REVIEW ARTICLE

Soil Recarbonization Potential of Crop Residues and their Management through Inter-Convertible Carbon Triangle ($ICC_{triangle}$)

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Abstract

Intensive cropping is a major cause of depleting soil organic carbon (SOC) eventually leading to soil infertility. Restoration of depleted SOC requires renewable sources of organic amendments. Crop residue (CR), mostly lost due to burning in many parts of the world, is a generously available renewable source of organic carbon (OC) that can be used for soil recarbonization. The study presents an overview of the OC losses and pollution due to residue burning in India and explores the perspective of using surplus CR to restore SOC and promote ecosystem services for sustainable agriculture. We reviewed and quantified the magnitude of CR generated, and its fertilization potential in the Indo-Gangetic Region (IGR), an intensively cultivated region of India where rice straw burning is prevalent. A novel concept of interconvertible carbon triangle (ΔICC) is proposed based on the three carbon pools, SOC from the soil, CO_2,/CO from the atmosphere and organic carbon (OC) from plant biomass to assess the instability of an agricultural land and estimate the SOC requirements based on the crop production data. The study reviews the availability of OC and other nutrients in CR and professes the need of technologies to divert the surplus CR to improving soil fertility and mitigate environmental pollution due to agricultural burnings.

Keywords: Crop residue burning, Ecosystem services, Indo-Gangetic Region, Interconvertible carbon triangle, Land degradation, Soil organic carbon.

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Introduction

Food security is a challenge for millions of people worldwide, majorly in developing regions (FAO, 2015). In India, 40% increase in food production will be required to feed the expected population of 1.6 billion by 2050 (ICAR-CSSRI, 2015). However, productive land is decreasing due to declining land fertility, urbanization, pollution and salinization (Rojas *et al.,* 2016). Intensive cropping and organic matter (OM) mismanagement have depleted organic carbon (OC) from agricultural soil leading to land degradation **(**Lal, 2011; Graves *et al.,* 2015; Bruun *et al.,* 2017). It is projected that by 2050, 16.2 million hectares (Mha) land resources in addition to the present 6.74 Mha will be affected by OC depletion in India (ICAR-CSSRI, 2015). Crop cultivation in the Indo-Gangetic Region (IGR), the 'food basket of India' has depleted 60% of the soil organic carbon (SOC) leaving little scope for agricultural expansion (Lal, 2004a; Biswas and Biswas, 2014).

A raise of *4‰* SOC per hectare has been targeted by the United Nations Framework Convention on Climate Change to increase C sequestration in soil microbial biomass carbon and reduce atmospheric CO_2 (Paustian *et al.,* 2016). The addition of OM to raise SOC by 1 t ha^{-1} would provide 32 Mt yr^{-1} additional food grain and presumed to remove 0.47 ppm/Gt C of atmospheric CO_2 (Lal, 2011). However, sustainable sources of OC are required to replenish the C deficiency in the agricultural soil. Application of plant biomass, crop rotation, cover crops, conservation tillage, compost, farmyard manure (FYM) has been extensively reviewed for increasing SOC (Lal, 2011; Paustian *et al.,* 2016). These sources have variable C sequestration potential and seem unsustainable due to their limited availability and quick loss in arid and semiarid regions. Amongst various available sources, cereal crop residue (CR) is recommended for degraded soils in arid and semi-arid areas, since they provide both labile and recalcitrant SOC pools and nutrients for a longer duration (Hu *et al.,* 2018). However, this readily available biomass C is annually lost owing to burning in various parts of the world (FAO, 2014; Wu *et al.,* 2018). The excessive biomass burning affects atmospheric CO_2 and the SOC, exhibiting enduring effects on climate (NASA, 2011). As the flux of C from burnt residues to atmosphere (CO_2) and then again to biomass is cyclic in nature and it may be considered that SOC, CO_2 and biomass C are readily inter-convertible sources of carbon among soil, atmosphere and biomass C pools. The balance of carbon among these three pools may be considered as a marker for environmental stability. An examination of the compiled/estimated data in the following section will show that the changes responsible for environmental pollution in the agricultural regions, and the reduced soil productivity are an outcome of the mismanagement of the three carbon pools (present in the residual biomass, soil and atmosphere). Based on this background a novel hypothesis of "Inter-Converticle Carbon

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Triangle (ΔICC)" to predict the environmental stability of a region, extent of land degradation and inputs for restoration is described. *The* paper reviews and quantifies the potential of rice straw residues to mitigate its burning and shows the application of the hypothesis to predict the instability of ΔICC in the IGR.

Data Sources and Formulae used to Estimate the Potential of Residual Biomass in Restoring Soil Fertility

List of all the data sources and formulae used for the study are given in Table 1. Production data for major crops grown in India and IGR during 2002–2016 was collected from different Government and Agriculture Institutes sources.

- The data were used to extrapolate residue generation, abundance and losses; GHG emissions; recarbonization and fertilization potentials using the formulae given below. The references and hyperlinks of various data sources and the factors used in the study/following equations are given in the data sources section.
- The crop residue generated in India and different states were calculated using the total crop production data and residue fraction as described by Jain *et al.* (2014) using the following equation (Eq.) where P is crop production in various years, R_f is residue fraction, DM_f is dry matter fraction

$$CR = P \times R_f \times DM_f \ldots\ldots(i)$$

- The burnt portion of CR was calculated from total production and burnt fraction data using equation ii as described by Jain *et al.* (2014), where CR_b is burnt CR and F_b is burnt fraction of residue

$$CR_b = CR \times F_b \ldots\ldots(ii)$$

- Crop residue abundance or availability per hectare (CR_{ab}) was calculated using CRs (surplus CR) value and area of the states (A)

$$CR_{ab} = \frac{CR}{A} \ldots\ldots(iii)$$

- Abundance or availability per hectare of crop residue (CRS_{ab}) was calculated by dividing surplus crop residue (CRS) by area of the state CR_{ab})

$$CR_{Sab} = \frac{CR_S}{A} \ldots\ldots(iv)$$

Table 1: List of data sources and formulae used for the study.

S.N.	*Data source*	*References and hyperlinks*
1.	Total production of major crops (2002-2016)	Agricultural Statistics at a Glance 2014 and 2015, Ministry of Agriculture, Government of India http://eands.dacnet.nic.in/PDF/Agricultural-Statistics-At-Glance2014.pdf; http://eands.dacnet.nic.in/PDF/Agricultural_Statistics_At_Glance-2015.pdf
2.	Total and surplus residue generated in other states	Pathak *et al*., 2012 file:///C:/Users/user/Downloads/Crop_Residues _Management_Booklet_Final _-2012.pdf
3.	Area of states	http://www.censusindia.gov.in
4.	Production of wheat, rice and sugarcane (2007-15)	Status paper on wheat, Directorate of Wheat Development, Ministry of Agriculture, Ghaziabad, U.P., India http://dwd.dacnet.nic.in/Publication/StatusPaper.pdf Status paper on rice, Directorate of Rice Development, State-wise area, production and productivity of rice http://www.nfsm.gov.in/Publicity/2014-15/Books/Status%20Paper%20Rice_Inner%20Pages_New.pdf Status paper on Sugarcane, Directorate of Sugarcane, Research, Govt. of India, Lucknow, India http://www.nfsm.gov.in/Publicity/2014-15/Books/Status%20Paper%20of%20Sugarcane_Final_New.pdf
5.	Wheat, rice and sugarcane production (2015-16) Punjab, Haryana and Uttar Pradesh	http://agripb.gov.in/agri_statistics/pdf/Annexure%20area. http://agriharyana.gov.in/assets/images/whatsnew/Five_Year_AYP_Targeted_2016-17__N__Ek_Patti.pdf State agriculture department, Lucknow, Uttar Pradesh, personal communication.
6.	Total Fertilizers (N, P_2O_5 and K_2O) consumption in Punjab, Haryana and Uttar Pradesh	Agricultural Statistics at a Glance 2014 and 2015, Ministry of Agriculture, Government of India. http://eands.dacnet.nic.in/PDF/Agricultural-Statistics-At-Glance2014.pdf; http://eands.dacnet.nic.in/PDF/Agricultural_StatisticsAt_Glance-2015.pdf
		Factors used
1.	Residue fraction (Rf)	Wheat (1.7), Rice (1.5), Sugarcane (0.4), Oilseed (3.0), Cotton (3.0), Jute and Mesta (2.15) (Jain *et al*., 2014).
2.	Dry matter fraction (DMf)	Wheat (0.88), Rice (0.86), Sugarcane (0.88), Oilseed (0.8), Cotton (0.8), Jute and Mesta (0.8) (Jain *et al*., 2014).
3.	Burnt fraction of residue (F_b)	Wheat (0.23); rice (0.8); sugarcane (0.25) (Jain *et al*., 2014).
4	Carbon fraction in CR (C_f)	Wheat (0.9876); rice (0.9836); sugarcane (0.99) obtained from residue C: N ratio. C:N wheat (80:1); rice (60:1) and sugarcane (100:1) file:///C:/Users/user/Downloads/C_N_ratios_cropping_systems.pdf
5.	Nutrient (N/P/K) assimilated in the crop (N_a)	Wheat N (24.4), P_2O_5 (8.6), K_2O (32.8); rice N (20.1), P_2O_5 (11.2), K_2O (30); and sugarcane N (1.7), P_2O_5 (0.2), K_2O (2) http://sap.ipni.net/article/punjab; http://sap.ipni.net/article/uttarpradesh http://sap.ipni.net/article/haryana
6.	Efficiency factor of the fertilizer (EF_f)	N (0.4) ; P_2O_5(0.3) and K_2O (0.7) (http://sap.ipni.net/article)
7.	Emission factors for GHGs (EF)	EF for wheat CO_2 (1470), CH_4 (3.36), CO (60), N_2O (0.07), NOx (3.3). EF for rice CO_2 (1460), CH_4 (1.2), CO (34.7), N_2O (0.07), NOx (3.1) (Gadde *et al*., 2009).
8.	CR nutrient content (CRN_{NPK}) kg/ton	Wheat N (6.9), P_2O_5 (0.8) K_2O (13.5); rice N (6.2) P_2O_5 (1.1), K_2O (18.9) (Van Duivenbooden, 1992); and sugarcane N (5.4), P_2O_5 (1.3), K_2O(3.1) (Singh and Soloman, 1995).

- GHG emissions from rice and wheat crops burnt in different states of IGR were calculated using the following equation. GHGe: GHG emissions; EF: Emission factors for GHGs (data sources); R/W = rice or wheat

$$GHGe_{R/W} = CR_{b\ R/W} \times EF_{R/W} \ldots\ldots(v)$$

- Nutrients depleted from soil (SND) were calculated by adding the different nutrients (NP&K) lost from the soil. The lost nutrient was obtained by multiplying the production data (P) with the assimilated nutrients fraction Na

$$SN_D = \sum P \times N_a \ldots\ldots(vi)$$

- The potential of burnt CR to provide NPK (CR_{NPK}) was calculated by multiplying the total CR burnt (CR_b) with CR nutrient fraction (CRN_{NPK}) for the crop

$$CR_{NPK} = CR_b \times CRN_{NPK} \ldots\ldots(vii)$$

- Percent NPK saving was calculated by the following equation using the Fertilizer requirement (F),the efficiency factor of the fertilizer (EF_f) (data sources) and equation vii using the following equation.

$$\%\ NPK\ saving = [\{(F \times EF) - CR_{NPK}\}] \times 100 \ldots\ldots(viii)$$

- The carbon assimilated (CR_C) in CR was calculated using CR data and the carbon fraction (C_f) of the CR

$$CR_C = CR \times Cf \ldots\ldots(ix)$$

- The assimilated carbon lost in CR burning (CR_{CL}) was calculated using the following equation

$$CR_{CL} = CR_b \times Cf \ldots\ldots(x)$$

Statistical Analysis

All the data presented here have been extrapolated from the existing primary yield data from the government sites for which replicates are absent; therefore, statistical analysis of the data was not possible.

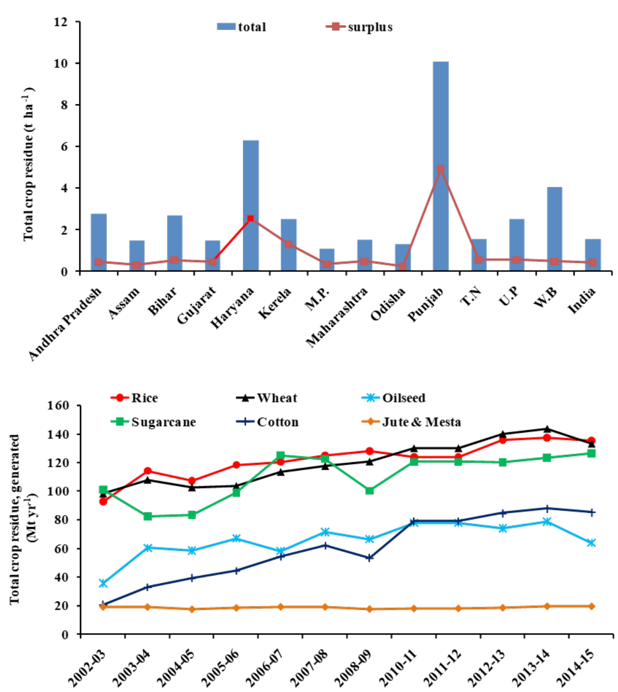

Fig. 1: Total and surplus crop residue abundance per hectare, generated in different states of India (A) $CR_{Sab} = CR_S/A$. All India residues generated from major crops cultivated during 2002-15 (B) $CR = P \times R_f \times DM_f$.

Crop Residue Carbon

Crop residue is the available plant biomass left after grains and other components of economic value have been harvested. The excess crop component left after the secondary use (compost, fuel, cattle feed and thatching) are called surplus (Pathak *et al.,* 2012). Crops like rice and sugarcane produce large volumes of undesired residue which are not used as good animal feed due to high silica content and therefore burnt (Singh and Sidhu, 2014). Calculations (Eq. iii & iv) show that a major fraction of the total waste generated is surplus in many States of India (Fig. 1A). Annual variations in the amount of residues generated (calculated using Eq. i) from major crops like rice, wheat, oilseed, sugarcane, cotton, during 2002-15 suggest a slow but steady increase by most crops (Fig. 1B). Large quantities of wheat, rice, and sugarcane residues are generated in many Indian states (Eq. i) (Table 2-4). By quantity, the highest wheat residue is produced in U.P. (Table 2) but is most abundantly available as surplus in Punjab followed by Haryana (Eq. i, iii & iv) (Fig. 2A). Similarly, highest rice residue is generated in West Bengal (Table 3), but more abundantly available as surplus in Punjab (Fig. 2B). Sugarcane residue generation (Table 4) and abundance (Fig. 2C) are highest in UP. India produces 500 Mt CR, of which 140 Mt is surplus (Sahai *et al.,* 2011; Pathak *et al.,* 2012) have reported production of 40%, 33% and 10% residue from the total biomass of rice, wheat and sugarcane crops respectively during 1980-2010. Thus, India produces abundant CR and surplus is available for conversion to

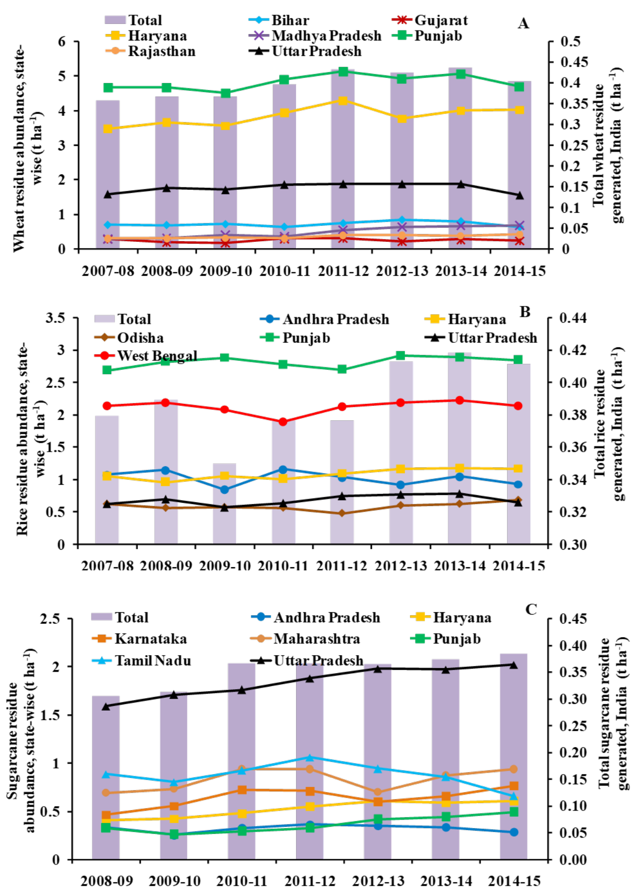

Fig. 2: Residue abundance (tonne/per hectare) in major wheat (A), rice (B) and sugarcane (C) producing states of India $CR_{ab} = CR/A$. Bars represent residue abundance in India and lines represent residue abundance in states.

Table 2: Wheat residue generated in major wheat producing states of India during 2007-15.

	Wheat Residue generation in Million tonnes (Mt)							
States	*2007-08**	*2008-09**	*2009-10**	*2010-11**	*2011-12**	*2012-13#*	*2013-14#*	*2014-15δ*
Assam	0.11	0.08	0.10	0.08	0.09	0.06	0.04	0.06
Bihar	6.66	6.60	6.84	6.13	7.07	8.02	7.60	6.06
Chhattisgarh	0.15	0.14	0.18	0.19	0.20	0.21	0.19	NA
Gujarat	5.74	3.88	3.52	6.01	6.09	4.40	5.46	4.82
Haryana	15.31	16.17	15.71	17.40	18.98	16.64	17.65	17.74
H.P.	0.75	0.82	0.49	0.82	0.89	0.91	0.81	1.08
J & K	0.74	0.72	0.43	0.67	0.75	0.69	0.69	0.52
Jharkhand	0.21	0.23	0.26	0.24	0.45	0.48	0.54	0.49
Karnataka	0.39	0.37	0.38	0.42	0.29	0.27	0.34	0.33
M.P.	9.03	9.76	12.58	11.41	17.26	19.64	20.84	21.21
Maharashtra	3.11	2.27	2.60	3.44	1.96	1.77	2.39	1.86
Punjab	23.49	23.53	22.68	24.64	25.85	24.82	25.49	23.61
Rajasthan	10.66	10.90	11.22	10.79	13.94	13.88	13.34	14.77
U.P	38.42	42.72	41.26	44.88	45.32	45.33	45.25	37.73
Uttarakhand	1.22	1.19	1.26	1.31	1.31	1.29	1.26	0.99
West Bengal	1.37	1.14	1.27	1.31	1.31	1.35	1.42	1.42
Others	0.19	0.18	0.09	0.22	0.17	0.13	0.15	0.37
Total	117.54	120.70	120.88	129.96	129.96	139.88	143.48	133.05

*Wheat production in various states from Status paper on wheat, Directorate of Wheat Development, Ministry Of Agriculture Ghaziabad, U.P., India

#Wheat production in various states from Agricultural Statistics at a Glance 2014, Ministry of Agriculture, Government of India

δWheat production in various states from Agricultural Statistics at a Glance 2015, Ministry of Agriculture, Government of India

H.P. (Himachal Pradesh); J&K (Jammu and Kashmir); M.P. (Madhya Pradesh); U.P. (Uttar Pradesh)

Equation (i)

Table 3: Rice residue generated in major rice producing states of India during 2007-15.

	Rice Residue generation in Million tonnes (Mt)							
States	*2007-08**	*2008-09**	*2009-10**	*2010-11**	*2011-12#*	*2012-13δ*	*2013-14δ*	*2014-15γ*
A.P.	17.19	18.37	13.59	18.60	16.63	14.84	16.81	14.93
Assam	4.28	5.17	5.59	6.11	5.83	6.62	6.17	6.27
Bihar	5.70	7.21	4.64	4.00	9.24	9.71	7.11	8.23
Chhattisgarh	7.00	5.66	5.30	7.95	7.78	8.53	8.67	7.77
Gujarat	1.90	1.68	1.67	1.93	2.31	1.99	2.09	2.12
Haryana	4.66	4.25	4.68	4.48	4.85	5.13	5.21	5.17
Jharkhand	4.34	4.41	1.98	1.43	4.04	4.08	3.53	4.28
Karnataka	4.79	4.90	4.76	5.40	5.10	4.33	4.85	4.72
Kerala	0.68	0.76	0.77	0.67	0.73	0.66	0.66	0.72
M.P.	1.88	2.01	1.63	2.29	2.93	3.57	5.68	4.68
Maharashtra	3.86	2.95	2.82	3.48	3.66	3.95	3.81	3.78
Odisha	9.73	8.79	8.92	8.81	7.49	9.42	9.78	10.69
Punjab	13.53	14.19	14.49	13.98	13.60	14.67	14.54	14.33
Tamil Nadu	6.50	6.68	7.31	7.47	9.62	5.22	7.15	7.53
U.P.	15.20	16.90	13.94	15.47	18.09	18.59	18.87	15.76
West Bengal	18.99	19.40	18.50	16.83	18.84	19.38	19.75	18.98
Others	2.70	2.81	2.61	3.21	3.21	5.06	4.94	5.25
Total	124.73	127.94	114.94	123.81	123.81	135.76	137.44	135.19

[*] Rice production in various states from Directorate of Rice Development, State-wise area, production and productivity of rice during 2006-2007 to 2010-2011

[#] Rice production in various states from A status paper on rice, Directorate of Rice Development, Govt. of India, Patna, Bihar, India

[δ] Rice production in various states from Agricultural Statistics at a Glance 2014, Ministry of Agriculture, Government of India

[γ] Rice production in various states from Agricultural Statistics at a Glance 2015, Ministry of Agriculture, Government of India

A.P. (Andhra Pradesh); M.P. (Madhya Pradesh); U.P. (Uttar Pradesh)

Equation (i)

Table 4: Sugarcane residue generated in major Sugarcane producing states of India during 2008-15.

	Sugarcane Residue Generation in Million tonnes						
States	*2008-09**	*2009-10**	*2010-11**	*2011-12**	*2012-13#*	*2013-14#*	*2014-15δ*
A.P.	5.41	4.12	5.27	5.89	5.60	5.41	4.63
Bihar	1.75	1.77	4.49	4.25	4.08	4.74	4.97
Gujarat	5.46	4.36	4.84	4.99	4.47	4.42	4.95
Haryana	1.81	1.88	2.13	2.45	2.67	2.62	2.69
Karnataka	8.92	10.71	13.96	13.66	11.52	12.64	14.75
M.P.	1.05	0.89	0.94	0.94	0.93	1.17	1.61
Maharashtra	21.35	22.58	28.83	28.81	21.58	26.95	28.82
Punjab	1.64	1.30	1.47	1.64	2.08	2.22	2.48
Tamil Nadu	11.55	10.47	12.06	13.83	12.30	11.18	8.61
U.P.	38.39	41.23	42.43	45.34	47.75	47.58	48.74
Uttarakhand	1.97	2.06	2.29	2.32	2.41	2.26	2.16
West Bengal	0.58	0.35	0.40	0.41	0.57	0.60	0.69
Others	1.18	1.15	1.42	1.36	0.74	0.75	0.77
Total	100.33	102.89	120.52	120.52	120.05	123.21	126.48

* Sugarcane production in various states from Satus paper on Sugarcane, Directorate of Sugarcane, Research, Govt. of India, Lucknow, India
Sugarcane production in various states from Agricultural Statistics at a Glance 2014 Ministry of Agriculture, Government of India
δ Sugarcane production in various states from Agricultural Statistics at a Glance 2015 Ministry of Agriculture, Government of India
A.P. (Andhra Pradesh); M.P. (Madhya Pradesh); U.P. (Uttar Pradesh)
Equation (i)

SOC pool. Ironically the asset is either burnt on-farm or left unused which disturbs the atmospheric carbon pool.

Crop Residue Burning (Atmospheric carbon) and Organic Carbon Loss

Burning of CR on the farm is a quick and inexpensive process to clear the fields before sowing of the succeeding crops and to get short-term benefits (Irwin, 2014; Jain *et al.,* 2014). The practice, is prevalent in many countries, worldwide (Gadde *et al.,* 2009; FAO, 2014; Irwin, 2014, Ni *et al.,* 2015; Wu *et al.,* 2018). Highest maize residue burning has been reported in the USA, China, and Brazil (FAO, 2014). Images released by NASA, USA confirm intense agricultural fires due to residue burning in China and Africa and India. In India the problem is pronounced in the well-irrigated mechanized rice-wheat cropping areas of the north-west IGR where a total of 23914; 23666; and 25819 fire counts were recorded during 2005, 2008 and 2012, of which more than 80% were in agricultural fields (Vadrevu and Lasko, 2015). Impact of crop residue burning on the ecosystem services of agro-ecosystem has been observed, affecting soil structure and function and global warming (Kumar *et al.,* 2019). In spite of the measures being taken by the government farmers in India resort to residue burning (Tore, 2019) owing to: (i) labour and transport constrains (Pathak *et al.,* 2011) (ii) mechanized harvesting (Pathak *et al.,* 2012; Irwin, 2014) and (iii) lack of proper residue recycle technology (Irwin, 2014; Singh and Kaskaoutis, 2014). To address the issue, quantification of the adverse effects of CR burning on environment, SOC, nutrients (NPK) and micro-flora losses is of immense importance.

Crop residue and biomass burning adds to GHGs affecting air quality on burning by emitting trace gases, particulate matter, and elemental C (Yadav *et al.,* 2017). We observed that the annual additions of C from CO_2, CO, and CH_4 emitted from residue burning ranges from 4474.21-1511.14 Gg C for wheat and 6249.04 -1407.44 Gg C from rice residue in different regions of IGR (Table 5-6; Eq. v). The extrapolated mean value of emissions of CO_2, CH_4, CO, N_2O, NO_x upon burning surplus residue have remained consistent (during 2007-16) in the IGR (Table 5-6; Eq. v). Rice straw burning causes more than 70% C loss as CO_2, CO, and CH_4, and large portions of N and S as NOx, N_2O and SO_2 respectively (Gupta *et al.,* 2004; Jain *et al.,* 2014). The daily C influx from agricultural fires is more than that from fossil fuel emissions in the 28 countries of the European Union. More than 213.15 Tg C is added to atmosphere from biomass burning in India (Streets *et al.,* 2003), of which 379 Gg C is contributed by burning residues of wheat, rice, maize, sugarcane and cotton (Lenka *et al.,*

Table 5: Annual GHG (CO_2, CH_4, CO, N_2O, NOx) emissions and C equivalents added to atmosphere during wheat residue burning.

		GHGs emitted upon wheat residue burning (Gg)					*C equivalents added to atmosphere (Gg)*			
State	*Year*	*CO_2*	*CH_4*	*CO*	*N_2O*	*NO_x*	*CO_2-C*	*CO-C*	*CH_4-C*	*Total C*
Punjab	2007-08	8688.13	17.50	136.62	3.90	8.27	2369.49	58.55	13.13	2441.17
	2008-09	8704.73	17.54	136.88	3.91	8.28	2374.02	58.66	13.15	2445.83
	2009-10	8390.96	16.90	131.95	3.77	7.98	2288.44	56.55	12.68	2357.67
	2010-11	9115.34	18.36	143.34	4.09	8.67	2486.00	61.43	13.77	2561.20
	2011-12	9562.47	19.26	150.37	4.29	9.10	2607.95	64.44	14.45	2686.84
	2012-13	9180.64	18.49	144.36	4.12	8.73	2503.81	61.87	13.87	2579.55
	2013-14	9429.66	19.00	148.28	4.23	8.97	2571.73	63.55	14.25	2649.52
	2014-15	8732.40	17.59	137.31	3.92	8.31	2381.56	58.85	13.19	2453.61
	2015-16*	8895.09	17.92	139.87	3.99	8.46	2425.93	59.95	13.44	2499.32

Cont...

Cont...

Haryana	2007-08	5664.44	11.41	89.07	2.35	5.39	1544.85	38.17	8.56	1591.58
	2008-09	5980.97	12.05	94.05	2.48	5.69	1631.17	40.31	9.04	1680.52
	2009-10	5810.53	11.71	91.37	2.41	5.53	1584.69	39.16	8.78	1632.63
	2010-11	6435.85	12.97	101.20	2.67	6.12	1755.23	43.37	9.72	1808.33
	2011-12	7020.23	14.14	110.39	2.91	6.68	1914.61	47.31	10.61	1972.52
	2012-13	6153.63	12.40	96.76	2.55	5.85	1678.26	41.47	9.30	1729.03
	2013-14	6529.93	13.15	102.68	2.70	6.21	1780.89	44.01	9.87	1834.76
	2014-15	6563.13	13.22	103.20	2.72	6.24	1789.95	44.23	9.92	1844.09
	2015-16**	6092.76	12.27	95.81	2.52	5.80	1661.66	41.06	9.21	1711.93
UP	2007-08	14210.34	28.63	223.45	5.88	13.52	3875.55	95.77	21.47	3992.78
	2008-09	15801.32	31.83	248.47	6.54	15.03	4309.45	106.49	23.87	4439.81
	2009-10	15262.88	30.75	240.00	6.32	14.52	4162.60	102.86	23.06	4288.52
	2010-11	16602.07	33.45	261.06	6.87	15.79	4527.84	111.88	25.08	4664.81
	2011-12	16763.66	33.77	263.60	6.94	15.95	4571.91	112.97	25.33	4710.21
	2012-13	16767.53	33.78	263.66	6.94	15.95	4572.96	113.00	25.33	4711.30
	2013-14	16739.86	33.72	263.23	6.93	15.92	4565.42	112.81	25.29	4703.52
	2014-15	13956.34	28.12	219.46	5.78	13.28	3806.27	94.05	21.09	3921.42
	2015-16***	14869.42	29.96	233.82	6.16	14.15	4055.30	100.21	22.47	4177.97

* Wheat production in Punjab http://agripb.gov.in/agri_statistics/pdf/Annexure%20area.pdf
** Wheat production in Haryana http://agriharyana.nic.in/Stat_Info/AYP%202015-16.pdf
*** Wheat production in Uttar Pradesh State agriculture department, Lucknow, Uttar Pradesh, personal communication
Equation (v)
** Rice production in Haryana http://agriharyana.nic.in/Stat_Info/AYP%202015-16.pdf
*** Rice production in Uttar Pradesh State agriculture department, Lucknow, Uttar Pradesh, personal communication
Equation (v)

Table 6: Annual GHG (CO_2, CH_4, CO, N_2O, NOx) emissions and C equivalents added to atmosphere during rice residue burning.

		GHGs emitted (Gg)					*C equivalents added to atmosphere (Gg)*			
State	*Year*	*CO_2*	*CH_4*	*CO*	*N_2O*	*NOx*	*CO_2-C*	*CH_4-C*	*CO-C*	*Total C*
Punjab	2007-08	15803.04	12.99	375.59	0.76	33.55	4309.92	9.74	160.97	4480.63
	2008-09	16573.92	13.62	393.91	0.79	35.19	4520.16	10.22	168.82	4699.20
	2009-10	16924.32	13.91	402.24	0.81	35.94	4615.72	10.43	172.39	4798.55
	2010-11	16328.64	13.42	388.08	0.78	34.67	4453.27	10.07	166.32	4629.65
	2011-12	15884.80	13.06	377.54	0.76	33.73	4332.22	9.79	161.80	4503.81
	2012-13	17134.56	14.08	407.24	0.82	36.38	4673.06	10.56	174.53	4858.16
	2013-14	16982.72	13.96	403.63	0.81	36.06	4631.65	10.47	172.98	4815.10
	2014-15	16737.44	13.76	397.80	0.80	35.54	4564.76	10.32	170.49	4745.56
	2015-16*	17813.95	14.64	423.39	0.85	37.82	4858.35	10.98	181.45	5050.78
Haryana	2007-08	5442.88	4.47	129.36	0.26	11.56	1484.42	3.36	55.44	1543.22
	2008-09	4964.00	4.08	117.98	0.24	10.54	1353.82	3.06	50.56	1407.44
	2009-10	5466.24	4.49	129.92	0.26	11.61	1490.79	3.37	55.68	1549.84
	2010-11	5232.64	4.30	124.36	0.25	11.11	1427.08	3.23	53.30	1483.61
	2011-12	5664.80	4.66	134.64	0.27	12.03	1544.95	3.49	57.70	1606.14
	2012-13	5991.84	4.92	142.41	0.29	12.72	1634.14	3.69	61.03	1698.86
	2013-14	6085.28	5.00	144.63	0.29	12.92	1659.62	3.75	61.98	1725.36
	2014-15	6038.56	4.96	143.52	0.29	12.82	1646.88	3.72	61.51	1712.11
	2015-16**	6245.35	5.13	148.43	0.30	13.26	1703.28	3.85	63.61	1770.74
UP	2007-08	17753.60	14.59	421.95	0.85	37.70	4841.89	10.94	180.84	5033.67
	2008-09	19739.20	16.22	469.14	0.95	41.91	5383.42	12.17	201.06	5596.65
	2009-10	16281.92	13.38	386.97	0.78	34.57	4440.52	10.04	165.85	4616.41
	2010-11	18068.96	14.85	429.45	0.87	38.37	4927.90	11.14	184.05	5123.09
	2011-12	21129.12	17.37	502.18	1.01	44.86	5762.49	13.02	215.22	5990.73
	2012-13	21713.12	17.85	516.06	1.04	46.10	5921.76	13.38	221.17	6156.31
	2013-14	22040.16	18.12	523.83	1.06	46.80	6010.95	13.59	224.50	6249.04
	2014-15	18407.68	15.13	437.50	0.88	39.08	5020.28	11.35	187.50	5219.12
	2015-16***	19744.06	16.23	469.26	0.95	41.92	5384.74	12.17	201.11	5598.03

*Rice production in Punjab http://agripb.gov.in/agri_statistics/pdf/Annexure%20area.pdf

2014). The N and C released as oxides in biomass burning increase the atmospheric burden of NOx, CH_4, and CO_2 which are potent greenhouse gases and cannot be ignored. The level of pollutants emitted during CR burning is expected to increase in future, which is a matter of concern (Pathak, 2015).

Nutrient Loss during Crop Residue Burning

Crop residue burning not only adds to atmospheric C but also removes the nutrients sequestered in the biomass from the soil. Multi-nutrient deficiency in agricultural soil has occurred globally due to imbalance in the amounts of nutrients being mined and replenished in the current agricultural practices (Shukla *et al.,* 2005; Jones *et al.,* 2013; Sanyal *et al.,* 2014). The rate of chemical fertilizers supplementation does not keep pace with nutrient removal as evident by the net negative balance of NPK in well-supplemented fields (Srinivasarao *et al.,* 2014). Rice-wheat cultivation extracts more than 300:30:300 kg NPK ha^{-1} from soil on the production of rice @ of 7 t per hectare and of wheat 4 t per hectare (Singh *et al.,* 2003). After several cropping seasons, this results in soil fatigue with insignificant increase in crop production, even with generally recommended rates of fertilizer. Under such conditions farmers are forced to apply higher than recommended doses of N and P fertilizers, without balancing other nutrients, thereby aggravating the deficiency of K, S and other micronutrients in soil (Shukla *et al.,* 2005; Srinivasarao *et al.,* 2014). The chemical fertilizer imbalance has created a net deficit of 142 kg K ha^{-1} in IGR, which is more for Punjab, Haryana and UP (Shukla *et al.,* 2005; Pathak *et al.,* 2010).

Of the total assimilated nutrients cereal residues retain about 25% of N and P, 50% of S and 75% of K (Singh and Sidhu, 2014). The waste burning causes loss of almost 100% C, 80-90% N, 25% P, 50-60% S and 20-25% K present in the waste which could be recycled in soil (Singh and Kaskaoutis, 2014). The nutrient depletion in soils of Punjab, Haryana and UP after rice, wheat and sugarcane cultivation are given in Table 7-9 (Eq. vi). The results show consistency in removal of nutrients since 2007 indicating negligible increase in nutrient uptake by the crops indicating saturation in the land's productivity inspite of the increasing fertilizer inputs. The vicious cycle of soil nutrient and OC loss generally trail with nutrient and C augmentation practices probably due to high C:N ratio. It has been estimated that 1 Gt C augmentation requires 80 Mt N, 20

Table 7: Removal of nutrients (NPK) from wheat cultivated soil, 2007-15 in major states of Indo-Gangetic Region.

Wheat	*State*	*2007-08*	*2008-09*	*2009- 10*	*2010-11*	*2011-12*	*2012-13*	*2013-14*	*2014-15*
Total production (Mt)	Punjab	15.7	15.7	15.2	16.5	17.3	16.6	17.0	15.8
	Haryana	10.2	10.8	10.5	11.6	12.7	11.1	11.8	11.9
	UP	25.7	28.6	27.6	30.0	30.3	30.3	30.3	25.2
N removed ('000't)	Punjab	378.4	379.1	365.4	397.0	416.4	399.8	410.7	380.3
	Haryana	246.7	260.5	253.1	280.3	305.7	268.0	284.4	285.8
	UP	618.9	688.2	664.7	723.0	730.1	730.2	729.0	607.8
P removed ('000't)	Punjab	135.0	135.3	130.4	141.7	148.6	142.7	146.5	135.7
	Haryana	88.0	92.9	90.3	100.0	109.1	95.6	101.5	102.0
	U P	220.8	245.6	237.2	258.0	260.5	260.6	260.2	216.9
K removed ('000' t)	Punjab	515.0	515.9	497.3	540.3	566.8	544.2	558.9	517.6
	Haryana	335.7	354.5	344.4	381.5	416.1	364.7	387.0	389.0
	U P	842.3	936.6	904.7	984.0	993.6	993.8	992.2	827.2
Total NPK ('000' t)	Punjab	515.0	515.9	497.3	540.3	566.8	544.2	558.9	517.6
	Haryana	670.5	707.9	687.8	761.8	830.9	728.4	772.9	776.8
	U P	1682.0	1870.3	1806.6	1965.1	1984.2	1984.7	1981.4	1651.9

* Equation (vi)

Table 8: Depletion of nutrients (NPK) from rice cultivated soil, 2007-15 in major states of Indo-Gangetic Region.

Rice	*State*	*2007-08*	*2008-09*	*2009-10*	*2010-11*	*2011-12*	*2012-13*	*2013-14*	*2014-15*
Total Production (Mt)	Punjab	10.5	11.0	11.2	10.8	10.5	11.4	11.3	11.1
	Haryana	3.6	3.3	3.6	3.5	3.8	4.0	4.0	4.0
	UP	11.8	13.1	10.8	12.0	14.0	14.4	14.6	12.2
N removed ('000't)	Punjab	210.8	221.1	225.8	217.8	211.9	228.5	226.5	223.3
	Haryana	72.6	66.3	72.9	69.8	75.6	80.0	81.2	80.6
	U P	236.8	263.2	217.2	241.0	281.8	289.6	294.1	245.6
P removed ('000't)	Punjab	117.5	123.2	125.8	121.4	118.1	127.3	126.2	124.4
	Haryana	40.5	36.9	40.6	38.9	42.1	44.6	45.2	44.9
	UP	131.9	146.7	121.0	134.3	157.0	161.4	163.9	136.9
K removed ('000't)	Punjab	314.7	330.0	337.1	325.1	316.3	341.1	338.1	333.3
	Haryana	108.4	98.9	108.8	104.2	112.8	119.4	121.2	120.3
	UP	353.4	392.9	324.2	359.8	420.7	432.3	438.9	366.6
Total NPK ('000't)	Punjab	643.0	674.3	688.8	664.3	646.2	697.0	690.9	681.0
	Haryana	221.5	202.2	222.2	212.8	230.4	244.0	247.7	245.8
	UP	722.1	802.8	662.5	735.1	859.5	883.3	896.8	749.1

* Equation (vi)

Table 9: Removal of nutrients (NPK) from sugarcane cultivated soil, 2007-15 in major states of Indo-Gangetic Region.

Sugarcane	*State*	*2008-09*	*2009-10*	*2010-11*	*2011-12*	*2012-13*	*2013-14*	*2014-15*
Total production (Mt)	Punjab	4.67	3.7	4.17	4.67	5.92	6.31	7.04
	Haryana	5.13	5.34	6.04	6.95	7.59	7.45	7.65
	UP	109.05	117.14	120.55	128.82	135.64	135.16	138.48
N removed ('000't)	Punjab	7.939	6.29	7.089	7.939	10.064	10.727	11.968
	Haryana	8.721	9.078	10.268	11.815	12.903	12.665	13.005
	UP	185.385	199.138	204.935	218.994	230.588	229.772	235.416
P removed ('000't)	Punjab	0.934	0.74	0.834	0.934	1.184	1.262	1.408
	Haryana	1.026	1.068	1.208	1.39	1.518	1.49	1.53
	UP	21.81	23.428	24.11	25.764	27.128	27.032	27.696
K removed ('000' t)	Punjab	9.34	7.4	8.34	9.34	11.84	12.62	14.08
	Haryana	10.26	10.68	12.08	13.9	15.18	14.9	15.3
	UP	218.1	234.28	241.1	257.64	271.28	270.32	276.96
Total NPK ('000't)	Punjab	18.21	14.43	16.26	18.21	23.09	24.61	27.46
	Haryana	20.01	20.83	23.56	27.11	29.60	29.06	29.84
	UP	425.29	456.85	470.15	502.40	529.00	527.12	540.07

*Equation (vi)

Mt P, and 15 Mt K to be supplemented in soil (Lal, 2014). Therefore, methods to optimally utilize the nutrients present in the residue by minimizing the constraints arising due to high C:N/C:P/C:S ratios are needed. Microbes could probably act as a catalyst in designing such strategies. This is all the more important since repeated episodes of CR burning raise soil temperature to such an extent that microbial populations are greatly reduced (Gupta *et al.*, 2004). Jiménez-Bueno *et al.* (2016) have reported that crop residue burning affects the bacterial communities at several taxonomic levels and that the signature microbes of the soil after stubble burning resembled that of the deserts and high pH soil.

Crop Residues Potential to Augment SOC and Nutrients in IGR

By extrapolations of the existing data, we could project the potential of CR to improve the soil fertility. Rice residue stores 40% N, 30-35% P, 80-85% K, and 40-50% S while wheat crops stores 25-30% N and P, 70-75% K and 35-40% S besides other micronutrients like Zn, Fe, Mn and Si extracted from soil (Singh and Sidhu, 2014). The P content in residues of rice, wheat, maize and sugarcane has an annual recycling potential of 4.35 Tg P in soil (Dai *et al.*, 2016). A consistency in assimilated C and loss on burning has been observed for wheat, rice and sugarcane residues since 2007 in India (Eq. ix & x) (Fig. 3A-D). Similarly potential N, P and K lost from wheat, rice and sugarcane residue burning are 0.11 Mt N, 0.02 Mt P and 0.29 Mt K in Punjab, 0.05 Mt N, 0.01 Mt P and 0.13 Mt K in Haryana and 0.22 Mt N, 0.04 Mt P and 0.44 Mt K in UP which are expected to reduce the N, P and K fertilization on soil incorporation (Table 10-12). Thus, the tables and figures summarize that substantial C and nutrient reserves are available for soil amendment in IGR, offering a scope to enhance the land productivity. Ability of CR in improving soil C sequestration and SOC has been shown by many workers (Pathak *et al.,* 2011; Lal 2014; Sapkota *et al.,* 2017). Potential of CR to provide different nutrients has also been reported (Shindo and Nishio, 2005; Singh and Sidhu, 2014).

Considering 100% utilization efficiency of nutrients from residues, extrapolations with NPK availability from surplus wheat, rice and sugarcane residues will ensure 13-17%, 21-26% and 19-24% reduction in total NPK demand in Punjab, Haryana and UP, respectively (Table 10-12). It would save consumption of fertilizers by 31-32% N and 24-26% P in Punjab; 33-35% N and 25-28% P in

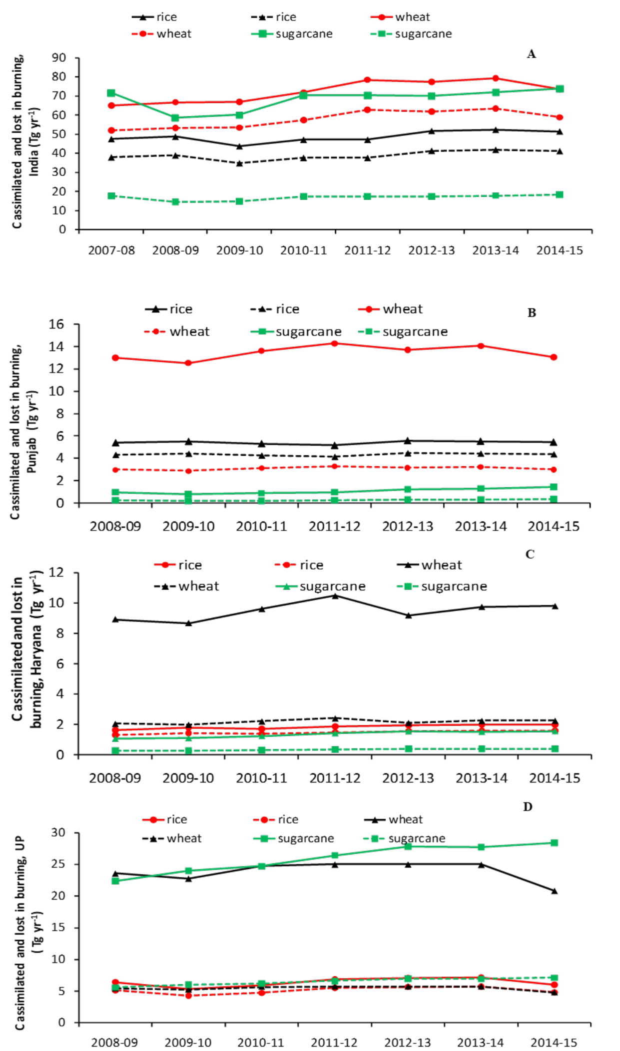

Fig. 3: Carbon assimilated and lost upon burning wheat, rice and sugarcane residues in major states of Indo-Gangetic Region (A) Punjab (B) Haryana (C) and UP (D). Bold lines represent total C assimilated and dotted lines represent C loss in burning $CR_C = CR \times Cf$ and $CR_{CL} = CRb \times Cf$.

Table 10: Expected reductions in N, P and K fertilizer supplementation after incorporation of surplus wheat, rice and sugarcane residues, in Punjab.

			Nutrients in burnt Fraction ('000' tonnes)			
Year	*Crop residue*	*Amount burnt (Mt)*	*N*	*P*	*K*	*Total NPK*
2011-12	Rice[1]	10.88	67.46	11.97	205.63	285.06
	Wheat[1]	5.95	41.05	4.76	80.32	126.13
	Sugarcane[1]	0.41	2.21	0.53	1.3	4.04
	Total amount burnt	17.24	110.72	17.26	287.25	415.23
	Fertilizer supplementation ('000' tonnes)		1416.56	448.65	52.85	1918.06
	Fertilizer efficiency [2]		566.62	134.60	37.00	738.21
	Envisaged reduction % in fertilizer usage[3]		32.18	26.15	-473.51	16.84
2012-13	Rice	11.73	72.73	12.90	221.70	307.33
	Wheat	5.71	39.40	4.57	77.1	121.07
	Sugarcane	0.52	2.81	0.68	1.61	5.10
	Total amount burnt	17.96	115.94	18.15	300.41	433.5
	Fertilizer supplementation ('000' tonnes)		1485.7	462.48	24.06	1972.24
	Fertilizer efficiency		594.28	138.74	16.84	749.87
	Envisaged reduction % in fertilizer usage		32.20	26.07	-1178.6	16.41
2013-14	Rice	11.63	72.11	12.79	219.81	304.71
	Wheat	5.84	40.30	4.67	78.84	123.81
	Sugarcane	0.56	3.02	0.73	1.74	5.49
	Total amount burnt	18.02	115.43	18.19	300.39	434.01
	Fertilizer supplementation ('000' tonnes)		1364.02	325.23	24.02	1713.27
	Fertilizer efficiency		545.61	97.57	16.81	659.99
	Envisaged reduction % in fertilizer usage		31.54	24.41	-1180.6	13.19
2014-15	Rice	11.46	71.05	12.61	216.59	300.25
	Wheat	5.43	37.47	4.34	73.30	115.11
	Sugarcane	0.62	3.35	0.81	1.92	6.08
	Total amount burnt	17.51	111.87	17.76	291.81	421.44
	Fertilizer supplementation ('000' tonnes)		1352.05	328.17	37.53	1717.75
	Fertilizer efficiency		540.82	98.45	26.27	665.54
	Envisaged reduction % in fertilizer usage		31.72	24.59	-707.54	14.21

[1]Equation ii; [2] Equation vii; [3] Equation viii
*Agricultural Statistics at a Glance 2014, Ministry of Agriculture, Government of India
**Agricultural Statistics at a Glance 2015, Ministry of Agriculture, Government of India

Table 11: Expected reductions in N, P and K fertilizer supplementation after incorporation of surplus wheat, rice and sugarcane residues, in Haryana.

			Nutrients in burnt Fraction ('000' tonnes)			
Year	*Crop residue*	*Amount Burnt (Mt)*	*N*	*P*	*K*	*NPK*
	Rice[1]	3.88	24.06	4.27	73.33	101.66
	Wheat[1]	4.37	30.15	3.5	58.99	92.64
	Sugarcane[1]	0.61	3.3	0.8	1.95	6.05
2011-12	Total	8.86	57.54	8.57	134.27	202.35
	Fertilizer supplementation ('000' tonnes)*		1020.9	369.62	37.53	1428.05
	Fertilizer efficiency[2]		408.36	110.89	26.27	545.52
	Envisaged reduction % in fertilizer usage[3]		34.36	27.68	-287.77	24.03
2012-13	Rice	4.11	25.48	4.52	77.68	107.68
	Wheat	3.83	26.43	3.06	51.70	81.19
	Sugarcane	0.67	3.62	0.87	2.08	6.57
	Total	8.60	55.53	8.45	131.46	195.44
	Fertilizer supplementation ('000' tonnes)		1022.99	310.56	16.65	1350.2
	Fertilizer efficiency		409.19	93.17	11.66	514.02
	Envisaged reduction % in fertilizer usage		34.57	27.28	-719.52	23.59

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2013-14	Rice	4.17	25.85	4.59	78.81	109.25
	Wheat	4.06	28.01	3.25	54.81	86.07
	Sugarcane	0.66	3.56	0.86	2.05	6.47
	Total	8.89	57.42	8.70	135.67	201.79
	Fertilizer supplementation ('000' tonnes)		950.56	198.46	15.65	1164.67
	Fertilizer efficiency		380.22	59.54	10.96	450.72
	Envisaged reduction % in fertilizer usage		33.96	25.62	-796.87	21.37
2014-15	Rice	4.14	25.67	4.55	78.25	108.47
	Wheat	4.08	28.15	3.26	55.08	86.49
	Sugarcane	0.67	3.62	0.87	2.08	6.57
	Total	8.89	57.44	8.68	135.41	201.53
	Fertilizer supplementation ('000' tonnes)**		1013.29	253.66	36.2	1303.15
	Fertilizer efficiency		405.32	76.09	25.34	536.76
	Envisaged reduction % in fertilizer usage		34.33	26.57	-304.06	25.72

[1]Equation ii; [2]Equation vii; [3]Equation viii
*Agricultural Statistics at a Glance 2014, Ministry of Agriculture, Government of India
**Agricultural Statistics at a Glance 2015, Ministry of Agriculture, Government of India

Table 12: Expected reductions in N, P and K fertilizer supplementation after incorporation of surplus wheat, rice and sugarcane residues, in Uttar Pradesh

			Nutrients in burnt fraction ('000' tonnes)			
Year	*Crop residue*	*Amount burnt (Mt)*	*N*	*P*	*K*	*Total NPK*
2011-12	Rice[1]	14.47	89.71	15.92	273.48	379.11
	Wheat[1]	10.42	71.90	8.34	140.67	220.91
	Sugarcane[1]	11.34	61.24	14.74	35.15	111.13
	Total	36.23	222.83	39.00	449.30	711.15
	Fertilizer supplementation ('000' tonnes)*		3067.1	1024.23	166.42	4257.75
	Fertilizer efficiency[2]		1226.84	307.27	116.49	1650.60
	Envisaged reduction % in fertilizer usage[3]		**32.73**	**26.19**	**-199.98**	**22.06**
2012-13	Rice	14.87	92.2	16.36	281.04	389.60
	Wheat	10.43	71.97	8.34	140.80	221.11
	Sugarcane	11.94	64.48	15.52	37.01	117.01
	Total	37.23	228.65	40.22	458.85	727.72
	Fertilizer supplementation ('000' tonnes)		3351.79	1166.43	132.76	4650.98
	Fertilizer efficiency		1340.72	349.93	92.93	1783.58
	Envisaged reduction % in fertilizer usage		33.18	26.55	-275.62	22.70
2013-14	Rice	15.10	93.62	16.61	285.39	395.62
	Wheat	10.41	71.83	8.33	140.53	220.69
	Sugarcane	11.89	64.21	15.46	36.86	116.53
	Total	37.40	229.66	40.40	462.78	732.84
	Fertilizer supplementation ('000' tonnes)		2972.6	764.65	104.77	3842.04
	Fertilizer efficiency		1189.04	229.40	73.34	1491.77
	Envisaged reduction % in fertilizer usage		**32.27**	**24.72**	**-371.71**	**19.75**
2014-15	Rice	12.61	78.18	13.87	238.33	330.38
	Wheat	8.68	59.89	6.94	117.18	184.01
	Sugarcane	12.18	65.77	15.83	37.76	119.36
	Total	**33.18**	**203.84**	**36.64**	**393.27**	**633.75**
	Fertilizer supplementation ('000' tonnes)**		3168.95	915.35	187.34	4271.64
	Fertilizer efficiency		1267.58	274.60	131.14	1673.32
	Envisaged reduction % in fertilizer usage		**33.57**	**26.00**	**-139.92**	**24.34**

[1]Equation ii; [2]Equation vii; [3]Equation viii
*Agricultural Statistics at a Glance 2014, Ministry of Agriculture, Government of India
**Agricultural Statistics at a Glance 2015, Ministry of Agriculture, Government of India

Haryana; 32-33% N and 24-27% P in UP. The residues of rice, wheat and sugarcane contain sufficient quantities of K which could meet the need of potassium-containing fertilizers in soil (Table 10-12). Besides macronutrients, the micronutrients such as Ca, Fe, Mg, S present in CR may be recycled in the soil as well. Crop residue amendment to soil also improves its physical, chemical and biological properties and stimulates soil enzymes and microbial population (Zhao *et al.,* 2017). Crop residue increases soil humus content which facilitates long-term nutrient release (Lal, 2014). Residue amendment has a stronger influence on soil microbial biomass N than chemical fertilizers and also reduces GHG emissions from agricultural fields (Pan *et al.,* 2017). Crop residue act as slow release nutrient sources which gradually mineralize nutrients for plant and microbial uptake (Chen *et al.,* 2014). Therefore, the methods that could augment SOC to maintain the threshold level of 1% C are essential to prevent and restore land degradation (Lal, 2008). However, the exact amount of CR to be added in the soil to meet the deficiencies has to be worked out, which may be variable with the type of residues, microbial flora and their ability to release nutrients in the soil.

Inter Convertible Carbon Triangle (ΔICC)

Based on the background of the mismanagement of the three carbon pools present in the residual biomass, soil and atmosphere, as discussed so far, the ΔICC hypothesis is proposed. It is assumed that if under natural equilibrium (ideal conditions) the three carbon pools, SOC, atmospheric C and biomass C represent the angles of an equilateral triangle (Fig. 4A) then disturbance in any of the pools will alter the other two pools, distorting the triangle [inter convertible C triangle (ΔICC)] (Fig. 4B). Of the three C pools, SOC acts as the sink for atmospheric CO_2 while biomass and fossil fuel burning are the sources. Soil OC is the main component in the CO_2 flux between the terrestrial ecosystem and the atmosphere affecting the global GHGs (Lal, 2004b; Lal, 2008). Therefore, SOC availability is a key component in maintaining the balance of ΔICC. Thus, considering SOC as a variable of biomass C appropriation, it is hypothesized that reallocation of the burnt residue fraction towards soil recarbonization will depreciate atmospheric C by reducing emissions and improving C sequestration and thus balance the ΔICC. The concept of ΔICC will help us to understand the interrelationship among the three carbon pools. This may prove to be a new method to quantify the balancing or the disproportionate elements of a micro-climate. The balance among the three carbon pools or the ΔICC may be unique for a region. The effects of amendments can be monitored by re-constituting the ΔICC and comparing its closeness to the ideal and initial triangles of the region. As an example we have prepared the existing ΔICC of the Indo Gangetic Region. In view of providing a promising solution for restoring the ΔICC equilibrium by increasing SOC, in the IGR the present study has reviewed the (i) magnitude of C/N/P/K assimilated in CR (ii) impact of residue burning on environment and (iii) predict the savings in chemical fertilizers upon sequestration of residue components in soil. Thus the study will be helpful in realizing the application potential of crop residues and initiate studies to develop technologies for its utilization in agriculture.

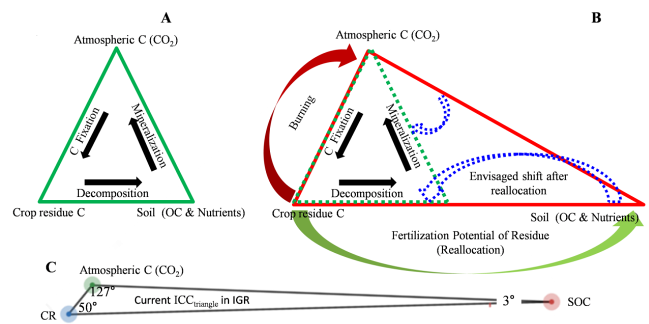
Calculations/data used to validate the ΔICC hypothesis

- Total area of Punjab, Haryana and Uttar Pradesh states of India (33.549 M ha) was considered to be the approximate area of the IGR.
- Ideal SOC was considered to be 2%, and current SOC present in IGR was taken to be 0.1% (Lal, 2011)
- Top soil, was considered to be 2260 t/ha which was used to calculate the ideal and current amount of SOC present in top soil. (Ideal SOC was 33.549 M ha × 44.8 t ha^{-1} SOC equalling to 1.5 Tg SOC in IGR, 2% of 2260 t ha^{-1} equals 44.8 t ha^{-1}; Current SOC was 33.549 M ha x 2.24 t ha^{-1} equals to 0.074 Tg SOC in IGR, 0.1% of 2260 t ha^{-1} equals to 2.24 t ha^{-1})
- Ideal CR_c (201.6 Tg) was considered to be 20% enhanced production from the current and calculated by adding current CRc (168 Tg) and envisaged increase (33.6 Tg)
- The C amount in three pools was converted from Tg to the degree of angles by equating ideals to 60° angle. Therefore, if 1.5 Tg SOC is 60° (ideal) then Current 0.074 Tg equals to 2.96° [(0.074 Tg/1.5Tg) x 60°]; Similarly 168 Tg CRc equals to 50° [(168/201.6) x 60°]
- The angle of atmospheric C was calculated by subtracting the sum of SOC and CRc from 180.

Components of the ΔICC Carbon pools

The hypothesis of biomass C appropriation among the three C pools shows that an increase in atmospheric C-angle of the triangle (carbon foot print) will decrease the SOC-angle and crop/residue-angle (Fig. 4). To maintain the crop-angle (productivity of soil), external inputs in the form of chemical fertilizers is required (currently in practice) which decreases the SOC-angle (soil fertility) (Fig. 4B). The following discussions will show how one pool affects the other and how they can be inter-converted to break the stagnancy in crop productivity and environmental pollution.

The sources of soil C influx are primary production, heterotrophic respiration and anthropogenic activities (Gougoulias *et al.,* 2014). The labile soil OC pool, plant residues, particulate OC, and humus



D

Angles in $ICC_{triangle}$	Ideal C pools (Tg)	Existing C pools (Tg)	Skewness in angles of $ICC_{triangle}$
$\angle SOC$	1.5 (= 60°)	0.074	$\angle SOC = 2.96°$
$\angle CRc$	201.6 (= 60°)	168.0	$\angle CRc = 50°$
$\angle atmospheric\ C$	X (= 60°)	X + excess C emissions	$\angle atmospheric\ C = 127.04°$

Ideal SOC = 1.5 Tg SOC
Current SOC = IGR area x SOC @ 0.1 % of soil with 2260 t top soil/h the amount of current SOC in top soil is 33.549 M ha × 2.24 t ha^{-1} = 0.074 Tg SOC
CR_C ideal = 201.6Tg [sum of current CRc (168 Tg) + envisaged increase @ 20% of current (33.6 Tg)]
X, is the unknown ideal value of atmospheric C.
Conversion of C amount in three pools from Tg to the degree of angles, $\angle SOC$ 1.5 Tg = 60° (ideal), Current $\angle SOC$ 0.074 t = (0.074/1.5) x 60° = 2.96°; $\angle CRc$ 168 t = (168/201.6) x 60° = 50° ;
$\angle atmospheric\ C$ 180°- 52.96° $[180° - (\angle SOC + \angle CRc)]$

Fig. 4: Schematic representation of the ΔICC showing carbon pools as a variable of biomass appropriation. ΔICC shows balanced carbon partitioning among the three carbon pools represented by the three angles (A) Anthropogenic activities lead to imbalance in biomass appropriation, disturbing the equilibrium (B) Skewness in angles of the ΔICC for the Indo Gangetic Region (C) Detail of the IGR carbon pools showing the conversion of carbon pools into ΔICC (D).

is predominant in humid regions while inorganic forms are recalcitrant and dominate arid and semi-arid regions (Lal, 2004a,b). The OC in upper layers (0-1.5m) of Indian soil is 21-27 Pg, while in IGR, it is relatively depleted (2 Pg OC) (Lal, 2004a; Sreenivas *et al.,* 2016). These regions, having a small share in total soil C stocks are impoverished compared to other tropical regions, suggesting the need to raise C content to sustain agriculture.

Through adequate management the agricultural soil in the arid and semi-arid tropical regions has potential to sequester 40-150 kg C ha^{-1} to as high as 250 kg C ha^{-1} (Lal, 2011). The annual C sequestration potential of Indian soil is 39-49 Tg (teragram = 10^{12} g) C (Lal, 2004a), which though low in a global context, could provide a significant share in reducing the carbon foot print (CO_2 from the atmosphere). The addition of CR to soil would create a negative atmospheric C flux and also boost soil productivity after humification and thus help in the carbon foot print management. Therefore, exploitation of CR is a unique opportunity in the endeavor to sustainable agricultural production and reducing atmospheric C burden to maintain the equilibrium of the ΔICC.

Validation of the ΔICC Hypothesis

The hypothesis of ΔICC was validated for the IGR to assess the skewness and analyze stability of the soil micro-climate based on the carbon pools present in soil, atmosphere and the plant biomass, and take necessary action to regain its balance. The ideal contents for CR and SOC defined and compared with the existing contents show the altered angles (Fig. 4C-D). The data obtained from the calculations in IGR (Fig. 4C-D) show highly skewed ΔICC for IGR with the angels at 127.04°, 50°, and 2.96° respectively for atmospheric C, CRc, and SOC. The high deviation of SOC and atmospheric C angles show that to regain the balance of the ΔICC of IGR and improve the soil productivity, SOC angle should be increased, and angle of atmospheric C should be decreased.

Conclusion

Addressing the increasing problem of land degradation owing to intensive cropping and decreasing SOC and nutrients is essential for sustainable agriculture. Future demands for the productive soil can be met by conserving the present agricultural soil as well as reclaiming the marginally degraded soils. The resources to maintain the fertility by increasing SOC and nutrients are limited. Here, we have presented the potential of crop residues as a renewable source to supplement SOC and essential nutrients. Approaches to divert the assimilated C in CR from atmospheric-CO_2 to SOC will prevent an irrevocable loss of this labile C reservoir and help to break the stagnancy in production of crops. Therefore, understanding the C and nutrient flow among the three carbon pools depicted in the ΔICC is important to address the regional problems. Research to critically address the problems related to CR sequestration in the soil to raise SOC is required. The limitations in the effective residue amendment in soil due to (i) high C:N/P/K ratio affecting the rate of decomposition (ii) high lingo-cellulosic content (iii) release of toxic (phenolic) products with allelopathic effects and (iv) possible sources of pest and pathogens provide opportunities to venture into translational research to solve the technical limitations which need to be addressed differently in different agro-climatic zones. Integrating the knowledge related to land degradation processes, availability of potential substrates and new technologies to tap their potential will be the key to provide a solution for restoring fertility and depleting OC of agricultural soil.

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