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METHOD

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A simple model for estimation of above and below ground carbon in cereal crops

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Abstract

Carbon (C) is an essential part of healthy soil. Healthy soils play an important role in improving the life of all living organisms on earth (plants, humans, animals, birds, insects, microbes etc.). Best agronomic practices for field crop production sequester more carbon (due to higher photosynthesis) below and above the ground that makes the soils healthy and sustainable. Healthy soils increase yield per unit area and so reduce the problem of food insecurity. Higher photosynthetic efficiency (higher CO_2 uptake by the plants) reduces the problem of global warming and climate change. According to an estimate, plants capture about 860 gigatons of CO_2 each year from the atmosphere, storing it in their shoots, and roots (1 kg of carbon is equal to 3.67 kg of CO_2). The aim of this study was to develop a simple calculation (model) for researchers to easily estimate the carbon content (CC) capture by plants in below (roots) and above ground (shoots) parts. Considerable variation in total CC (TCC) accumulation and its partitioning into above ground parts (ACC) and below ground parts (BCC) exists which depends on crop species and genotypes, crop nutrition, crop competitions and intercropping, fertilizers application, irrigation, tillage, biotic and abiotic stresses, soil types and environment etc. The CC estimation is explained in detail with four examples on major cereal crops (wheat, rice, maize and barley) for the world leading countries in 2018–2019. In the first example using wheat, the TCC estimated for wheat crop in Pakistan was 37.4 metric tons (MT) of which 30.5 MT was allocated into ACC (shoots) and 6.9 MT into BCC (roots). The highest value of TCC accumulation for wheat crop was estimated for the European Union which was 216.3 MT (176.4 ACC + 39.9 BCC). In the second example using rice crop, TCC for the world leading countries was estimated and the leading country was China with TCC of 161.7 MT (131.9 ACC + 29.8 BCC). Example three is about the CC estimation for maize crop, and the leading country was USA having the highest TCC value of 505.3 MT (ACC = 412.1 MT, BCC = 93.2 MT). The Russian Federation ranked first for barley crop and the highest TCC value of 29.2 MT was recorded (23.8 MT ACC + 5.4 MT BCC). It was confirmed while using this model that out of the 100% (TCC) fixed, about 82% CC is partitioned into above ground parts (ACC) and the remaining 18% CC is allocated into below ground parts (BCC). Due to this model, we can easily calculate the TCC accumulation and its partitioning into ACC and BCC per unit area ($kg \cdot ha^{-1}$). For example, the TCC was easily calculated for the 40 world leading countries for wheat, rice, maize and barley during 2019. The results revealed that the TCC ranged from 4,414 to 13,243 $kg \cdot ha^{-1}$ for wheat, 4,578 to 11,444 $kg \cdot ha^{-1}$ for rice**,** 5,150 to 15,450 $kg \cdot ha^{-1}$ for maize, and 3,443 to 13,733 $kg \cdot ha^{-1}$ for barley among the top 40 countries. This is the most simplified approach for estimating carbon content in the below-ground (roots) and above-ground (shoots) parts of field crops.

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Introduction

Crop growth and yield depends on the fixed carbon content (CC) and their distribution to plant parts (e.g. roots and shoots). Understanding and calculating the total CC (TCC) accumulated in field crops is very important due to the current issues of food security and global warming. However, there is a lack of research that shows how much CC is partitioned into the roots and shoots. Our previous research work confirmed that the increase in CC in plant tissues (roots and shoots) depends on total dry matter accumulation and partitioning[1−4], because plant growth and yield correlates with net carbon gain on a whole plant basis[5,6].

The IPCC report[7] revealed that about 1.2 billion tonnes of carbon at annual rate of 4‰ could be stocked every year for the sustainability of agricultural systems. As the crop growth and yield depends on the total CC (TCC) of plants, therefore, any agronomic practices that help the plants to sequester more atmospheric CO_2 (photosynthesis) increases the TCC accumulation in plants in its distribution to below ground CC to roots (BCC) and above ground CC to shoots (ACC). Therefore, crop production may be defined as: maximizing photosynthetic efficiency of crops to store more carbon above (ACC) and below (BCC) ground parts. The increase in CC above ground part (ACC) depends on: number and size of leaves, number of tillers, reproductive tillers, stems, seed size and number, grain yield and harvest index etc., increase partitioning of CC for better roots development depends on: roots number and length, root proliferation and total root biomass. The increase in CC of roots (BCC) will help the plants to uptake more water and nutrients from the soil and transfers it for better shoot development (ACC) e.g. increase in grain yield, yield components and harvest index.

The TCC accumulation and its partitioning in plant bodies depends on three major factors: (1) plant genotypes e.g. plant species, varieties, hybrids, exhaustive (grasses) and restorative (legumes) crops, growth habit, growth stages, photosynthesis, C_4 crops (e.g. maize, sorghum, millets, etc.) and C_3 crops (e.g.

wheat, rice, and barley etc.); (2) agronomic practices (chemical fertilizers, organic fertilizers, biofertilizers, plant nutrition, irrigation, tillage practices, soil types, SOC, plant density, seed rates, sowing time, etc.); and (3) environmental condition viz. biotic stresses (plant competition, weeds, diseases, insects, pests, etc.) and abiotic stresses (low and high temperature stress, low and high water stress, light quality and duration, wind, chemicals, gases, soil pollution, water pollution, etc.).

In recent years, many international organizations[8−18] and researchers[19−43] reported about the importance of carbon footprints in plants, animals, soil, water, environment, ecosystems etc. There is still a lack of comprehensive research and reports on the precise amount of carbon sequestered or stored by individual plants. Because carbon estimation in field crops, especially in roots, is very difficult, costly and time consuming.

The primary objective of this paper is to create a simplified model for estimating the allocation of above-ground carbon content (ACC) and below-ground carbon content (BCC) in field crops, specifically cereals. The purpose of developing a simplified model is to facilitate the estimation of carbon content partitioning in field crops, such as winter crops (e.g., wheat and barley) and summer crops (e.g., maize and rice), specifically targeting students and researchers. This model aims to simplify the process and make it more accessible for those interested in studying carbon content allocation in field crops.

Methodology

Estimating the total carbon content (TCC) accumulation and its distribution above ground (shoots) and below ground (roots) parts in cereals

For the estimation of the total carbon content (TCC) accumulated by plants and its distribution (partitioning) into above ground (shoots) and below ground (roots) parts, efforts were made to calculate the two important factors for above ground parts (ACC) and below ground parts (BCC), 0.42 (% CC in shoot biomass) and 0.38 (% CC in root biomass), respectively. Then three simple equations (1, 2 and 3) were developed to easily estimate the CC in above ground biomass (AGB), below ground biomass (BGB) and total biomass (TBM):

$$ACC = AGB \times 0.42 \quad (1)$$

$$BCC = BGB \times 0.38 \quad (2)$$

$$TCC = ACC + BCC \quad (3)$$

The total CC (TCC) per plant or per unit area can be easily calculated in field crops by just adding ACC with BCC as shown in Eqn (3).

Based on the model developed in this study: Out of the 100% total carbon content (TCC) fixed/accumulated by field crops, 82% is partitioned into shoots or above ground carbon content (ACC) and 18% into roots or below ground carbon content (BCC). On the other hand, out of the 100% total biomass (shoots biomass + roots biomass on dry basis) (TBM) accumulation by field crops, 80% is partitioned into above ground biomass (AGB) and 20% into below ground biomass (BGB).

Note: Multiplying the amount of CO_2 by 12/44 or 0.27 is equal to the amount of carbon, means that 1 kg of CO_2 is equal to 0.27 kg of carbon. On other hand, multiplying the amount of carbon by 44/12 or 3.67 (44/12) is equal to the amount of CO_2, means that 1 kg of carbon is equal to 3.67 kg of CO_2 (where 12 is the molecular weight of carbon, and 44 is the molecular weight of CO_2 ($C + O_2 = 12 + 16 \times 2 = 44$).

Results

Examples for validation of the model

Example 1 (wheat)

In 2018, wheat produced in metric tonnes (MT) and the total carbon content (TCC) accumulated and partitioned into roots or below ground CC (BCC) and shoots, or above ground CC (ACC) for the world leading countries was calculated through this model (Table 1). For example, in 2018, the total wheat produced in Pakistan was 25.4 MT[2,44].

The above ground biomass (AGB) or shoot dry weight (shoot biomass) was calculated using Eqn 4:

Table 1. Approximate estimation of carbon content (CC) fixed by wheat crop in metric tons (MT) for the leading countries in the world during 2018–2019.

Countries	Metric tons (MT)						
	GY	AGB	ACC	BGB	BCC	TBM	TCC
European Union	147.0	420.0	176.4	105.0	39.9	525.0	216.3
China (mainland)	126.7	362.0	152.0	90.5	34.4	452.5	186.4
India	98.6	281.7	118.3	70.4	26.8	352.1	145.1
Russian Federation	72.0	205.7	86.4	51.4	19.5	257.1	105.9
United States of America	49.7	142.0	59.6	35.5	13.5	177.5	73.1
Canada	31.3	89.4	37.6	22.4	8.5	111.8	46.1
Pakistan	25.4	72.6	30.5	18.1	6.9	90.7	37.4
Ukraine	23.4	66.9	28.1	16.7	6.4	83.6	34.4
Australia	21.9	62.6	26.3	15.6	5.9	78.2	32.2
Turkey	21.0	60.0	25.2	15.0	5.7	75.0	30.9
Argentina	20.0	57.1	24.0	14.3	5.4	71.4	29.4
Kazakhstan	14.0	40.0	16.8	10.0	3.8	50.0	20.6
Iran Islamic Rep.	13.4	38.3	16.1	9.6	3.6	47.9	19.7
Other countries	71.7	204.9	86.0	51.2	19.5	256.1	105.5
World	736.1	2103.1	883.3	525.8	199.8	2628.9	1083.1

Source: FAO outlook[11] and Amanullah et al.[64]. Where: CC = Carbon content, MT = Metric tons, GY = Grain yield, AGB = Above ground biomass, ACC = Above ground CC, BGB = Below ground biomass, BCC = Below ground CC, TBM = Total biomass (AGB + BGB), TCC = Total CC (ACC + BCC).

$$\begin{aligned} \boldsymbol{AGB} &= \boldsymbol{Grain\ Production} \div \mathbf{0.35}(\boldsymbol{Factor}) \\ &= 25.4 \div 0.35 \\ &= 72.6\ (MT) \end{aligned} \tag{4}$$

The carbon content of the AGB or shoot CC (ACC) was calculated using the following equation:

$$\begin{aligned} \boldsymbol{ACC} &= \boldsymbol{AGB} \times \boldsymbol{factor}\ (\mathbf{0.42}) \\ &= 72.6 \times 0.42 \\ &= 30.5 MT\ (\mathbf{82\%}) \end{aligned} \tag{1}$$

The total biomass (TBM) (shoots + roots) was calculated using Eqn 5:

$$\begin{aligned} \boldsymbol{TBM} &= \boldsymbol{AGB} \times \mathbf{1.25}\ (\boldsymbol{Factor}) \\ &= \mathbf{72.6 \times 1.25} \\ &= \mathbf{90.7} \boldsymbol{MT} \end{aligned} \tag{6}$$

The below ground biomass (BGB) or root biomass was calculated using Eqn 6:

$$\begin{aligned} \boldsymbol{BGB} &= \boldsymbol{TBM} \times \mathbf{0.20}\ (\boldsymbol{Factor}) \\ &= 90.7 \times 0.20 \\ &= 18.1 MT \end{aligned} \tag{7}$$

The CC of the BGB or root biomass (BCC) was calculated using Eqn 2:

$$\begin{aligned} \boldsymbol{BCC} &= \boldsymbol{BGB} \times \boldsymbol{factor}\ (\mathbf{0.38}) \\ &= 18.1 \times 0.38 \\ &= 6.9 MT\ (\mathbf{18\%}) \end{aligned} \tag{2}$$

The total CC (TCC) fixed by wheat in Pakistan during 2018 was calculated using Eqn 3:

$$\begin{aligned} \boldsymbol{TCC} &= \boldsymbol{ACC} + \boldsymbol{BCC} \\ &= \mathbf{30.5\ (82\%) + 6.9\ (18\%)} \\ &= \mathbf{37.4} \boldsymbol{MT}\ (\mathbf{100\%}) \end{aligned} \tag{3}$$

Example 2 (rice)

In 2018, rice produced in metric tonnes (MT) and the total carbon content (CC) fixed in rice below (BCC) and above (ACC) ground parts for the world leading countries was calculated (Table 2). For example, in 2018 the total rice produced in China was 141.3 MT[2,44].

The above ground biomass (AGB) or shoots dry weight (shoot biomass) was calculated using Eqn 4:

$$\begin{aligned} \boldsymbol{AGB} &= \boldsymbol{Grain\ Production} \div \mathbf{0.45}\ (\mathbf{Factor}) \\ &= 141.3 \div 0.45 \\ &= 314.0\ (MT) \end{aligned} \tag{4}$$

The carbon content of the AGB or shoots (ACC) was calculated using the following Eqn 1:

$$\begin{aligned} \boldsymbol{ACC} &= \boldsymbol{AGB} \times \boldsymbol{factor}\ (\mathbf{0.42}) \\ &= 314.0 \times 0.42 \\ &= 131.9 MT\ (82\%) \end{aligned} \tag{1}$$

The total biomass (TBM) (shoots + roots) was calculated using Eqn 5:

$$\begin{aligned} \boldsymbol{TBM} &= \boldsymbol{AGB} \times \mathbf{1.25} \\ &= \mathbf{314 \times 1.25} \\ &= \mathbf{392.5} \boldsymbol{MT} \end{aligned} \tag{5}$$

The below ground biomass (BGB) or root biomass was calculated using Eqn 6:

$$\begin{aligned} \boldsymbol{BGB} &= \boldsymbol{TBM} \times \mathbf{0.20}\ (\boldsymbol{Factor}) \\ &= 392.5 \times 0.20 \\ &= 78.5\ MT \end{aligned} \tag{6}$$

The CC of the BGB or root biomass (BCC) was calculated using Eqn 2:

$$\begin{aligned} \boldsymbol{BCC} &= \boldsymbol{BGB} \times \boldsymbol{factor}\ (\mathbf{0.38}) \\ &= 78.5 \times 0.38 \\ &= 29.8\ MT\ (\mathbf{18\%}) \end{aligned} \tag{2}$$

The total CC (TCC) fixed by rice crop in china during 2018 was calculated using Eqn 3:

$$\begin{aligned} \boldsymbol{TCC} &= \boldsymbol{ACC} + \boldsymbol{BCC} \\ &= \mathbf{131.9\ (82\%) + 29.8\ (18\%)} \\ &= \mathbf{161.7}\ \boldsymbol{MT}\ (\mathbf{100\%}) \end{aligned} \tag{3}$$

Example 3 (maize)

In 2018, maize produced in metric tonnes (MT) and the TCC, BCC and ACC for maize in world leading countries was calculated (Table 3). For example, in 2018 the total maize produced in USA was 392.5 MT[2,44].

The above ground biomass (AGB) or shoot biomass was calculated using Eqn 4:

$$\begin{aligned} \boldsymbol{AGB} &= \boldsymbol{Grain\ Production} \div \mathbf{0.40}\ (\boldsymbol{Factor}) \\ &= 392.5 \div 0.40 \\ &= 981.1\ (MT) \end{aligned} \tag{4}$$

Table 2. Approximate estimation of carbon content (CC) fixed by rice crop in metric tons (MT) for the leading countries in the world during 2018.

Countries	Metric tons (MT)						
	GY	AGB	ACC	BGB	BCC	TBM	TCC
China (mainland)	141.3	314.0	131.9	78.5	29.8	392.5	161.7
India	113.5	252.2	105.9	63.1	24.0	315.3	129.9
Indonesia	46.7	103.8	43.6	25.9	9.9	129.7	53.4
Bangladesh	35.3	78.4	32.9	19.6	7.5	98.1	40.4
Viet Nam	28.7	63.8	26.8	15.9	6.1	79.7	32.8
Thailand	22.8	50.7	21.3	12.7	4.8	63.3	26.1
Myanmar	18.2	40.4	17.0	10.1	3.8	50.6	20.8
Philippines	12.9	28.7	12.0	7.2	2.7	35.8	14.8
Brazil	8	17.8	7.5	4.4	1.7	22.2	9.2
Japan	7.5	16.7	7.0	4.2	1.6	20.8	8.6
Pakistan	7.6	16.9	7.1	4.2	1.6	21.1	8.7
United States of America	6.5	14.4	6.1	3.6	1.4	18.1	7.4
Cambodia	6.4	14.2	6.0	3.6	1.4	17.8	7.3
Egypt	4.2	9.3	3.9	2.3	0.9	11.7	4.8
Nigeria	4.3	9.6	4.0	2.4	0.9	11.9	4.9
World	511.4	1136.4	477.3	284.1	108.0	1420.6	585.3

Source: FAO outlook [11] and Amanullah et al.[64]. Where: CC = Carbon content, MT = Metric tons, GY = Grain yield, AGB = Above ground biomass, ACC = Above ground CC, BGB = Below ground biomass, BCC = Below ground CC, TBM = Total biomass (AGB + BGB), TCC = Total CC (ACC + BCC).

Table 3. Approximate estimation of carbon content (CC) fixed by maize crop in metric tons (MT) for the leading countries in the world during 2018.

Countries	Metric tons (MT)						
	GY	AGB	ACC	BGB	BCC	TBM	TCC
United States of America	392.5	981.1	412.1	245.3	93.2	1226.4	505.3
China (mainland)	257.2	642.9	270.0	160.7	61.1	803.7	331.1
Brazil	82.3	205.7	86.4	51.4	19.5	257.2	105.9
Argentina	43.5	108.7	45.6	27.2	10.3	135.8	56.0
Ukraine	35.8	89.5	37.6	22.4	8.5	111.9	46.1
Indonesia	30.3	75.6	31.8	18.9	7.2	94.5	39.0
India	27.8	69.6	29.2	17.4	6.6	86.9	35.8
Mexico	27.2	67.9	28.5	17.0	6.5	84.9	35.0
Romania	18.7	46.7	19.6	11.7	4.4	58.3	24.0
Canada	13.9	34.7	14.6	8.7	3.3	43.4	17.9
France	12.7	31.7	13.3	7.9	3.0	39.6	16.3
South Africa	12.5	31.3	13.1	7.8	3.0	39.1	16.1
Russian Federation	11.4	28.5	12.0	7.1	2.7	35.7	14.7
Nigeria	10.2	25.4	10.7	6.3	2.4	31.7	13.1
Hungary	8.0	19.9	8.4	5.0	1.9	24.9	10.3
Philippines	7.8	19.4	8.2	4.9	1.8	24.3	10.0
Ethiopia	7.4	18.4	7.7	4.6	1.7	23.0	9.5
Egypt	7.3	18.3	7.7	4.6	1.7	22.8	9.4
Serbia	7.0	17.4	7.3	4.4	1.7	21.8	9.0
Pakistan	6.3	15.8	6.6	3.9	1.5	19.7	8.1
World	–	–	–	–	–		–

Source: FAO outlook [11] (Accessed on 5-5-2020). Where: CC = Carbon content, MT = Metric tons, GY = Grain yield, AGB = Above ground biomass, ACC = Above ground CC, BGB = Below ground biomass, BCC = Below ground CC, TBM = Total biomass (AGB + BGB), TCC = Total CC (ACC + BCC).

The carbon content of the AGB or shoot CC (ACC) was calculated using the following Eqn 1:

$$\begin{aligned} \boldsymbol{ACC} &= \boldsymbol{AGB \times factor}\ (\mathbf{0.42}) \\ &= 981.1 \times 0.42 \\ &= 412.1\ MT\ (\mathbf{82\%}) \end{aligned} \quad (1)$$

The total biomass (TBM) (shoots + roots dry weights) was calculated using Eqn 5:

$$\begin{aligned} \boldsymbol{TBM} &= \boldsymbol{AGB \times 1.25} \\ &= \mathbf{981.1 \times 1.25} \\ &= \mathbf{1226.4}\ \boldsymbol{MT} \end{aligned} \quad (5)$$

The below ground biomass (BGB) or root dry weight (root biomass) was calculated using equation-6:

$$\begin{aligned} \boldsymbol{BGB} &= \boldsymbol{TBM \times 0.20}\ (\boldsymbol{Factor}) \\ &= 1226.4 \times 0.20 \\ &= 245.3\ MT \end{aligned} \quad (6)$$

The CC of the BGB or root biomass (BCC) was calculated using Eqn 2:

$$\begin{aligned} \boldsymbol{BCC} &= \boldsymbol{BGB \times factor}\ (\mathbf{0.38}) \\ &= 245.3 \times 0.38 \\ &= 93.2\ MT\ (\mathbf{18\%}) \end{aligned} \quad (2)$$

The total CC (TCC) accumulated by maize crop in the United States of America (USA) during 2018 was calculated using Eqn 3:

$$\begin{aligned} \boldsymbol{TCC} &= \boldsymbol{ACC + BCC} \\ &= \mathbf{412.1}\ (\mathbf{82\%}) + \mathbf{93.2}\ (\mathbf{18\%}) \\ &= \mathbf{505.3}\ \boldsymbol{MT}\ (\mathbf{100\%}) \end{aligned} \quad (3)$$

Example 4 (barley)

In 2018, barley produced in MT and the TCC fixed in the barley growing area in the world leading countries was estimated (Table 4). For example, in 2018 the total barley produced in the Russian Federation was 17.0 MT[2,44].

The above ground biomass (AGB) or shoot biomass was calculated using Eqn 4:

$$\begin{aligned} \boldsymbol{AGB} &= \boldsymbol{Grain\ Production \div 0.30}\ (\boldsymbol{Factor}) \\ &= 17.0 \div 0.30 \\ &= 56.6\ (MT) \end{aligned} \quad (4)$$

The carbon content of the AGB or shoot CC (ACC) was calculated using the following Eqn 1:

$$\begin{aligned} \boldsymbol{ACC} &= \boldsymbol{AGB \times factor}\ (\mathbf{0.42}) \\ &= 56.6 \times 0.42 \\ &= 23.8\ MT\ (\mathbf{82\%}) \end{aligned} \quad (1)$$

The total biomass (TBM) (shoots + roots dry weights) was calculated using Eqn 5:

$$\begin{aligned} \boldsymbol{TBM} &= \boldsymbol{AGB \times 1.25} \\ &= \mathbf{56.6 \times 1.25} \\ &= \mathbf{70.8}\ \boldsymbol{MT} \end{aligned} \quad (5)$$

The below ground biomass (BGB) or root dry weight (root biomass) was calculated using Eqn 6:

$$\begin{aligned} \boldsymbol{BGB} &= \boldsymbol{TBM \times 0.20}\ (\boldsymbol{Factor}) \\ &= 70.8 \times 0.20 \\ &= 14.2\ MT \end{aligned} \quad (6)$$

The CC of the BGB or root biomass (BCC) was calculated using Eqn 2:

$$\begin{aligned} \boldsymbol{BCC} &= \boldsymbol{BGB \times factor}\ (\mathbf{0.38}) \\ &= 14.2 \times 0.38 \\ &= 5.4\ MT\ (\mathbf{18\%}) \end{aligned} \quad (2)$$

The total CC (TCC) fixed by wheat in Pakistan during 2018 was calculated using Eqn 3:

$$\begin{aligned} \boldsymbol{TCC} &= \boldsymbol{ACC + BCC} \\ &= \mathbf{23.8}\ (\mathbf{82\%}) + \mathbf{5.4}\ (\mathbf{18\%}) \\ &= \mathbf{29.2}\ \boldsymbol{MT}\ (\mathbf{100\%}) \end{aligned} \quad (3)$$

The TCC (shoots + roots), ACC (shoots) and BCC (roots) for cereal crops can be easily calculated:

Parameter	Equal to	Parameter	Symbol	Factor	Equation
ACC	=	AGB	×	0.42	1
BCC	=	BGB	×	0.38	2
TCC	=	ACC	+	BCC	3
AGB	=	GY	÷	0.35*	4
TBM	=	AGB	×	1.25	5
BGB	=	TBM	×	0.20	6
TBM	=	AGB	+	BGB	7

Where: W, R, M and B stands for wheat, rice, maize and barley, respectively. Factor: * 0.35 for wheat, 0.45 for rice, 0.40 for maize, and 0.30 for barley. GY = Grain yield; AGB = Above ground biomass; ACC = Above ground CC; BGB = Below ground biomass; BCC = Below ground CC; TBM = Total biomass (AGB + BGB); TCC = Total CC (ACC + BCC).

Discussion

This model was used to calculate the TCC (kg·ha^{-1}) accumulated by the four major cereal crops (wheat, rice, maize and barley) and its distribution into ACC (kg·ha^{-1}) and BCC (kg·ha^{-1}) for the 40 leading countries during 2019 (USDA). The grain yield data (t ha^{-1}) was accessed on the USDA website on 8th May 2020 and converted into kg·ha^{1} (t·ha^{-1} × 1,000 = kg·ha^{-1}). The results revealed that remarkable variations were observed in TCC, ACC and BCC among the 40 countries for each crop. For example, the TCC for wheat crop ranged from 4,414 for Pakistan to 13,243 kg·ha^{-1} for New Zealand (Table 5). For the rice crop, the TCC ranged from 4578 (Philippines) to 11,444 kg·ha^{-1} (Australia) as shown in Table 6. The lowest TCC (5,150 kg·ha^{-1}) in the case of maize crop was calculated for Korea Democratic and the highest (15,450 kg·ha^{-1}) for Chile (Table 7). In the case of barley, the TCC ranged from 3,443 (Algeria) to 13,733 kg·ha^{-1} (Chile), respectively (Table 8). These results revealed that out of the TCC (100%) accumulated by the crops (wheat, rice, maize and barley), 82% was partitioned into ACC (shoots) and 18% to BCC (roots). The higher TCC partitioning into shoots (ACC) than roots (BCC) in different crop species was the possible cause of higher shoot dry matter (shoot biomass) than total root dry matter (roots biomass) production[45−47]. The differences in the ACC and BCC among the four crop species was attributed to the genetic differences among the crops species[4,46,47]. Variation in C content among plant organs are also reported in previous research[48,49].

The TCC accumulation in crop plants and its partitioning into above ground parts (ACC) and below ground parts (BCC) depends on these three major factors: (1) plant genotypes (species, varieties, hybrids, growth habit, growth stages); (2) agronomic practices (chemical fertilizers, organic fertilizers, biofertilizers, plant nutrition, irrigation, tillage practices, soil types, SOC, plant density, seed rates, sowing time, etc.); and (3) environmental condition viz. biotic stresses (plant competition, weeds, diseases, insects, pests, etc.) and abiotic stresses (low and high temperature stress, low and high water stress, light quality and duration, wind, chemicals, gases, soil pollution, water pollution etc.). Total dry matter accumulation and its partitioning into roots and shoots depends on plant nutrition[46,49], light availability[50], soil types[45], plant competitions[51], organic sources[52], beneficial microbes[52,53], plant species[4,45,54], plants genotypes[2,55], plant tissues[48,56−58], and plant growth stages[46,59,60], etc.

The differences in the TCC accumulation and its partitioning into ACC and BCC in different crop species under study may be attributed to the differences in genetic makeup and differences in plant heights, leaf area, leaf area index and crop growth rate, water and nutrients use efficiency[45,46,61]. Bagrintseva & Nosov[62] and Mut et al.[63] reported changes in the total biomass accumulation in different crops. Therefore, crops which could sequester more carbon above (shoots) and below ground (roots) indicating more carbon dioxide sequestration

Table 4. Approximate estimation of carbon content (CC) fixed by barley crop in metric tons (MT) for the leading countries in the world during 2018–2019.

Countries	Metric tons (MT)						
	GY	AGB	ACC	BGB	BCC	TBM	TCC
Russian Federation	17.0	56.6	23.8	14.2	5.4	70.8	29.2
France	11.2	37.3	15.7	9.3	3.5	46.6	19.2
Germany	9.6	31.9	13.4	8.0	3.0	39.9	16.5
Australia	9.3	30.8	13.0	7.7	2.9	38.6	15.9
Spain	9.1	30.4	12.8	7.6	2.9	38.0	15.7
Canada	8.4	27.9	11.7	7.0	2.7	34.9	14.4
Ukraine	7.3	24.5	10.3	6.1	2.3	30.6	12.6
Turkey	7.0	23.3	9.8	5.8	2.2	29.2	12.0
United Kingdom	6.5	21.7	9.1	5.4	2.1	27.1	11.2
Argentina	5.1	16.9	7.1	4.2	1.6	21.1	8.7
Kazakhstan	4.0	13.2	5.6	3.3	1.3	16.5	6.8
Denmark	3.5	11.6	4.9	2.9	1.1	14.5	6.0
United States of America	3.3	11.1	4.7	2.8	1.1	13.9	5.7
Poland	3.0	10.2	4.3	2.5	1.0	12.7	5.2
Morocco	2.9	9.5	4.0	2.4	0.9	11.9	4.9
Iran	2.8	9.3	3.9	2.3	0.9	11.7	4.8
Ethiopia	2.1	7.0	2.9	1.8	0.7	8.8	3.6
Algeria	2.0	6.5	2.7	1.6	0.6	8.2	3.4
Romania	1.9	6.2	2.6	1.6	0.6	7.8	3.2
India	1.8	5.9	2.5	1.5	0.6	7.4	3.1
World	–	–	–	–	–	–	–

Source: FAO outlook[11] (Accessed on 5-5-2020). Where: CC = Carbon content, MT = Metric tons, GY = Grain yield, AGB = Above ground biomass, ACC = Above ground CC, BGB = Below ground biomass, BCC = Below ground CC, TBM = Total biomass (AGB + BGB), TCC = Total CC (ACC + BCC).

Table 5. Carbon content (kg·ha^{-1}) calculation for wheat crop in 40 leading countries in the world during 2019–2020.

Countries	Kilograms per hectare (kg·ha^{-1})			
	GY	ACC	BCC	TCC
New Zealand	9000	10800	2443	13243
Namibia	6000	7200	1629	8829
Saudi Arabia	6000	7200	1629	8829
Switzerland	6000	7200	1629	8829
Chile	6000	7200	1629	8829
China	6000	7200	1629	8829
EU-27	6000	7200	1629	8829
Egypt	6000	7200	1629	8829
Zambia	6000	7200	1629	8829
Uzbekistan	5000	6000	1357	7357
Japan	5000	6000	1357	7357
Mexico	5000	6000	1357	7357
Norway	5000	6000	1357	7357
Macedonia	4000	4800	1086	5886
Mali	4000	4800	1086	5886
Serbia	4000	4800	1086	5886
Ukraine	4000	4800	1086	5886
Korea, Republic	4000	4800	1086	5886
Belarus	4000	4800	1086	5886
Albania	4000	4800	1086	5886
Bosnia-Herzegovina	4000	4800	1086	5886
Bangladesh	4000	4800	1086	5886
Zimbabwe	4000	4800	1086	5886
South Africa	3000	3600	814	4414
Azerbaijan	3000	3600	814	4414
Armenia	3000	3600	814	4414
Argentina	3000	3600	814	4414
Canada	3000	3600	814	4414
Brazil	3000	3600	814	4414
Iran	3000	3600	814	4414
India	3000	3600	814	4414
United States of America	3000	3600	814	4414
Uruguay	3000	3600	814	4414
Tajikistan	3000	3600	814	4414
Turkey	3000	3600	814	4414
Russian Federation	3000	3600	814	4414
Pakistan	3000	3600	814	4414
Sudan	3000	3600	814	4414
Syrian Arab Rep.	3000	3600	814	4414
Lebanon	3000	3600	814	4414

Grain yield data of 2019 taken from USDA website accessed on 8 May 2020. *GY (grain yield), CC (carbon content), ACC (above ground CC), BCC (below ground CC) and TCC (total below and above ground CC).

Table 6. Carbon content (kg·ha^{-1}) calculation for rice crop in 40 leading countries in the world during 2019.

Countries	Kilograms per hectare (kg ha^{-1})			
	GY	ACC	BCC	TCC
Australia	10000	9333	2111	11444
Turkey	9000	8400	1900	10300
Peru	8000	7467	1689	9156
Morocco	8000	7467	1689	9156
Egypt	8000	7467	1689	9156
United States of America	8000	7467	1689	9156
Uruguay	8000	7467	1689	9156
EU-27	7000	6533	1478	8011
Japan	7000	6533	1478	8011
Argentina	7000	6533	1478	8011
Chile	7000	6533	1478	8011
China	7000	6533	1478	8011
Korea	7000	6533	1478	8011
Mexico	6000	5600	1267	6867
Paraguay	6000	5600	1267	6867
Russian Federation	6000	5600	1267	6867
El Salvador	6000	5600	1267	6867
Taiwan	6000	5600	1267	6867
Brazil	6000	5600	1267	6867
Guyana	6000	5600	1267	6867
Viet Nam	6000	5600	1267	6867
Ukraine	5000	4667	1056	5722
Indonesia	5000	4667	1056	5722
Iraq	5000	4667	1056	5722
Iran	5000	4667	1056	5722
Dominican Republic	5000	4667	1056	5722
Bangladesh	5000	4667	1056	5722
Colombia	5000	4667	1056	5722
Suriname	5000	4667	1056	5722
Mauritania	5000	4667	1056	5722
Niger	5000	4667	1056	5722
Kazakhstan	5000	4667	1056	5722
Sri Lanka	4000	3733	844	4578
Nicaragua	4000	3733	844	4578
Nepal	4000	3733	844	4578
Panama	4000	3733	844	4578
Korea, Democratic	4000	3733	844	4578
Malaysia	4000	3733	844	4578
Senegal	4000	3733	844	4578
Philippines	4000	3733	844	4578

Grain yield data of 2019 taken from USDA website accessed on 8 May 2020. * GY (grain yield), CC (carbon content), ACC (above ground CC), BCC (below ground CC) and TCC (total below and above ground CC).

from the atmosphere and therefore the cultivation of these crops could help reduce global warming. Therefore, plant breeder's efforts to produce crop species and ideotypes with higher TCC accumulation could be useful. As the cereals and grasses are executive crops[64], so the use of sustainable soil management practices[8,11,65], could also increase the TCC accumulation and reduce CO_2 in the atmosphere.

In our previous experiments[45,66], the NPK source which was associated with higher total biomass (TCC) also increases both root biomass (BCC) and shoot biomass (ACC). The increase and decrease in the CC accumulation in both roots (BCC) and shoots (ACC) in this study showed positive relationship with increase in biomass production and partitioning[1] and better growth[45,46]. Bagrintseva & Nosov[62] reported more DM partitioning in wheat and barley with combined application of N + P + K than N + P. Amanullah & Stewart[67] reported that N toxicity had reduced total biomass formation and partitioning into shoots (ACC) and roots (BCC).

In other studies[59] where both organic and inorganic soils were compared. The results revealed that the higher BCC under three organic soils (S_3, S_4 and S_5) at different growth stages was attributed to the longer root lengths and formation of a greater number of roots per plant[59], that increased water use efficiency that allocated more total biomass (TCC) into below ground biomass (BCC)[45,46]. In contrast, the lesser BCC obtained under inorganic soils (S_1 and S_2) was attributed the shorter root lengths and less number of roots per plant produced[59], and low WUE with lesser allocation of dry matter into roots[45]. Likewise, the higher ACC under three organic soils (S_3, S_4 and S_5) at different growth stages was attributed to formation of taller plants with more number of leaves and larger leaf area, and

Table 7. Carbon content ($kg \cdot ha^{-1}$) calculation for maize crop in 40 leading countries in the world during 2019.

Countries	Kilograms per hectare ($kg \cdot ha^{-1}$)			
	GY	ACC	BCC	TCC
Chile	12000	12600	2850	15450
Turkey	12000	12600	2850	15450
United States	11000	11550	2613	14163
New Zealand	11000	11550	2613	14163
Uzbekistan	10000	10500	2375	12875
Jordan	10000	10500	2375	12875
Switzerland	9000	9450	2138	11588
Canada	9000	9450	2138	11588
Argentina	8000	8400	1900	10300
Bangladesh	8000	8400	1900	10300
Egypt	8000	8400	1900	10300
EU-27	7000	7350	1663	9013
Albania	7000	7350	1663	9013
Australia	7000	7350	1663	9013
Iran	7000	7350	1663	9013
Kyrgyzstan	7000	7350	1663	9013
Uruguay	7000	7350	1663	9013
Ukraine	7000	7350	1663	9013
Serbia	7000	7350	1663	9013
Russian Federation	6000	6300	1425	7725
Saudi Arabia	6000	6300	1425	7725
Paraguay	6000	6300	1425	7725
Taiwan	6000	6300	1425	7725
Tajikistan	6000	6300	1425	7725
Iraq	6000	6300	1425	7725
Kazakhstan	6000	6300	1425	7725
Lao	6000	6300	1425	7725
Malaysia	6000	6300	1425	7725
Azerbaijan	6000	6300	1425	7725
Bosnia-Herzegovina	6000	6300	1425	7725
Brazil	6000	6300	1425	7725
Belarus	6000	6300	1425	7725
China	6000	6300	1425	7725
Korea, Republic	5000	5250	1188	6438
Cambodia	5000	5250	1188	6438
Viet Nam	5000	5250	1188	6438
South Africa	5000	5250	1188	6438
Pakistan	5000	5250	1188	6438
Thailand	4000	4200	950	5150
Korea, Democratic	4000	4200	950	5150

Grain yield data of 2019 taken from USDA website accessed on 8 May 2020.
* GY (grain yield), CC (carbon content), ACC (above ground CC), BCC (below ground CC) and TCC (total below and above ground CC).

Table 8. Carbon content ($kg \cdot ha^{-1}$) calculation for barley crop in 40 leading countries in the world during 2019–2020.

Countries	Kilograms per hectare ($kg \cdot ha^{-1}$)			
	GY	ACC	BCC	TCC
Chile	8000	11200	2533	13733
New Zealand	7000	9800	2217	12017
Zimbabwe	6000	8400	1900	10300
Switzerland	6000	8400	1900	10300
EU-27	5000	7000	1583	8583
Saudi Arabia	5000	7000	1583	8583
Ukraine	4000	5600	1267	6867
United States	4000	5600	1267	6867
Uruguay	4000	5600	1267	6867
Serbia	4000	5600	1267	6867
Norway	4000	5600	1267	6867
Korea, Republic	4000	5600	1267	6867
Brazil	4000	5600	1267	6867
Belarus	4000	5600	1267	6867
Canada	4000	5600	1267	6867
Argentina	4000	5600	1267	6867
Azerbaijan	3000	4200	950	5150
Bosnia- Herzegovina	3000	4200	950	5150
China	3000	4200	950	5150
Japan	3000	4200	950	5150
Kenya	3000	4200	950	5150
India	3000	4200	950	5150
Mexico	3000	4200	950	5150
South Africa	3000	4200	950	5150
Tunisia	2000	2800	633	3433
Turkey	2000	2800	633	3433
Ethiopia	2000	2800	633	3433
Russian Federation	2000	2800	633	3433
Peru	2000	2800	633	3433
Uzbekistan	2000	2800	633	3433
Tajikistan	2000	2800	633	3433
Iran	2000	2800	633	3433
Georgia	2000	2800	633	3433
Kyrgyzstan	2000	2800	633	3433
Lebanon	2000	2800	633	3433
Moldova	2000	2800	633	3433
Macedonia	2000	2800	633	3433
Colombia	2000	2800	633	3433
Algeria	2000	2800	633	3433

Grain yield data of 2019 taken from USDA website accessed on 8 May 2020.
* GY (grain yield), CC (carbon content), ACC (above ground CC), BCC (below ground CC) and TCC (total below and above ground CC).

formation of a greater number of tillers per plant[59] and high WUE with greater allocation of dry matter into shoots[45]. In contrast, the lesser ACC obtained under inorganic soils (S_1 and S_2) was attributed to development of shorter plants with less number of leaves and less leaf area and formation of a less number of tillers per plant[59] and low WUE with and so lesser allocation of DM into shoots[45].

Integrated nutrients management in field crop production, especially plant residue incorporation improve soil fertility that improves crop growth and total biomass[2−4,68] and reduces the problem of food security. Amanullah,[69] in a FAO global conference (Rome, Italy) reported that integrated use of organic carbon source (animal manures and plant residues), plant nutrients (macro and micro nutrients) and bio-fertilizers (beneficial microbes) is key to improve soil organic carbon and field crops productivity. The best management practices that increase SOC could reduce soil pollution and improve the health of all on the earth[70]. According to Lal,[71] field crop production in Africa, Asia and South America could be increased by millions every year, by increasing soil organic matter by one ton per hectare.

The variations in the TCC estimated for different countries and it's partitioning into roots (BCC) and shoots (ACC) may be attributed to the differences in the genetic make of the crop varieties used in different countries, the variation in the environmental conditions among the countries, and different agronomic practices used in different countries. The review of global data[72] showed that TCC transfer was highest in maize, which yielded the greatest soil C sequestration potential (1.0 Mg C ha^{-1} yr^{-1} or 19% total assimilation), followed by sorghum (1.0 Mg C ha^{-1}, 17%) and wheat (0.8 Mg C ha^{-1} yr^{-1}, 23%). Variation in TCC among cereals such as maize, sorghum, wheat and rice has been earlier reported by McKendry[73]. According to

Zengeni et al.[72] higher TCC transfer to soils occurred under clayey soils and warmer climates provided that exudation is high enough to offset respiration C losses. According to Ma et al.[21], plant organ C content is 45.0% in reproductive organs, 47.9% in stems, 46.9% in leaves and 45.6% in roots.

For increasing TCC accumulation in plants and it's partitioning into ACC and BCC it is important to (1) select high yielding plants genotypes, (2) use best agronomic (management) practices and (3) planting of crops in suitable environmental conditions. The best agronomic practices that improve crop growth and development, increase grain and total biomass thus increase TCC in different crop species (Tables 5–8). Any biotic or abiotic stress that could reduce the productivity (yield or biomass) of field crops could reduce the TCC and its partitioning into ACC and BCC under different environments. The agronomists study various crop production problems and work for better soil and crop management practices to obtain higher yield[74].

Conclusions

The increase in carbon sequestration (1 kg of carbon is equal to 3.67 kg of CO_2) through the process of photosynthesis in field crops is essential to combat the issue of food security and global warming. However, the lack of simplified and easy way of carbon estimation restricts researchers to estimate data on total carbon content (TCC) sequestered or captures by the field crops and it's partitioning into roots and shoots. In this study, highly simplified calculations have been developed to provide easy estimation of carbon content in below-ground parts (BCC) and above-ground parts (ACC) of various field crops, including wheat, rice, maize, barley, and more. Best agronomic practices that improve or increase the rate of photosynthesis under field conditions significantly increase the capture or sequestration carbon. Crops with higher TCC took more CO_2 (higher photosynthetic efficiency) from the atmosphere therefore increase the yield per unit area and decrease the negative impacts of global warming and food security. The simplified approach for carbon content (CC) estimation utilized in this study can be highly beneficial for researchers and students. It allows for easy estimation of the carbon content fixed in the roots and shoots of diverse field crops, including wheat, rice, maize, and barley. The total carbon content (TCC) in plants exhibited a positive correlation with total biomass. Furthermore, both below-ground carbon content (BCC) and above-ground carbon content (ACC) demonstrated a positive association with TCC. It was confirmed from the model, that out of the total 100% TCC accumulation by field crops, 82% is partitioned into ACC (shoots) and 18% into BCC (roots). The practices that increase grain yield, harvest index, and total biomass increased carbon content in roots and shoots of different crop species. The best agronomic practices that increase grain yield in field crops per unit area will also increase the TCC accumulation and it's portioning into ACC and BCC. Selecting carbon superior genotypes of crop species along with best management practices including sustainable soil management practices will significantly reduce CO_2 emission and increase soil health, productivity and sustainability with more carbon sequestration into the soils.

Conflict of interest

The author declares that there is no conflict of interest.

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