

Assessment of agricultural crop and soil carbon pools in Madhya Pradesh, India

NISHA WANI, A. VELMURUGAN* & V.K. DADHWAL

*Indian Institute of Remote Sensing, NRSC, ISRO, Dehradun 248 001, India
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Abstract: A geospatial analysis of agricultural carbon pools (crop biomass and soil organic matter) of Madhya Pradesh, India for the year 2005-06 is reported. Remote sensing data, district boundaries, and the agro-ecological sub-regions (AESR) were integrated in GIS with land cover and an FAO-UNESCO soil map. District-wise crop production statistics of agricultural crops of M.P. for the year 2005-06 were used to estimate crop biomass by using conversion factors. Point-based data of soil organic carbon (0-30 cm) was regionalized for all five AESR, and total soil carbon density and stock were estimated. Total crop and soil C stocks of the study area were 34.94 and 790.61 Tg, respectively. Malwa plateau and Narmada valley with hot dry sub-humid condition (AESR III) recorded the maximum crop biomass carbon (14.12 Tg) while Satpura range and Wainganga Valley with hot moist sub-humid condition (AESR V) reflected the minimum crop biomass carbon (2.71 Tg). Maximum (3.95 Mg C ha⁻¹) and minimum (0.50 Mg C ha⁻¹) crop biomass C densities were recorded in Indore and Shahdol districts, respectively. AESR-wise soil organic carbon stocks varied from 74.7 Tg (AESR V) to 263.23 Tg (AESR III). The estimates were found to be positively correlated ($R^2=0.65$) with the remote-sensing derived max. NDVI. Positive correlation was also seen with the cropping intensity, net irrigated area, and per capita N consumption.

Resumen: Se reporta un análisis geoespacial de los contenidos agrícolas de carbono (biomasa de la cosecha y materia orgánica del suelo) de Madhya Pradesh, India, para el año 2005-06. Los datos de percepción remota, los límites distritales y las subregiones ageoecológicas (AESR, siglas en inglés) fueron integradas en un SIG con las coberturas de suelo y un mapa de suelos de la FAO-UNESCO. Se usaron las estadísticas distritales de producción de los cultivos agrícolas de Madhya Pradesh para ese año, con el fin de estimar la biomasa de la cosecha usando factores de conversión. Los datos puntuales de carbono orgánico del suelo (0-30 cm) fueron regionalizados para las cinco AESR, y se estimaron la densidad total y el almacén de carbono del suelo. Los almacenes totales de carbono de la cosecha y el suelo del área de estudio fueron 34.94 y 790.61 Tg, respectivamente. En la Meseta de Malwa y el Valle Narmada, ambos con una condición cálida, seca y subhúmeda (AESR III), se registró el valor más alto de carbono en la biomasa de la cosecha (14.12 Tg), mientras que en la cordillera Satpura y el Valle Wainganga, con una condición cálida, húmeda o subhúmeda (AESR V) se obtuvo el valor mínimo de carbono en la biomasa de la cosecha (2.71 Tg). Las densidades de C en la biomasa de la cosecha máxima (3.95 Mg C/ha) y mínima (0.50 Mg C/ha) fueron registradas en los distritos Indore y Shahdol, respectivamente. Los almacenes de carbono orgánico del suelo por AESR variaron entre 74.7 Tg (AESR V) y 263.23 Tg (AESR III). Las estimaciones estuvieron correlacionadas positivamente ($R^2=0.65$) con el valor máximo de NDVI obtenido por percepción remota. También se observó una correlación positiva con la intensidad de la cosecha, el área neta irrigada y el consumo de N per capita.

* Corresponding Author; e-mail: vels@iirs.gov.in

Resumo: Neste trabalho reporta a análise geoespacial dos stocks de carbono (na biomassa da cultura e na matéria orgânica do solo) em Madhya Pradesh, Índia, para o ano de 2005-06. Os dados de detecção remota, e as áreas agro-ecológicas (AESR) foram integradas num SIG com o coberto do solo e um mapa de solos FAO-UNESCO. Os estatísticos de produção agrícola ao nível distrital de M. P. para o ano 2005-2006 foram usados para estimar a biomassa da cultura usando factores de conversão. Os dados do carbono orgânico do solo (0-30 cm) com base em pontos localizados foram regionalizados para todas as cinco AESR, e a densidade total do carbono no solo e do seu stock foram estimados. O stock de carbono total na cultura e no solo foi de 34,94 e 790,61 Tg, respectivamente. O planalto de Malwa e o vale de Narmada com condições quentes secas e sub-húmidas (AESR III) registaram o valor máximo de carbono na biomassa da cultura (14,12 Tg) enquanto a linha de colinas de Satpura e o vale de Wainganga, com condições quentes húmidas sub-húmidas (AESR V), reflectiram o mínimo de carbono na biomassa vegetal (2,71 Tg). O valores máximos (3,95 Mg C/ha) e mínimos (0,5/ Mg C/ha) da densidade de carbono na biomassa da cultura foram registados nos distritos de Indore e Shahdol, respectivamente. Os stocks de carbono orgânico em termos de AESR variaram entre 74,7 Tg (AESR V) e 263,23 Tg (AESR III). As estimativas encontravam-se positivamente correlacionadas ($R^2=0,65$) com a detecção remota máx. NDVI. Uma correlação positiva foi também encontrada com a intensidade da cultura, a área irrigada líquida, e capitação do consumo de N.

Key words: Agro-ecological sub-region, crop biomass, cropping intensity, soil organic carbon, SPOT-VGT NDVI, standing carbon.

Introduction

Human use of fossil-fuel and land use changes have led to increased concentration of CO₂ in the atmosphere. In terrestrial ecosystems, both vegetation and soil play an important role in absorbing atmospheric carbon dioxide. This has prompted renewed interest in increasing the stocks of carbon (C) in the world's croplands to mitigate climate change and also improve soil quality (IPCC 2000; Lal 2004). Simultaneously, importance of terrestrial vegetation and soil to act as significant sinks of atmospheric CO₂ and its other derivatives is highlighted under *Kyoto Protocol*. C fixed in plants by photosynthesis and added to soil as above and below ground litter is the primary source of C in ecosystems (Warembourg & Paul 1977). However, there exists large temporal and spatial variation in the capacity of crops and soils to act as a net sink for atmospheric carbon dioxide. Hence, accurately assessing crop and soil carbon stocks becomes significant to understanding anthropogenic effects on the C cycle, the potential of soils to act as a sink for atmospheric carbon, and proper management of the various production systems.

Agro-ecosystems are defined as ecosystems that produce food under human guidance (Mitchell 1979) and the role of agricultural ecosystem in global C cycle is being increasingly realized. There are several estimates worldwide of NPP and the phytomass C pool (Ajtay *et al.* 1979; Leith & Whittaker 1976; Olson *et al.* 1983). Indian agro-ecosystems occupy >43.2% of the country's geographic area (142 M ha out of total area of 328.8 M ha) and is the most dominant terrestrial ecosystem in the country. Preliminary estimates of major pools and fluxes of carbon in India for the mid-1980s were made by Dadhwal & Nayak (1993). The estimated crop primary production increased from 136.9 Mg C in 1950-51 to 337.3 Mg C in 1985-86. A continuously increasing crop NPP would lead to an increase in all the dynamic storage pools within the vegetation of the agro-ecosystem, the upper limit being an increase in NPP of ~6 Mg C per year (Dadhwal *et al.* 1996). Soil, the other major components of the agro-ecosystem can act as a net sink for atmospheric carbon in the form of soil organic carbon that is primarily plant derived. Soil C pools depend on the balance between input and output of carbon in soil. The results of long-term agricultural

experiments indicates that soil organic matter and soil carbon are lost during intensive cultivation but that soil carbon can be increased to new higher equilibria with sustainable management practices (RCEP 1996; Rasmussen *et al.* 1998; Robert *et al.* 2001).

Modern tools like satellite remote sensing (RS) and geographic information systems (GIS) have been providing new opportunities to monitor and manage natural resources and have enormous potential in assessing terrestrial carbon pools. NOAA AVHRR, SPOT Vegetation and ASTER satellite data have been used globally for biomass and productivity estimations. Vegetation indices and derived matrices have been extensively used for monitoring and detecting vegetation and leaf area index, which in turn are positively correlated to biomass and productivity (de Fries *et al.* 1995; Wylie *et al.* 2002). This RS-derived information can be suitably linked to crop statistics, bioclimate, terrain, and soil resource information that are essential in assessing terrestrial carbon stocks and dynamics in a region. The present study aims to estimate the carbon pools in agricultural crop biomass and soil organic carbon for the state of Madhya Pradesh (M.P.) as a component of National Carbon Project (NCP) of India. Agricultural crop biomass and soil organic carbon pools were estimated from crop production statistics and soil organic carbon content estimated through field surveys and published literature sources.

Materials and methods

Study area

The study was conducted for Madhya Pradesh, the second largest state of India. Madhya Pradesh has a geographical area of 30.82 M ha (9.4% of the country) and is located in the central part of India (Fig. 1). It lies between 21°17' to 26°52' N latitude and 74°08' to 82°49' E longitude. Forests occupy 28.2% of the geographical area of the state whereas the cultivated area covers about 56.3% (FSI 2008). Madhya Pradesh consists of four physiographic regions: the low lying areas in north and north-west of Gwalior, Malwa plateau, Satpura, and Vindhyan ranges. Madhya Pradesh experiences a tropical climate with summer temperature ranging from 33 to 44 °C and winter temperatures ranging from 27 to 10 °C. The mean annual temperature ranges from 22.5 to 25 °C. The average annual rainfall varies from 800 mm to

about 1800 mm. Monsoon in Madhya Pradesh lasts from June till September. The rainfall decreases from south east and east to north-west and west. The total population of the state is 60.4 M which constitutes 5.9% of the country's population. Of this, rural population is 73.5% and urban 26.5%.

The wide climatic range, varied physiography, geology and natural vegetation of Madhya Pradesh has resulted in a diversity in soil development, and in turn soil properties and land use. The soils of Madhya Pradesh are grouped into 5 orders, 7 suborders and 11 great groups (NBSS & LUP 1996). The Inceptisols are the dominant soils followed by Entisols, Alfisols, Vertisols and Mollisols. The soils range from rich clayey to gravelly. The major groups of soils found in the state can be divided in to alluvial, medium and deep black, shallow and medium black, and mixed red and black soils. The black soils of the Malwa region are good for cultivation of cotton. Rice, wheat, soybean, rapeseed and mustard are among the principal crops of the state. The cropping intensity of Madhya Pradesh is 135% and varies from 176% in Harda district (highest) to 108% in Bhind district (lowest). Madhya Pradesh is the leading state in the country in the production of pulses such as black gram, red gram and green gram.

Methods

The procedure adopted in this includes (i) delineation of cropped area using remote sensing (SPOT-Vegetation Index) derived products, (ii) assessment of crop biomass from crop statistics, (iii) estimation of soil carbon stock from point measurement using GIS, (iv) understanding the relationship of crop biomass C with cropping intensity, net irrigated area and nitrogen consumption using regression analysis. We have adopted the UTM projection and WGS84 datum for all the input layers so as to bring them into a common GIS framework and facilitate GIS analysis. Agricultural area pixels were obtained by aggregating land use/cover classes prepared from the SPOT vegetation index by Agrawal *et al.* (2003). The district boundaries of Madhya Pradesh were overlaid on the delineated cropped area and the spatial distribution of district-wise cropped area was extracted omitting other land cover classes. The extracted area corresponded to the district-wise reported net sown area. District-wise crop production statistics (DES 2006) of all agricultural crops of Madhya Pradesh for the year

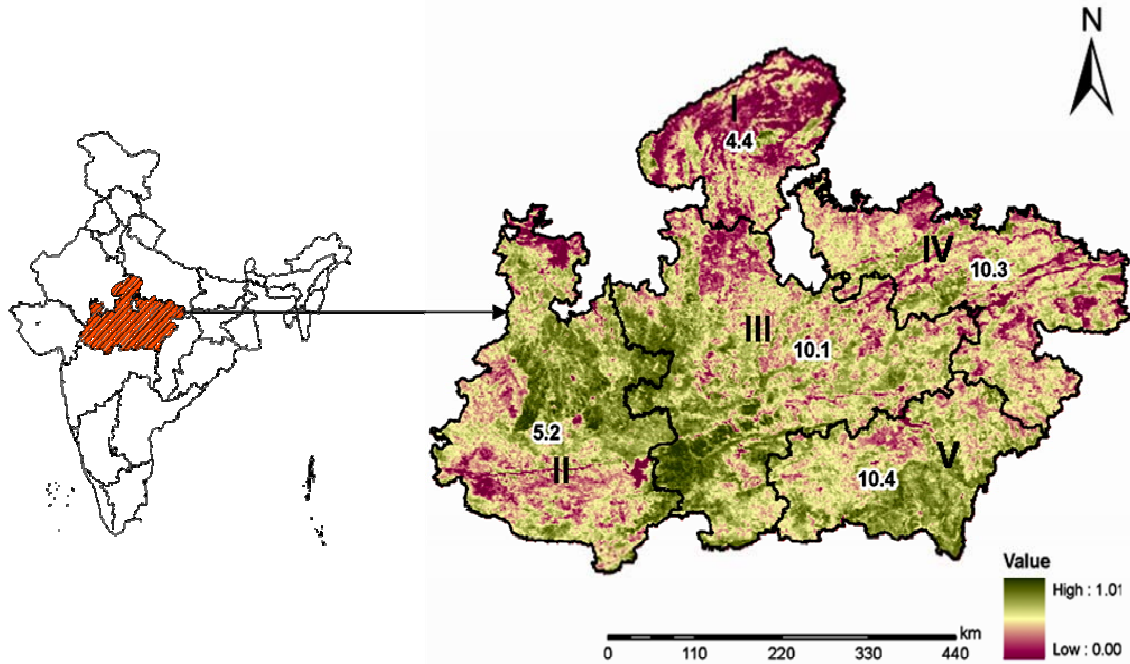


Fig. 1. Location of the study area and agro-ecological sub-regions overlaid on a 10-day composite of SPOT-VGT Maximum NDVI (May 2005 to April 2006).

2005-06 were converted into biomass using crop-wise conversion factors (Dadhwal *et al.* 1994) by following the equation given below:

$$B_c = Y_{EX} (1 - MF_g) * CF \quad (1)$$

where,

B_c - Total biomass of crop considered; Y_E - economic yield/production; MF_g - moisture fraction in grain/economic part and CF - conversion factor *i.e.*, $1/HI$ where, HI is harvest index. The carbon content in biomass was calculated by multiplying biomass by 0.47.

The biomass carbon was a spatially distributed estimate of various districts whereas soil carbon was a point estimate converted into spatially representative values. For this purpose, a point data base of soil organic carbon was prepared from field surveys and published literature sources. The FAO soil map was extracted for Madhya Pradesh as a base map and the soil database was converted into point layers and integrated along with FAO soil map, AESR map and district layers in a GIS framework. The point measurement of soil C was averaged (mid-point approach) within each mapping units. The same approach was followed to estimate the quantity and spatial variability of soil carbon in the USA (Guo *et al.* 2006). In the present study soil organic carbon

stocks were estimated only for the surface soils (0-30 cm) and an area-weighted method was used to convert the soil C content of different layers up to 0-30cm. Soil organic carbon density Q_i ($Mg\ m^{-2}$) in a soil layer or sampling level i with a depth of E_i (m) depends on the carbon content C_i ($g\ C\ g^{-1}$), bulk density D_i ($Mg\ m^{-3}$) and on the volume fraction of coarse elements G_i , given by the formula (Schwartz & Namri 2002):

$$Q_t = \sum_{i=1}^k Q_i = \sum_{i=1}^{ku} C_i D_i E_i (1 - G_i) \quad (2)$$

The estimated district crop biomass carbon was compared to satellite-derived NDVI using regression. For this, 10-day composites of NDVI were used from 1-km resolution SPOT-Vegetation (VGT) data for the period May 2005 to April 2006. A Savitzky-Golay filter was applied on the SPOT-VGT NDVI data to smooth out noise in the NDVI time series caused by cloud contamination and atmospheric variability. The NDVI products for the crop growing season alone were stacked and the district maximum NDVI was extracted. A linear regression analysis was performed between district maximum NDVI and the estimated district crop biomass C. Further, the relationship of estimated crop biomass C to three important

agricultural factors (cropping intensity, net irrigated area and nitrogen fertilizer use) was investigated using regression analysis.

An agro-ecological zone is a homogenous land unit in terms of climate, length of growing period and soil physiographic conditions that are suitable for a group of crops and cultivars. It is more appropriate to analyze the estimated crop and soil carbon stock and density for a natural boundary like agro-ecological regions. Agro-ecological regions (Sehgal *et al.* 1992) and agro-ecological sub-regions (Mandal *et al.* 1995) were generated based on the superimposition of three basic maps: physiography, bio-climate, and length of growing period. Madhya Pradesh contains five agro-ecological sub-regions (AESR I, II, III, IV and V) which are described in Table 1.

Results and discussion

Agricultural area map of Madhya Pradesh

The total geographical area of the state is 30.8 M ha, of which total net sown area in 2005-06 was 14.9 M ha (48.5%), net irrigated area is 5.5 M ha (36.9% of agricultural area) and total forest area is

8.68 M ha (DES 2006). District-wise agriculture area distribution was delineated from the base map and is shown in Fig. 2. Guna and Umari districts had the highest (6337 km²) and lowest net sown area (1109 km²), respectively which was attributed to extent of geographical area and forest cover. Among all other districts of Madhya Pradesh, Hoshangabad had the maximum net irrigated area (79.2% of net sown area) due to the availability of an irrigation canal and Dindori had the minimum net irrigated area (0.40%) as the district was mostly covered with forest and mountainous terrain. The majority of the crops in Madhya Pradesh were rainfed and only 36.9% of the net sown area was under irrigation. The aggregation of agricultural area for AESR indicated that AESR III had the highest net sown area whereas AESR I had the lowest net sown area. AESR III is a hot dry sub-humid region with a 150-180 day growing period while AESR I is a moist semi-arid region with a shorter growing period (Table 1). While intensive and double cropping is possible in AESR III, AESR I can support only a single crop and hence, the former would have a higher crop biomass carbon density than latter.

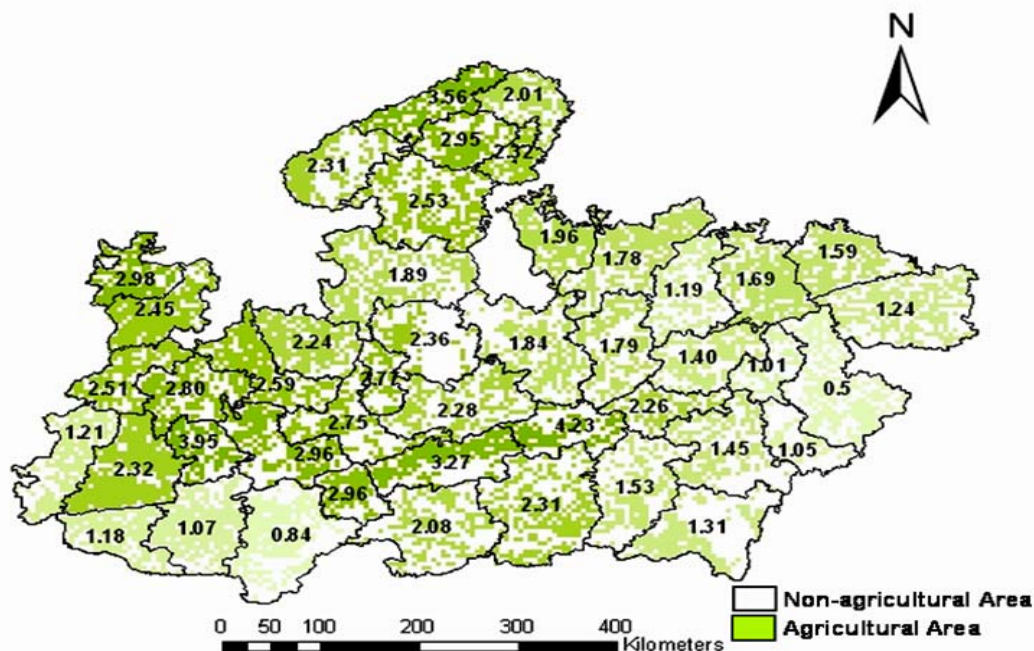


Fig. 2. Agricultural biomass carbon density (Mg C ha⁻¹) in M.P. (numbers denote carbon density in each district).

Table 1. Description of agro-ecological sub-regions (AESR) of Madhya Pradesh (NBSS & LUP 1999).

AESR	NBSS & LUP Code	Description
I	4.4	Madhya Bharat plateau and Bundelkhand uplands, hot, moist semi-arid ESR with deep loamy and clayey mixed red and black soils, medium to high available water capacity (AWC), length of growing period (LGP) 120 – 150 days.
II	5.2	Madhya Bharat plateau, Western Malwa plateau, Eastern Gujarat plains, Vindhyan and Satpura range and Narmada valley, hot moist semi-arid ESR with medium and deep, clayey black soils (shallow black soils as inclusions), medium to high AWC and LGP 120 – 150 days.
III	10.1	Malwa plateau, Vindhyan scarpland and Narmada valley, hot dry subhumid ESR with medium and deep clayey black soils (shallow loamy black soils as inclusions), high AWC and LGP 150 – 180 days.
IV	10.3	Vindhyan scrapland and Baghelkhand plateau, hot dry subhumid ESR with deep loamy to clayey mixed red and black soils, medium to high AWC, LGP 150 – 180 days.
V	10.4	Satpura range and Wainganga Valley, hot moist subhumid ESR with shallow to deep loamy to clayey mixed red and black soils, low to medium AWC, LGP 180 – 210 days.

Crop biomass carbon density and stock

The cropping pattern in the state was much diversified and dependent on soil type, rainfall, water resources development, and socio-economic status. Millet and wheat were the major crops in the central and northern regions, paddy in eastern and southeastern regions and cotton in the southwestern parts of Madhya Pradesh. The introduction of soybean during the 1980s enhanced the oilseed production. The state contributed nearly 75% of soybean production and 36% of gram production to the national production. Food grain production of the state has increased from 8.9 Mt in 1964-65 to 14.1 Mt in 2004-05.

As a result of adoption of high yielding crops and varieties and intensification of agriculture in the state the total crop biomass has increased. Crop distribution and intensity patterns played a dominant role in deciding the total crop biomass and density. District crop biomass carbon density (Mg C ha^{-1}) and AESR crop biomass carbon stock (Tg) is shown in Fig. 2 and Table 2, respectively. The results indicated that total estimated crop biomass C for the state is 34.94 Tg. AESR III had the maximum crop biomass carbon (14.12 Tg) and AESR V had the minimum crop biomass carbon (2.71 Tg). The Maximum (3.95 Mg C/ha) and minimum (0.50 Mg C ha^{-1}) crop biomass C density

Table 2. AESR soil and crop biomass carbon stocks in M.P.

AESR	*NBSS & LUP code	Net sown area (M ha)	Agril. C density (Mg/ha)		Agril. C stock (Tg C)		
			Soil	Crop	Soil	Crop	Total
I	4.4	2.27	42.35	1.30	96.13	2.95	99.08
II	5.2	5.90	37.00	1.23	218.32	7.23	225.56
III	10.1	6.99	37.66	2.01	263.23	14.12	277.35
IV	10.3	3.92	35.26	1.99	138.23	7.93	146.16
V	10.4	1.99	37.54	1.36	74.70	2.71	77.41
Total		20.97	-	-	790.61	34.94	825.56

* Numbering as per National Bureau of Soil Survey & Land Use Planning, Nagpur, India

were recorded in Indore and Shahdol districts, respectively.

Soil organic carbon density and stock

Soil organic carbon holds a very important role in global carbon cycle, as it is the largest terrestrial carbon pool. Soil can be a source (CO_2 , CH_4 and N_2O) or sink (CO_2 and CH_4) of greenhouse gases depending on land use and management (Lal 2002). The high diversity of soil types in M.P. resulted in high variation in soil organic carbon distribution both spatially and in profile. The total estimated soil C pool of the state is 790.61 Tg. AESR I had the maximum SOC density ($42.3 \text{ Mg C ha}^{-1}$) and AESR IV had the minimum SOC density ($35.3 \text{ Mg C ha}^{-1}$). This was likely caused by climate and agricultural development: AESR I is the moist and semi-arid uplands with irrigation facilities and AESR IV is the dry, sub-humid plateau region. The estimated AESR soil organic carbon stock varied widely (Table 2) with maximum SOC stock observed in AESR III (263.2 Tg) and minimum in AESR V (74.7 Tg) followed by 96.13 Tg in AESR I. The wide difference is mainly because of larger area of AESR III and deep to moderate clay soils. Bhattacharya *et al.* (2007) studied changes in carbon levels in soils (up to a depth of 150 cm) from 1980 to 2005 of two important food production zones of India, the Indo-Gangetic Plains and the black soil region in semi-arid tropics, and reported that soils in Kheri (a benchmark location in Jabalpur district of Madhya Pradesh) showed an increase of 87 % of SOC stock over 1980. It was also observed that the top 50 cm depth of these soils, which was non-calcareous during 1980, is now calcareous. This suggested that although intensive agriculture increased the SOC, simultaneously it caused an increase in soil CaCO_3 .

Total agricultural carbon pool

The total estimated crop biomass C and soil carbon stock of Madhya Pradesh was 34.94 Tg and 790.6 Tg, respectively. Soil C stock was approximately 25 times higher than biomass C stock which underlines the role of soil in sequestering atmospheric CO_2 . Similar conclusions were also drawn by Dadhwal & Chhabra (2002). Total agricultural C stock was estimated to be 825.56 Tg with AESR III recording the highest C stock and V the lowest C stock (Table 2). In case of total agricultural carbon density AESR I recorded the highest agricultural C density and AESR IV

recorded the lowest agricultural C density. The estimated crop biomass density (2.1 Mg C ha^{-1}) for the state of Madhya Pradesh is less than the crop NPP (2.9 Mg C ha^{-1}) estimated by Dadhwal *et al.* (1995) as the state was divided into Chhattisgarh and Madhya Pradesh in 2000 and the rain-fed/low productivity western region included in Madhya Pradesh. It can be concluded that crop biomass C and SOC pool varies with intensity and type of cropping, soil type and climatic regions.

Relationship between crop biomass carbon density and NDVI

The maximum NDVI indicates the greenness of the vegetation at the time of peak vegetative growth during the season (Ray *et al.* 2005). We used SPOT-VGT maximum NDVI for the crop growing season to extract the mean district maximum NDVI. Maximum NDVI of the year May 2005 to April 2006 of each district was correlated with the total crop biomass carbon density of the corresponding districts. The results (exponential relationships) indicated a correlation coefficient (R^2) value of 0.65 (Fig. 3). Thenkabail *et al.* (2000) also reported similar relationships between SPOT-NDVI with crop biomass. This reveals a highly dependent relationship between satellite data and ground information from crop statistics. In some districts a low correlation is observed mainly due to uncertainty in crop statistics and contribution of vegetation from waste land and fallow land to the observed NDVI.

In order to understand the relationship of crop biomass C with cropping intensity, net irrigated area and nitrogen input regression analyses were performed (Fig. 4). Crop biomass C density was positively correlated with cropping intensity ($R^2=0.52$, $P = 0.002$) and per hectare nitrogen consumption ($R^2=0.45$, $P=0.003$). It is evident that with an increase in cropping intensity and nitrogen fertilizer consumption the crop biomass production increased. Crop biomass C was also positively correlated with net irrigated area ($R^2=0.60$, $P=0.001$). Dadhwal *et al.* (1995) also reported a high correlation ($R^2=0.93$) between crop net primary productivity and nitrogen fertilization, cropping intensity ($R^2=0.68$) and net irrigated area ($R^2=0.80$) in the state level comparison of crop NPP variability in India. These factors are themselves also correlated since under irrigated conditions; cropping intensity increases and the technological inputs including N fertilizer application are higher than on un-irrigated fields

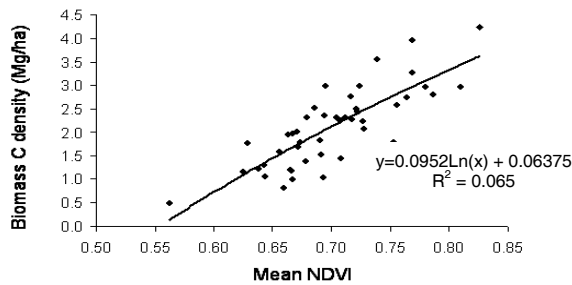


Fig. 3. Relationship between biomass carbon density and mean NDVI.

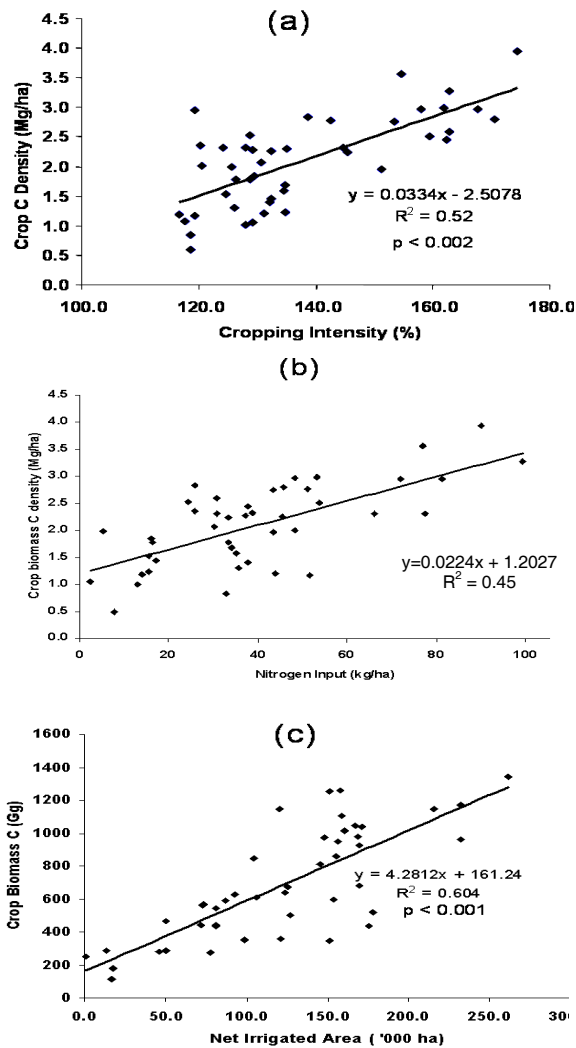


Fig. 4. Relationships between district agricultural crop biomass carbon (Gg) and carbon density (Mg ha⁻¹) with (a) cropping intensity, (b) net irrigated area and (c) nitrogen use.

(Dhawan 1988). However, Madhya Pradesh is mostly rainfed, hence cropping intensity is low and nutrients could be supplied through organic manure. These factors could lead to variations in the estimates.

Conclusions

The present analysis revealed that out of estimated 825.56 Tg of agricultural C stock for Madhya Pradesh soil C and crop biomass C contributed 95.7% and 4.3%, respectively. Variations in C stocks by agroecological sub-region were primarily the result of geographic size of the regions and climate. Carbon densities varied by less than 20% across the AESRs and were related to irrigation, fertilizer additions, and cropping intensities. Crop biomass was positively correlated with cropping intensity, net irrigated area and per capita N consumption. The estimate were very well correlated with the RS derived max NDVI illustrating the potential to use NDVI to monitor the crop production through biomass status. Remote sensing and GIS play a vital role in delivering information and integrating them allowed for the assessment of spatial patterns of carbon pools. The methodology can be used to estimate the historical agricultural carbon stocks and densities from reported crop statistics and point measurements of soil carbon as well as at a national scale to estimate agricultural C pools.

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References

- Agrawal, S., P.K. Joshi, Y. Shukla & P.S. Roy. 2003. SPOT VEGETATION multi-temporal data for classifying vegetation in south and central Asia. *Current Science* 84: 1440-1448.
- Ajtay, G.L., P. Ketner & P. Duvigneaud. 1979. Terrestrial primary production and phytomass. pp. 129-182. In: B. Bolin & R.B. Cook (eds.) *The Global Carbon Cycle (SCOPE- 13)* Wiley, Chichester.
- Bhattacharyya, T., P. Chandran, S.K. Ray, D.K. Pal, M.V. Venugopalan, C. Mandal & S.P.Wani. 2007. Changes in levels of carbon in soils over years of two

- important food production zones of India. *Current Science* **93**: 1854-1863.
- Dadhwal, V.K. & A. Chhabra. 2002. Land use/cover change in Indo-Gangetic plains: cropping pattern and agro-ecosystem carbon cycle. pp. 249-276. In: Yash P. nAbrol, S. Sangwan & M.K. Tiwari (eds.) *Land Use- Historical Perspectives: Focus on Indo-Gangetic Plains*. Allied Publishers Pvt. Ltd., New Delhi.
- Dadhwal, V.K. & S.R. Nayak. 1993. A preliminary estimate of biogeochemical cycle of carbon for India. *Science and Culture* **59**: 9-13.
- Dadhwal, V.K., A.K. Shah & A.B. Vora. 1994. Carbon flow through Indian Agro-ecosystem: A preliminary account. pp. 203-226. In: B.H. Subbaraya, D.P. Rao, P.S. Desai & P. Rajaratnam (eds.) *Global Change Studies: Scientific Results from ISRO-GBP*. Indian Space Research Organisation, Bangalore.
- Dadhwal, V.K., A.K. Shah & A.B. Vora. 1995. Interstate variation in crop and its relation to cultural factors. *Geobios* **22**: 163-168.
- Dadhwal, V.K., A.K. Shah, & A.B. Vora. 1996. Changes in carbon flow through Indian agro-ecosystem between 1950-51 and 1985-86. *Journal of Environmental Biology* **17**: 311-316.
- de Fries, R., M. Hansen & J. Townshend. 1995. Global discrimination of land cover types from metrics derived from AVHRR Pathfinder data. *Remote Sensing of Environment* **54**: 209-222.
- DES. 2006. *Agriculture at a Glance*. Directorate of Economics and Statistics. Ministry of Agriculture, Govt. of India, New Delhi.
- Dhawan, B.D. 1988. *Irrigation in India's Agricultural Development-Productivity, Stability, Equity*. Sage Publications India Pvt. Ltd., New Delhi, India.
- FSI. 2008. *State of Forest Report 2005*. Forest Survey of India. Ministry of Environment and Forests, Govt. of India, Dehradun.
- Guo, Y., R. Amundson, P. Gong & Yu Quan. 2006. Quantity and spatial variability of soil carbon in the conterminous United States. *Soil Science Society of America Journal* **70**: 590-600.
- IPCC. 2000. *Land Use, Land Use Change and Forestry*. Cambridge University Press, Cambridge, U.K.
- Lal, R. 2002. Soil carbon dynamics in cropland and rangeland. *Environmental Pollution* **116**: 353-362.
- Lal, R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* **123**: 1-22.
- Lieth, H. & R.H. Whittaker. 1976. *Primary Productivity of Biosphere*. Springer-Verlag, Berlin.
- Mandal, D.K., C. Mandal, J. Sehgal & M. Velayutham. 1995. *Agro-Ecological Sub-Regions in India*. 2nd edn. Tech. Bull No. **35**, NBSS & LUP, Nagpur.
- Mitchell, R. 1979. *The Analysis of Indian Agro-ecosystems*. Interprint Publications, New Delhi, India.
- NBSS & LUP. 1996. *Soils of Madhya Pradesh for Optimizing Land Use*. National Bureau of Soil Survey & Land Use Planning Technical Bulletin No. **24**, Nagpur, India.
- NBSS & LUP. 1999. *Soils Series of Madhya Pradesh*. National Bureau of Soil Survey & Land Use Planning. Technical Bulletin No. **78**, Nagpur, India.
- Olson, J.S., J.A. Watts & L.J. Allison. 1983. *Carbon in Live Vegetation of Major World Ecosystems*. ORNL-5862, Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A.
- Rasmussen, P.E., K.W.T. Goulding, J.R. Brown, P.R. Grace, H.H. Janzen & M. Körschens. 1998. Long-term agro-ecosystem experiments: assessing agricultural sustainability and global change. *Science* **282**: 893-896.
- Ray, S.S., A. Sood, S. Panigrahy & J.S. Parihar. 2005. Derivation of Indices using remote sensing data to evaluate cropping systems. *Journal of Indian Society of Remote Sensing* **33**: 475-481.
- RCEP. 1996. *Sustainable Use of Soil*. 19th Report of the Royal Commission on Environmental Pollution. 3165, HMSO, London.
- Robert M., J. Antoine & F. Nachtergaele. 2001. Carbon sequestration in soils. Proposals for Land Management in Arid Areas of the Tropics. AGLL, FAO, Rome.
- Schwartz, D. & M. Namri. 2002. Mapping total organic carbon in the soils of the Congo. *Global and Planetary Change* **33**: 77-93.
- Sehgal, J., D.K. Mandal, C. Mandal & S. Vadivelu. 1992. *Agroecological Regions of India*. 2nd edn. National Bureau of Soil Survey & Land Use Planning Technical Bulletin **24**, Nagpur, India.
- Thenkabail, P.S., R.B. Smith & E. de Pauw. 2000. Hyperspectral vegetation indices and their relationships with agricultural crop characteristics. *Remote Sensing of Environment* **71**: 158-182.
- Warembourg, F.R. & E.A. Paul. 1977. Seasonal transfers of assimilated ¹⁴C in grassland: plant production and turnover, translocation and respiration. pp. 133-149. In: J.K. Marshall (ed.) *The Below-ground Ecosystem: A Synthesis of Plant-Associated Processes*, Range Science Department, Science Series No. **26**, Colorado State University, Fort Collins.
- Wylie, B.K., D.J. Meyer, L.L. Tieszen & S. Mannel. 2002. Satellite mapping of surface biophysical parameters at biome scale over the North American grasslands: A case study. *Remote Sensing of Environment* **79**: 266-278.