]:

- initial 'establishment' costs;
- annual fixed costs, independent of the number of plots sampled; and
- annual variable costs (the cost of monitoring each sampling plot).

The costs of monitoring will vary depending on which method is chosen. The costs are also likely to vary depending on which forestry option is chosen. The monitoring requirement for the different land-use strategies are listed in Table 7.

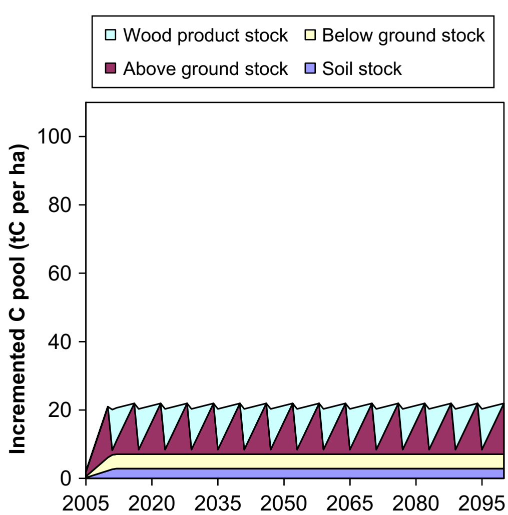

Fig. 3 – Incremented C pool in the short rotation scenario (tC/ha). The total C pool varies over the rotation cycle due to variation in the AGB stock.

Table 6 – Land-use efficiency for carbon benefits (A. bioenergy replacing coal, B. bioenergy replacing diesel).

	Biomass for bioenergy		C sequestration via A&R	
	A. coal	B. diesel	Short rotation	Long rotation
Total C-benefit per 30 year period (tC)	860	788	478	1054
Annual mitigation potential (tC/ha/year)	1.43	1.31	0.80	1.76
Mitigation potential_30 years (tC/ha/30 years)	43	39.4	23.9	52.7
Mitigation potential_100 years (tC/ha/100 years)	104	92.5	23.9	45.2

Table 7 – The monitoring efforts in the different scenarios.

	Parameters	Frequency	Methods
Biomass for bioenergy	- Soil C	5 years	- Field sampling - Laboratory estimation
	- Power generation	Weekly	- Field observation
	- Wood consumption	Weekly	- System monitoring
Short rotation C sequestration	- AGB	6 years	- Field sampling - Analysis
	- Soil C	5 years	- Field sampling - Laboratory estimation
Long rotation C sequestration	- AGB	3 years	- Field sampling - Analysis
	- Soil C	5 years	- Field sampling - Laboratory estimation

Several measures could limit the transaction costs. Involvement of the local community in the monitoring process will not only lower the cost but it would also strengthen the local participation and local control. Another way to lower the transaction costs is to bundle several smaller LULUCF projects in one portfolio.

5.5. *Cost effectiveness of bioenergy C-sequestration*

One way of ranking different mitigation strategies is to compare the cost effectiveness of the different options. A case specific comparison of the different options is given in Table 8. The management costs include the costs of minimizing the risk for non-permanence and leakage.

Table 8 – Comparison of the cost effectiveness (Rs/tC) for the mitigation strategies (1US$ = 40 Rs).

	Biomass for bioenergy		C sequestration via A&R	
	A. coal	B. diesel	Short rotation	Long rotation
Establishment cost (Rs/ha)	21000[a]		21000	29500
Variable costs (Rs/ha/year):				
- Management costs	600		600	600
- Monitoring costs	300[b]		370[c]	540[d]
Cost (Rs/tC)[e]	918	1001	2080	908

a Does not include costs for establishing the gasification system.
b Cost of monitoring soil C once every 5th year (1150 Rs) and recording wood consumption and power generation weekly.
c Cost of monitoring AGB C and soil C once every 5th year, 2200 Rs.
d Cost of monitoring AGB C every 3rd year, 1050 Rs and AGB C and soil C once every 5th year, 2200 Rs.
e With a discount rate of 6%.

The unit abatement cost range from 908 to 2080 Rs/tC (23 to 50 US$/tC) depending on which strategy is chosen. The price of carbon on a future market is not easy to predict. As a comparison the future price for 2008 emission allowances (EUADEC08) within the EU Emission Trading Scheme has so far remained relatively stable between 15 and 25 €/tC (approximately 22–37 US$/tC) [14]. Both the bioenergy option and the long rotation wood product option would be cost effective with a C price above 30 US$/tC. One should note that the external effects were not included in this comparison. All of the three options compared are accompanied by significant social and environmental benefits that are briefly outlined in the next Section.

5.6. *Social and environmental benefits*

The social benefits of forestry projects like those treated in this paper are difficult to monetize. The bioenergy project in Hosahalli provided several positive socio-economic benefits [4]. The operation, maintenance and monitoring of the system has created employment. Access to clean drinking water improved the health situation and the irrigation increased the yields. Electricity for lightning improved the domestic situation and made it easier for the school children to study.

The project as a whole, involving the local community in the planning, implementation and management of the bioenergy system, strengthened the society. Disagreements occurred during the 15 years of operation concerning issues like the sharing of water, forest protection and recovery of fee-for-service. These conflicts were resolved by local institutions helping to improve the self-reliance and local control. If the expansion of the system is carried out in the same manner, positive social side effects are likely to occur, both direct and indirect.

The establishment and good management of forest plantations on the degraded land will not only lead to carbon sequestration in soil and standing trees. It will also reduce soil erosion and help improve the soil and water quality. By reducing pressure on natural forests the plantations indirectly lead to reduced deforestation and contribute to biodiversity conservation [2]. Mixed species plantations can – if planted in appropriate density – have direct positive effects on the biodiversity on degraded land.

6. Concluding discussion

This study compared the relative attractiveness of two different land-use strategies for climate change mitigation in India. The effectiveness of using land for bioenergy was compared with using the same land for C sequestration in short or long rotation plantations providing wood products for non-energy purposes.

The results indicate that the ranking of the different strategies depends to a large extent on the system boundaries and time horizon adopted for the evaluation.

The small scale of the Hosahalli project makes the expenditures relatively high compared to the potential income from C trading. However, initiatives like the CDM can provide the incentive needed to make LUCF projects more attractive by providing revenues at in the beginning of the project.

All of the LUCF strategies assessed in this study represent potential CDM activities and would if introduced in a sustainable manner have beneficial environmental, social and economical effects.

Considering the facts that there are tens of thousands of villages around India that depend on unreliable power from the centralized grid for electricity supply, and that a further 15% of the Indian villages are still not electrified, the potential for bioenergy projects can be considerable. Hosahalli, with its 218 inhabitant, could serve as a representative for the 587 000 villages in India, with a majority of them having a population of less than 500 [2]. Previous studies have shown that small biomass gasifier-based decentralized power generation systems can contribute to a considerable share of the electricity needs in rural India [6].

Around 60 million ha, or approximately 20% [15] of the total amount of geographical land in India is classified as degraded land or wasteland, which urgently require revegetation to prevent further degradation. Plantations for the supply of bioenergy or non-energy wood products (possibly with additional income from C sequestration in soils and standing biomass) could play an important role in the reclamation of these lands.

REFERENCES

[1] UNFCCC. Clean development mechanism (CDM). CDM project search. Retrieved April 2008, from, <www.cdm.unfccc.int>.

[2] Ravindranath NH, Murthy IK. Clean development mechanism and forestry projects: strategy for operationalization in India. The Indian Forester 2003;129(6):691–706.

[3] Berndes G, Hoogwijk M, van den Broek R. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass and Bioenergy 2003;25(1):1–28.

[4] Ravindranath NH, Bhat PR. Monitoring of carbon abatement in forestry projects – case study of Western Ghat Project. Mitigation and Adaptation Strategies for Global Change 1997; 2:217–30.

[5] Ravindranath NH, Hall DO. Biomass, energy and the environment – a developing country perspective from India. New York: Oxford University Press Inc; 1995.

[6] Ravindranath NH, Somashekar HI, Dasappa S, Jayasheela Reddy CN. Sustainable biomass power for rural India, case study of biomass gasifier for village electrification. Current Science 2004;87(7):932–41.

[7] Somashekhar HI, Dasappa S, Ravindranath NH. Rural bioenergy centers based on biomass gasifiers for decentralized power generation: case study of two villages in southern India. Energy for Sustainable Development 2000; 4(3):55–63.

[8] Sathaye JA, Meyers S. Greenhouse gas mitigation assessment: a guidebook. AH Dordrecht: Kluwer Academic Publishers; 1995.

[9] IPCC. Revised 1996 IPCC guidelines for national greenhouse gas inventories. In: The reference manual, vol. 3. Geneva: IPCC Secretariat; 1996.

[10] Marland B, Schlamadinger G. Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. Biomass and Bioenergy 1997;13(6):389–97.

[11] Cacho OJ, Wise RM, MacDicken KG. Carbon monitoring costs and their effect on incentives to sequester carbon through forestry. Mitigation and Adaptation Strategies for Global Change 2004;9(3):273–93.

[12] Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ. Land use, land-use change, and forestry. Special report of the intergovernmental panel on climate change. United Kingdom: Cambridge University Press; 2000.

[13] Ravindranath NH, Ostwald M. Carbon inventory methods. Handbook for greenhouse gas inventory, carbon mitigation and round wood production projects. In: Advances in global change research, vol. 29. Heidelberg: Springer; 2008.

[14] Pool Nord. Carbon contracts closing price on the nordic power exchange. Nordpool market data services. Retrieved February 2008, from, <www.nordpool.com>.

[15] GOI, Wastelands Atlas of India. Government of India, Ministry of rural development, National Remote Sensing Agency, New Delhi and remote Sensing Agency, Dept. of Space. Balanagar, India: Government of India; 2005.