CM-PD-1101

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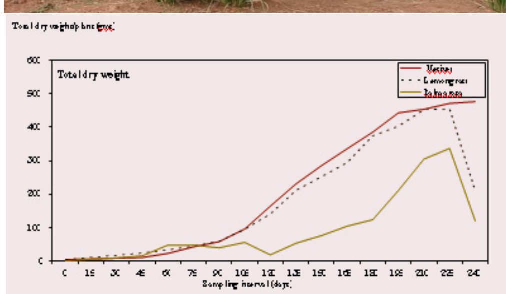
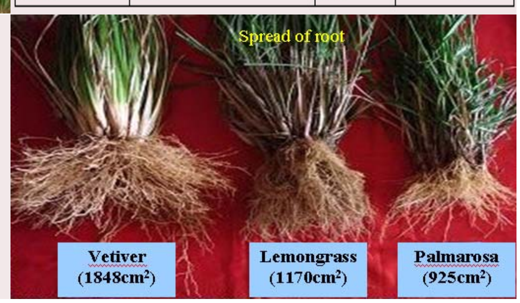
Soil	50	11.5	0.6
Total	200	46.1	2.4





A Project Document under the CSIR Network Project

Integrated Analysis for Impact, Mitigation and Sustainability (IAIMS)

July 2011

Project Document CM PD-1101
July 2011

Publication Status: Internal Report
Distribution: Unrestricted

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A Strategy for Sustainable Carbon Sequestration using Vetiver *(Vetiveria zizanioides* (L.)): A Quantitative Assessment over India

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Summary

Sequestration of atmospheric carbon is one of the mitigation measures for countering the anthropogenic climate change due to emission of green house gases. However, such sequestration measures need to be sustainable and significant, without conflict between groups with diverse priorities. Identification of a system for efficient land-based carbon sequestration therefore requires a quantitative estimate on a regional setting. Based on a field experiment and analysis, it is shown that vetiver, an economically viable crop due to its essential oil and medicinal properties, also provides an efficient carbon sequestration system. A comparison of normalized (to 12-month growth cycle) carbon sequestered by different trees and crops with that by vetiver shows it to be more efficient. Similarly, the carbon sequestered is found to be the highest by vetiver in comparison to two other aromatic grasses viz. lemongrass (*Cymbopogon flexuosus*)and palmarosa *(Cymbopogon martinii* var. *motia*). Our study also provides first time estimates of differential carbon sequestered by root and shoot; once again vetiver is found to be significantly more efficient. It is further pointed out that plantation of vetiver as an inter-crop in short rotation forest plantations and in agro-forestry systems can provide significant lift to the rural economy without any adverse effect on the eco-system. Based on a number of estimates it is suggested that utilization of waste and degraded lands and social forestry systems for vetiver plantations can provide multiple benefits including significant carbon sequestration in India.

1. Introduction

Rising levels of CO_2 leading to global warming has triggered a search for methods to control and bring down the levels of atmospheric carbon. Carbon sequestration in biomass and soil has been proposed to be a key strategy to reduce atmospheric CO_2; these sequestration strategies are likely to play a major role in the next 20-30 years, until new technologies, particularly in

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the energy sector, are developed and implemented to bring down emission levels. Soil C-sequestration is expected to account for about 90% of the total global mitigation potential available in agriculture by 2030 (Smith *et al.*, 2008). While there has been considerable interest in carbon sequestration through iron fertilization in the oceans, forest and agricultural lands may also play a key role in the overall strategy for slowing the atmospheric accumulation of carbon. Further, ocean fertilization to sequester CO_2 by phytoplankton can be ecologically disruptive and is unlikely to be effective for climate mitigation (Strong *et al.*, 2009). Though land-based carbon capture and storage has been proposed the high cost involved is often used as an argument against it (Noorden, 2010)

1.a Carbon Sequestration through Land Biomass

The various strategies proposed for C-sequestration on land include soil restoration and woodland regeneration, no-till farming, cover crops, nutrient management, manuring and sludge application, improved grazing, water conservation and harvesting, efficient irrigation, agro-forestry practices and growing energy crops on spare lands (Lal, 2004).Conversion of arable agriculture to perennial plants (trees, grasses, shrubs) can also contribute to sequestration of C (Powlson *et al.*, 2011).

It is, however, important to carefully identify the plant/crop in planning C- sequestration through vegetation. Success with C sequestration using plants critically depends on avoiding conflict between economic interest and long-term environmental concerns. In particular, sustainability issues and measures that include distributed and small-scale C- sequestration with multiple livelihood benefits are likely to play a major role in mitigation efforts (Lehman, 2009). In tropical countries, land resources being degraded and limited, alternative agricultural strategies which combine environmental benefits (such as C- sequestration) and economic returns to sustain livelihoods need attention.

1.b: Vetiver as a Candidate for Carbon Sequestration

The present study examines the significance of a perennial aromatic grass, vetiver *(Vetiveria zizanioides)* for its C-sequestration potential and economic benefits. Lavania and Lavania (2009) suggested that vetiver could be a potential candidate for C- sequestration, though no field level estimates of C – sequestration by vetiver appear available.

Vetiver is a perennial grass which grows in the tropical and sub-tropical parts of the world. This grass grows in a wide range of conditions, at different temperatures (- 15^{0}C to > 55^{0}C), soil pH (< 3 to > 10), annual rainfall (< 300 mm to > 5000 mm) and tolerant to salinity, prolonged waterlogged conditions and is resistant to pests and diseases (Grimshaw, 2008).Vetiver has significant environmental and economic benefits and is used in soil conservation, phytoremediation, essential oil production, medicinal preparations, handicrafts, production of forage, mulch, thatches etc. Its wide adaptability and multiple uses make it an ideal candidate for mitigation strategies such as C- sequestration. The annual world trade in vetiver oil is estimated to be around 250 tons. However, annual consumption and demand is likely to increase further. In India, about 20 tons of vetiver oil is produced annually which is below the current domestic demand. Also, vetiver roots are widely used in traditional (Ayurvedic) medicine India. Thus, there is a great scope for economic utilization of vetiver, besides environmental benefits (Prakasa Rao *et al.*, 2008) .

2. Field Experiments and Analysis

All the three test plants, vetiver, lemongrass and palmarosa, are perennial in nature; however, periodic harvesting of lemongrass (two to three cuts per year) and palmarosa (three to four cuts per year) restrict biomass accumulation and C sequestration unlike in vetiver where the harvest can be taken after one year.

2.a: Field Site and Soil Characteristics:

Field studies have been conducted during 2010-2011 at the Central Institute of Medicinal and Aromatic Plants, Research Centre, Bangalore, India, a constituent laboratory of Council of Scientific & Industrial Research, India (CSIR). The field site (Bangalore) is located at an altitude of 930 m , at a latitude of 12° 59’ N, 77° 35' E; its climate is semi-arid tropical. The soil is a red sandy loam with pH 6.15, E.C 0.09, organic carbon ranging from 0.37% to 0.69% , available nitrogen 195 kg ha^{-1} , Olsen’s available P 12.5 kg ha^{-1} and exchangeable K 109 kg ha^{-1}.

2.b: Agronomic and Analysis Procedure:

Adjacent field plots measuring 200 m^2 were used for the three crops. Standard agronomic practices were followed in cultivation of these crops (Prakasa Rao, 2007; Patra *et al.,*2004). Sample plants (5 nos) were harvested at random periodically up to 240 days to study biomass accumulation pattern and for carbon analysis. Finally, the crops were harvested as: one harvest of vetiver after one year; 2 harvests of lemongrass (8 and 12 months after planting) and 4 harvests of palmarosa (3,6,9 and 12 months after planting) along with roots.

2.c: Processing and Analysis:

Shoot and root biomass were recorded and total values are presented. The samples of shoot and root were dried in oven (at 80 °C) to constant weight to derive dry matter production. The dried samples were ground to pass through 0.2 mm mesh and were analyzed for carbon content(Walkley and Black,1934). Carbon accumulated in shoots and roots were derived from the values of C concentration and dry matter. Fresh herb (lemongrass and palmarosa) and fresh roots (vetiver) were distilled in a clevenger type apparatus(Langenau,1948) to estimate essential oil content. Essential oil yields were calculated based on essential oil concentration (%) and fresh herb/root biomass yields.

The herb, after extraction of essential oil in case of lemongrass and palmarosa and harvested shoots in case of vetiver was converted to vermicompost following standard methods(Puttanna and Prakasa Rao, 2003) The conversion ratio of the dry herb residue and vetiver shoot biomass to vermicompost (40%) and organic C in the compost (26 % C) were used to arrive at C recycled into soil when applied. Soil samples at 2 depths (0-15 cm and 15-30 cm) were collected before planting of the crops and at the end of the study period. Organic C in the soil samples was estimated (Walkley and Black,1934). C- sequestered in the soil was calculated separately for both the depths (2e) and total C- sequestered was presented. Economics of vetiver, lemongrass and palmarosa cultivation for their oil production were calculated (Table 4).

Spread of Root (SOR) is measured as the approximately circular horizontal spread when the root mass is placed on a smooth horizontal surface with the tip of the stem touching the surface.

2.d: Additional Data:

Field plots of vetiver were maintained in the experimental area to study soil organic carbon (SOC) for periods up to 5 years. Also, vetiver plantations in western Ghat region of south India were studied to assess the feasibility of vetiver cultivation in forest areas and along with existing cropping systems.

2.e: Calculating C sequestration in soil:

$$\text{C-sequestered (Mg ha}^{-1}) = \%\text{ C /100 x BD x SD x 10 000 m}^2\text{ /hectare} \quad (1)$$

Where, %C = Increase in soil organic C in treatment over control plot

BD = bulk density of soil horizon under study (Mg m^{-3}) ; Mg = megagrams (metric tons)

SD = soil depth under study (meters)

2.f: Vermicompost production from vetiver shoot biomass:

Fresh biomass:	106.2 (megagrams ha^{-1})
Drymatter:	45.3 (megagrams ha^{-1})
Vermicompost (@ 40 % of drymatter)	18.1 (megagrams ha^{-1})
Organic carbon (@ 26% of drymatter)	4.71 (megagrams ha^{-1})

3. Results

3.a: Biomass and spread of root (SOR)

A comparison of biomass in shoot, root as well as spread of root (SOR) from the field studies shows (Fig.1) vetiver possessed higher potential than lemongrass and palmarosa to absorb CO_2. Vetiver produced a SOR of 1848 cm^2 at the end of an 8-month period; the corresponding numbers for lemongrass and palmarosa are, respectively, 1170 cm^2 and 925 cm^2 (Figure 1).

Spread of root (SOR)

(A) Vetiver: 1848cm^2
(B) Lemongrass: 1170cm^2
(C) Palmarosa: 925cm^2

Figure 1: Root growth of the aromatic grasses after 8 month of plantation (A) Vetiver (B) Lemongrass (C) Palmarosa . The 8 month period signifies maturity period for lemongrass and palmarosa, while for vetiver it is an early part of its maturity time period (typically 18 months and extends even upto 60 months).

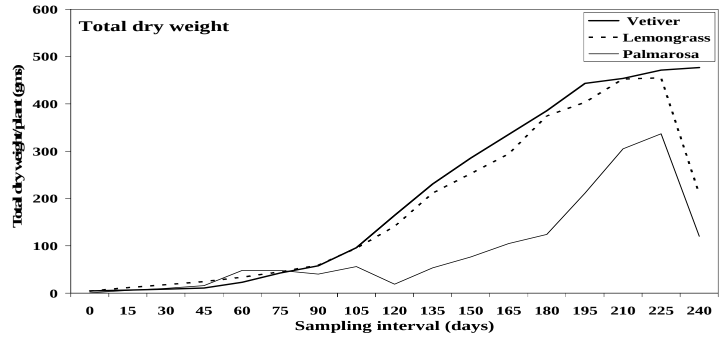
Figure 2. A sample vetiver root system after 18 months, showing substantial growth in spread as well as length compared to those after 8 months (Figure 1).the large mass and length of root (~30 cm) make vetiver efficient in sequestering carbon in soil.

The higher SOR of vetiver makes it a larger reservoir of carbon; further, the total root mass of vetiver at maturity can be much higher (Figure 2), with significantly longer (deeper) root length than either lemongrass or palmarosa.

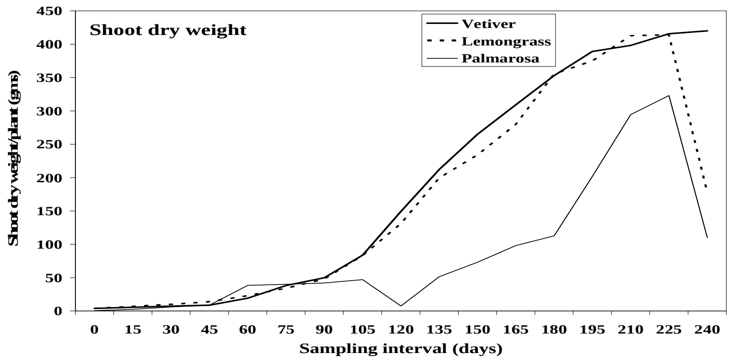
3.b: Growth Curves

Growth curves of total dry weight (Figure 3a), shoot dry weight (Figure 3b) and root dry weight (Figure 3c) show vetiver and lemongrass to have similar characteristics until harvest time; the growth curve of palmarosa is much slower, with a peak value of total dry weight (337 grams per plant) that is much below the corresponding value for vetiver (470 grams per plant). It should be noted that while the peak values of vetiver and lemongrass are very similar, the growth curve for vetiver, unlike that of lemongrass, has not saturated at the time of harvest for total and shoot dry matter (Figure.3a and 3b). Significantly, the dry weight in root, which is more effective a measure for C sequestration in soil, in vetiver is significantly higher than that for either lemongrass or palmarosa (Figure 3c).

(a)



(b)



(c)

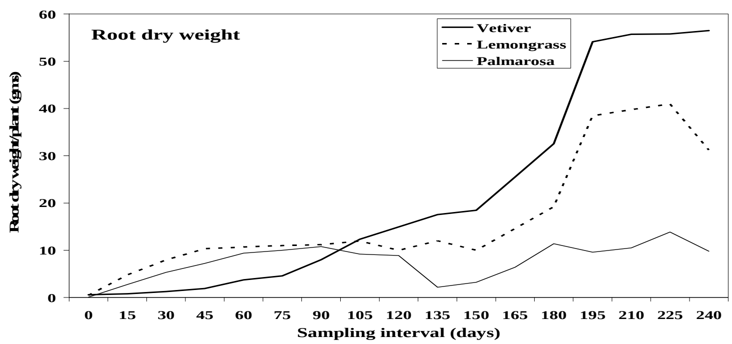


Figure 3: Growth curves for three aromatic grasses vetiver (solid line), lemongrass (dash line) and palmarosa (thinner line) during a crop cycle of 240 days, starting September, 2010, for accumulation of dry matter (a) total (b) in shoot (c) in root. Each curve represents an average of 5 plants harvested at specified time from randomly selected field points.

3.c: Comparative Analysis of C Sequestration by Vetiver

The high potential of vetiver as a candidate for cultivation to absorb atmospheric CO_2 is clear from the very high biomass produced (table 3). Even marginal and degraded lands can be utilized for vetiver cultivation. Since vetiver can tolerate high soil pH and saline soil conditions, it is a potential candidate for cultivation in large areas of salt effected soils in India (6.63 m ha), besides in the areas affected by soil acidity (17.9 m ha), soil erosion(83.3 m ha)(ICAR, 2010).

Considering the estimates for the C- sequestration potential of activities such as land management, grazing land management and restoration of organic soils and degraded lands which range from about 0.3 to 0.8 t C ha $^{-1}$ year $^{-1}$ (Smith *et al.*, 2008), the potential for C-sequestration by vetiver could be substantially significant.

Forest Trees: The amount of C sequestered by vetiver was high in comparison with some of the tree species widely considered for afforestation projects in India (table 1).

Table 1. C- sequestration by different species (normalized to 12 month crop cycle)

Tree/Crop/Cropping System	C- sequestration (megagrams ha^{-1} year^{-1})
Albizzia lebbek[1]	1.04
Tectonia grandis[1]	1.33
Artocarpus integrifolia[1]	1.21
Shorea robusta[1]	0.87
Poplar[2]	8
Eucalyptus[2]	6
Teak[2]	2
Vetiveria zizanioides	15.24
Lemongrass	5.38
Palmarosa	6.14
Vetch(V)-maize(M)-oat(O)-soybean(S)-wheat(W)-soybean(S)[3]	7.26
O-M-W-S[3]	8.56
V-M-W-S[3]	7.58
Ryegrass(R)-M-R-S[3]	8.44
Alfalfa(A)-M[3]	7.52
Rice-rice [4]	1.54-2.48(residues)
Maize-rice[4]	2.1-3.51(residues)

[1]Jana *et al.*,(2009); [2]Kaul *et al.*,(2010); [3] Santos *et al.*,(2011); [4]Witt *et al.*,(2000)

Crop Systems: A comparison of carbon sequestered by vetiver in soil with that by some common tree/cropping systems in India and elsewhere in the world shows vetiver to have significant advantage (Table 2).

Table 2: Comparison of C sequestration in soil by vetiver and some trees/cropping systems

Trees/crops/cropping systems	C- sequestration (Mg ha $^{-1}$ year $^{-1}$)	Ref.
V-M-O-S-W-S O-M-W-S V-M-W-S R-M-R-S A-M	0.12 0.16 0.28 0.32 0.44	Santos et al.,2011
Rice-maize Maize-rice	0.92-1.37 -0.11-0.23	Witt et al.,2000
Rice-wheat Maize-wheat	0.13-0.31 0.03-0.14	Kukal et al.,2009
Eucalyptus Poplar Teak	1.11 3.88 0.70	Kaul et al.,2010
Vetiver lemongrass	5.54 3.08	

Other Aromatic Plants: While there exist a large number of economically viable aromatic plants, the present study considered the three most widely cultivated aromatic plants: Vetiver, lemongrass and palmarosa. A comparison shows vetiver to be superior in carbon sequestration in general (Table 3).

Table 3. Comparative drymatter production and C- sequestration by aromatic grasses

Crop	Carbon (%)		Drymatter (Mg ha^{-1} year^{-1})		C – sequestered (Mgha^{-1} year^{-1})		
	shoot	root	Shoot	root	shoot	root	total
vetiver	50.53	50.27	28.62	1.56	14.46	0.78	15.24
lemongrass	44.45	48.14	10.5	1.57	4.83	0.55	5.38
palmarosa	52.77	43.49	11.11	0.65	5.86	0.28	6.14

4. Economic Implications and Feasibility

A major barrier in implementation of land-based mitigation measures is economic constraints (Smith, 2008). The vetiver system can provide alternate sources of income from its essential oil, from its use in handicrafts, in traditional medicine and compost. The economic returns from vetiver oil production can be quite attractive for small and marginal farmers to take up cultivation of vetiver (table 4). Comparison of various strategies such as irrigation and afforestation of deserts in Africa and Austalia, indicates (Lehman, 2009) that biological C-sequestration is an important strategy to withdraw atmospheric CO_2 and that small scale and distributed activities which provide returns to farmers from various sources could be an important strategy to sequester carbon. Thus, the vetiver system under study can have several sustainable and livelihood benefits.

Table 4: Comparative Economics of three aromatic plants and rice

Crop	Fresh biomass ($Mg\ ha^{-1}\ year^{-1}$)	Essential oil (%)	Cost ($Rs\ ha^{-1}$)	Net returns ($Rs\ ha^{-1}\ year^{-1}$)
Vetiver	4.25 (roots)	0.8	100 000	230 000
Lemongrass	27.7	0.8	42 800	84 550
Palmarosa	30.0	0.5	40 000	110 000
Rice[1]			15 400	30 200

[1]Chengappa *et al.*,(2003)

The annual world trade in vetiver oil is estimated to be around 250 tons. However, the annual consumption and demand is likely to increase further. In India, about 20 tons of oil is produced annually which is below the current domestic demand (Thwaites, 2010). Also, vetiver roots are widely used in traditional (Ayurvedic) medicinal systems in India.

5. Potential Implementation Strategies

(a) **Recycling Practice:** While it is a practice to burn vetiver shoots at the time of harvest by farmers in India, conversion of this biomass to vermicompost and subsequent incorporation in soil helps in preventing emissions of CO_2 into atmosphere and sequester carbon in soil. Powlson (2011) suggested revegetation of degraded lands and additions of organic matter to soil as positive approach. Our estimates in the field have shown that 18 t vemicompost ha^{-1} from vetiver could be produced which added 4.7 t C ha^{-1}

(b) **Incentive and Popularization:** Growing of vetiver for environmental benefits may be included in the National Developmental Programmes on watershed development, afforestation, horticulture etc. and subsidies to the farmers can be provided as an incentive for the cultivation of vetiver not only for economic considerations but for environmental benefits such as carbon sequestration.

(c) **Land Management:** Vetiver can be incorporated in social forestry (Figure 4) and existing cropping system (Figure 5). One important feature of vetiver cultivation is that the soil is not disturbed for more than 1 year, in comparison to other agricultural systems where seasonal crops require frequent tillage operations. This helps in building SOC.

Figure 4. Vetiver plantation in interspaces of a social forestry system in western Ghats region of south India . Such sites provide non-obstructive, eco-friendly implementation of vetiver plantation for carbon sequestration.

However, in systems which warrant harvest of vetiver roots for essential oil, alternate strategies such as incorporation of vetiver in agro-forestry systems, in field boundaries, in degraded lands, recycling of vetiver residues need to be adopted to sequester carbon.

Figure 5. Vetiver cultivation near forests on hill slopes (rice cultivation in the foreground) in western Ghats area of south India. Vetiver has been incorporated in the existing cropping systems of this region for both economic and environmental benefits(Prakasa Rao et al.,2008)

(d) **Impact Assessment:** Vetiver appears to be a potential carbon sequestration system both in terms of environmental compatibility and economic benefit; in particular, adaptation of vetiver is unlikely to create any difficulty for small and marginal farmers in India. On the other hand, systematic and large-scale plantation of vetiver in otherwise non-arable land can provide significant environmental and economic benefits. In terms of carbon sequestration, vetiver can potentially sequester nearly 20 t C ha $^{-1}$ and at same time provide net returns to the farmers in the range of Rs 2 lacs ha $^{-1}$.Further studies are required to develop more developed crop management strategies in varying agro-climatic conditions to derive better environmental and economic benefits.

Table 5: CO_2 (carbon) Emission by India and World

Total CO_2 emissions ($TgCO_2$)					
Country	**Year**				
	2005	2006	2007	2008	2009
India	1183.28 (323.0)	1282.68 (350.2)	1368.38 (373.5)	1463.3 (399.4)	1591.13 (434.3)
World	28366.15 (7743.9)	28939.22 (7900.3)	29724.51 (8114.7)	30400 (8299.2)	30313.25 (8275.5)

In parenthesis, values for Carbon (TgC)): Source:U.S.Energy Information Administration http://tonto.eta.doe.gov/)

Thus carbon sequestered through a vetiver system can be a significant fraction of regional (Indian) and the world emission (Table 5) of carbon.

Table 6: Estimates of sequestration CO_2 (carbon) Emission through vetiver

C-sequestered by Vetiver			
Vetiver System	**C-sequestered(Tg $year^{-1}$) in India (10 m ha of degraded soils)**	**% of emissions (2009)**	
		India	**World**
Biomass	150	34.6	1.8
Soil	50	11.5	0.6
Total	200	46.1	2.4

As a broad estimate, utilization of about 10 m ha of degraded soil in India could potentially sequester up to 46% (Table 6) of total carbon emission by India (in 2009). While the sequestration in practice is naturally likely to be much less, it is still expected to be significant.

6. Concluding Remarks

Many aromatic crops have high rates of biomass production and hence offer potential candidates for carbon sequestration in both biomass and in soil. While there is a tendency to overestimate the C- sequestration in agricultural systems in general (Powlson, 2011) and in vetiver in particular (Lavania and Lavania, 2009), the present study provides field estimates of biomass production and C- sequestration by vetiver. Increasing SOC (soil organic carbon) from a low of 0.1% - 0.2% to a critical level of 1.1% is a major challenge for tropical ecosystems (Lal, 2004). The soil planted with vetiver in our study has shown SOC of 1.12-1.39% compared to 0.64-0.70 % in cultivated soil at the end of 5 years.

While there has been considerable interest in carbon sequestration through iron fertilization in the oceans, forest and agricultural lands may play a key role in the overall strategy for slowing the atmospheric accumulation of carbon. Further, ocean fertilization to sequester CO_2 by phytoplankton can be ecologically disruptive and is unlikely to be effective for climate mitigation (Strong *et al*., 2009).

Thus carbon sequestration using land biomass is a potential method for controlling and reducing GHG. Carbon can be sequestered in biomass and in soil. Changes in agricultural management can potentially increase the accumulation rate of soil organic C (SOC), thereby sequestering CO_2 from the atmosphere.

Emerging methods like crop modelling provide cost-effective and unobtrusive ways of identification of conditions and comparative evaluation for efficient land-based carbon sequestration systems using a set of parameters for optimum configuration. Supported and constrained by field studies and laboratory analysis, such systems can provide multiple benefits as well as efficient land-based carbon sequestration systems.

Acknowledgement: The work was supported by the project Integrated Analysis for Impact, Mitigation and Sustainability (IAIMS), funded by CSIR, India.

Appendix: Abbreviations, conversions and units:

gms	gram
ha	hectare
m	million
Mg	megagrams
Rs	rupees
Tg	teragram
SOC	Soil organic carbon
SOR	Spread of root
A	alfalfa
O	oat
M	maize
R	ryegrass
S	soybean
V	vetch
W	wheat

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