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Carbon and nitrogen accumulation by agricultural crop residue under three cropping systems

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Abstract. Agricultural crops produce different biomass during their growth, including varying amounts of residue which accumulate a significant amount of carbon (C) and nitrogen (N). Assimilation capacity depends largely on species, variety and growing condition. Carbon accumulation in soil contributes to both - the agricultural production and maintenance of environmental quality reducing atmospheric C and greenhouse gas emissions. In this study, the amount of plant residue left on the field by above-ground and below-ground residue and the amount of C and N accumulated in them in three different cropping systems: organic (Bio); integrated with a low input of N fertiliser (Int-low-N) and; integrated with a high input of N fertiliser (Int-high-N) were evaluated. The most commonly grown cereal crops in Latvia were tested: winter wheat (WW); summer wheat (SW); winter rye (WR); winter triticale (WT); summer barley (SB); summer oat (SO); and buckwheat (BW) as pseudo-cereal crop. The highest biomass of dry matter of total harvest residue in all cropping systems was recorded in WR: 853.3 ± 40.76 g m^{-2}; 1,482.0 ± 105.06 g m^{-2}; 1,628.3 ± 115.49 g m^{-2} - in Bio; Int-low-N; Int-high-N cropping systems, respectively. The highest amount of carbon (g C m^{-2}) using organic cropping system was accumulated by residue of: WR (268.6 ± 28.68), BW (239.4 ± 10.50) and WW (234.5 ± 27.41). The highest amount of carbon (g C m^{-2}) using integrated cropping system was accumulated by residue of: WR - 473.8 ± 64.9; 496.6 ± 62.54 and WT - 458.2 ± 32.57; 521.1 ± 46.26 in Int-low-N and Int-high-N, respectively. Higher proportion of root biomass cereals formed using organic cropping system.

Key words: above-ground and below-ground residue, cereal crops, integrated cropping system, organic cropping system.

INTRODUCTION

Increase of carbon and nitrogen storages can improve soil quality and reduce of atmospheric carbon dioxide (CO_2) and nitric oxide (N_2O) concentration in the atmosphere which results in a decrease the greenhouse effect (Nath et al., 2017; Lal et al., 2021). Carbon management in agriculture could be a very efficient measure to mitigate the increased concentration of CO_2 in the atmosphere maximizing the uptake and promoting its storage in soil organic matter (Tariq et al., 2023). Soils represent a massive stock of terrestrial organic carbon (C) and act both as a buffer against atmospheric CO_2 increase and as a potential sink for additional C depending on the balance between photosynthesis, the respiration of decomposer organisms, and stabilization of C in soil (Rodrigues et al., 2023).

There is a great potential to increase carbon sequestration in agricultural soils using different management practices - crop rotation, minimal soil disturbance, crop residue incorporation could be key elements for the success of conservation agriculture (Giller et al., 2015). A range of agricultural measures, including use of purposeful crop rotation in different farming systems can significantly affect the capture of atmospheric carbon and store it within the soil (Avasiloaiei et al., 2023).

Given the significant role of soil as a carbon sink, preserving and increasing soil organic carbon (SOC) stocks are current priorities. The European Commission has suggested increasing focus on carbon farming initiatives to contribute to the land carbon sink that is required to meet the 2030 climate target of the net removal of 310 Mt CO_2 from the atmosphere (European Commission, 2021). Moreover, there has set the ambitious goal of increasing soil carbon stocks by 0.4% a year as a way to offset the global emissions of GHG and mitigate climate change (Minasny et al., 2017; Latorre et al., 2024).

Carbon input into the soil using various methods, including retention of C bound in plants is an essential prerequisite for organic matter conservation in the soil. Carbon supply is usually related to the build-up of soil fertility, which in turn allows for a reduction of external inputs, such as synthetic fertilizers and pesticides. Crop residue incorporation to the soil is an essential strategy to improve soil quality and crop productivity in order to attain sustainable development goals (Hamelin et al., 2019). Stubble retention that increase residue inputs typically facilitate SOC storage. Agricultural crops having large root system and high biomass translates to better weed management, soil moisture conservation, and fertility improvement, in addition to protection of soil from erosion (Murungu et al., 2011).

The appropriate management of soil organic matter (SOM) in an agricultural production system is an essential issue in reducing the greenhouse gas (GHG) emmissions. The decomposition of organic matter releases C and contributes to the increase in GHG emissions. Therefore, it is important to ensure a continuous inflow of organic matter to the soil. A good solution is the incorporation of various plant material, including harvest residues, root mass and organic fertilizer into the soil. This could help to neutralize the effects of SOM degradation, which raises concerns about C loss in the form of CO_2 emissions into the atmosphere (Lal, 2004; Navarro-Pedreno, 2021).

Leaving as large as possible amounts of post-harvest residue on the soil surface can contribute to the reducing GHG emissions directly - through the accumulation of organic C and indirectly - reducing fuel consumption and mineral fertilizer production volumes

(Hussain et al., 2022). It is estimated that 15% of photosynthetically fixed carbon is allocated into the soil via plant roots (Farrar et al., 2003). Incorporating crop residue into the soil enhances nutrient cycling, improves soil structure and promotes plant growth through their contribution to the SOC pools (Liu et al., 2014; Poeplau et al., 2015). Returning crop residue to soil using proper methods is beneficial to soil health, promoting crop productivity and sustainable agriculture (Fu et al., 2021).

Using sustainable agricultural methods, such as organic farming, can contribute in increase of organic carbon sequestration in the long term. At the same time it can reduce GHG emissions from the agricultural sector due to the fact that this system does not use synthetic nitrogen fertilizers. When used in combination with other environmentally friendly farming practices, this can lead to significant reductions in greenhouse gas emissions (Holka et al., 2022). Some studies show that organic farming practices increased SOM content by 1.90 t C per ha per year, while conventional farming practices decreased it by 1.24 t C per ha per year (Stalenga & Kawalec, 2007). Other studies also agree with the above mentioned, confirming the trend of higher SOM using organic farming practice (Brock et al., 2012).

Carbon input into the soil by plant root system is one of the most important variables driving soil C dynamics in agroecosystems and ensuring C sequestration in the long term (Kell et al., 2017). Below ground carbon (BGC) inputs reside in soil considerably longer than C derived from above-ground harvest residue and organic soil amendments (Rasse et al., 2005). As it is inherently difficult to measure BGC input in the field, it is usually estimated from yield in order to supply soil C models with input data. Several findings (Bolinder et al., 2007; Kell at al., 2017; Hirte et al., 2018) imply that yield-independent values provide closer estimates for BGC inputs to soil of cereals in different farming systems than yield-based functions. Subsequently they conclude that fertilization has only little potential to alter absolute amounts of BGC inputs to deep soil in order to sequester C in the long term. Different factors including cropping system, fertilization rate, species etc. might have a considerable impact on plant C allocation and uptake capacity. There is no definite answer, whether C inputs with below-ground residue can be reliable estimated from yield. In contrast to the concept of allometry, recent findings suggest that BGC inputs are not proportional to net primary productivity in agroecosystems and are rather a function of year, species, and farming system (Taghizadeh-Toosi et al., 2016; Hu et al., 2018).

The objectives of our studies were to quantify amount of above-ground and below-ground residue and accumulated carbon (C) and nitrogen (N) for most commonly grown cereal crops in Latvia: winter and summer wheat; winter rye; winter triticale; summer barley; summer oat; and, buckwheat using three farming systems: organic (Bio); integrated with a low input of N fertiliser (Int-low-N) and; integrated with a high input of N fertiliser (Int-high-N).

MATERIALS AND METHODS

Experimental design and background

In the field experiment most commonly grown cereals in Latvia were included - winter crops: wheat (WW), rye (WR), triticale (WT); and summer crops: wheat (SW), barley (SB), oat (SO), buckwheat (BW). Each crop in the field trials was represented by two biologically/morphologically distinct varieties (V1 and V2) which were grown using a respectable integrated (Int) and organic (Bio) farming practices. Since wheat and barley are more intensively cultivated species, the most suitable and most frequently used varieties were chosen for each cropping system. The list of all crop varieties and their brief characteristic is summarized in the Table 1.

Table 1. A brief description of the varieties included in the trial and information on their use in different cropping systems and seasons

Crop	Variety	Earliness	Stem length	Cropping system		
				2018	2019	2020
Winter wheat	Fredis	early	short stem	Int	Int	Int
	Brencis	semi early	long stem	-	Int	Int
	Edvins	early	long stem	Bio	Bio	Bio
	Talsis	semi early	long stem	-	Bio	Bio
Winter rye	Su Nasri (hybrid)	early	short stem	-	Int, Bio	Int, Bio
	Kaupo	semi early	long stem	-	Int, Bio	Int, Bio
Winter triticale	Ruja	semi late	long stem	-	Int, Bio	Int
	Ramico	semi early	short stem	-	Int, Bio	Int
Spring wheat	Taifun	semi late	short stem	Int	Int	Int
	Uffo	semi early	long stem	Int, Bio	Int, Bio	Int, Bio
	Robijs	semi late	long stem	Bio	Bio	Bio
Spring barley	Ansis	semi late	short stem	Int	Int	Int
	Kristaps	semi early	long stem	Int	Int	Int
	Rasa	early	long stem	Bio	Bio	Bio
	Jumara	semi late	long stem	Bio	Bio	Bio
Spring oat	Laima	semi early	long stem	Int, Bio	Int, Bio	Int, Bio
	Suymphony	semi late	long stem	Int, Bio	Int, Bio	Int, Bio
Buckwheat	Aiva	semi late	long stem	Int, Bio	Int, Bio	Int, Bio
	Nojas	early	long stem	Int, Bio	Int, Bio	Int, Bio

The field trials were carried out in the Stende Research Centre of the Institute of Agroresources and Economics (57.1867N, 22.5477E) in the fields of stationary plant rotation corresponding to the integrated and organic farming system. The soil type in both plant rotations was *Eutric Abeluvisols* (WRB), the soil texture - light loam (Int and Bio-1) and clay sand (Bio-). Characteristics of the experimental fields are summarized in the Tables 2, 3.

Table 2. The soil characteristic and pre-crops in integrated experimental fields

Soil indicators	2018		2019		2020	
	winter crops	spring crops	winter crops	spring crops	winter crops	spring crops
pH KCl	5.6–5.8	5.1–5.8	5.9–6.3	5.0–5.6	6.3–6.7	5.3–5.6
Organic matter, %	1.8–2.0	1.8–2.0	1.5–2.1	1.8–2.0	3.3–3.4	1.9–2.3
K_2O mg kg^{-1}	200–218	189–204	144–165	201–232	158–160	218–240
P_2O_5 mg kg^{-1}	161–192	160–206	147–150	150–186	122–144	161–193
Pre-crop	winter rape	field bean	green manure	potatoes	winter rape	potatoes

Table 3. The soil characteristic and pre-crops in organic cropping experimental fields

Soil indicators	2018 winter crops	2018 spring crops	2019 winter crops	2019 spring crops	2020 winter crops	2020 spring crops
Organic field Bio-1						
pH KCl	6.8	6.4	6.8	6.4	5.9	6.0
Organic matter, %	2.3	2.7	1.9	2.8	3.2	1.9
K_2O mg kg^{-1}	90.8	127	114	127	122	108
P_2O_5 mg kg^{-1}	183	206	199	206	201	171
Pre-crop	green manure	winter wheat	spring barley	spring oat	potatoes	winter wheat
Organic field Bio-2						
pH KCl	5.8	6.1	6.4	6.4	-	6.7
Organic matter, %	3.8	4.9	2.5	4.9	-	4.5
K_2O mg kg^{-1}	135	42	132	52	-	75
P_2O_5 mg kg^{-1}	83	19	188	39	-	39
Pre-crop	green manure	green manure	potatoes	green manure	-	buckwheat

In integrated farming practice, studies were implemented by observing two levels of cultivation intensity, which differ in the amount of nitrogen fertilizer used: Int-low-N (the lowest fertilizer rate) and Int-high-N (the highest fertilizer rate) and correspond to the most commonly used N fertilizer rate for a specific species in farm practice. In an integrated farming system, complex mineral fertilizer was incorporated into the soil before sowing: NPK (10-26-26) 330 kg ha^{-1} for winter crops; NPK (8-20-20) 350 kg ha^{-1} for summer crops. These mineral fertilization rates for each field plant species are listed in the Table 4.

Table 4. The nitrogen fertilizer rates for different crops in an integrated farming system

Cereals	Fertilization rate in spring (N, kg ha^{-1} in pure matter)	
	Int-low-N	Int-high-N
Winter wheat (WW)	75*	135*
Winter rye (WR)	75*	115*
Winter triticale (WT)	75*	135*
Spring wheat (SW)	100	140
Spring barley (SB)	100	140
Spring oat (SO)	80	100
Buckwheat (BW)	80	100

* before winter crop sowing, soil was fertilized with basic complex (NPK) mineral fertilizer, including 33 N kg ha^{-1} in pure matter.

In organic farming practice, experiments were conducted in two fields with different soil fertility indicators (Bio-1 and Bio-2). In organic farming plant rotations, nutrients were provided by growing green manure plants and incorporating the residue of the previous crop into the soil (straw, roots, etc.).

The soil cultivation was carried out by plowing in the fall to a depth of 15 to 18 cm. Before sowing the soil was leveled using a harrow and cultivated to a depth of 5 cm. Sowing was done for each species in optimal sowing terms, observing the distance between rows of 12.5 cm. Sowing rate was 450–500 germinating seeds per m^2 for cereal species; 220 germinating seeds per m^2 for buckwheat. In the field experiments, each research variant was arranged in a 20 m^2 plot area in four replicates. Research options were arranged on the field in blocks. Plant biomass samples were collected at the stage of Zadoks Growth Stage

GS84–89. The grain from all plot was harvested with a small-sized grain harvester Wintersteiger Delta at the stage GS95–99.

Collection and analysis of samples

The cereal plant biomass samples were taken from 0.125 m^2 area in two locations in each plot. For below-ground (BG) residue sampling, the 0.0–0.2 m soil profile was taken using the same accounting area used for the above-ground (AG) residue. Roots were rinsed on a sieve with a mesh size of 1.0×1.0 mm. Below-ground and above-ground residue samples were air-dried and weighed separately using a laboratory scale (with an accuracy of 0.01 g). The dry matter (DM) of each sample was determined according to the standard ISO 6496:1999 at the Laboratory of Cereal Technology and Agricultural Chemistry of the Institute of Agricultural Resources and Economics. To determine the carbon content in biomass, the following methods according to the LVS ISO standards LVS ISO 10694:2006 and LVS ISO 13878:1998 were used: total carbon (C) and total nitrogen (N) by an elemental analyser (dry combustion) vario EL cube.

Description of the meteorological conditions

In all three growing seasons when field experiments were conducted, the monthly air temperatures exceeded the long-term averages. Separate short periods of extreme drought and heat were also been observed in all seasons (Fig. 1).

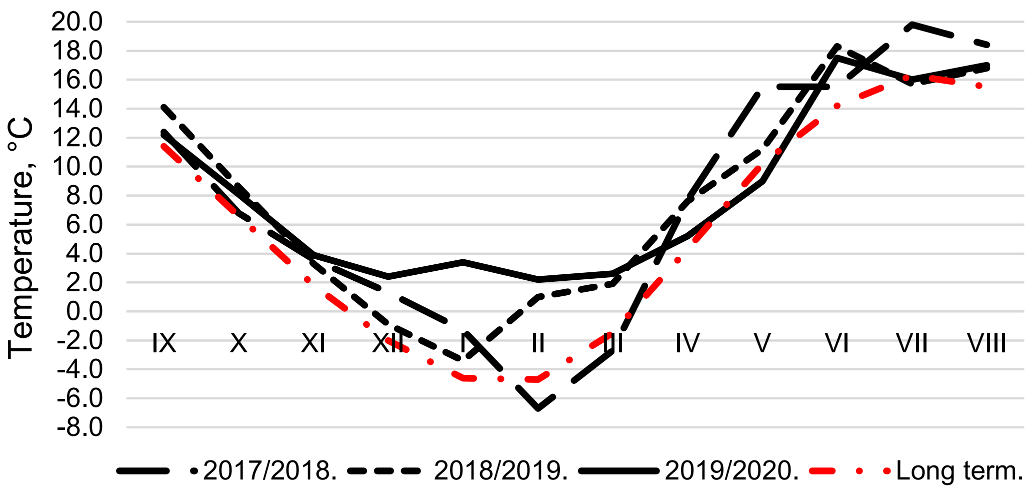

Figure 1. Average air temperatures °C (2018–2020) at Stende RC compared to the long-term averages.

During the winter period, the daily average air temperatures were favourable for wintering of wheat, rye and triticale. In April, when plant vegetation recovered, the average air temperatures in all trial years were higher than that of long-term averages. This contributed to more rapid plant development.

The spring of 2018 turned out to be very dry with only 14 mm of precipitation in May and the first two ten-day periods of June, and air temperature at that time was higher than the long-term average. Such conditions were not favourable for the optimal development of spring crops and significantly affected the production of plant biomass.

Precipitation in July and August only partially compensated the lack of moisture at the beginning of the vegetation season.

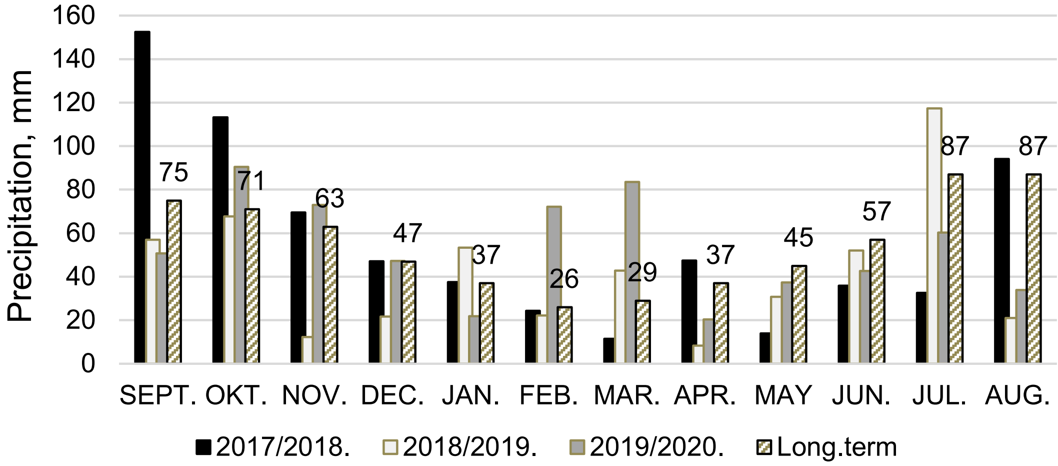

Figure 2. The amount of precipitation by month (2018–2020) at Stende RC compared to the long-term averages.

In July of 2019 and 2020, monthly air temperatures were close to long-term averages (Fig. 1). The highest amount of precipitation in the years of the experiment was observed in late July and August (Fig. 2). This is consistent with long-term observations. Part of the precipitation during this period came with heavy rains and thunderstorms, such precipitation quickly flows away from the field to water bodies (rivers, ditches), does not accumulate in the soil, and plants can use it only partially. Winter crops usually reach maturity in the first days of August, the amount of precipitation received until the last ten days of July is crucial for increasing their biomass whereas for summer crops it is the amount of precipitation until the first ten days of August.

Statistical analysis

The experimental data were statistically processed using descriptive statistics methods and Pearson correlation by Microsoft Excel and IBM SPSS Statistics for Windows. The normal distribution of the data was checked using Kurtosis and Skewness values. Regression and analysis of variance (ANOVA) were performed using R Studio for Windows (RStudio, PBC). The statistical indicators for regression and ANOVA are the p-value for the model parameters, and the R2 for the usefulness of the regression model. The entire database was used for regression ANOVA. To determine significant differences, a t-Test: Two-Sample Assuming Unequal Variances was used. Pairs were compared with each other, i.e.: Bio (a) and Int-low-N (b) cropping system; Int-low-N (b) and Int-high-N (c) cropping system; Bio (a) and Int-high-N (c) cropping system.

RESULTS AND DISCUSSION

Research data show that cereal harvest residue varied significantly with farming system and cereal species. Significant differences in the amount of above-ground (AG) residue were found between different cropping systems. The dry matter (DM) of AG residue depending of cropping system and species ranged within: 308.68 ± 11.92 g m^{-2} (s. barley) – 682.93 ± 32.18 g m^{-2} (w. rye); 568.90 ± 24.99 g m^{-2} (s. barley) – 1,250.29 ± 86.22 g m^{-2} (w. rye); and 638.70 ± 17.76 g m^{-2} (s. wheat) – 1,386.71 ± 136.15 g m^{-2} (w. triticale) in organic cropping system (Bio); integrated with low N input (Int-low-N) and; integrated with high N input (Int-high-N), respectively (Table 5). Above-ground crop residue yields are approximately 60% of grain yield, meaning large inputs of residue carbon into soils (Gosling et al., 2017). High biomass translates to better weed management, soil moisture conservation, and fertility improvement (Murungu et al., 2011). Crop residues used as mulch are central to the success of moisture conservation, weed suppression, and SOM improvement, and as a result high soil and crop productivity (Hatfield, 2001; Hamelin et al., 2019).

Table 5. Above-ground residue (DM, g m^{-2}) of different cereals in different cropping systems

Species	Cropping system		
	Bio	Int-low-N	Int-high-N
W. wheat	525.99 ± 35.30^{a}	776.19 ± 25.52^{b}	867.09 ± 25.81^{c}
S. wheat	368.99 ± 18.40^{a}	589.40 ± 17.67^{b}	638.70 ± 17.76^{c}
W. rye	682.93 ± 32.18^{a}	1,250.29 ± 86.22^{b}	1,380.88 ± 93.95^{c}
W. triticale	454.94 ± 32.89^{a}	1,231.92 ± 103.69^{b}	1,386.71 ± 136.15^{c}
S. barley	308.68 ± 11.92^{a}	568.90 ± 24.99^{b}	643.08 ± 23.82^{c}
S. oat	374.09 ± 16.07^{a}	688.60 ± 22.24^{b}	745.87 ± 22.96^{c}
Buckwheat	543.58 ± 23.24^{a}	580.39 ± 32.21^{a}	748.14 ± 36.34^{b}

The table shows the mean values and standard error; abc – different lowercase letters in the superscript denote significant differences ($p < 0.05$) between the average values in cropping systems and species.

Also, with respect to the biomass of below-ground (BG) residue, significant differences were found both between different cropping systems and species used. The lowest amount of BG residue in all systems was produced by buckwheat. Among cropping systems, the DM of BG residue ranged within: 63.93 ± 1.81 g m^{-2} (buckwheat) – 170.36 ± 12.33 g m^{-2} (w. rye); 66.71 ± 3.78 g m^{-2} (buckwheat) – 232.41 ± 20.78 g m^{-2} (w. triticale); 84.10 ± 5.01 g m^{-2} (buckwheat) – 275.16 ± 26.16 g m^{-2} (w. triticale) in Bio system; Int-low-N and; Int-high-N input system, respectively (Table 6).

Table 6. Below-ground residue (DM, g m^{-2}) of different cereals in different cropping systems

Species	Cropping system		
	Bio	Int-low-N	Int-high-N
W. wheat	113.36 ± 9.60^{a}	143.94 ± 12.41^{b}	141.63 ± 10.84^{c}
S. wheat	80.00 ± 3.91^{a}	123.50 ± 5.32^{b}	134.26 ± 6.51^{c}
W. rye	170.36 ± 12.33^{a}	231.73 ± 21.65^{b}	247.40 ± 24.62^{b}
W. triticale	132.22 ± 10.08^{a}	232.41 ± 20.78^{b}	275.16 ± 26.16^{c}
S. barley	78.15 ± 6.62	83.64 ± 2.13	87.59 ± 1.83
S. oat	105.28 ± 6.19^{a}	141.50 ± 5.73^{b}	145.76 ± 6.30^{c}
Buckwheat	63.93 ± 1.81^{a}	66.71 ± 3.78^{a}	84.10 ± 5.01^{b}

The table shows the mean values and standard error; abc – different lowercase letters in the superscript denote significant differences ($p < 0.05$) between the average values in cropping systems and species.

In our research, BG residue accounted for an average of 23% of AG residue in the Bio system (among crops it ranged within 12–29%). The differences in integrated cropping system between Int-low-N and Int-high-N input systems were insignificant: in the Int-low-N system BG residue accounted for an average 18% (11–21% depending on crop species); in the Int-high-N input system 17% (11–21% depending on crop species). Relatively higher cereal root biomass was formed in the organic cropping system (Fig. 3). This indicates to proportionally larger contribution of organic matter from the cereal BG residue even in cases when the AG residue is taken away from the field. When used together with other environmentally friendly farming practices, significant increase in soil C and reductions of GHG emissions can be achieved (Holka et al., 2022).

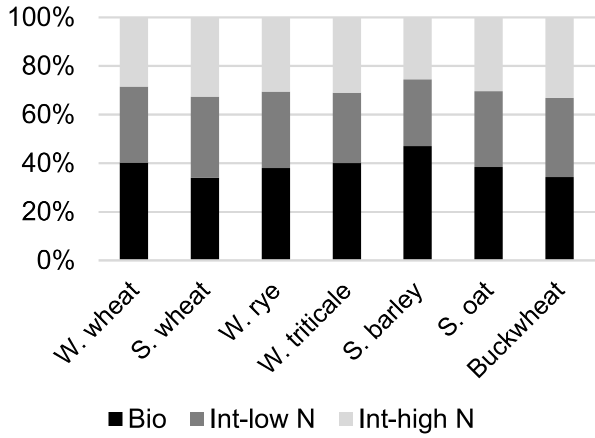

Figure 3. Proportion of root biomass (below-ground residue) in cereal crops using different farming systems.

The DM of total harvest residue (AG + BG residue) ranged within: 386.83 ± 15.53 m^{-2} (s. barley) – 853.28 ± 40.76 g m^{-2} (w. rye); 647.1 ± 35.02 g m^{-2} (buckwheat) – 1,482.02 ± 105.06 g m^{-2} (w. rye); 730.68 ± 24.92 g m^{-2} (s. barley) – 1,661.87 ± 134.95 g m^{-2} (w. triticale) in Bio; Int-low-N and; Int-high-N, respectively (Fig. 4).

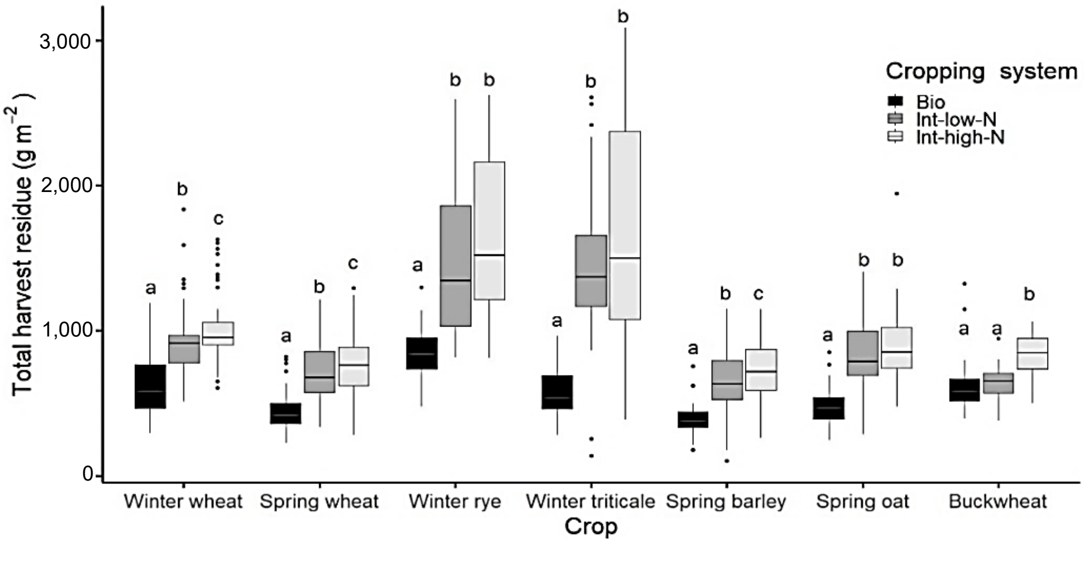

Figure 4. Total harvest residue (AG + BG residue) (DM g m^{-2}) of cereal crops in different cropping systems.

Crops that during vegetation produce large biomass and leave significand amount of crop residue in the field, such as winter rye and winter triticale, could have a beneficial effect on the growth of soil organic matter (SOM). An effective way to improve the resources of the SOM is to increase the productivity of crops, including the total amount of biomass thereby increasing the amount of crop residue (Sarkar et al., 2020).

Plants accumulate considerable amounts of C during growth. The average C content in cereal straw or AG harvest residue fluctuates around 450 g kg^{-1} C, while the C content in root mass (BG residue) is lower, it fluctuates around 370 g kg^{-1} C on average (Rancane et al., 2023). Together with the relatively lower ratio of BG residue to AG residue, the amount of accumulated C in BG residue was lower, but it still makes a significant contribution to both soil quality improvement and overall C sequestration.

In the Bio system, the amount of accumulated C in the AG residue ranged from 103.78 g m^{-2} C (s. barley) to 221.96 g m^{-2} C (w. rye) and almost the same amount – 218.8 g m^{-2} C was also accumulated in the buckwheat AG harvest residue (Table 7). The amount of C accumulated in the integrated system was at least twice as much, ranging from: 251.02 g m^{-2} C (s. barley) to 414.29 g m^{-2} C (w. rye) using Int-low-N input system and; from 281.53 g m^{-2} C (s. barley) and 288.49 g m^{-2} C (s. wheat) to 451.11 g m^{-2} C (w. triticale) using Int-high-N input system.

Table 7. Accumulated C (g m^{-2}) in DM of above-ground residue using different cropping systems

Species	Cropping system		
	Bio	Int-low-N	Int-high-N
W. wheat	195.18 ± 23.08^{a}	343.62 ± 11.52^{b}	381.73 ± 11.68^{c}
S. wheat	139.85 ± 11.11^{a}	265.51 ± 7.70^{b}	288.49 ± 7.97^{c}
W. rye	221.96 ± 22.66^{a}	414.29 ± 55.11^{b}	434.87 ± 52.40^{c}
W. triticale	142.23 ± 17.05^{a}	393.36 ± 29.34^{b}	451.11 ± 40.78^{c}
S. barley	103.78 ± 6.58^{a}	251.02 ± 11.12^{b}	281.53 ± 10.63^{c}
S. oat	138.54 ± 8.69^{a}	264.02 ± 14.95^{b}	309.19 ± 13.69^{c}
Buckwheat	215.80 ± 9.92^{a}	259.39 ± 14.36^{b}	334.61 ± 16.84^{c}

The table shows the mean values and standard error; abc – different lowercase letters in the superscript denote significant differences ($p < 0.05$) between the average values in cropping systems and species.

Both for the purpose of improving soil fertility and greatest possible C assimilation, it is desirable to increase the proportion of crops in the crop rotation that form a voluminous root system and large above-ground biomass also. This could help for the sequestration of a significant amount of C and will contribute to the increase in soil organic matter, especially in cases where the contribution of organic matter will be formed not only from the root mass, but also the surface crop residues will be left on the field. It would be especially important to follow this using organic system management, where crop productivity is usually lower and crops are forced to compete with weeds 'in a natural way' and there are limited opportunities to achieve a rapid increase in yield by using mineral fertilizers.

The amount of C accumulated in BG residue was significantly lower (11–27% depending on crop species, 21% on average) than that accumulated in AG residue (Table 8). In Bio system it ranged from 23.64 ± 0.95 g m^{-2} C (buckwheat) and 24.96 ± 1.42 g m^{-2} C (s. barley) to 46.62 ± 6.89 g m^{-2} C (w. rye). Relatively high uptake by the root system was also ensured by other winter cereals - w. triticale (37.89 ± 6.16 g m^{-2} C) and w. wheat (28.01 ± 1.78 g m^{-2} C). Among spring cereals, the greatest C uptake was provided by s. oat (36.05 ± 2.76 g m^{-2} C), as during growing season they develop a large root system even in more modest soil conditions. This crop is also perfectly suitable for cultivation using organic cropping system. Below ground carbon input to soil by root biomass is among the most important variables driving soil C dynamics in agroecosystems. As C allocation below ground is the primordial pathway for C to enter soil, promotion of crop growing with large root system may play a decisive role in soil C sequestration (Pierret et al., 2016; Kell et al., 2017). Roots often contribute more to SOC due to a higher degree of carbon stabilization than that of aboveground biomass (Poeplau et al., 2015; Bjornsson & Prade, 2021).

Table 8. Accumulated C in below-ground residue (g m^{-2}) in different cropping systems

Species	Cropping system		
	Bio	Int-low-N	Int-high-N
W. wheat	39.26 ± 5.26^{a}	55.72 ± 4.46^{b}	54.58 ± 4.15^{c}
S. wheat	28.01 ± 1.78^{a}	48.22 ± 1.71^{b}	48.05 ± 1.69^{c}
W. rye	46.62 ± 6.89	59.46 ± 10.46	61.70 ± 10.55
W. triticale	37.89 ± 6.16^{a}	64.83 ± 8.36^{b}	70.0 ± 9.53^{c}
S. barley	24.96 ± 1.42^{a}	35.83 ± 0.98^{b}	37.27 ± 0.81^{c}
S. oat	36.05 ± 2.76^{a}	47.70 ± 1.40^{b}	46.35 ± 1.37^{c}
Buckwheat	23.64 ± 0.95^{a}	26.82 ± 1.05^{b}	31.37 ± 1.14^{c}

The table shows the mean values and standard error; abc – different lowercase letters in the superscript denote significant differences ($p < 0.05$) between the average values in cropping systems and species.

Using the integrated system, the greatest C uptake by root biomass among winter crops was caused by w. triticale (64.83 ± 8.36 g m^{-2} C and 70.0 ± 9.53 g m^{-2} C in Int-low-N and Int-high-N system, respectively) rather than w. rye (59.46 ± 10.46 g m^{-2} C, and 61.70 ± 10.55 g m^{-2} C); among spring crops it was s. wheat (48.22 ± 1.71 g m^{-2} C and 48.05 ± 1.69 g m^{-2} C in Int-low-N and Int-high-N system, respectively) rather than s. oat (47.70 ± 1.40 g m^{-2} C and 46.35 ± 1.37 g m^{-2} C). The mentioned crops are intensively grown crops that are very responsive to N fertilizers. Data analysis show that more stable species in all cropping systems was w. rye, for which C uptake by BG residue did not differ significantly among cropping systems. Hirte et al. (2018) concluded that fertilization has only little potential to alter absolute amounts of BGC inputs to deep soil in order to sequester C in the long term.

In previously conducted studies found that root biomass C of winter wheat ranges between 40 and 125 g m^{-2}; median of 9 studies – 60 g m^{-2} (Hoad et al., 2001; Williams et al., 2013; Hu et al., 2018). Root biomass in low-intensity systems was found to be similar as or even higher than that in high-intensity systems (Chirinda et al., 2012; Lazicki et al., 2016; Hirte et al., 2018). This is in line with the results of our research, where we found that below-ground residue and accumulated C of w. wheat in the integrated system with low N input be equivalent and even slightly higher than in the system with high N input (Tables 6, 8).

Proportionally, the largest amount of accumulated C in the BG residue compared to that accumulated in the AG residue in Bio system was for w. triticale and s. oat - 27 and 25%, respectively; the lowest – only 11% was for buckwheat. In the integrated system, the amount of C accumulated by BG residue was proportionally lower - on average 15% in Int-low-N (fluctuated between 10–18% depending on the species) and 14% in Int-high-N (fluctuated between 10 - 18% depending on the species).

In integrated system, the total amount of accumulated C in AG and BG residue varied within the following limits: 128.74 ± 7.01 g m^{-2} C (s. barley) - 268.57 ± 28.68 g m^{-2} C (w. rye) using Bio cropping system; 286.21 ± 15.24 g m^{-2} C (buckwheat) and 286.85 ± 11.59 g m^{-2} C (s. barley) – 473.75 ± 64.85 g m^{-2} C using Int-low-N system; 318.79 ± 11.09 g m^{-2} C (s. barley) – 521.11 ± 46.26 g m^{-2} C (w. triticale) using Int-high-N system (Fig. 5). Hirte et al. (2018) found that the shift in whole-plant C allocation for wheat towards AG biomass with increasing fertilization intensity entailed 10% higher C allocation below ground in organic than conventional farming.

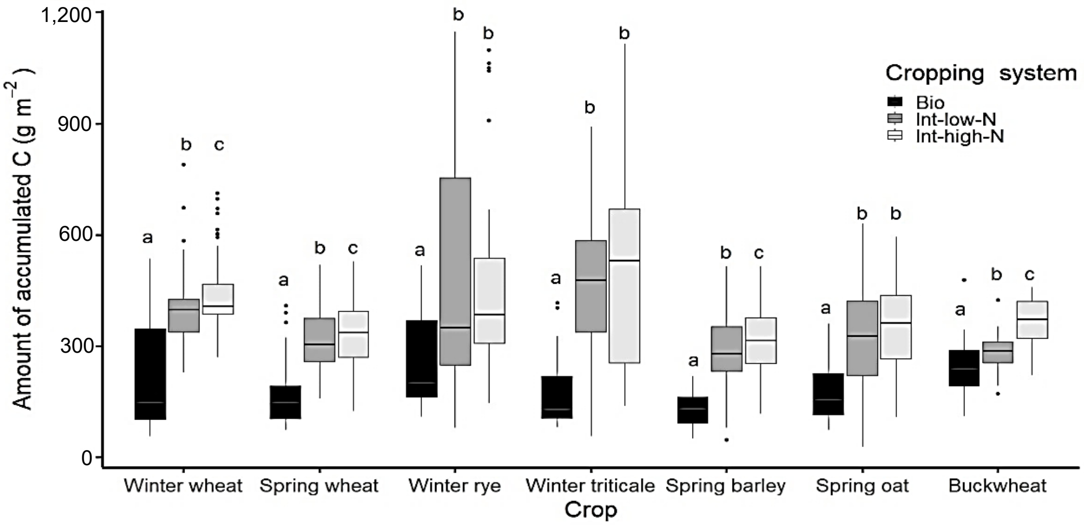

Figure 5. Total amount of accumulated C (g m^{-2}) by cereal in AG and BG residue in different cropping systems.

The amount of N accumulated by AG residue ranged within the following limits: 3.18 ± 0.47 g m^{-2} N (w. triticale) – 6.45 ± 0.3 g m^{-2} N (buckwheat) in Bio system; 8.29 ± 0.50 g m^{-2} N (s. oat) – 11.33 ± 0.98 g m^{-2} N (w. triticale) in Int-low-N system; 11.1 ± 0.45 g m^{-2} N (s. barley) – 15.67 ± 1.69 g m^{-2} N (w. triticale) in Int-high-N system (Fig. 6).

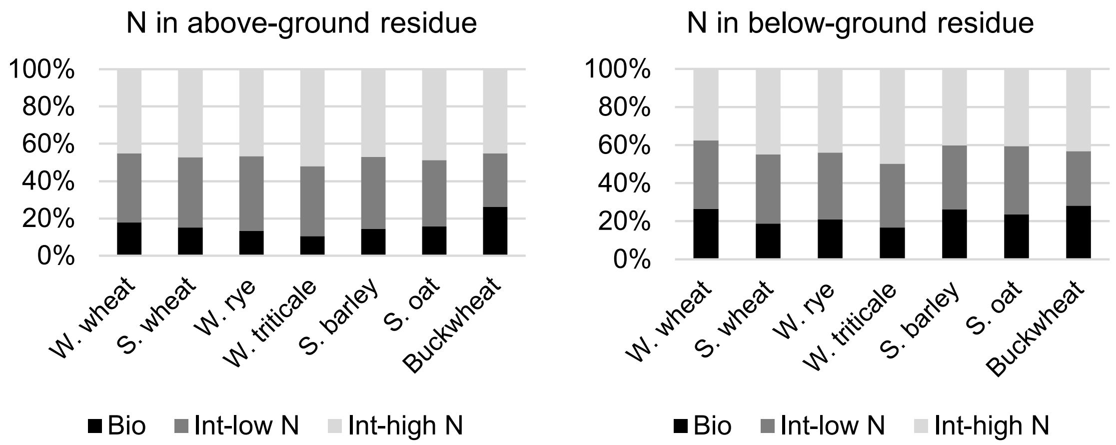

Figure 6. The proportion of nitrogen (N) accumulated by above-ground and below-ground residue in different management systems.

The amount of N accumulated by below-ground residue ranged within the following limits: 0.43 ± 0.04 g m^{-2} N (buckwheat) – 0.82 ± 0.13 g m^{-2} N (w. rye) in Bio system; 0.44 ± 0.03 g m^{-2} N (buckwheat) – 1.36 ± 0.27 g m^{-2} N (w. rye) in Int-low-N system; 0.66 ± 0.04 g m^{-2} N (buckwheat) – 1.71 ± 0.36 g m^{-2} N (w. rye) in Int-high-N system. Comparing the systems, proportionally the highest amount of N with both above-ground and below-ground residue was accumulated in the Int-high-N system; the lowest in the Bio system (Fig. 6).

CONCLUSIONS

The amount of cereal crop residue and accumulated carbon (C) and nitrogen (N) varied significantly depending on the crop species and cropping system. The highest amount of total harvest residue and accumulated C in all cropping systems was produced by winter cereals - rye was on the top: 268.57 ± 28.68 g m^{-2} C using Bio cropping system; 496.57 ± 62.54 g m^{-2} C using Int-high-N system. In the Bio system, high biomass of buckwheat allowed them stably to compete with rye - the total amount of accumulated C by crop residues was 239.4 ± 10.50 g m^{-2} C.

Although a higher total harvest residue was produced using integrated system with high N input, higher proportion of root biomass cereals formed using organic cropping system.

The amount of accumulated N, depending on the crop and cropping system, varied quite significantly: the highest amount by BG and AG residue in the Bio system bound buckwheat – 6.88 g m^{-2} N; in the integrated system w. triticale – 12.6 g m^{-2} N (Int-low-N) and 17.56 g m^{-2} N (Int-high-N).

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