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Carbon and nitrogen uptake in above- and below-ground biomass of cereal crops in the integrated farming system

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Abstract. A significant reduction in greenhouse gas (GHG) emissions, as well as technologies that ensure removal of CO_2 from the atmosphere, are necessary to achieve the set goals for the transition to carbon neutrality. During the crop growth cycle, a significant amount of biomass is produced, and carbon (C) and nitrogen (N) are captured both by the harvested crop removed from the field and by residues left on the field. The trials were conducted to find out patterns between crop and residues while trying to figure out the amount of captured C and N. In this study data of the most widely grown cereal crops in Latvia are summarized. The data are representative, obtained in different agroclimatic conditions, they vary both by species and variety, by year and fertilizers applied. The mean amount of biomass from cereal crops left on the field was 1,070.9 g m^{-2} DM, besides, 906.7 g m^{-2} of that was made up of above-ground (AG) residues and 164.2 g m^{-2} of below-ground (BG) residues. On average, 471.8 g m^{-2} C and 14.3 g m^{-2} N were captured, including: 411.2 g m^{-2} C and 12.9 g m^{-2} N by AG residues; 60.7 g m^{-2} C and 1.4 g m^{-2} N by BG residues. Regularities between grain yield and residues were found, however, they were not very strong. The dataset should be enlarged to reduce uncertainty. As the data calculated from crop have a greater uncertainty, the GHG inventory should be calculated according to the average AG and BG biomass, which provide more accurate data.

Key words: cereal crops, crop residues, harvest index, shoot/root ratio.

INTRODUCTION

To achieve the goals of the Paris Agreement adopted by the 21st Conference of Parties (COP21) of the United Nations Framework Convention on Climate Change

(UNFCCC)[1], which foresees limiting global warming well below 2 °C, major greenhouse gas (GHG) emission reductions are needed together with technologies for removal of CO_2 from the atmosphere.

Soil and its management practices has an essential role in a global C cycle, while C cycle together with changes of GHG concentration in atmosphere can have a significant impact on global biochemical cycle (Heikkinen et al., 2013). Soils are the largest terrestrial reservoir and may provide the best way to remove carbon from the atmosphere (FAO, 2004). Management practices that capture the atmospheric CO_2 and enhance carbon (C) sequestration in the soil are needed. The input of organic matter from plant residues contribute to carbon storage and sequestration in soil and may help to mitigate greenhouse gas emissions (Powlson et al., 2011). Organic matter storage in soil is directly related to the amount of C input through residue retention, below-ground root biomass, and rhizodepositions (Pasricha, 2017). Carbon storage in the soil mostly is the balance between the input of complicated mixture of dead plant material, soil fauna, root exudates, microbial residues and losses from decomposition and mineralization processes. Soil organic C stocks are altered by biotic activities of plants which are the main source of C through litter and root system, microorganisms (fungi and bacteria) and 'ecosystem engineers' (earthworms, termites, ants) (Dignac et al., 2017).

Depending on the land use, management activities and environmental conditions agricultural mineral soils can be either source or sink of carbon (FAO, 2004; Paustian et al., 2007; Eglin et al., 2010; Bardule et al., 2017). Terrestrial ecosystems could increase C sequestration readily by restoring vegetation and incorporating organic soil amendments (Fang et al., 2018). Carbon capture by crops can make a significant contribution in the reduction of the anthropogenic carbon dioxide (CO_2) emissions into the atmosphere, therefore concerted effort to reduce CO_2 emissions and increase C sequestration have to be provided.

Today, the agricultural sector has a significant carbon (C) footprint and accounts for > 25% of worldwide anthropogenic GHG emissions (Jat et al., 2022). At the same time agricultural soils have a significant CO_2 sink capacity. Plants, including cultivated crops, during their growing cycle accumulate from atmosphere large amount of C and N both by yield and by below-ground and above-ground residues. Crop residue is defined as the portion of plant biological yield left in the field after harvesting the grain (Chintala et al., 2014). Crop yields vary with time and space due to the spatial and temporal heterogeneity of environmental and management factors (Bakker et al., 2005; Williams et al., 2008). One of the most important variables determining the projections of crop response at regional scale models is climate (Challinor, 2003; Bakker et al., 2005). However, crop species, variety, soil conditions, fertilizer and other factors can also play a role. Crop residues improve the agronomic productivity through nutrient cycling and improved soil quality.

Understanding the processes that govern N fluxes, particularly N uptake and distribution in crops, is of major importance with respect to both environmental concerns and the quality of crop products. Nitrogen uptake and accumulation in crops represent two major components of the N cycle in the agrosystem. Nitrate ions not taken up by a

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[1] The Paris Agreement https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

crop, may potentially be leached to underground water. Modelling N uptake is, therefore, key in quantifying and preventing nitrate leaching (Gastal & Lemaire, 2002).

One of the most important and cultivated cereal crops in the world and in Latvia is wheat, especially winter wheat. According to the data of the Central Statistical Bureau of Latvia, in 2021, the area sown with cereals in Latvia accounted for 776.4 thousand ha or almost 60% of the total sown area, of which 426.4 thousand ha, or almost 55%, was sown with winter wheat. The second most widely grown crop was spring wheat - an area of 113.4 thousand ha or 14.6% was sown with spring wheat. The third most widely grown crop was oats - area sown with outs accounted for 90.1 thousand ha or 1.6% of total sown area (FAOSTAT, 2018; Central Statistical Bureau, 2020; Official statistics..., 2022).

To find out the possible amount of C and N accumulated in the biomass during growing cycle the trials of different agricultural crop species were established. The aim of these studies was to find out the amount of cereal crop residues: i.e., above-ground and below-ground residues left on the field and assess the extent to which it was affected by different factors such as species, variety, fertilizer, soil and meteorological conditions. As well amount of C and N captured and left on the field, and the possible regularities between the yield and the amount of C and N bound in the residues, were assessed.

MATERIALS AND METHODS

Experimental design and background

The conventionally grown cereals - winter crops: wheat (WW), rye (WR), and triticale (WT), as well as following summer crops: wheat (SW), barley (SB), and oats (OA), were included in the field experiment. Each crop was represented in field trials by two biologically/ morphologically different varieties (V1 and V2), and they were grown using a two-level cultivation technology, which is widely used by farmers in Latvia and differs according to the rate of nitrogen fertilization (F1 and F2). The field trials were set up in two locations (L1 and L2) with different soil and agroclimatic characteristics: in Dizstende 57. 1867 N, 22.5477 E and in Priekuli 57. 3152 N, 25.3376 E. The soil type was sod-podzolic which is typical soil in Latvia. The characteristics of experimental fields are summarized in Table 1.

Field experiments were carried out from 2018 to 2020 using a block design with four replicates, size of each plot - 20 m^2. The soil was ploughed in the autumn and each crop was sown in its optimal sowing period. The sowing rate used was 450–500 germinating seeds per m^2, row spacing was 12.5 cm. Complex mineral fertilizer at the rate of 330 kg ha^{-1} was applied for winter crop (33 kg ha^{-1} N, 85 kg ha^{-1} P, 85 kg ha^{-1} K) and at the rate of 350 kg^{-1} for spring crop (30 kg ha^{-1} N, 72 kg ha^{-1} P, 72 kg ha^{-1} K). The fertilizer was applied to the soil before sowing. In the spring, additional nitrogen fertilizer was applied to the winter cereals immediately after re-vegetation and to the summer cereals in the tillering stage (Table 2). During the growing season, plant protection products were applied according to the needs of the species. Plant biomass samples were collected at the stage of yellow ripeness of cereals (Zadoks Growth Stage GS84-89). The total grain mass was harvested with a small-size grain harvester *Wintersteiger Delta* at the stage of grain full ripening (GS95-99).

Table 1. The characteristics of soil and pre-crops in the experimental fields

Trial Year	Location	pH $_{KCl}$	Organic matter, %	K_2O mg kg^{-1}	P_2O_5 mg kg^{-1}	Soil type	Pre-crop
Winter crops							
2018	L1	5.6–5.8	1.8–2.0	201–218	161–192	light loam	winter oilseed rape
	L2	5.5–5.6	1.5–2.1	144–165	147–150	clay sand	green manure - buckwheat
2019	L1	5.9–6.3	2.2–2.6	239–322	159–197	heavy loam	green manure - buckwheat
	L2	5.1–5.6	1.5.–1.9	115–145	187–202	clay sand	spring barley
2020	L1	6.3–6.7	3.3–3.4	158–160	122–144	light loam	winter oilseed rape
	L2	5.1–5.6	1.5–1.9	115–145	187–202	clay sand	spring barley
Spring crops							
2018	L1	5.1–5.8	1.8–2.0	189–204	160–206	light loam	field bean
	L2	5.5– 6.2	1.7–2.1	183–202	177–203	clay sand	potatoes
2019	L1	5.0–5.6	1.8–2.0	201–232	150–186	light loam	potatoes
	L2	5.5–5.8	1.7–2.1	149–183	174–196	clay sand	potatoes
2020	L1	5.3–5.9	1.9–2.3	218–240	161–193	light loam	potatoes
	L2	5.5–5.6	1.5–2.1	144–165	147–150	clay sand	potatoes

Table 2. Information about the cereal varieties and fertilization rates

Cereal species	Varieties (origin, short description)		N fertilizer rate used in spring (kg ha^{-1} N)	
	V1	V2	F1	F2
Winter crops				
Winter wheat (WW)	*Fredis* (LV) early, short stem	*Brencis* (LV) semi early, long stem	33 + 75	33 + 135
Winter rye (WR)	*Su Nasri* (DE) hybrid, early, short stem	*Kaupo* (LV) semi early, long stem	33 + 75	33 + 115
Winter triticale (WT)	*Ruja* (LV) semi late, long stem	*Ramico* (DE) semi early, short stem	33 + 75	33 + 135
Spring crop				
Spring wheat (SW)	*Taifun* (DE) semi late, short stem	*Uffo* (LV) semi early, long stem	100	140
Spring barley (SB)	*Ansis* (LV) semi late, short stem	*Kristaps* (LV) semi early, long stem	100	140
Spring oat (OA)	*Symphony* (DE) semi late, long stem	*Laima* (LV) semi early, long stem	80	100

Description of meteorological conditions and plant development

Overall, the growing seasons of 2018, 2019 and 2020 were characterised by average monthly temperatures slightly above long-term averages (Fig. 1). Some short periods of extreme drought were observed during all vegetation periods. In 2018, hot and dry conditions were observed during the first days of May and at the end of June. During the autumn and winter months, the average daily air temperatures were a little higher than the long-term averages and, in general, wintering conditions were favourable. Also in April, in all three seasons, the air temperature was higher than that of long- term average, which contributed to the earlier recovery of the vegetation of winter cereals. Overall, the growing seasons of 2018, 2019 and 2020 were characterised by average temperature slightly above long-term averages. Moist conditions in July were favourable for plant development.

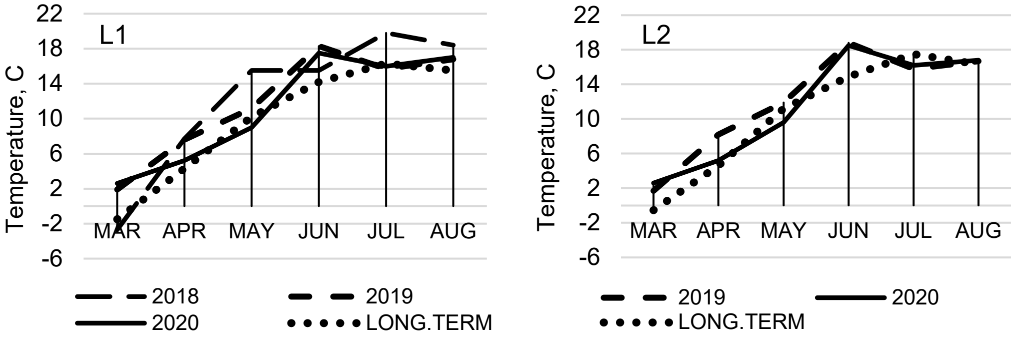

Figure 1. Temperature by month in both locations (L1, L2) during the growing season, over the three trial years compared to the long-term averages.

For spring crops an optimal air temperature and precipitation are important during the period of tillering and stem elongation in May and June. In 2018, only 14 mm of precipitation fell in location L1 in May and the first half of June. During this period, the average daily air temperature was also higher, which contributed to the rapid development of plants, while the moisture deficit prevented the creation of optimal plant biomass.

Agroclimatic conditions in the post-flowering period are also important for biomass formation. The average daily air temperature and the amount of precipitation per month at both experimental sites were optimal in July 2019 and 2020, but in 2018, in location L1, there was significant decrease in the precipitation compared to the long-term averages (Fig. 2). Over the three years, while the experiment was carried out, more precipitation was observed at the end of July and August, which corresponds to the long-term observations. During this period, some days were characterized by heavy rains and thunder alternating with sunny and dry days. Precipitation in August did not significantly influence the formation of biomass of the crops, because winter crops reach their maturity stage in the first decade of August, and spring crops - by August 20.

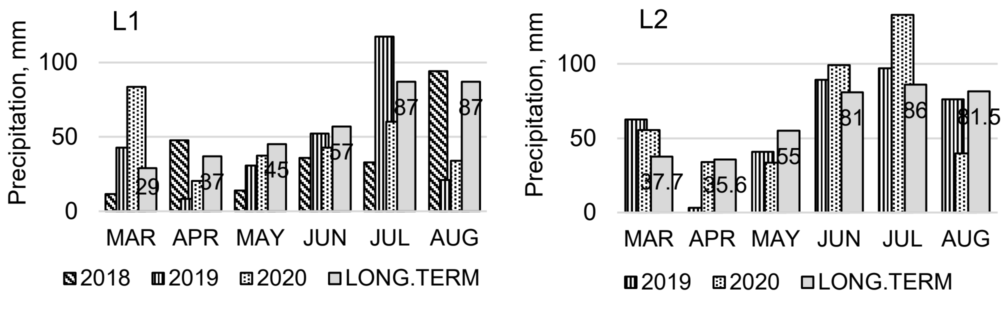

Figure 2. Precipitation by month in both locations (L1, L2) during the growing season over the three trial years compared to the long-term averages.

Collection and analysis of samples

The cereal biomass samples were taken from area of 0.125 m^2 in 2 places in each repetition of trial variant. The plant roots were dug out from the soil at a depth of 20 cm in the area of above-ground biomass recording, rinsed on a sieve (mesh size 1.0×1.0 mm), and collected. The roots and above-ground biomass samples were air-dried and weighed separately, using a laboratory balance (having readability of 0.01 g). The dry matter of each sample was determined (ISO 6496:1999) in the Laboratory of Cereal Technology and Agricultural Chemistry of the Institute of Agricultural Resources and Economics. The following methods (according to the LVS ISO standard) for determination of carbon content in biomass were used: total carbon (C) - using elemental analyser (dry combustion) LECO CR-12 (LVS ISO 106940; total nitrogen (N) - Kjeldahl procedure (LVS ISO 11261).

Data analyses

Descriptive statistics and Pearson correlation of experimental data were performed using Microsoft Excel 2019 for Windows (© Microsoft 2023) and SPSS. Normal distribution was tested using Kurtosis and Skewness values. Regression and variance analyses (ANOVA) were perfomed with R Studio for Windows(© 2009-2022 RStudio, PBC). Multifactorial analyse (MANOVA) were performed to evaluate significance of various factors on the amount of residues and C and N uptake. The following factors and their interactions were evaluated: variety, nitrogen fertilization level, location, year.

RESULTS AND DISCUSSION

Biomass from cereals

The total biomass of cereals consisted of grain yield removed from the field (GY); roots or below-ground (BG) residues; and above-ground (AG) residues (straws, leaves and stubbles) left on the field. The amount of biomass was strongly influenced by the species, variety, amount of N fertilizer applied, year, and location or agrochemical properties of the soil. The significance of individual factors and their interaction effects by species are summarized in the Table 3. It can be seen, that the effect of year was significant (*p*-value < 0.001) for all species. The studies conducted elsewhere have also concluded that meteorological conditions have a very significant impact on the biomass formation. Generally, the interannual variation in yields there was larger than the variation between regional mean yields (Palosuo et al., 2015).

Table 3. The significance (significance codes) of the effects of various factors and their mutual interaction by species

Cereal	Factors				Interaction of factors				
species[1]	Year (Y)	Variety (V)	N-fert (Nf)	Location (L)	Y×V	Y×Nf	V×Nf	V×L	Nf×L
WW	***	***	*	***	-	-	-	*	-
SW	***	***	***	-	-	-	-	-	-
OA	***	***	***	***	***	-	**	*	***
WT	***	***	**	***	-	*	-	-	**
WR	***	***	***	***	-	-	-	-	-
SB	***	-	***	***	-	-	-	-	**

[1] Cereal species: WW – winter wheat; SW – spring wheat; OA – oats; WT – winter triticale; WR – winter rye; SB – spring barley. Transcript of statistically significant difference codes: *** *p*-value < 0.001; ** *p*-value < 0.01; * *p*-value 0.05.

Mean total biomass of all cereal species was 1,628.8 g m^{-2} of dry matter (DM). Higher biomass was formed by winter cereal species, which is explicable given their longer growth cycle. The highest total biomass formed winter triticale (WT) - 2272.3 g m^{-2} DM, only slightly smaller biomass formed winter rye (WR), accounting for 2137.0 g m^{-2} DM. The amount of total biomass produced by spring cereals was almost half lower, it ranged from 1,165.5 g m^{-2} for spring barley (SB) to 1,386.8 g m^{-2} for oats (OA) (Table 4).

Table 4. The distribution of the total biomass accumulated during the growth cycle for different cereal species (DM, g m^{-2})

Cereal species[1]	Dry matter of different fractions, g m^{-2}			Total biomass, g m^{-2}
	BG residues	AG residues	Grain yield	
WW	142.8 ± 86.82*	821.6 ± 196.56	615.3 ± 210.52	1,579.7 ± 310.22
SW	128.9 ± 58.35	614.0 ± 174.89	488.6 ± 131.08	1,231.5 ± 219.92
OA	155.7 ± 64.06	700.7 ± 206.69	530.4 ± 113.75	1,386.8 ± 239.24
WT	232.6 ± 141.02	1,382.3 ± 760.93	657.4 ± 244.72	2,272.3 ± 608.10
WR	239.6 ± 125.33	1,315.6 ± 557.00	581.9 ± 221.50	2,137.0 ± 645.85
SB	85.6 ± 15.94	606.0 ± 198.08	473.9 ± 143.89	1,165.5 ± 249.84
On average	164.2	906.7	557.9	1,628.8

[1]Cereal species: WW – winter wheat; SW – spring wheat; OA – oats; WT – winter triticale; WR – winter rye; SB – spring barley; * – standard deviation.

The largest proportion – more than half of the total biomass was calculated for above-ground residues. Percentage distribution of cereal biomass was as follows: BG residues 9–11.2%; AG residues; 49.9–61.6%; grain yield 27.2–40.7% (Fig. 3).

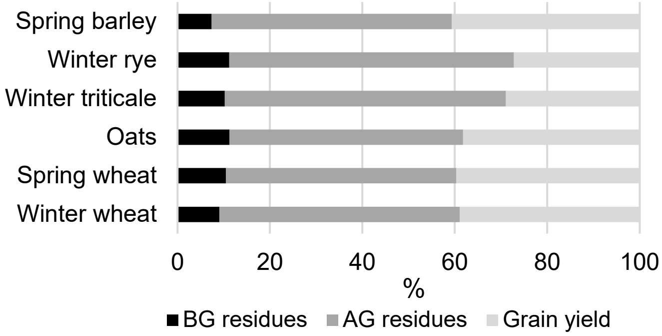

Figure 3. Percentage distribution of cereal biomass, %.

Distribution of average weight by cereal species was as follows: 164.2 g m^{-2} BG residues; 906.7 g m^{-2} AB residues; 557.9 g m^{-2} GY and (Table 4). Among species, AG residues varied greatly from 606.0 g m^{-2} (SB) to 1,382.3 g m^{-2} (WT). Grain yield varied from 473.9 g m^{-2} to 657.4 g m^{-2}, the highest yield produced winter triticale and winter wheat - 657.4 g m^{-2} DM and 615.3 g m^{-2} DM, respectively. Data regarding BG residues varied greatly from 85.6 g m^{-2} DM (SB) to 239.6 g m^{-2} (WR), and 232.6 g m^{-2} (WT). Published data from the research carried out in Denmark (Chirinda et al., 2012; Hu et al., 2018) shows that the average root dry matter in conventional farming systems at the depth 0–25 cm was 142 g m^{-2} DM (ranged 92–194 g m^{-2}) for wheat and 129 g m^{-2} DM (ranged 108–133 g m^{-2}) for barley. It can be concluded, that mentioned data of winter wheat root biomass are very close to our data (142.8 g m^{-2}). Trends by species are also consistent, in the mentioned experiment it was similarly concluded that the biomass of barley roots is lower if compared to the biomass of wheat. Mean DM of WW shoot generally was higher, ranged around 1,509 g m^{-2} DM (1,175–1,907 g m^{-2}). It could be greatly influenced by the variety as well as agrometeorological conditions. Williams et al (2013) reported significant variation for WW AG residues ranging from 537 g m^{-2} to 1,096 g m^{-2} depending on year, site and management.

Captured carbon and nitrogen

Carbon (C) and nitrogen (N) content was determined in below-ground and above-ground residues. The content of both C and N was significantly higher in AG residues. An average carbon (C) content in BG residues of cereal crops was 373.1 g kg^{-1} C; it varied from 307.7 g kg^{-1} C (WR) to 427.1 g kg^{-1} C (SB). An average carbon (C) content in AG residues was 447.2 g kg^{-1} C for all cereal crops. Here, among species it varied relatively less: from 439.5 g kg^{-1} C (SB) to 453.3 g kg^{-1} C (WR) (Table 5). An average nitrogen (N) content was 8.1 g kg^{-1} N in BG residues: and 14.3 g kg^{-1} N in AG residues. Nitrogen content varied within the following limits: from 7.2 g kg^{-1} N (WT) to 10.2 g kg^{-1} N (SB) in BG residues and from 11.6 g kg^{-1} N (WW) to 16.6 g kg^{-1} N (SB) in AG residues.

Table 5. Carbon (C) and nitrogen (N) content in above-ground (AB) and below-ground (BG) residues (g kg^{-1}) of cereal crops

Cereal species[1]	N	C, g kg^{-1}		N, g m^{-2}	
		in BG residues	in AG residues	in BG residues	in AG residues
WW	112	391.2 ± 29.71*	441.5 ± 13.36	7.5 ± 1.30	11.6 ± 2.20
SW	161	399.3 ± 55.22	451.0 ± 16.10	8.5 ± 2.33	16.3 ± 2.75
OA	157	390.1 ± 56.93	449.1 ± 28.87	8.0 ± 2.25	15.2 ± 3.44
WT	96	323.4 ± 68.39	448.7 ± 7.42	7.2 ± 1.81	13.8 ± 3.04
WR	96	307.7 ± 79.94	453.3 ± 10.91	7.4 ± 2.72	12.4 ± 2.55
SB	128	427.1 ± 29.35	439.5 ± 13.28	10.2 ± 2.09	16.6 ± 2.51
On average		373.1	447.2	8.1	14.3

[1] Cereal species: WW – winter wheat; SW – spring wheat; OA – oats; WT – winter triticale; WR – winter rye; SB – spring barley; *– standard deviation.

The amount of sequestered carbon and nitrogen per unit area was calculated (g m^{-2}). Like the data of total biomass distribution, a significantly greater amount of C and N was captured by AG residues: on average 6–7 times more C and about 9 times more N per m^{2}. Such ~~a~~ distribution was determined by both the amount of dry matter produced and a relatively higher C and N content in the AG residues (Table 6).

Average amount of sequestered C in the AG residues was 411.2 g m^{-2} C, among species it ranged from 266.3 g m^{-2} (SB) to 636.9 g m^{-2} (WR). Average amount of sequestered carbon in BG residues was 60.7 g m^{-2} C. Among cereal species it ranged from 36.6 g m^{-2} (SB) to 90.0 g m^{-2} (WR) proving once again that during growth, rye forms a very extensive root system (Table 5). Often the inputs of C from both above-ground and below-ground residues are generally calculated from plant biomass by multiplying with specific transfer coefficients (Kätterer et al., 2011; Chirinda et al., 2012). Such method is chosen due to the fact, that unlike above-ground plant biomass, root biomass and thus the amount of C captured by roots is difficult to sample and quantify. However, the C captured in roots can represent an important source for soil C storage (Warembourg & Paul, 1977), because it may contribute to more stable soil organic C pools than aboveground inputs (Kätterer et al., 2011). This is why simple estimation methods have been proposed for estimating belowground C inputs (Keel et al., 2017; Hu et al., 2018).

The amount of captured N was much lower than that of C, furthermore, it varied relatively less among individual cereal species: from 0.9 g m^{-2} to 2.3 g m^{-2} in below-ground residues; and from 9.6 g m^{-2} to 19.1 g m^{-2} in above-ground residues (Table 5).

Table 6. The amount of carbon (C) and nitrogen (N) accumulated in the above-ground (AG) and below-ground (BG) residues of cereal crops (g m^{-2})

Cereal species[1]	C, g m^{-2}		N, g m^{-2}	
	in BG residues	in AG residues	in BG residues	in AG residues
WW	55.2 ± 32.1*	362.7 ± 88.5	1.1 ± 0.8	9.6 ± 3.6
SW	45.3 ± 15.1	274.9 ± 74.7	1.0 ± 0.4	10.0 ± 3.5
OA	54.1 ± 15	323.6 ± 95.7	1.1 ± 0.3	11.0 ± 4.3
WT	82.8 ± 51.1	602.6 ± 320.7	1.9 ± 1.3	19.1 ± 12.9
WR	90.0 ± 52.4	636.9 ± 267.5	2.3 ± 1.5	17.5 ± 8.3
SB	36.6 ± 7.2	0.9 ± 0.2	0.9 ± 0.2	10.1 ± 3.7
On average	60.7	411.2	1.38	12.88

[1] Cereal species: WW – winter wheat; SW – spring wheat; OA – oats; WT – winter triticale; WR – winter rye; SB – spring barley; * – standard deviation.

The box plot figures (Fig. 4) show very different distribution of accumulated amount of carbon by different cereal crops. The highest content of carbon was established in winter rye and winter triticale both in the above-ground and in the below-ground residues. In turn, for spring cereals the level of captured carbon was generally lower, and the dispersion of the data here was much smaller. The amount of C accumulated in the BG residues was far lower than that in the AG residues for all cereal species.

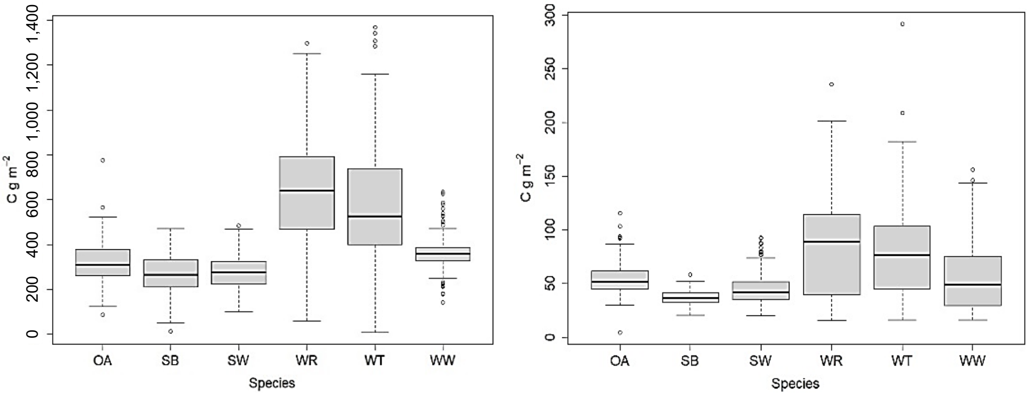

Figure 4. Accumulated amount of carbon (C) by different cereal crops: in the above-ground residues (picture at the left side); and in the below-ground residues (picture at the right side), C g m^2: OA – oats; SB – spring barley; SW – spring wheat; WR – winter rye; WT – winter triticale; WW – winter wheat.

Similar trend was observed for the distribution of the accumulated amount of nitrogen both in the above-ground and in the below-ground residues (Fig. 5). The highest content of nitrogen was established in winter rye and winter triticale both in the above-ground and in the below-ground residues. In general, it can be concluded - if the arrangement of medians and boxes shows the conditional similarity of the accumulated C and N between winter wheat and spring cereal species - wheat, barley and oats, then this is not applicable to winter rye and triticale.

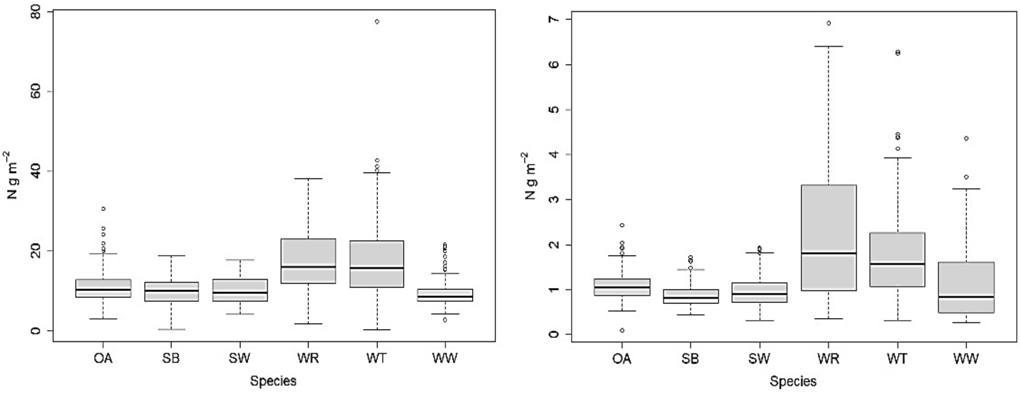

Figure 5. Accumulated amount of nitrogen (N) by different cereal crops: in the above-ground residues (picture at the left side); and in the below-ground residues (picture at the right side), N g m^2: OA – oats; SB – spring barley; SW – spring wheat; WR – winter rye; WT – winter triticale; WW – winter wheat.

C input

Conservation of crop residues in fields should be mandatory to maintain soil quality and offset agricultural C emissions (Stella et al., 2019). Carbon input often is calculated using allometric equations that describe the amount of C returned to the soil relative to yield. A set of crop-specific coefficients allows to estimate of C input to soil for individual species or groups of crops, such as cereals. Typically, allometric equations include a conversion from dry matter to C units and a factor that relates yield to the amount of above- and below-ground residues remaining in the field (e.g. straw, roots and rhizodeposition) (Keel et al., 2017). In order to increase the accuracy of calculations, it is necessary to collect and analyze the widest possible set of data specific to a particular region.

Carbon (C) input from above-ground residues can be calculated using C amount of harvested product and harvest index (HI) which is the ratio of harvested product (grain yield) to total above-ground biomass (grain yield and AG residues). Carbon input from the root biomass (BG residues) of cereal crops can be calculated using crop annual root biomass C, harvest index (HI) and SR - the ratio of shoot (AG residue) and root (BG residue) biomass of crop (Palosuo et al., 2015). Mean SR ratio of cereal crops studied was 5.6. However, by species it varied within quite wide limits - from 4.5 (OA) to 7.1 (SB). For winter cereal species, SR ratio fluctuated closely around the mean: 5.5 (WR); 5.8 (WW) and 5.9 (WT) (Table 7). Previous studies have concluded that the

SR ratio of 5.6 can be used as a constant in calculations for all cereals (Palosuo et al., 2015).

Harvest indexes fluctuated from 0.31 (WR) and 0.32 (WT) to 0.43–0.44 for other cereal crops. Previously published data of HI (Palosuo et al., 2015) agree very well with the data obtained in our trials for WW and SW (0.42), and oats (0.46). For the other species, the differences could have been influenced by specificities of the varieties and meteorological conditions.

Table 7. Parameter values used for converting statistical yield data to carbon input from crops to soil

Parameter	Winter wheat	Spring wheat	Oats	Winter triticale	Winter rye	Spring barley
SR (shoot/root ratio)	5.8	4.8	4.5	5.9	5.5	7.1
HI (harvest index)	0.43	0.44	0.43	0.32	0.31	0.44

Using different allometric equations the annual C inputs to 0–1 m depth from plant residues averaged accross all crop types and treatments ranged from 2.1 Mg C m^{-2} $year^{-1}$ to 5.3 Mg C m^{-2} $year^{-1}$ (Bolinder, 2007). It was considered that the upper 0.20 m of soil contained about 33% of soil organic content (SOC) in the 0–1 m profile (Fliessbach et al., 1999).

Correlations with yield

Winter wheat. The analysis of variance shows that the total biomass (B_{tot}) of winter wheat varied significantly by year, variety, N fertilizer, soil agrochemical parameters, and it was significantly dependent on the interaction of the mentioned factors ($p < 0.05$). The average biomass ($n = 112$) of the variety 'Brencis' 1526.1 g m^{-2} was significantly higher compared to that of variety 'Fredis' 1347.6 g m^{-2} with a reliable probability (> 95%, p-value = 0.002). The linear equation between grain yield harvested (GY) and total biomass was found: $B_{tot} = 729.51 + 1.15 \times GY$. With an increase in yield by 1 g m^{-2}, the total biomass increased by 1.15 g m^{-2} with almost 100% confidence. The determination coefficient ($R^2 = 0.61$) shows that 61% of the biomass data dispersion can be explained by the grain yield (Table 8). In turn, no correlation was found between grain yield and above-ground residues (AG_{resid}). The regression equation $AG_{resid} = 729.5 + 0.15\ GY$ shows that with the yield increase by 1 g m^{-2}, the above-ground residues increased by 0.15 g m^{-2} with a rather weak, only 90.9%, reliability ($R^2 = 0.03$). Similarly, the linear equation of the analysis of variance does not statistically significantly explain the dispersion of the above-ground residues value depending on the grain yield factor.

A close positive correlation ($r = 0.82$) was found between WW grain yield and below-ground residues (BG_{resid}). Regression analysis resulted in the equation $BG_{resid} = -64.7 + 0.34 \times GY$. With the GY increase by 1 g m^{-2}, amount of the below-ground residues increased by 0.34 g m^{-2} with almost 100% reliability ($R^2 = 0.67$). Total residues (Resid), i.e., above-ground and below-ground biomass remaining on the field and in the soil, depending on the GY, can be calculated with almost 100% reliability (p-value almost 0, $R^2 = 0.18$) using the following equation: $Resid = 664.77 + 0.49 \times GY$. The close positive correlation (0.81) between grain yield and both C and N captured by BG residues (g m^{-2}) was established and such linear equations were developed: $C_{BG} = -20.94 + 0.12 \times GY$, ($R^2 = 0.66$); $N_{BG} = -0.76 + 0.003 \times GY$, ($R^2 = 0.67$).

Spring wheat. The grain yield of spring wheat varied significantly ($p < 0.05$) by year, variety and N fertilizer rate, but the interaction of these factors was insignificant. A weak correlation was found between grain yield and: BG residues (0.4), C_{BG} (0.48), and N_{BG} (0.56).

Table 8. Regression equations between grain yield of cereals and residues; and captured carbon and nitrogen

Equation	r/R^2	Equation	r/R^2
	Winter wheat (WW)		
$B_{tot} = 729.51 + 1.15 \times GY$	0.78/0.61	$Resid = 664.77 + 0.49 \times GY$	0.49/0.18
$AG_{resid} = 729.5 + 0.15 \times GY$	0.16/0.03	$C_{BG} = -20.94 + 0.12 \times GY$	0.81/0.66
$BG_{resid} = -64.7 + 0.34 \times GY$	0.82/0.67	$N_{BG} = -0.76 + 0.003 \times GY$	0.81/0.67
	Oats (OA)		
$B_{tot} = 667.1 + 1.1 \times GY$	0.51/0.18	$C_{AG} = -97.8 + 0.34 \times B_{tot}$	0.88/0.78
$C_{AG} = 133.1 + 17.33 \times N_{AG}$	0.78/0.61	$N_{AG} = -1.8 + 0.01 \times B_{tot}$	0.60/0.35
	Winter triticale (WT)		
$AG_{resid} = 2859.3 - 2.2 \times GY$	0.72/0.52	$C_{AG} = 1277.26 - 0.95 \times GY$	0.69/0.48

r/R^2 – correlation coefficient/ determination coefficient.

Oats. Oat grain yield was significantly influenced by all factors: year, variety, N fertilizer rate, and location. Significant was also the interaction of mentioned factors (Table 3). There was found a weak linear correlation (0.51) between the grain yield and total amount of biomass: $B_{tot} = 667.1 + 1.1 \times GY$ ($R^2 = 0.18$). Strong correlations between total biomass and C amount captured by above-ground residues as well as between N and C captured by aboveground residues were found: $C_{AG} = -97.8 + 0.34 \times B_{tot}$ ($r = 0.88$; $R^2 = 0.78$); $C_{AG} = 133.1 + 17.33 \times N_{AG}$ ($r = 0.78$; $R^2 = 0.61$).

Winter triticale. Grain yield and biomass of winter triticale differed significantly by year, variety, N fertilizer rate, and location or soil properties. The interactions of mentioned factors were also significant (Table 3). Grain yield correlated with the above-ground residues, and linear equation was developed: $AG_{resid} = 2{,}859.3 - 2.2 \times GY$. With the yield increase by 1 g m^{-2}, the AG residues decreased by 2.2 g m^{-2}, $R^2 = 0.52$. Grain yield correlated (0.69) also with the accumulated carbon amount (C, g m^{-2}) in AG residues: $C_{AG} = 1{,}277.26 - 0.95 \times GY$. With the yield increase by 1 g m^{-2}, the amount of C_{AG} decreased by 0.95 g m^{-2} ($R^2 = 0.48$).

CONCLUSIONS

Biomass data on various cereal species collected are representative considering both the different soil and meteorological conditions during the three trial years, different varieties and rates of nitrogen fertilizers applied.

It can be concluded that cereal crops with above-ground and below-ground residues accumulate a significant amount of carbon and nitrogen. The amount of residues and, therefore, the amount of accumulated C and N are strongly influenced by various factors - species, variety, fertilizer, soil conditions. A very important role plays the year and interaction of the above-mentioned factors. It is important to understand the role of each factor and find options to drive them to increase C and N sequestration in the soil and reduce the environmental impact of intensive agriculture.

Average values of dry matter of cereal crop residues left on the field were 906.7 g m^{-2} DM of above-ground (AG) residues and 164.2 g m^{-2} of below-ground (BG) residues.

Average C amount captured by cereal crop residues was as following: 411.2 g m^{-2} C in AG residues and 60.7 g m^{-2} C in BG residues. An average amount of captured N was as following: 12.88 g m^{-2} N in AG residues and 1.38 g m^{-2} N in BG residues.

Regularities between grain yield and residues were found, however, they were not very strong. The closest were found for winter wheat whose data approached the average values of all cereal species. This study demonstrated a medium strong linear relationship between WW grain yield and: total biomass; BG residue; C_{BG}; $N_{BG.}$ The dataset should be enlarged to reduce uncertainty.

The obtained results allow us to conclude that the data calculated from the yield will have a greater uncertainty, therefore the GHG inventory should be calculated according to the average AG and BG biomass, which is more accurate.

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