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# Carbon Footprint and Sustainability of Agricultural Production Systems in India

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*The agriculture sector, which accounts for about 52% of the total workforce despite a steady decline of its share in the gross domestic product (GDP), is still the largest economic sector that plays a significant role in the overall socio-economic development of India. Sustainability of agricultural production systems depends on their carbon (C) footprint and the C output-input ratio. Thus, the present study was conducted with the objectives to: (i) assess C emissions in relation to predominant agricultural systems in India; (ii) evaluate C-use efficiency of production systems; and (iii) determine the relative sustainability of agronomic production systems as determined by their C footprints. The data collated on C-based input into the soil for predominant agricultural and horticultural crops included the amounts of fertilizers (N, P, K), herbicides, and pesticides used for crops annually, cropland area, total production of each crop, water-management practices, energy used for different operations, and total number of livestock. These data were used to compute C equivalent (Ce) per hectare of input and output, and the relative sustainability indices as a measure of the C-production efficiency. Beginning with low C-based input of 69.7 Tg Ce/yr (1 Tg = teragram = $10^{12}$g = 1 million ton) in 1960–61, input of fertilizers, pesticides, farm power, feed, fodder, and electricity*

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*increased to 281.2 Tg Ce/yr by 2008–09. The output in agriculture increased from 578.6 Tg Ce/yr in 1960–61 to 1239.1 Tg Ce/yr in 2008–09. The C-sustainability index was high in 1960, and was indicative of the minimum usage of inputs prior to the onset of the Green Revolution. Thereafter, the C-sustainability index decreased during 1970s and 1980s because of increased C-based inputs. There existed a linear relationship between C input and C output, indicating that an increase of 1 Tg Ce/yr of C input resulted in a corresponding increase in C output of ~21 Tg Ce/yr. Total food grain production in India increased from 89 million ton in 1960–61 to 262 million ton in 2008–09.*

*KEYWORDS* *agricultural input, carbon footprint, carbon output, greenhouse gas, India, sustainability index*

*ABBREVIATIONS* (BMPs) best management practices; (C) carbon; ($CO_2e$) carbon dioxide equivalent; (Ce) carbon equivalent; (GWP) global warming potential; (GHGs) greenhouse gases; (Gt) gigaton (1 billion ton or Pg); (INM) integrated nutrient management; (Mt) million ton; (OM) organic matter; (RMPs) recommended management practices; (SIC) soil inorganic carbon; (SOC) soil organic carbon; (Tg) teragram (1 million metric ton).

## INTRODUCTION

India ranks second worldwide in farm output. Agriculture accounted for 16.62% of the GDP in 2007–08 (Wikipedia 2011) and for about 52% of the total workforce. Despite a steady decline of its share in the GDP, agriculture is still the largest economic sector and plays a significant role in the overall socio-economic development of India. There are about 116 million farm holdings, with an average size of 1.4 ha (FAO 2005). India is the world's largest producer of milk, vegetables, cashew nut (*Anacardium occidentale* L.), coconut (*Cocos nucifera* L.), tea (*Camellia sinensis*), ginger (*Zingiber officinalis* R.), turmeric (*Curcuma longa* L.), and black pepper (*Piper nigrum* L.), and it also has the world's largest cattle population. It is the second largest producer of wheat (*Triticum aestivum* L), rice (*Oryza sativa* L), sugar (*Saccharum spp.* L.), groundnut (*Arachis hypogaea* L.), and inland fish. It is the third largest producer of tobacco (*Nicotiana tabacum* G.). India accounts for 10% of the world fruit production with first rank in the production of banana (*Musa* spp.) and sapota (*Achras sapota* L.) (Directorate of Economics and Statistics 2009).

The arable land area of India is about 161.8 million hectare (Mha), and it has remained constant for the past 30 years, although the cropping intensity has increased from 118% to 135% during this period (FAO 2005). Cropland area equipped with irrigation facilities is almost 57 Mha (Directorate of Economics and Statistics 2009). The country comprises 20 agro-ecological zones and eight major soil groups (FAO 2005). Soil organic carbon (SOC) content of most Indian soils is low, and nitrogen (N) deficiency is common. Most soils are low to medium in phosphorus (P), and potassium (K) and sulphur (S) deficiencies have developed across time (FAO 2005). Soil-fertility depletion and the increasing deficiencies of certain micronutrients are among principal soil-related constraints (FAO 2005). The prevalent low levels of SOC concentrations are attributed to the soil-mining practices of excessive tillage, imbalance in fertilizer use, little or no crop residues returned to the soil, and severe soil degradation (Lal 2004b). Technological progress has made it possible to achieve remarkable improvements in land productivity, increasing per-capita food availability, despite a consistent decline in per-capita agricultural land area in India. Increase in population leads to decrease in farm size on the one hand and reduction in per capita arable land area on the other. In India, the increase in food production will have to come from increased production per unit area from existing land, because there is little, if any, potential for bringing new land under cultivation.

Along with fossil fuel combustion, agricultural practices have a major impact on the global C cycle (GCC), leading to an increase in the global temperature during the 20$^{th}$ century by 0.6 ± 0.2°C at an average rate of increase of 0.17°C per decade since 1950 (Lal 2004a; Intergovernmental Panel on Climate Change [IPCC] 2007). Eleven of the past 12 years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature since 1850 (IPCC 2007). The linear warming trend across the 50 years from 1956 to 2005 (0.13°C per decade) is nearly twice that for the 100 years from 1906 to 2005 (IPCC 2007). Agriculture has been a major source of greenhouse gases (GHGs), especially of $N_2O$ (from fertilizers) and $CH_4$ (from rice paddies and livestock; IPCC 2007). Yet, agriculture can be an important part of the solution to mitigate climate change by reducing the net GHG emissions from both industrial and agricultural sectors, and by the sequestering of C in soils and biota (Lal 2004a).

*Carbon footprint* has become a widely used term and concept because of the recent awareness and spotlight on the global climate change. The *carbon footprints of agriculture* are measured as the impact that agricultural activities have on the environment in the amount of GHGs produced, measured in $CO_2$ equivalent ($CO_2$e). Thus, the objective of this analysis was to evaluate the carbon footprints of agriculture by preparing the ecosystem

C budget of the predominant production systems in India. Specific objectives of determining the C footprints of agriculture in India are to: (i) assess the C emissions of predominant agricultural systems, (ii) evaluate the C-use efficiency, and (iii) compute the relative sustainability index. The study was designed to test the following hypothesis: (i) total production and crop yields will increase with increase in C-based input; and (ii) sustainability of a production system will increase with an increase in use efficiency of C-based input.

## MATERIAL AND METHODS

The data on C-based input into the soil for predominant crops was collated from the published reports (Directorate of Economics and Statistics 2009; FAO 2005; National Horticultural Board [NHB] 2010). Crops taken into account were rice, wheat, coarse cereals like maize (*Zea mays* L.), sorghum (*Sorghum bicolor L.*), barley (*Hordeum vulgare* L.), and pearl millet (*Pennisetum glaucum* (L.) R. Br.); pulses like pigeon pea (*Cajanus cajan* (L.) Millsp.), chickpea (*Cicer arietinum* L.), greengram (*Vigna radiata*), blackgram *(Vigna mungo)*, and lentil (*Lens culinaris*); oilseeds like groundnut, rape, mustard (*Brassica* spp.), sunflower (*Helianthus annuus L)*, soybean (*Glycine max* (L) Merr., sesamum (*Sesamum indicum*), niger (*Guizotia abyssinica* (L.f.), safflower (*Carthamus tinctorius* L.), castor *(Ricinus communis* L.), and linseed (*Linum usitatissimum* L.); cotton (*Gossypium hirsutum* L.), sugarcane, and horticultural crops (fruits, vegetables, spices, and plantation crops).

### Carbon Input

The C-based inputs considered in this study are:

i. Annual rates of fertilizers (N, P, K), herbicides, and pesticides consumed for agriculture in India;
ii. Specific farming practices, including crop residue-management systems;
iii. Cropland area, and total production of each crop, fodder (on dry basis), and concentrates provided to animals, and
iv. Irrigation-management practices and farm power used for various operations.

These data were used to calculate C equivalent per hectare (Ce/ha) of input and output, C-use efficiency, and sustainability indices. The C footprints of agriculture were calculated from 1960–61 to 2008–09 for a total period of about 50 years.

### Fertilizers, animal fodder and feed concentrates and pesticides

Manufacture and use of fertilizers and animal feed concentrates have high hidden C cost. Manufacture and soil application of N fertilizer is 1.23 kg Ce/kg of N (Izaurralde et al. 1998). Manufacture of different fertilizers have different hidden C costs of 0.81 kg Ce/kg N, 0.101 kg Ce/kg $P_2O_5$, and 0.08 kg Ce/kg $K_2O$ (West & Marland 2002). On the basis of numerous studies, estimates of hidden C cost of fertilizers for production, packaging, storage, and distribution range from 0.9–1.8 kg Ce/ kg N to 0.1–0.3 kg Ce/kg $P_2O_5$ or 0.1–0.2 kg Ce/kg $K_2O$. In comparison, hidden C costs range from 1.2–8.1 kg Ce/kg for insecticides and 1.7–12.6 kg Ce/kg for herbicides (Lal 2004c). For the purpose of this study, mean value of kg Ce per kg of inputs used was as follows: N = 1.35, P = 0.2, K = 0.15, and pesticide = 6.0 (Lal 2004c). The data on amount of fertilizers and pesticides used during 1960–61 to 2008–09 are presented in Table 1. The fertilizer consumption increased from 0.2 million ton (Mt) in 1960–61 to 15.1 Mt in 2008–09 for N, 0.05 Mt in 1960–61, to 6.5 Mt in 2008–09 for P; and 0.03 Mt in 1960–61 to 3.3 Mt in 2008–09 for K. The pesticide consumption was only 2.1 thousand ton (Tt) during 1960–61; it increased to 61.28 Tt during 1990–91 and decreased to 37.95 Tt during 2008–09. The animal feed concentrate consumption was 1.2 Mt during 1960–61 and it increased to 48.3 Mt during 2008–09, whereas the fodder consumption was 172 Mt and 570 Mt in 1960 and 2008, respectively (Table 1) (Chakravarti 1987; Rawal 2008). It is assumed that biomass contains 40% C (Bowen 1979), and total C input was calculated accordingly for all feed and fodder commodities.

### Plowing, irrigation and other farm operations

Tillage is among the important sources of $CO_2$ emission. Conventional tillage involves mechanical soil disturbance for seedbed preparation (Lal 2004c). There are different methods of tillage, including disc plowing, harrowing, etc. It was assumed that the entire cropland area was under the conventional tillage system of basic seedbed and land preparation. Data pertaining to the energy-use pattern in the form of diesel (MJ/ha) for engines, farm tractors, and power tillers, and electricity (GWh) consumption for agricultural purposes were utilized to calculate the Ce input (De 2000; IASRI 2003; Kulakarni 2009; Singh 2009) (Table 1). The C emission from different sources/energy was estimated using the emission coefficient of $7.25\text{x}10^{-2}$ kg Ce for kilowatt hours (kWh) of energy and 20.15 kg Ce for gigajoule (GJ) (Boustead & Hancock 1979; Fluck 1992). The C emission from electricity use in agriculture showed an increasing trend from 0.06 Tg Ce/yr in 1960–61 to 7.55 Tg Ce/yr in 2008–09. Energy use as diesel for tractor, tiller and engines was $2.88\text{x}10^{-2}$ Tg Ce/yr during 1960–61 and increased to 3.92 Tg/yr during 2008–09. The net total C input was computed by adding up all the inputs: C

**TABLE 1** The Inputs Like Fertilizers, Power, Pesticide, and use of Farm Power in Agriculture

| Year | Fertilizer consumption ('000t) | | | Pesticide consumption ('000t) | Electric power consumption in agriculture (GWh) | Energy use by tractor, tiller, and diesel engines (MJ/ha) | Total Fodder consumption (mt) | Feed/ concentrates consumption (mt) |
|---|---|---|---|---|---|---|---|---|
| | N | P | K | | | | | |
| 1960–61 | 210.0 | 53.1 | 29.0 | 2.10 | 0.003 | 10 | 172 | 1.2 |
| 1970–71 | 1487.0 | 462.0 | 228.0 | 45.53 | 0.042 | 23 | 250 | 11.05 |
| 1980–81 | 3678.1 | 1213.6 | 623.9 | 62.15 | 1.292 | 148 | 278 | 19.6 |
| 1990–91 | 7997.2 | 3221.0 | 1328 | 61.28 | 3.648 | 288 | 535 | 30.2 |
| 2000–01 | 10920.2 | 4214.6 | 1567.5 | 43.58 | 6.143 | 550 | 543 | 41.9 |
| 2008–09 | 15090.5 | 6506.2 | 3312.6 | 37.95 | 7.553 | 1050 | 570 | 48.3 |

Source: Directorate of Economics and Statistics 2009; De 2000; Kulakarni 2009.

equivalent in fertilizers, pesticides, tractor or tiller use, irrigation, electricity for farm operations, and feed and fodder for livestock.

## Carbon Output

The annual production and total biomass were used to calculate the C output from total agriculture systems of India (Table 2). The data were collected from the Directorate of Statistics and Economics (2009) and NHB (2010).

### Crop yield

For the annual production of different crops, data were obtained from the Directorate of Statistics and Economics (2009), part of India's Ministry of

**TABLE 2** Area, Production, Total Biomass, and Total C Output of Different Crops in India

| Crops/Year. | Parameter | 1960–61 | 1970–71 | 1980–81 | 1990–91 | 2000–01 | 2008–09 |
|---|---|---|---|---|---|---|---|
| Rice | Area (M ha) | 34.13 | 37.59 | 40.15 | 42.69 | 44.71 | 45.35 |
| | Production (Mt) | 34.58 | 42.22 | 53.63 | 74.29 | 84.98 | 99.15 |
| | Total biomass (Mt) | 69.16 | 84.44 | 107.26 | 148.58 | 169.96 | 198.3 |
| | Total C Output (Mt) | 27.66 | 33.77 | 42.90 | 59.43 | 67.98 | 79.32 |
| Wheat | Area (M ha) | 12.93 | 18.24 | 22.28 | 24.17 | 25.73 | 27.88 |
| | Production (Mt) | 11.00 | 23.83 | 36.31 | 55.14 | 69.68 | 80.58 |
| | Total biomass (Mt) | 27.50 | 59.58 | 90.78 | 137.85 | 174.20 | 201.45 |
| | Total C Output (Mt) | 11.00 | 23.83 | 36.31 | 55.14 | 69.68 | 80.58 |
| Coarse cereals | Area (M ha) | 44.96 | 45.95 | 41.78 | 36.32 | 30.26 | 27.62 |
| | Production (Mt) | 23.74 | 30.55 | 29.02 | 32.70 | 31.08 | 39.48 |
| | Total biomass (Mt) | 59.35 | 76.38 | 72.55 | 81.75 | 77.70 | 98.70 |
| | Total C Output (Mt) | 23.74 | 30.55 | 29.02 | 32.70 | 31.08 | 39.48 |
| Pulses | Area (M ha) | 23.56 | 22.54 | 22.46 | 24.66 | 20.35 | 22.37 |
| | Production (Mt) | 12.70 | 11.82 | 10.63 | 14.26 | 11.07 | 14.66 |
| | Total biomass (Mt) | 42.33 | 39.40 | 35.43 | 47.53 | 36.90 | 48.87 |
| | Total C Output (Mt) | 16.93 | 15.76 | 14.17 | 19.01 | 14.76 | 19.55 |
| Oilseeds | Area (M ha) | 13.77 | 16.64 | 17.6 | 24.15 | 22.72 | 27.46 |
| | Production (Mt) | 6.98 | 9.63 | 9.37 | 18.61 | 18.44 | 28.16 |
| | Total biomass (Mt) | 23.27 | 32.10 | 31.23 | 62.03 | 61.47 | 93.87 |
| | Total C Output (Mt) | 9.31 | 12.84 | 12.49 | 24.81 | 24.59 | 37.55 |
| Sugarcane | Area (M ha) | 2.42 | 2.62 | 2.67 | 3.69 | 4.32 | 4.40 |
| | Production (Mt) | 110.00 | 126.37 | 154.25 | 241.05 | 295.96 | 271.25 |
| | Total biomass (Mt) | 407.41 | 468.04 | 571.30 | 892.78 | 1096.15 | 1004.63 |
| | Total C Output (Mt) | 162.96 | 187.21 | 228.52 | 357.11 | 438.46 | 401.85 |
| Cotton | Area (M ha) | 7.68 | 7.60 | 7.82 | 7.44 | 8.58 | 9.41 |
| | Production* (Mt) | 5.64 | 4.76 | 7.86 | 9.84 | 9.52 | 23.16 |
| | Total biomass (Mt) | 3.20 | 2.70 | 4.45 | 5.58 | 5.39 | 13.12 |
| | Total C Output (Mt) | 1.28 | 1.08 | 1.78 | 2.23 | 2.16 | 5.25 |
| Hort. Crops | Area (M ha) | NA | NA | NA | 12.77 | 16.59 | 20.66 |
| | Production (Mt) | NA | NA | NA | 96.56 | 145.78 | 214.72 |
| | Total biomass (Mt) | NA | NA | NA | 96.56 | 145.78 | 214.72 |
| | Total C Output (Mt) | NA | NA | NA | 38.62 | 58.31 | 85.89 |

*Million bales of 170 kg each.
(NA) not available: (Mha) million hectare; (Mt) million ton.
Source: Directorate of Economics and Statistics 2009; NHB 2010.

Agriculture. There was a progressive increase in the production of food crops by a factor of 2.85 since 1960. Rice production increased from 34.6 Mt in 1960–61 to 99.15 Mt in 2008–09 (Table 2), and by 39% during 1980–81 to 1990–91, followed by only a modest increase. Wheat production increased by 59.58 Mt since 1960, and the increase was 117% during 1960–61 to 1970–71, followed by a modest decrease thereafter. The production of coarse cereals increased by 29% during 1960–61 to 1970–71, and it decreased and showed a negative trend during 1970–71 to 1980–81 and 1990–91 to 2000–01; however, an increase of 27% during 2008–09 was observed. Pulse production followed a negative trend from the 1960s to the 1980s, with an increase of 34% from 1980–81 to 1990–91, followed by a severe decline (-22%) from 1990–91 to 2000–01. Production of oilseeds increased from by 38% 1960–61 to 1970–71, followed by a decline of 3% during the next decade. There was an increase in the oilseeds production by 99% from the 1980s to the 1990s, followed by a 1% decline in the next decade and an increase of 53% from 2000–01 to 2008–09. Sugarcane production increased between 1960–61 and 1990–91, decreased during the next decade, and was followed by an 8% growth from 2000–01 to 2008–09. Cotton lint production declined during the 1960s, but increased by 65% during the 1970s and by 145% from 2000–01 to 2008–09. The production of horticultural crops increased by 47 % to 51% from 1990–91 to 2008–09.



### Total biomass production

Published data on the harvest index (HI) of different crops was used to assess total biomass production (Donald & Hamblin 1976; Sinha, Bhargava, & Goel 1982; Venugopalan & Pundarikakshudu 1999; Thangavelu 2006). Specific values of the HI were used for cereals, pulses, and oilseeds for estimating total biomass (Table 3). To compute the total biomass of each crop the agronomic yield of the different crops was divided by the HI. Total economic yield was the total biomass produced for the horticultural crops.

**TABLE 3** Harvest Index of Different Crops

| Crop | Harvest index |
|---|---|
| Rice | 0.5 |
| Wheat | 0.4 |
| Coarse cereals | 0.4 |
| Pulses | 0.3 |
| Oilseeds | 0.3 |
| Sugarcane | 0.27 |
| Cotton | 0.3 |

### Total C produced in biomass

Total C output was computed by assuming C concentration of 40% in the biomass (Bowen 1979). Total biomass produced and the C output for each crop is shown in Table 2.

### Greenhouse gas emission from Indian agriculture: Rice cultivation in India

Rice is an important crop in India and occupies about 42.5% of the area under cereal cultivation. It is grown under flooded conditions, and the seedbed preparation involves puddling or plowing when the soil is wet to destroy aggregates and reduce rate of water infiltration. The anaerobic conditions thus created lead to emissions of methane ($CH_4$) and possibly nitrous oxide ($N_2O$) through inefficient fertilizer use and anaerobiosis (Bronson & Singh 1994). Thus, $CH_4$ and $N_2O$ emissions from rice fields were assessed by calculating the C budget of agriculture. Total seasonal emissions of $CH_4$ and $N_2O$ were estimated for irrigated rice fields of India at 4 Tg/yr for $CH_4$ and 167.9 g/ha/yr for $N_2O$ emissions by Parashar et al. (1994) and Ghosh, Majumdar, and Jain (2003), respectively, and were used for computing the C budget. The global warming potential (GWP) is 21 for $CH_4$ and 310 for $N_2O$ (IPCC 2007). Therefore, total $CH_4$ and $N_2O$ emissions were multiplied by the respective GWP factors to compute the C footprint of rice cultivation.

### Agricultural residue biomass burning

Data on total potentially available agriculture-based biomass was obtained from the Agricultural Statistics at a Glance 2009 from the Directorate of Economics and Statistics (2009) (Table 4). The IPCC (1996) methodology was used for estimation of emission from open burning of crop residue, assuming that one-fourth of the total available residue is burnt in the field (Gupta et al. 2004). It is estimated that one Mg of straw on burning releases

**TABLE 4** Available Agriculture-Based Residue Biomass and Total Carbon Equivalent Emission by Burning in India

| Year | Biomass (Mt) | Total Ce (Tg/yr) |
|---|---|---|
| 1960–61 | 84.58 | 8.33 |
| 1970–71 | 92.22 | 9.08 |
| 1980–81 | 169.8 | 16.73 |
| 1990–91 | 238.3 | 23.47 |
| 2000–01 | 285.4 | 28.11 |
| 2008–09 | 329.7 | 32.48 |

Source: Directorate of Economics and Statistics 2009.

3 kg particulate matter, 60 kg CO, 1460 kg $CO_2$ (or 394 kg C), 199 kg ash, and 2 kg $SO_2$ (Gupta et al. 2004).

### Ruminants (Livestock)

Livestock are an important part of Indian agriculture and are closely integrated into agricultural systems. Ruminants are an important source of $CH_4$ emissions, and the data on population of the livestock comprising cattle, buffaloes, sheep, pigs, goats, and camels were collected from the Department of Animal Husbandry, Dairying and Fisheries, Ministry of Agriculture, Government of India (Directorate of Economics and Statistics 2009) (Table 5). The data from the published literature were used for calculating emission factors for different species of animals (Crutzen, Aselmann, & Seiler 1986) (Table 6), and the total emission is presented in Table 5.

Animal dung is widely used as household fuel in India. The dung production was calculated by using the production rate of 4.5 kg per cattle per day, 10.2 kg per buffalo per day, and an assumption was that 50% is used as manure and 50% as fuel (Ravindranath et al. 2005; INCCA 2010). The C emission from dry dung was estimated at 334 g Ce/kg of dung on dry weight basis (Smith et al. 2000), and the total dung production and Ce emission are

**TABLE 5** Population (Million Numbers) and Total Emission of Carbon from Different Livestocks in India

| Year | Cattle | Buffalo | Sheep | Goat | Camel | Pig | Total | Total emission (Tg Ce/yr) |
|---|---|---|---|---|---|---|---|---|
| 1960–61 | 175.6 | 51.2 | 40.2 | 60.9 | 0.9 | 5.2 | 334.0 | 194.6 |
| 1970–71 | 178.3 | 57.4 | 40.0 | 67.5 | 1.1 | 6.9 | 351.2 | 204.1 |
| 1980–81 | 192.4 | 69.8 | 48.8 | 95.2 | 1.1 | 10.1 | 417.4 | 231.4 |
| 1990–91 | 204.6 | 84.2 | 50.8 | 115.3 | 1.0 | 12.8 | 468.7 | 257.8 |
| 2000–01 | 185.2 | 98.0 | 61.5 | 124.4 | 0.6 | 13.5 | 483.2 | 259.5 |
| 2008–09 | 185.2 | 98.0 | 61.5 | 124.4 | 0.6 | 13.5 | 483.2 | 259.5 |

Source: Directorate of Economics and Statistics 2009.

**TABLE 6** An Illustration of the Methodology Used to Calculate the Annual C Equivalent Output for 100 Heads of Livestock

| Animal | $CH_4$ Emission factor per individual (kg/yr)* | $CH_4$ Emission (kg/yr) | Annual C equivalent output (kg Ce/yr) |
|---|---|---|---|
| Cattle | 35 | 3500 | 73500 |
| Buffaloes | 50 | 5000 | 105000 |
| Sheeps | 5 | 500 | 10500 |
| Pigs | 1 | 100 | 2100 |
| Goats | 5 | 500 | 10500 |
| Camels | 58 | 5800 | 121800 |

*Source: Crutzen, Aselmann, and Seiler 1986.

**TABLE 7** Dung Production (Mt) And Ce Emission from Cattle and Buffalos in India

| Year | Cattle | Buffalo | Total | Ce (Tg/yr) |
|---|---|---|---|---|
| 1960–61 | 288.42 | 190.62 | 479.04 | 24.0 |
| 1970–71 | 292.86 | 213.70 | 506.56 | 25.4 |
| 1980–81 | 316.10 | 259.79 | 575.89 | 28.9 |
| 1990–91 | 336.02 | 313.51 | 649.54 | 32.5 |
| 2000–01 | 304.16 | 364.56 | 668.71 | 33.5 |
| 2008–09 | 304.16 | 364.56 | 668.71 | 33.5 |

**TABLE 8** Milk Production (Mt) and Total C Emission from Milk Production in India

| Year | Milk production | Total emission (Tg Ce/yr) |
|---|---|---|
| 1960–61 | 20.0 | 14.6 |
| 1970–71 | 23.2 | 16.9 |
| 1980–81 | 31.6 | 23.0 |
| 1990–91 | 53.9 | 39.3 |
| 2000–01 | 80.6 | 58.8 |
| 2008–09 | 110.0 | 80.2 |



given in Table 7. Total dung production was 668.71 Mt during 2008-09 and the total Ce emission was 33.50 Tg/yr from the dung burning alone.

Total milk production during 1960–61 to 2008–09 is given in Table 8. Ce emission from milk production was calculated using 729.2 g Ce/kg of milk (Pathak et al. 2010).

All the outputs were added to calculate the net total C output, which included C present in total crop biomass, emissions from other agricultural operations, rice cultivation, agricultural waste biomass, dung burning, and emissions from livestock. Total C input and output for Indian Agricultural Systems across the period of 1960–61 to 2008–09 are presented in Table 7.

## Sustainability Index

Sustainability indices for each year were calculated by dividing the difference between total C output and input by C input (Lal 2004c).

$$Cs = (Co - Ci)/Ci \qquad \text{(Equation 1)}$$

where Cs is sustainability index, Co is C output, and Ci is C input.

## RESULTS AND DISCUSSION

Agricultural production increased with the onset of the Green Revolution, and agronomic production increased 3.77 times between 1960–61 and

2008–09. The Green Revolution involved growing input-responsive varieties on irrigated soils with intensive use of fertilizers and other off-farm inputs; thus, there was a substantial increase in the use of fertilizers, pesticides, and irrigation with mechanization of farm operations. The rate of increase in grain production exceeded that of the population growth, which increased the per capita grain production. Prasad (2005) estimated that by 2020 India would need 294 Mt of food grains, or 82 Mt more than what was produced in 2002. India is home to more than 200 million food-insecure people or about 17% of the total population of the country (Elder 2006). While the increase in food production has been impressive, the environmental consequences have not been quantified. Principal environmental concerns are those related to the pollution of water resources and the increase in emission of $CO_2$ and other GHGs.

## C-Equivalence of Inputs

Beginning with low input of merely 69.7 Tg Ce/yr in 1960–61, C-based input of fertilizer, pesticides, tillage, fodder, feed concentrates, and irrigation increased to 277.3 Tg Ce/yr by 2008–09 (Figure 1). The average rate of input increased by 4.2 Tg Ce/decade; the decadal average increase was 37.50 Tg Ce/yr in the 1960s, 18.9 Tg Ce/yr in the 1970s, 115.7 Tg Ce/yr during the 1980s and 14.5 Tg Ce/yr during the 1990s and 21.1 Tg Ce/yr in the 2000s. The quantum increase in C equivalent of inputs during the 1980s was mainly due to the increase in feed and fodder usages (Table 1) for increased milk

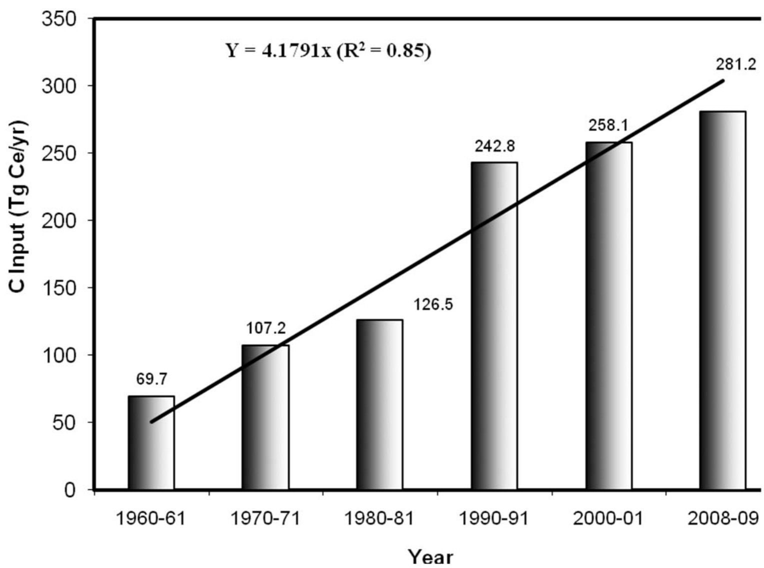


**FIGURE 1** Trends in C-based inputs in Indian agriculture (Y is Tg Ce, x is years since 1960).

production under the so called "White Revolution," and to the adoption of intensive farming in Indo-Gangetic rice-wheat area compared to 1990s (Sangar, Abrol, & Gupta 2004). Since the onset of the Green Revolution in the late 1960s, there was a strong increase in inputs, such as seeds of high-yielding varieties, chemical fertilizers, pesticides, and insecticides. The increased usage of C-based input was supported by a well-assured irrigation system, farmers' willingness to adopt the new technologies, and government encouragement by lending its support through investment and assured procurement price. Use of farm machinery also increased since 2000. Animal power contributed 60.3% of the total farm power in 1970–71 and 83.6% in 2000–2001 (De 2000; Kulakarni 2009), which increased C input. Dubey and Lal (2009) also reported an increase in C equivalent in Punjab during late 1960s, with an attendant increase in use of chemical fertilizers, pesticides diesel, and electricity.

## C-Equivalence of Outputs

C output includes an aggregation of C present in grains and straw biomass of the predominant crops, and also takes into account $CH_4$ emissions by ruminants and rice paddies and burning of agricultural biomass. In accord with the input, there was a corresponding increase in productivity, which increased from 578.6 Tg Ce/yr in 1960–61 to 1239.1 Tg Ce/yr in 2008–09 (Figure 2). The mean decadal increase in C output was 66.1 Tg Ce/yr in the

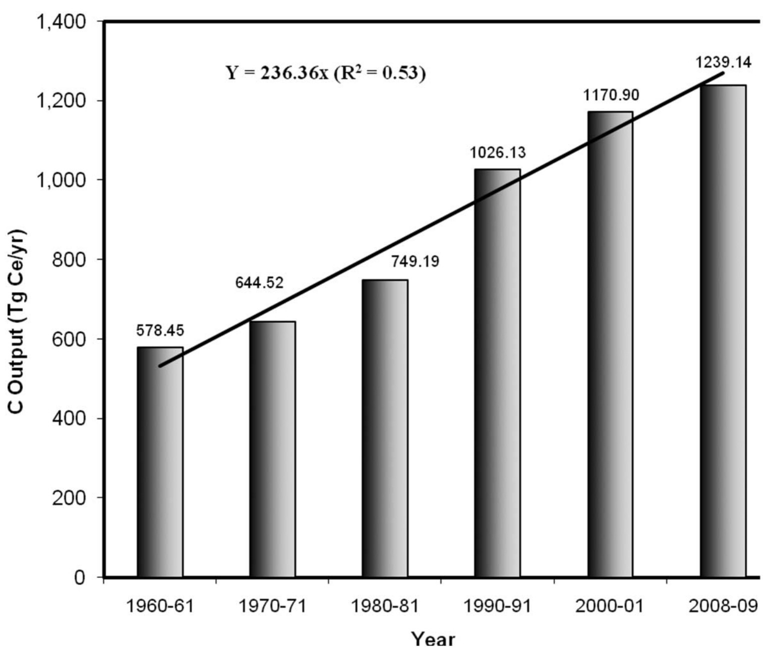


**FIGURE 2** Trends in C-based outputs in Indian agriculture (Y is Tg Ce, x is years since 1960).

1960s, 104.7 Tg Ce/yr in the 1970s, 276.9 Tg Ce/yr in the 1980s, 144.8 Tg Ce/yr in the 1990s, and 68.2 Tg Ce/yr in the 2000s. The mean decadal rate of growth was 236.4 Tg Ce/decade.

Despite the adoption of Green Revolution technology, there have been some adverse effects on soil properties, including the negative nutrient budget of 5.1 Tg of N, 2.5 Tg of P, 4.7 Tg of K, and 0.75 Tg of S for production of food grains between 1978 and 2003 (Roy 2003). Imbalanced and inefficient use of fertilizers has been a major constraint in improving soil and crop productivity. The deficiency of N is widespread, although the $N:P_2O_5:K_2O$ use ratio is in favor of N. This ratio was 8.9:2.2:1 in 1961–62 and 5.9:2.4:1 in 1991–92, in contrast to the balanced fertilizer use ratio of 4:2:1 for NPK. Relatively more balanced use of fertilizers improved the food grain production with an overall increase of 61% in total agricultural production. With decontrol of P and K fertilizers in 1992/93, the ratio widened to 9.7:2.9:1 in 1993–94. Despite the introduction of a price concession on P and K fertilizers and other measures taken to increase their consumption, the ratio remained wide and in 1996–97 it was 10:2.9:1. In general, the ratio has improved, reaching 6.9:2.6:1 in 2003/04 (FAO 2005). There is a need to increase the input-use efficiency through best management practices and balanced use of fertilizers.

The agriculture sector contributed >80% of all-India $CH_4$ emissions in 1995, including 42% from livestock-related activities, 23% from rice paddies, and 16% from biomass consumption (Bhattacharya & Mitra 1998). Emissions of $CH_4$ and $N_2O$ from Indian agriculture are responsible for only about 0.85% and 0.29% of the radiative forcing by global emissions, respectively, and are 11.8 Tg and 0.24 Tg, respectively (ALGAS 1998). Bhatia, Pathak, and Aggarwal (2004) have reported the current estimate of $CH_4$ and $N_2O$ emissions from agricultural soils as 2.9 Tg and 0.1 Tg, respectively.

## C-Sustainability Indices

The high C-sustainability index in 1960–61 may be because of the minimum usage of inputs prior to the onset of the Green Revolution (Figure 3). The use of fertilizer, pesticides, and other inputs increased from the mid-1960s, thereby decreasing the C-sustainability index during the 1970s and 1980s. The sustainability index also decreased during the 1990s, the early 2000s, and from 2008–09. In contrast, agricultural production increased from 1980–81 onwards (Figure 3).

## C Output Vs. C Input

There was a linear relationship between C-based input and output (Table 9). The C output-input ratio was 4.41 during 2008–09, compared with 8.30 in the pre-Green Revolution era and 5.9 in 1980–81. An increase of 1 Tg/yr

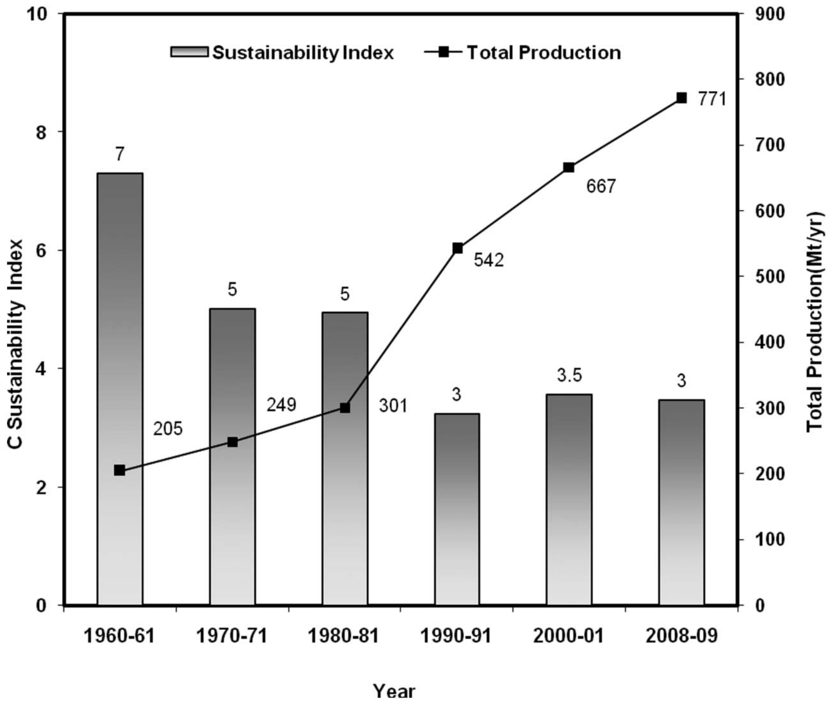


**FIGURE 3** Trends in sustainability index and total production in Indian agriculture.

**TABLE 9** Total C Input and Output (Tg/yr) of Indian Agricultural Systems

| Year | Total C input | Total C output |
|---|---|---|
| 1960–61 | 69.7 | 578.5 |
| 1970–71 | 107.2 | 644.5 |
| 1980–81 | 126.5 | 749.2 |
| 1990–91 | 242.8 | 1026.1 |
| 2000–01 | 258.1 | 1170.9 |
| 2008–09 | 281.2 | 1239.1 |

of C input resulted in a corresponding increase in C output of 20.6 Tg/yr (Figure 4). Despite an increase in use of fertilizers, the fertilizer-use efficiency decreased because of an imbalance in major nutrients. The fertilizer-use efficiency (kg of food grains per kg of fertilizer) was 15 during the 1970s, compared with 6 during 2002–07 (FAI 2008).

Enhancing soil quality is important to increasing input-use efficiency (e.g., fertilizers, irrigation), increasing biomass/agronomic yields, and improving the environment. Improving quality and quantity of soil organic carbon (SOC) concentration is important to enhancing soil quality. In fact, there is a strong linkage between low SOC concentration in soils of India and the widespread problem of soil degradation. Therefore, reversing trends

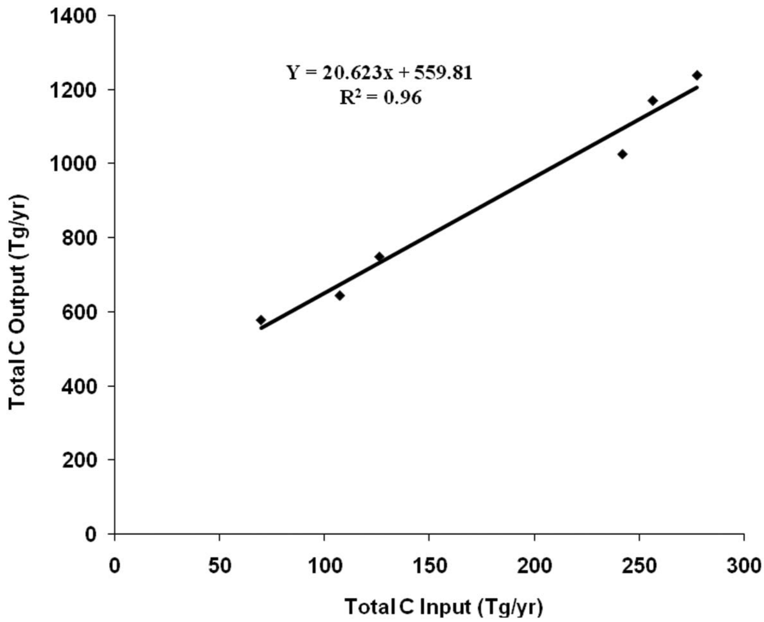


**FIGURE 4** Relationship between total C input and C output in Indian agriculture from 1960–61 to 2008–09.



in soil degradation necessitates increasing SOC concentration through adoption of no-till farming, use of crop residue mulch and compost, and complex rotations. A major constraint in adopting conservation agriculture and mulch farming in India is the removal of crop residues for other uses (i.e., fodder and fuel). Further, >95% of household energy until 1970 was derived from wood and other biomass (firewood, wood chips/ sticks, agro waste, and dung cakes). In 2005, >80% of the household energy use was derived from biomass, although share of the useful energy declined to 42.3% because of the advent of more efficient fuels (Reddy, Balachandra, & Nathan 2009). Adoption of mulch farming necessitates economic availability of alternative sources of fuel (Lal 2004b). Reddy, Balachandra, and Nathan (2009) estimated 93.8 and 126.0 Tg of total $CO_2$ emission-reduction potential per year for 2015 and 2020, respectively, by adopting alternatives to biomass fuel for household cooking and lighting.

## SUMMARY AND CONCLUSIONS

Adoption of the Green Revolution technology of agricultural intensification improved productivity. The C output-input ratio decreased to 4.50 compared with 8.0 during the pre-Green Revolution period. The ratio also decreased to 5.9 during 1980–81, indicating higher input losses. There is a need to increase the input-use efficiency through best management practices and applying balanced dose of fertilizers. The C sustainability index ranged between 3.4 and 4.9 from 1980 to 2008–09. Eliminating subsidies may enhance balanced use of fertilizers. Carbon trading is another strategy to offset $CO_2$ and promote adoption of best management practices. Burning of crop residues must be minimized, and residues used as mulch or compost to enhance soil properties.

Emissions from fossil fuel combustion in India are increasing. Agricultural soils in India have sequestration potential of 39.3 to 49.3 Tg Ce/yr (mean of 43.3 Tg Ce/yr), which can reduce the net emissions from fossil fuel combustion. Further, there is an additional potential of C sequestration in biomass, especially by forest and other biota. This potential can be realized through the Clean Development Mechanisms defined in the IPCC and by trading C in the national and international markets (Lal 2004b).

Biosequestration of C, both by soil and biota, is truly a win-win situation. Despite vast soil resources, a wide range of climates, innovative farmers with a “can do” attitude, and availability of high-caliber research and extension support services, agronomic production in India is either declining or stagnant. The regressive trend is attributed to a decline in quality of soil and water resources attributed to extractive faming practices, and low use efficiency of fertilizers and water (Lal 2008). While improving agronomic/biomass productivity, adoption of best management practices can improve water quality and mitigate climate change by offsetting anthropogenic emissions. Policy interventions are needed to promote use of mulch farming and conservation tillage, integrated nutrient management, manuring, and agroforestry systems; reduce methane emission from rice cultivation and livestock rearing; restore eroded and salinized soils; and convert agriculturally marginal lands into restorative land uses. Recommended technologies must be based on modern innovations, including nanotechnology, biotechnology, information technology, and synergy among these (Lal 2008). With low prices of C, dominant strategies involve changes in tillage, fertilizer application, livestock diet formulation, and manure management. With high price of C, changes in land use and farming systems are important strategies. While there is no one universally applicable practice, there is a wide range of recommended practices based on climate, edaphic, social setting, and historical patterns of land use and management.



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