Importance of agriculture and crop residues in carbon sequestration and nutrient enrichment at agricultural farms of East Kolkata Wetland area, a Ramsar site

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In the present study, species-specific carbon sequestration efficiency of eight most extensively cultivated agricultural plants in East Kolkata Wetland (EKW) ecosystem has been measured. They altogether sequester about 6343.7 kg ha^{-1} C, from which 4030 kg ha^{-1} C is exported from the EKW as edible agricultural product and 2313.6 kg ha^{-1} C is retained in the field as residual parts. Also, the crop residue of these eight plants contains 373.62 kg ha^{-1} N, 3.84 kg ha^{-1} Na, 7.95 kg ha^{-1} K, 1.85 kg ha^{-1} Ca, 0.21 kg ha^{-1} Mg and 2.41 kg ha^{-1} Fe, 0.36 kg ha^{-1} Mn and 0.17 kg ha^{-1} Zn, which enrich the soil micronutrient and may decrease the fertilizer cost. The present study is also aimed at the construction of a beneficial and sustainable crop management system, allowing farmers to get carbon credit from the practice.

Keywords: Agricultural plants, carbon credit, carbon sequestration, crop residue, nutrient enrichment.

THE concentration of atmospheric carbon dioxide has risen from ~280 ppm during preindustrial era to ~390 ppm in 2010 (ref. 1). The reasons behind this increase are combustion of fossil fuel, deforestation, biomass burning, soil cultivation and tillage, land cover change and drainage of wetlands or peat soils. Thus, identifying feasible sinks with long residence time for atmospheric CO_2 is a high priority. The carbon is sequestered in terrestrial ecosystems in biomass and soil. A part of the biomass is returned in the soil with varied residence time. In agricultural soil, crop residues are the principal source of C, which usually have a long residence time[2]. Several management and adaption options can reduce the emission of CO_2 in agricultural fields[3]. Minimization of soil erosion, scientific selection of paddy cultivars, integrated nutrient management and integrated pest management could reduce the emissions. Alongside, increased sequestration of C could be achieved through restoration of degraded soils and integrated no-till farming systems. Scientific management of crop residues could maximize the C sequestration in agricultural lands. Any biomass that is left in the field after harvest could be considered as crop residue. The amount of crop residues produced in the world in 2001 is estimated at ~4×10^{15} g year^{-1} (ref. 4). The crop residues present at the soil–atmosphere interface change the entire soil ecology[2,5]. On an average ~0.8% nitrogen, 0.1% phosphorus and 1.3% potassium are present in the crop residues, i.e. a total of 81×10^6 Mg NPK is present in the crop residues[6]. So, use of crop residues in agriculture results in high productivity, and profitability and also provides habitat for microorganisms and other soil-inhabiting detritivores and decomposers. The practice of retaining crop residues as mulch is reported by various workers[5,7–10]. The crop residues contain high amounts of C, i.e. about 40% of the total dry biomass[6]. It is estimated that the amount of C accumulation in the world through crop residues per year is about 1.6 Petagram (ref. 6). Application of nitrogenous fertilizer and other elements enhances the humification, resulting in increase of C sequestration[11]. The adverse impacts of crop residue removal have been investigated by several experiments[12–14]. In most parts of Asia and Africa, the poor farmers remove crop residues for use as fodder, fuel and construction materials[15–17]. As a result, agricultural soils have significantly low levels of soil organic C concentration (<0.5% in contrast to the critical level of 1.1%). Alongside, removal of crop residues from the agricultural fields results in low levels of nutrient concentration of about 30–40 kg ha^{-1} year^{-1} of NPK (ref. 4), one of the major reasons for low productivity and increased soil erosion. Presently, in many cases the crop residues are being extensively used as biofuels to substitute for fossil fuels. However, from the perspective of environmental economics, it would be wiser to use the crop residues in supplementing nutrients in agriculture practices rather than using them as biofuels.

East Kolkata Wetland (EKW) is the example of unique waste recovery natural system in India[18]. Over the last 100 years the East Kolkata Wetland receives wastewater (50,000 m^3 d^{-1}) from industrial establishment (including tanneries) and municipality of Kolkata city and this composite wastewater is productively used for piscicultural and agricultural purpose in EKW area. Around 29.9 tonnes of fish and 150 tonnes of vegetables are produced daily from EKW area[19]. Individually, the average annual yield of boro paddy is highest (5 tonnes ha^{-1}), followed by amon (3 tonnes ha^{-1}). It has been recorded that in the EKW during post-monsoon season, altogether 24 plant species are cultivated as crops and vegetables, and a huge amount of crop residues is produced. The present study records the species-specific carbon sequestration efficiency of the eight most extensively cultivated plant species in the region. C is measured in the residue portions (RP) and the marketed portions (MP) of selected agricultural plant produce. Also, important limiting

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nutrients like N, Na, Ca, Mg, Fe, Mn and Zn are measured in the residual portions of these plants.

The area of interest is located between Dhapa and Kultigong in the EKW ecosystem (12,741 ha; 22′33′–22′40′N; 88′25′–88′35′E), a Ramsar site (no. 1208). The elevation profile of the area ranges between 1 and 5 m with a gradual slope towards southeast. The average temperature is 22–35°C and rainfall is 1000–1600 mm/year.

Among the several agricultural plants in the EKW region, the eight most extensively cultivated species have been selected as a model to demonstrate the C sequestration process. These include *Brassica oleracea* var. *botrytis* L., *Raphanus sativus* L., *Solanum melongena* L., *Amaranthus gangeticus* L., *Basella alba* L., *Spinacia oleracea* L., *Oryza sativa* L. (boro) and *Oryza sativa* L. (amon). For each species 20 samples of almost similar age and mass were chosen. Each plant was uprooted carefully and for collection of fine root parts, the soil beneath the plant was sieved through a 0.5 mm mesh net. For each species, 20 plant samples were taken to determine the average C content in a plant and from the same samples the nutrients content in the crop residues was determined. To estimate the amount of C (kg ha^{-1}) being assimilated in agricultural soil, for each species, 10 quadrats ($10 \times 10\ m^2$) were laid randomly, and three such randomly chosen sections of the EKW agricultural farming area were surveyed and the number of cultivated plants counted. The number of plants of each species varies a little (±1 plant) in the three randomly chosen sections of the agricultural land, because the farmers maintained specific distance for each plant species when they planted the saplings/rowing seeds.

The wet weights of the samples were taken and then they were fully dried in a hot air oven at 60°C. From the dry biomass the proportion of root, stem and leaf of a plant body was determined in each species. The C and nitrogen (N) contents were separately determined for root, stem and leaf of each plant. Then 2 ± 0.10 mg of each of the dried samples was weighed using Perkin Elmer AD6 Auto balance and analysed using a CHN analyser (Perkin Elmer CHNS/O 2400). The total C content of a plant was determined by the following equation:

$$\text{Total C in a plant} = (\text{TDB} \times \%\text{ of root of TDB} \times \text{CR}) + (\text{TDB} \times \%\text{ of stem of TDB} \times \text{CS}) + (\text{TDB} \times \%\text{ of leaf of TDB} \times \text{CL}).$$

where TDB is the total dry biomass of the plant (g), CR the C content in root (g g^{-1}), CS the C content in stem (g g^{-1}) and CL the C content in leaf (g g^{-1}).

The cumulative C values in crop residue (RP) and in the marketed portion of a crop (MP) were also calculated. For each species, the number of plants was counted in the respective quadrats and it was multiplied by the average value of dry biomass (RP and MP) of 20 plant samples. Based on these the C assimilation and exportation of a species in a defined area of EKW were measured.

For the measurement of nutrients, i.e. sodium, potassium, calcium and magnesium, iron, manganese and zinc in crop residues, the samples were prepared following the standard method[20]. The concentration of Na, K, Ca and Mg was measured using the 761 Methrom Ion Exchange chromatograph and Fe, Mn, Zn were measured using an atomic absorption spectrophotometer (Perkin-Elmer AAnalyst-100). The nutrient content of a plant species was determined using the above-mentioned formula from which the C content was determined. The regression equations were generated using STATISTICA 5.0 and all the graphs were made using Origin 6.1.

The mean dry biomass (DB) of 20 plant samples of *B. oleracea* var. *botrytis* was 245.21 ± 25.8 g. The carbon present in root, stem, leaf and flower varied as 0.2414–0.2811, 0.2546–0.285 and 0.3215–0.3674 and 0.2716–0.312 g g^{-1} respectively. In this plant species, the root and stem are the RP, whereas the leaf and flower are the MP. The mean DB of RP was 35.81 ± 3.8 g which contained 9.54 ± 1.2 g C and the mean DB of MP was 209.47 ± 22.0 g, which contained 65.75 ± 8.4 g C per individual plant. The measured mean DB of *R. sativus* was recorded as 74.58 ± 11.9 g. The C present in its root, stem and leaf was 0.2485–02812, 0.3411–0.3646 and 0.4389–0.4387 g g^{-1} respectively. The mean DB of RP per plant was 0.23 ± 0.04 g, which contained 0.06 ± 0.01 g C and the DB of MP was 74.4 ± 11.9 g, which contained 27.23 ± 4.6 g C. In case of *S. melongena*, the DB and C of RP (root, stem, leaf) and MP (fruit) were estimated separately. The average DB of RP was 189.93 ± 36.0 g per plant and the DB of MP was 28.51 ± 3.7 g. The root contained 0.2341–0.2684 g g^{-1} C, while stem contained 0.2622–0.2987 g g^{-1} C, leaf contained 0.3318–0.3537 g g^{-1} C and fruit contained 0.3305–0.3456 g g^{-1} C. On an average in a *S. melongena* plant 55.57 ± 11.9 g C was present in RP and 9.66 ± 1.33g C was present in MP. *A. gangeticus* had a mean DB of 3.89 ± 0.84 g and out of the total DB, RP (root) was 0.12 ± 0.03 g and MP (leaf and stem) was 3.45 ± 0.75 g. *A. gangeticus* root contained 0.2447–0.2859 g g^{-1} C, whereas the stem contained 0.3115–0.3506 g g^{-1} C and leaf 0.383–0.4068 g g^{-1} C. The average C present in *A. gangeticus* was 1.65 ± 0.38 g, of which 0.44 ± 0.09 g was RP and 1.21 ± 0.28 g was MP. The average DB of *B. alba* plant was 45.1 ± 15.3 g. Similar to *A. gangeticus*, the RP of *B. alba* was the root and the MP was stem and leaf. In *B. alba*, 0.2719–0.2962 g g^{-1} C was present in root, 0.3251–0.349 g g^{-1} C in stem and 0.4129–0.4356 g g^{-1} C in leaf. On an average, 15.99 ± 5.6 g C was present in a *B. alba* plant, of which 0.31 ± 0.11 g C was assimilated in the soil and 15.68 ± 5.5 g C was exported to the market. The average DB (2.58 ± 0.5 g) of *S. oleracea* was the lowest among the eight selected plants in this study. Also, in this plant the root was the RP, whereas the stem and

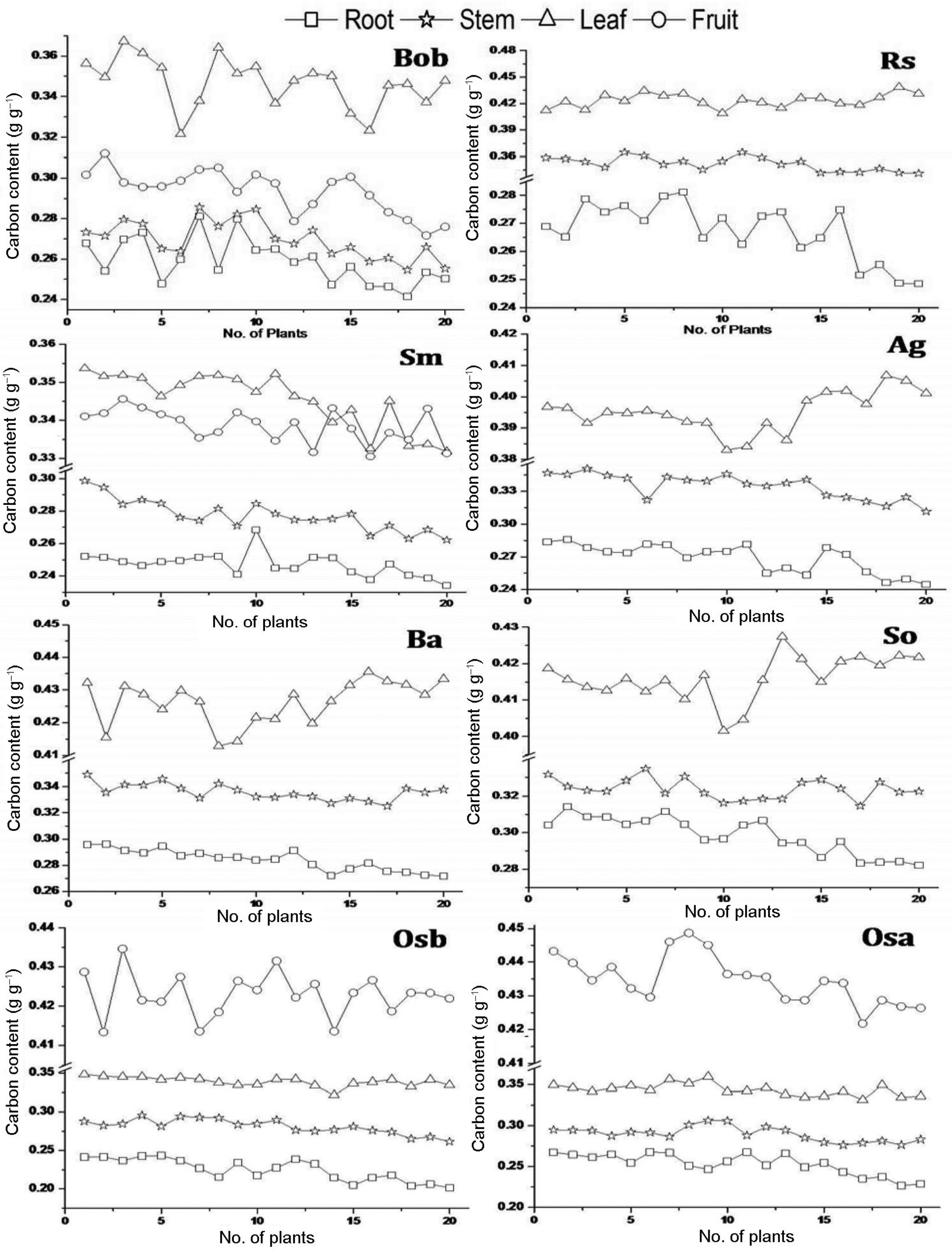

Figure 1. Carbon content in root, stem and leaf dry biomass (g g^{-1}) of 20 samples of each of the eight selected plants in East Kolkata wetland ecosystem.

root were the MP. The root, stem and leaf of *S. oleracea* plant contained 0.2822–0.3142, 0.3146–0.3347 and 0.4016–0.1274 g g^{-1} C respectively. The C (0.06 ± 0.02 g) present in RP of a *S. oleracea* plant was less little, while C present in MP was 0.82 ± 0.16 g. In case of two varieties of *O. sativa* the DB and C in RP (root, stem, leaf) and MP (seeds) were measured separately. The average DB of *O. sativa* (boro) plant was 29.22 ± 0.89 g and seed was 45.32 ± 7.22 g. Likewise, the DB of *O. sativa* (amon) plant was 29 ± 0.66 g and seed was 37.9 ± 5.57 g. The average DB of RP (leaf, stem, root) of both paddy varieties was 29.21 ± 0.89 g (boro) and 29 ± 0.66 g (amon) respectively, while DB of MP was 45.32 ± 7.23 g (boro) and 37.9 ± 5.57 g (amon) respectively. The root, stem, leaf and seed of boro contained 0.2015–0.2434, 0.2615–0.2956, 0.3216–0.3485 and 0.4134–0.4346 g g^{-1} C

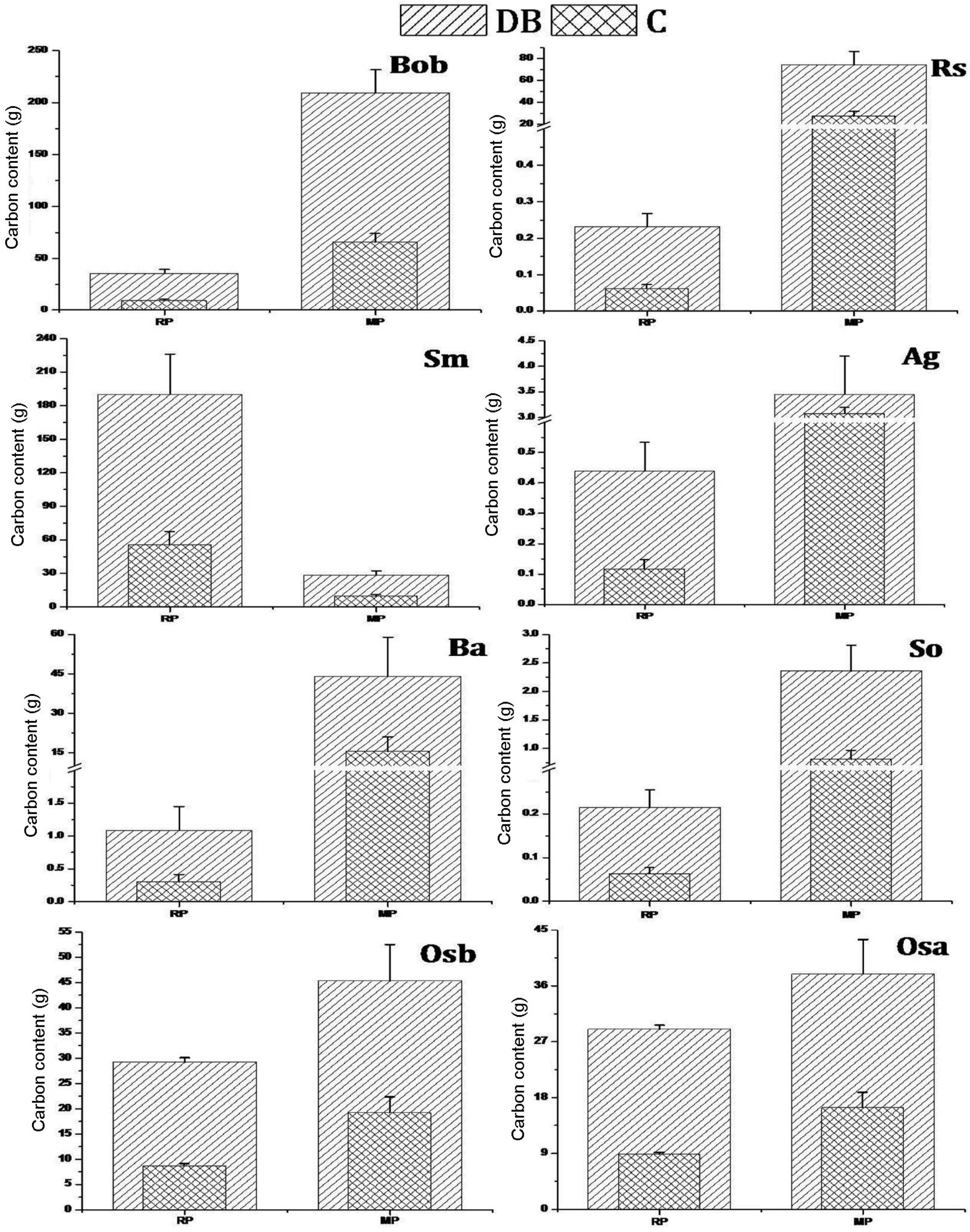

Figure 2. Average carbon (C) content (g plant^{-1}) in the dry biomass (DB) of residual parts (RP) and marketed parts (MP) of the eight selected plant species.

respectively. In case of amon, the root contained 0.2264-0.2678 g g^{-1} C, the stem contained 0.2763–0.3064 g g^{-1} C, the leaf contained 0.3316–0.3596 g g^{-1} C and the seed contained 0.4218–0.4487 g g^{-1} C. A boro plant contained a total of 27.88 ± 3.09 g C, out of which 8.7 ± 0.37 g C is present in RP and 19.18 ± 3.14 g C is present in MP. While in case of amon plant, each plant contained on an average 25.44 ± 2.42 g C, of which 8.95 ± 0.3 g C is present in RP and 16.49 ± 2.49 g C is present in MP (Figures 1 and 2).

From Table 1 it can be estimated that the selected eight plant species altogether contained 6343.7 kg ha^{-1} C, indicating that this amount of C was sequestered by all those eight plant species. Also, from the total C captured by those plants, 4030 kg ha^{-1} C was exported (MP) from the EKW area and 2313.6 kg ha^{-1} C remained in the field as RP. Table 2 represents species-wise relationships between DB (both RP and MP) and C. Figure 3 provides a graphical representation in the average concentration of N, Na, K, Ca, Mg, Fe, Mn and Zn in different residual

Table 1. Total amount of carbon (C) present within the residual parts (RP) and marketed parts (MP) of eight selected plants (*Brassica oleracea* var. *botrytis* (*Bob*), *Raphanus sativus* (*Rs*), *Solanum melongena* (*Sm*), *Amaranthus gangeticus* (*Ag*), *Basella alba* (*Ba*), *Spinacia oleracea* (*So*), *Oryza sativa* (*boro*) (*Osb*) and *Oryza sativa* (*amon*) (*Osa*))

Plant	Amount of dry biomass (DB) of RP (kg ha^{-1})	Amount of C of RP (kg ha^{-1})	Amount of DB of MP (kg ha^{-1})	Amount of C of MP (kg ha^{-1})
Bob	6875.52	1831.68	40218.17	12624
Rs	99.36	25.92	32140.8	11806.56
Sm	20513.5	6001.56	6577.66	2232.82
Ag	337.92	92.16	6531.48	2031.65
Ba	205.2	58.9	1649.98	587.72
So	298.2	85.2	6849.34	2379.85
Osb	17296	5150.4	916.85	388.02
Osa	17070.8	5262.6	441.71	192.18
Average (kg ha^{-1})	7837.06	2313.55	11915.75	4030.35

Table 2. Relationship between DB and C in RP and MP of eight agricultural plants in the East Kolkata Wetland ecosystem

	RP		MP	
Plant	Regression equation	Correlation coefficient (R^2)	Regression equation	Correlation coefficient (R^2)
Bob	$y = 0.307x - 1.460$	0.937	$y = 0.377x - 13.35$	0.980
Rs	$y = 0.303x - 0.008$	0.979	$y = 0.387x - 1.458$	0.993
Sm	$y = 0.328x - 6.834$	0.995	$y = 0.355x - 0.483$	0.993
Ag	$y = 0.316x - 0.020$	0.989	$y = 0.378x - 0.094$	0.996
Ba	$y = 0.306x - 0.021$	0.999	$y = 0.365x - 0.395$	0.998
So	$y = 0.343x - 0.009$	0.993	$y = 0.351x - 0.011$	0.995
Osb	$y = 0.339x - 1.199$	0.659	$y = 0.432x - 0.431$	0.992
Osa	$y = 0.318x - 0.286$	0.487	$y = 0.444x - 0.359$	0.988

Table 3. Total amount (kg ha^{-1}) of essential nutrients present within the crop residue of eight selected plants

Plant	N	Na	K	Ca	Mg	Fe	Mn	Zn
Bob	264.915	4.399	8.779	1.401	0.411	2.744	0.570	0.265
Rs	3.685	0.085	0.169	0.031	0.011	0.036	0.012	0.007
Sm	964.229	11.006	30.990	4.561	0.612	6.342	0.872	0.355
Ag	14.024	0.373	0.615	0.170	0.019	0.275	0.032	0.021
Ba	2.721	0.059	0.091	0.024	0.003	0.039	0.006	0.003
So	3.365	0.131	0.142	0.034	0.006	0.060	0.007	0.007
Osb	870.745	6.992	12.152	4.107	0.281	4.851	0.649	0.344
Osa	865.270	7.708	10.657	4.454	0.314	4.911	0.706	0.368
Average (kg ha^{-1})	373.619	3.844	7.949	1.848	0.207	2.407	0.357	0.171

parts of each plant species. The essential nutrients present in the residual part of eight selected agricultural plants (kg ha^{-1}) were also measured. It was estimated that the crop residues of the eight plants contained 373.62 kg ha^{-1} N, 3.84 kg ha^{-1} Na, 7.95 kg ha^{-1} K, 1.85 kg ha^{-1} Ca, 0.21 kg ha^{-1} Mg, 2.41 kg ha^{-1} Fe, 0.36 kg ha^{-1} Mn and 0.17 kg ha^{-1} Zn (Table 3).

Agricultural production has a direct effect on water, soil and a variety of biological processes. Agriculture also has an effect on the climate and its role in the global C cycle makes it a foremost contributing factor to climate change. From the present situation it is evident that not only is the agricultural process dependent upon the environmental conditions, but the reverse condition also exists. To overcome the problem of generation of greenhouse gases, excess CO_2 from the atmosphere needs to be sequestered into a long-lived stable form. Thus agricultural practices could be a significant option as the immediate sink of C. The C sequestration by agricultural plants is positively correlated with the cropping intensity. The biomass input is greater when the frequency of cropping is increased and results in more C captured in nature. In

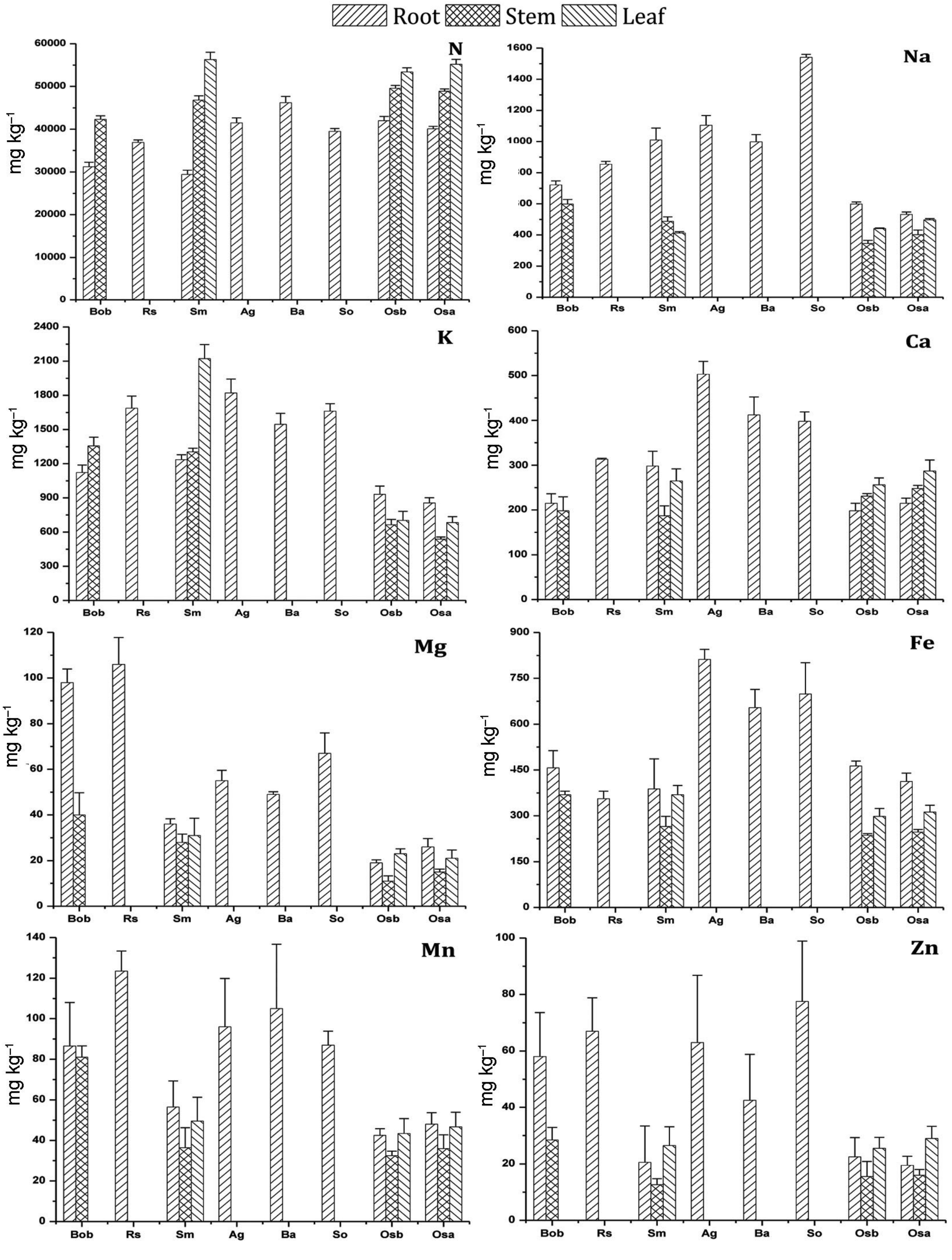

Figure 3. Average nutrients content (mg kg^{-1} plant^{-1}) in different RP of the eight selected plant species.

the EKW area three varieties of *O. sativa* are cultivated throughout the year, whereas other vegetables are rotationally cultivated mostly during rainy and winter seasons. The agricultural practice of the concerned area uses wastewater for irrigation. Composite wastewater carries high amounts of essential nutrients, which influence the plant growth as well as plant biomass. *B. oleracea* var. *botrytis*, *R. sativus*, *S. melongena* and *O. sativa* (both boro and amon) capture plenty of C. For the three leafy vegetables like *A. gangeticus*, *B. alba* and *S. oleracea*, the whole of the plants is not marketed. After full growth of these plants, they are cut down from the base of the stem and these portions are marketed. From the remaining portion, the plants are allowed to grow further. Though with regard to the dry biomass all these three leafy vegetables contain lower amount of C compared to other crops grown in the concerned areas, the net biomass production is very high and consequently C sequestration, due to multiple generation of the leafy parts. In case of *S. melongena*, the residual C is the highest because only the fruits are marketed. However, in case of all three leafy vegetables, viz. *A. gangeticus*, *B. alba* and *S. oleracea*, except the root, all the other parts are marketed from time to time according to their edibility. For the two varieties of *O. sativa*, only seed parts are marketed. Small amounts of the residual parts of *O. sativa* remain in the field, because other portions are mainly used for livestock feed. It is noted that roots are the common residual parts of all plants. The plant roots act as a medium to transfer the atmospheric C into the soil in the form of C-containing compounds, viz. organic acid, phenolic acid, amino acid, etc.[21,22]. The root exudates contribute significant amounts of C that is deposited in the subsurface soil. Due to slow oxidation, these deposits have the potential for long-term C sequestration in the soil[21]. However, the main barrier to the use of crop residues in soil fertility management is the numerous competing uses as fodder and biofuel. Controlled grazing and establishment of select foraging plots for direct grazing could reduce conflict between soil organic matter accumulation and grazing needs.

Among all of the studied crops, the marketable biomass yields of *R. sativus* and *B. oleracea* var. *botrytis* are the highest and thereby contribute maximum export of C from the EKW agricultural fields. Of the total C captured by the selected plant species, 2313.6 kg ha^{-1} C remained in the field with the residual parts of the plants. These residual parts not only enhance the soil C content, but also improve the soil physical, chemical and biological properties[4]. In case of edible parts, i.e. the marketed part of these plants, 4030.1 kg ha^{-1} C is exported from the agriculture field of EKW. However, some amount of these crops is used as a food by the farmers, but most portions of these crops are marketed outside the EKW areas. Thus, it is evident that the EKW agricultural ecosystem is vital, both for providing food for human consumption and for C sequestration. Further, substantial amount of different essential nutrients like N, Na, K, Ca, Mg, Fe, Mn and Zn, that is present in crop residues is lost from the EKW ecosystem. The present study indicates that had the total crop residues been left in the agricultural field itself, the soil would have become more fertile for next crop production.

In addition to storing the soil C in the EKW, sustainable land management technologies and crop residue management can be beneficial to farmers by increasing yields and reducing production costs[23]. The land management technologies should be employed in the EKW to maintain soil organic matter, different nutrient contents and biological activities that increase the soil fertility, which in turn enhance the crop yield. According to the World Bank report[24], the synergies occur when there is a positive correlation between C sequestration and profitability, whereas trade-offs occur when the attempts to increase C storage reduce productivity or the profits of the farmers[25]. Further analysis and improvement of land management in the EKW ecosystem are necessary to maximize synergies and minimize trade-offs[24,25] in order to make the ecosystem services sustainable under changed climatic conditions. The present study suggests to hold the crop residues in the field for better productivity rather than exporting them to other uses. More holistic studies on species-specific estimations of carbon sequestration potentiality and nutrient values of crop residues are needed. Results of such studies would be important to adopt proper crop management system in the concerned area to gain sustainable ecological as well as economical benefits. The present study reveals that the agricultural plants of the EKW area sequester a significant amount of C. However, as the C credit market in India is yet to be popularized and introduced from the base level, farmers of the EKW area are not aware and are yet to benefit from the ecological service they provide unknowingly. Therefore, the present study has social relevance. The farmers need to be made aware of the C credit market and the ecological and monetary gains that they could foresee from their agricultural practices. In the near future, if the famers could monetarily gain from the C credit, it would be a major step forward towards the sustainable development of the EKW area. Century-long agricultural and piscicultural practices have externalized the ecological values of the wetland ecosystem in terms of economic uplift of the rural artisans. This can be regarded as a potential option for Kolkata city to become an exemplary participant in mitigating the global climate change.

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Incidence of alien Asteraceae in Telangana and residual Andhra Pradesh and possible ecological implications

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The introduction of alien Asteraceae into the states of Telangana and residual Andhra Pradesh is described based on extensive field studies, together with screening available herbarium specimens, floras and taxonomic reports. The centres of origin, growth and life-form nature, habit, habitats they occupy, year of first report, minimum residence time, and district-wise occurrence are compiled. Possible ecological implications of the incidence of these alien species are discussed.

Keywords: Alien Asteraceae, invasives, introductions, natural ecosystem.

INVASIONS by exotic plant species are occurring at unprecedented rates due to human activities that have increased the number of introductions and the rate of spread of many species[1]. Elton[2], 'the father of invasion ecology', introduced the words 'invaders' and 'invasion'. A biological invader is a plant, animal or microbe species which, most usually transported inadvertently or intentionally by humans, colonizes and spreads into new territories some distance from its native range[3]. Plant invasions have been recognized as one of the most serious environmental problems which impact the structure, composition and function of natural and semi-natural ecosystems[4,5]. Plant invasions are found to reduce native species diversity and induce alterations in ecosystem functioning[6]. Increase in the number and spread of alien invasive plants into productive ecosystems causes significant economic losses[7]. Also, biological invasion has been homogenizing the world's flora and fauna[8]. For these reasons, the study of plant invasions not only provides fascinating tests of ecological and evolutionary theory, but also lends a hand in resolving major challenges to natural resource management. The importance of invasive species is underlined by Article 8(h) of the Convention on Biological Diversity[9], which asks for measures 'to prevent the introduction, control or even root out of those alien species which threaten ecosystems, habitats or species'.

The Asteraceae (Compositae) form one of the largest of flowering plant families in the world, with an estimated 22,750 species in 1528 genera[10]. This family is of economic, ecological and environmental importance since

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