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CAN CATCH CROPS BE AN IMPORTANT FACTOR IN CARBON DIOXIDE SEQUESTRATION?

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Abstract

The sequestration of carbon dioxide in the biomass of plants, especially the ones which can be cultivated as catch crops is described. It has been shown that the cultivation of catch crops may play an important role in the mitigation of CO_2 emissions. A study on the importance of catch crops (in relation to the main crop) in carbon dioxide sequestration was conducted over the period of 2016-2018 under the soil and climatic conditions of the central Lublin region, Poland. Subsequently, ploughed-in catch crop biomass is a kind of 'soil CO_2 bank'. It was proven that in the case of successful catch crops one can expect carbon dioxide sequestration by these crop cultures to be at a level from 4 to 6 tons CO_2 $ha^{-1}\cdot yr^{-1}$. The quantity of CO_2 absorbed from the atmosphere by a catch crop is directly proportional to biomass yield produced by it. The following species, which are resilient to adverse weather conditions during seeding and initial plant growth, proved to be particularly useful in carbon dioxide sequestration by catch crops: white mustard, tansy phacelia, winter rye, winter wheat + winter vetch mixture. Catch crops also positively affect the amount of soil organic C compared to soils where they are not grown. Based on the obtained study results, it can be tentatively stated that catch crops are an important factor in carbon dioxide sequestration in broadly understood agricultural activity. It is advisable to promote catch crops on a wide scale due to relatively small costs of such crops compared to the benefits arising from them (phytosanitary effects on soil, CO_2 sequestration, and soil carbon storage). It is however necessary to conduct further research in this area in order to determine the suitability of specific catch crop species for CO_2 sequestration in various climatic and soil zones.

***Keywords**: Climate change; Carbon dioxide sequestration; Organic carbon content; Main crops; Catch crops; Soil*

Introduction

In a low-emission economy, rural areas and agriculture can be of paramount importance. Many studies [1-6] stress the important role of crops in mitigating the CO_2 emissions into the atmosphere. The use of plants as a source of energy is widely advocated as a remedy for CO_2 emissions. Nevertheless, the role of terrestrial ecosystems, including agriculture, in mitigating the increase of CO_2 concentration in the atmosphere remains underappreciated. It should be noted that the emissions from fossil fuels combustion and cement production constitute only about 4.7% of CO_2 emissions from the natural sources, i.e. terrestrial ecosystems and oceans [4, 7, 8].

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The advantages of most rural areas in Poland include, among others, large agricultural land resources and the possibility of using their potential to grow catch crops. A catch crop is a crop grown in pure stand or in mixtures, cultivated in a crop rotation between the main crops. In this way, a third additional yield from a field over a two-year period is obtained. The plants with a short growing period (with a fast growth rate) are primarily grown as catch crops, and they are used during the vegetative growth period or at the initial stage of generative growth, most frequently for the so-called green manure (mixed with soil/ploughed under) or as mulch (plants cut in autumn and left on the field surface to early spring, undergoing slow mineralization) [9, 10].

Catch crops, as an additional plant cover on a field during the growing season, can significantly contribute to sequestration of CO_2 from the atmospheric air and subsequently to trapping CO_2 in soil [11, 12].

Currently, a certain barrier to the development of a low-emission economy in rural areas in Poland can also be observed – plants for crop rotation are frequently selected inappropriately (without promoting catch crops). Moreover, farmers rarely grow proper catch crop species (those that are adapted to local soil and climatic conditions and which leave a large amount of biomass in the form of crop residues incorporated into soil) [13, 14].

Thus, the assumed increase in the importance of catch crops – growing crops with a soil organic matter reproduction rate (e.g. large-seed and small-seed legumes as well as their mixtures with cereals and grasses, white mustard, tansy phacelia) – constitutes an opportunity for the rural areas and agriculture [15-17]. In Poland catch crops are very popular as an in-between crop in cereal monocultures [18].

Taking into account the above considerations, this study hypothesized that: an assumption was made that successful catch crops producing large aboveground and belowground biomass in a short time can absorb substantial amounts of CO_2 ha^{-1} per year. Promoting this type of crops across the whole continent would contribute to realistically greater CO_2 sequestration by crop plants, thus being an added value in total sequestration of CO_2 by agriculture.

The aim of the present study was to determine the possibility and range of CO_2 sequestration by some plant species grown as catch crops (stubble crops, winter cover crops, undersown crops) relative to eighteen species (cereal, root and tuber, legume, oilseed, and meadow and pasture plants) grown as the main crop (a list of crop plant species is below - in the Methods section). This study evaluated CO_2 sequestration by aboveground organs (primary and secondary yield) and belowground organs of these plants. It also analyzed the importance of catch crops in soil organic carbon storage.

Methods

Over the period 2016-2018, studies of two types were conducted in production fields at the Czesławice Experimental Farm (51°30′N; 22°26′E - Lubelskie Voivodeship, Poland) on loess soil [19] with the grain size distribution of silt loam (PWsp) and classified as good wheat soil complex (soil class II). The experiment was set up as a split-plot design with 3 replicates in $12m^2$ plots (single plot: 3×4m).

CO_2 sequestration by aboveground and belowground plant parts

The first type of study related to CO_2 sequestration by aboveground and belowground plant parts. This study was carried out on 18 selected agricultural crops being the main crop: winter wheat (*Triticum aestivum* L.), spring wheat (*Triticum aestivum* L.), spring barley (*Hordeum vulgare* L.), winter rye (*Secale cereale* L.), winter triticale (*x Triticosecale*), oats (*Avena sativa* L.), maize (*Zea mays* L.), proso millet (*Panicum miliaceum* L.), buckwheat (*Fagopyrum esculentum* L.), amaranth (*Amaranthus cruentus* L.), winter oilseed rape (*Brassica napus* L. var. *napus*), soybean (*Glycine max* (L.) Merr.) lentil (*Lens culinaris* L.), narrow-leafed lupin (*Lupinus angustifolius* L.), potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L. subsp. *vulgaris* convar. *vulgaris* var. *altissima*), carrot (*Daucus carota* L.) and meadow hay; and 14 catch crops being an additional crop during the growing season, grown in pure stand and in mixtures: white mustard (*Sinapis alba* L.), spring oilseed rape (*Brassica napus* L. var. *napus*), tansy phacelia (*Phacelia tanacetifolia* L.), red clover (*Trifolium pretense* L.), serradella (*Ornithopus sativus* Brot.), westerwolds ryegrass (*Lolium multiflorum* L. var. *westerwoldicum*), spring vetch (*Vicia sativa* L.) + field pea (*Pisum sativum subsp. arvense* (L.) Asch.), narrow-leafed lupine (*Lupinus angustifolius* L.), yellow lupine (*Lupinus luteus* L.), oats (*Avena sativa* L.) + spring vetch (*Vicia sativa* L.) + field pea (*Pisum sativum* subsp. *arvense* (L.) Asch.), winter rye (*Secale cereale* L.), perennial ryegrass (*Lolium perenne* L.) + winter vetch (*Vicia villosa* Roth.), winter wheat (*Triticum aestivum* L.) + winter vetch (*Vicia villosa* Roth.). All the plant species analyzed in this research design were grown in the conventional farming system; conventional (plough) tillage was used, while fertilization and plant protection products were applied at dates and rates recommended for the specific species. At the agronomically optimal harvest date of the particular main crop plant, plant material samples were collected (plants were pulled out from 1.0m^2 of each study plot) in order to determine the following parameters (expressed on a t/ha basis): primary yield (grain, seeds, roots, tubers, biomass), secondary yield (straw, stems, leaves), belowground crop residues (roots) and total yield (primary yield + secondary yield + crop residues). At the agronomically optimal harvest date of the particular catch crop plant, plant material samples were collected from an identical area (1.0m^2) of each cover-cropped plot in order to determine total biomass yield (aboveground parts and roots). Samples were taken at 4 randomly selected places in each plot, according to the design shown in figure 1, within a 0.25×1.00m frame.

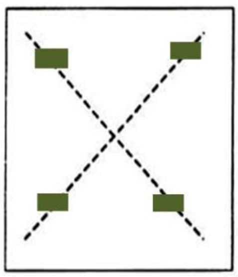

Fig. 1. The plant sampling scheme in a single plot (12m^2) for primary yield of catch crops

The collected samples were segregated into individual yield fractions and dried under laboratory conditions at a temperature of 40°C to determine yield (t·ha^{-1}). Next, carbon (C) content in plant tissues was determined for the individual yield fractions [20] and expressed as CO_2 content. CO_2 sequestration efficiency was calculated taking into account primary yield of the crop (whose dry matter was 85-88%, depending on the crop plant species) and carbon (C) content determined on a dry matter basis in the individual crop species. The determined carbon content was expressed on a CO_2 basis by multiplying C × 3.67 (t·ha^{-1}). Then, CO_2 sequestration (t CO_2 ha^{-1}·yr^{-1}) was calculated based on the yield of the individual plants (t·ha^{-1}).

Determination of soil organic C content

The second type of study involved the determination of organic C content (with a carbon analyzer) in the soil under the selected plants grown as catch crops (white mustard, spring oilseed rape, tansy phacelia, red clover, serradella, Westerwolds ryegrass, spring vetch + field pea, narrow-leafed lupine, yellow lupine, oats + spring vetch + field pea, winter rye, perennial ryegrass + winter vetch, winter vetch, winter wheat + winter vetch) relative to the control treatment without catch crop. Organic carbon content was expressed in g kg^{-1} soil. To determine the comprehensive effect of catch crops on soil chemistry (organic carbon content), soil samples were taken from the 0-20cm layer of soil. Soil samples were taken using a soil sampling tube from an area of 0.20m^2 in each plot in autumn.

Statistical analysis

Analysis of variance (ANOVA) was used to statistically analyze the results by employing Statistica PL 13.3, while Tukey's test was applied to determine HSD (Honest Significant Difference) values at $p < 0.05$. The mean for the study period is given in the results tables because the year-to-year differences between the characteristics analyzed were statistically insignificant. No significant interaction was found between the experimental factors: A (main crops/catch crops), and years (B). For the resulting data presented in tables 1, 2 and 4 the following were calculated: SD - standard deviation and CV - coefficient of variation. Moreover, to determine dependencies and relationships between the studied characteristics, correlation (r) analysis was applied.

Results

Productivity of main crops and CO_2 sequestration

The productivity of crops specified in table 1, grown under the soil and climatic conditions of the central Lublin region (Czesławice Experimental Farm), is generally higher that the average yield of these species in Poland [21].

Table 1. Primary and secondary yield of major crops based on data obtained for crops grown and CO_2 sequestration

Crop	Primary yield (grain/seeds, roots, tubers, biomass) t·ha^{-1}	CV (%)**	Secondary yield (straw, stems, leaves) t·ha^{-1}	CV (%)	Below ground crop residues (roots) t·ha^{-1}	CV (%)	Total carbon sequestration in biomass of primary yield, secondary yield, and roots (t CO_2 ha^{-1}·yr^{-1})	CV (%)
Winter wheat	6.36 ±0.51*	5.7	4.22 ±0.40	4.8	0.12 ±0.03	1.9	16.6 ±2.77	6.1
Spring wheat	5.57 ±0.46	5.2	3.94 ±0.33	5.1	0.11 ±0.02	2.5	14.9 ±1.92	5.4
Spring barley	5.34 ±0.43	3.6	3.70 ±0.25	3.1	0.10 ±0.01	2.8	14.2 ±1.64	3.9
Winter rye	4.51 ±0.39	4.5	3.65 ±0.21	4.9	0.13 ±0.02	2.7	12.9 ±1.21	5.1
Winter triticale	5.46 ±0.52	3.7	3.98 ±0.35	5.2	0.12 ±0.02	2.2	14.9 ±1.32	4.0
Oats	4.03 ±0.49	4.9	3.26 ±0.17	3.5	0.09 ±0.01	1.6	11.5 ±1.07	5.3
Maize	8.39 ±0.68	5.8	4.12 ±0.41	6.0	0.45 ±0.09	3.5	20.2 ±2.86	6.2
Proso millet	3.33 ±0.21	3.9	2.17 ±0.12	3.3	0.06 ±0.01	2.0	8.66 ±0.99	4.5
Buckwheat	3.05 ±0.18	4.6	2.11 ±0.09	2.8	0.07 ±0.01	2.4	8.15 ±0.67	5.2
Amaranth	3.29 ±0.23	5.1	2.28 ±0.11	3.5	0.07 ±0.01	1.8	8.79 ±0.73	5.7
Winter oilseed rape	4.56 ±0.39	4.4	3.67 ±0.26	5.9	0.14 ±0.03	2.9	13.0 ±1.12	4.9
Soybean	3.47 ±0.22	5.0	3.12 ±0.19	3.7	0.25 ±0.05	2.6	10.6 ±0.98	5.5
Lentil	1.14 ±0.13	4.2	0.85 ±0.06	4.5	0.17 ±0.03	1.1	3.3 ±0.25	4.6
Narrow-leafed lupin	3.94 ±0.25	3.5	3.73 ±0.22	2.6	0.32 ±0.07	2.7	12.4 ±1.16	3.8
Potato	32.3 ±1.98	9.5	18.9 ±1.16	7.0	0.19 ±0.04	3.9	43.2 ±2.49	9.9
Sugar beet	60.2 ±3.26	9.7	47.1 ±2.94	7.5	-	5.2	80.4 ±3.75	10.3
Carrot	55.4 ±2.33	8.4	44.2 ±2.04	7.9	-	4.2	71.8 ±3.26	9.5
Meadow hay (in total from 2 cuts)	5.42 ±0.33	5.9	-	-	0.06 ±0.01	3.3	8.54 ±0.80	6.6
$HSD_{(0.05)}$	0.53	-	0.39	-	0.08		1.61	-

$HSD_{(0.05)}$ for years - not significant differences
$HSD_{(0.05)}$ for interaction: years × crops - not significant differences

*SD – standard deviation; **CV – coefficient of variation.

The data included in table 1 show that root crops (beetroot, carrot) and tuber crops (potato) are characterized by the highest primary and secondary yield (significantly higher relative to the other crops). This means that species producing the largest biomass in primary and secondary yield are characterized by the greatest CO_2 sequestration (Table 1). Nevertheless, the above-mentioned species are not leading crops in Poland's crop structure [21] because cereal crops dominate by far in it, occupying about 75% of the total cropped area, while among them in particular winter and spring wheat, spring barley, winter triticale, and for several years also maize. The data contained in table 1 reveal that the above-mentioned cereal species produce yields at a high level. Winter oilseed rape, which is becoming increasingly popular in the crop structure in Poland, is also characterized by high yield potential. The yield potential of soybean (a plant that is also gaining popularity among farmers). The meadow vegetation should also be considered to be an important link of the CO_2 sequestration (meadow hay is generally a mixture of several grass species, possibly together with a small-seed legume crop). Under the conditions prevailing in Czesławice, the yield potential of such crops is high – at a level of $5.4 t \cdot ha^{-1}$ (Table 1). The above-mentioned crop species exhibit significantly higher primary and secondary yield as well as significantly greater CO_2 sequestration in comparison to the species that produce low yields: buckwheat, proso millet, amaranth, and lentil. The species such as maize, narrow-leafed lupine, and soybean were characterized by significantly the highest belowground crop residues, while meadow hay, proso millet, buckwheat and amaranth by significantly the lowest belowground crop residues.

Table 2. Correlation coefficients (r) between yield (primary, secondary, belowground crop residues) of major crops and CO_2 sequestration

Crop	Primary yield	Secondary yield	Belowground crop residues
Winter wheat	0.71*	0.59*	0.21
Spring wheat	0.65*	0.56*	0.18
Spring barley	0.59*	0.55*	0.12
Winter rye	0.57*	0.60*	0.19
Winter triticale	0.56*	0.56*	0.13
Oats	0.53*	0.52*	0.12
Maize	0.77*	0.62*	0.24
Proso millet	0.43	0.47	0.09
Buckwheat	0.48	0.53*	0.14
Amaranth	0.40	0.43	0.10
Winter oilseed rape	0.59*	0.60*	0.18
Soybean	0.57*	0.58*	0.23
Lentil	0.45	0.54*	0.15
Narrow-leafed lupin	0.67*	0.68*	0.33
Potato	0.75*	0.57*	0.20
Sugar beet	0.81*	0.62*	-
Carrot	0.66*	0.60*	-
Meadow hay (in total from 2 cuts)	0.59*	-	0.11

*significant correlation coefficient $_{(0.05)}$.

The scale of both CO_2 sequestrations by main crop plants (seed/tuber/root yield), secondary yield (straw/stems and leaves), and crop residue yield (roots), and of CO_2 sequestration by catch crops is directly proportional to biomass produced by them (as confirmed by the calculated coefficients of correlation (r) – (Table 2). This table shows that in most of the crop plants analyzed, primary yield and secondary yield exhibit a significantly positive correlation with CO_2 sequestration by these crops. A particularly high relationship between yield and CO_2 sequestration is confirmed by the calculated correlation coefficients for the root crops (beetroot, potato, carrot), but also for winter and spring wheat, maize, and narrow-leafed lupin. The plants with lower yielding potential (buckwheat, proso millet, amaranth, and lentil) showed a statistically insignificant (though positive) relationship with CO_2 sequestration. To sum up, the correlation coefficients presented in table 2 prove that primary and secondary yield are strongly correlated to CO_2 sequestration. Crop residues, on the other hand, have a much smaller relationship with CO_2 sequestration (Table 2).

Productivity of catch crops and CO_2 sequestration

Unreliable yields due to agro-climatic conditions are a drawback of catch crops. The average biomass dry matter yield of catch crops grown in the central Lublin region (Poland) ranges from 2.64 to 4.26t·ha^{-1} (Table 3).

Table 3. Average yield of catch crop dry matter and average carbon dioxide content in biomass; and correlation coefficients (r) between the dry biomass of catch crop (plants + roots) and carbon content in biomass (plants + roots)

Catch crops	Dry biomass (t·ha^{-1})				Carbon content in biomass (t CO_2 ha^{-1}·yr^{-1})				
	Plants	CV (%)**	Roots	CV (%)	Plants	CV (%)	Roots	CV (%)	r***
White mustard	4.26 ±0.45*	5.7	0.13 ±0.04	5.1	6.64± 0.51	6.9	0.20 ±0.05	5.4	0.82***
Spring oilseed rape	3.40 ±0.37	6.1	0.11 ±0.03	5.3	5.32± 0.46	7.3	0.17 ±0.04	6.1	0.61***
Tansy phacelia	3.98 ±0.25	5.8	0.08 ±0.02	4.9	6.23± 0.30	6.3	0.12 ±0.04	5.5	0.72***
Red clover	2.69 ±0.19	4.5	0.06 ±0.01	3.6	4.22± 0.22	4.9	0.09 ±0.03	4.2	0.45
Serradella	3.05 ±0.22	6.3	0.07±0.02	5.0	4.77± 0.35	7.1	0.10 ±0.03	5.7	0.48
Westerwolds ryegrass	2.42 ±0.15	6.5	0.05±0.02	5.2	4.03± 0.19	7.4	0.07 ±0.02	6.0	0.25
Spring vetch + field pea	3.46 ±0.30	7.2	0.21±0.06	6.0	5.39± 0.39	8.3	0.32 ±0.04	7.5	0.63***
Narrow-leafed lupine	2.64 ±0.17	4.6	0.29 ±0.06	3.1	4.11± 0.26	5.8	0.45 ±0.09	3.5	0.52***
Yellow lupine	2.72 ±0.20	6.0	0.30 ±0.07	5.4	4.28± 0.32	8.0	0.46 ±0.08	5.9	0.55***
Oats + spring vetch + field pea	3.22 ±0.33	5.9	0.16±0.03	3.5	5.02± 0.41	7.2	0.24 ±0.05	3.8	0.59***
Winter rye	4.07 ±0.22	7.0	0.13±0.03	4.8	6.34 ±0.44	8.8	0.20 ±0.04	5.2	0.79***
Perennial ryegrass + winter vetch	3.11 ±0.18	3.9	0.12±0.02	2.7	4.85 ±0.25	5.5	0.18 ±0.03	3.3	0.44
Winter vetch	2.97 ±0.16	3.7	0.12±0.03	3.9	4.64 ±0.20	5.4	0.18 ±0.04	4.0	0.39
Winter wheat + winter vetch	4.01 ±0.28	5.2	0.15±0.05	4.6	6.29 ±0.36	6.6	0.23 ±0.06	4.9	0.75***
Mean for cover crops	3.28	-	0.14	-	5.15	-	0.21	-	-
$HSD_{(0.05)}$	0.41	-	0.02	-	0.49	-	0.04	-	-

$HSD_{(0.05)}$ for years - not significant differences

$HSD_{(0.05)}$ for interaction: years × catch crops - not significant differences

*SD – standard deviation; **CV – coefficient of variation ; ***significant correlation coefficient $_{(0.05)}$.

This table shows that the divergence in yields of the specific catch crop species (sole cropped or grown in mixtures) is very large. Stubble crops (white mustard, tansy phacelia, mixed spring vetch + field pea) and some winter cover crops (winter rye, winter wheat + winter vetch) give the most reliable yields. The biomass of these catch crops was significantly higher than the biomass of the other catch crop species included in this study. The above-mentioned catch crops are characterized by significantly the highest CO_2 sequestration (expressed as t $ha^{-1}\cdot yr^{-1}$). Undersown crops (red clover, serradella, Westerwolds ryegrass) and some sole cropped legume species (yellow lupin, narrow-leafed lupin, winter vetch) produce significantly the lowest yields. To sum up, it should be noted that all the catch crop species studied exhibited high carbon dioxide sequestration by aboveground biomass, ranging from 4.03 (Westerwolds ryegrass) to 6.64 (white mustard) t CO_2 $ha^{-1}\cdot yr^{-1}$. Roots of the catch crops sequestration from 0.07 (Westerwolds ryegrass) to 0.46 (narrow-leaved lupine, yellow lupine) t CO_2 $ha^{-1}\cdot yr^{-1}$.

The statistical calculations confirmed a close relationship (a significant coefficient of correlation) between the highest biomass yield of the catch crops (white mustard, spring oilseed rape, tansy phacelia, narrow-leafed lupine, yellow lupine, winter rye, and mixtures: spring vetch + field pea, oats + spring vetch + field pea, winter wheat + winter wheat) and CO_2 sequestration by these catch crops (dry biomass: plants + roots). It should however be noted that it is the aboveground part of the catch crop biomass that predominantly determines the scale of CO_2 sequestration.

This means that catch crops are a significant added value (e.g. + 30%) in carbon dioxide sequestration relative to the cultivation of main crops (in particular cereal plants, which are dominant in the crop structure in Poland, as well as oilseed and legume plants) – table 4. As a matter of fact, catch crops are primarily grown as an in-between crop between cereals cultivated as the main crop. Thus, they are an important factor in CO_2 sequestration by agriculture. The lower percentage of the catch crops in total CO_2 sequestration relative to the root crops (e.g. 7.6%) is due to both the high primary yield of the root crops (roots) and the high biomass yield of leaves sorbing CO_2. In turn, a comparison of CO_2 sequestration by catch crops with carbon dioxide sorption by meadow plants is purely theoretical (because catch crops are not grown as an in-between crop for meadow plants).

Table 4. CO_2 sequestration by catch crops as an added value compared to CO_2 sequestration by various groups of main crop plants

CO_2 sequestration ($t\cdot ha^{-1}\cdot yr^{-1}$) by particular groups of main crop plants (on average for the studied plant species from particular groups)		**CO_2 sequestration ($t\cdot ha^{-1}\cdot yr^{-1}$) by catch crops (on average for the studied species)**	**Total value of CO_2 sequestration by main crop plants and catch crops**	**Percentage of catch crops (%) in total CO_2 sequestration by crop plants**
Cereal plants[1]	13.08	5.36[*]	18.44	29.06
Oilseed plants[2]	11.80	5.36	17.16	31.23
Root plants[3]	65.13	5.36	70.49	7.60
Legume plants[4]	7.85	5.36	13.21	40.57
Meadow plants[5]	8.54	5.36	13.90	38.56

[1](on average for: winter wheat, spring wheat, spring barley, winter rye, winter triticale, oats, maize, proso millet, buckwheat, amaranth); [2](on average for: winter oilseed rape, soybean); [3](on average for: potato, sugar beet, carrot); [4](on average for: lentil, narrow-leafed lupin); [5](Meadow hay in total from 2 cuts). [*](on average for: white mustard, spring oilseed rape, tansy phacelia, red clover, serradella, Westerwolds ryegrass, spring vetch + field pea, narrow-leafed lupine, yellow lupine, oats + spring vetch + field pea, winter rye, perennial ryegrass + winter vetch, winter vetch, winter wheat + winter vetch).

Organic carbon content in soil depending on catch crop biomass

Over the three-year study period (2016-2018), the organic carbon content in soil under control treatment (without catch crops) was determined compared to treatments where some catch crop species were additionally grown. The results contained in table 5 demonstrate that regardless of catch crop species, ploughing in of catch crop biomass resulted in a significantly higher carbon content in the soil. But the differences in soil organic C content between the individual catch crop species were statistically insignificant. Nonetheless, the following trend was found - a particularly high carbon content in the soil in the case of biomass of white mustard and mixed spring vetch and field pea.

Table 5. Organic carbon content in soil depending on some catch crop biomass

Catch crops	Organic carbon content in $g \cdot kg^{-1}$ soil	CV (%)**	Correlation coefficients (r) between the carbon content in biomass of catch crop and organic carbon content in soil
Control – without catch crop	21.4 ±1.9*	7.3	-
White mustard	36.7 ±1.5	5.2	0.81***
Spring oilseed rape	34.9 ±1.2	4.9	0.64***
Tansy phacelia	33.3 ±0.9	3.8	0.72***
Red clover	31.6 ±1.3	5.0	0.39
Serradella	32.2 ±0.8	3.7	0.44
Westerwolds ryegrass	30.5 ±0.6	2.9	0.35
Spring vetch + field pea	35.4 ±1.7	5.4	0.69***
Narrow-leafed lupine	31.0 ±0.5	3.1	0.49
Yellow lupine	31.6 ±0.7	3.0	0.47
Oats + spring vetch + field pea	34.1 ±1.4	5.2	0.68***
Winter rye	34.7 ±1.6	5.4	0.76***
Perennial ryegrass + winter vetch	31.9 ±1.0	4.6	0.55***
Winter vetch	30.9 ±0.9	3.9	0.48
Winter wheat + winter vetch	32.8 ±1.1	4.2	0.50
$HSD_{(0.05)}$	7.42	-	-
$HSD_{(0.05)}$ for years - not significant differences			
$HSD_{(0.05)}$ for interaction: years × catch crops - not significant differences			

*SD – standard deviation; **CV – coefficient of variation ; ***significant correlation coefficient $_{(0.05)}$.

The organic C content in the soil was rather stable throughout the study period (it was statistically insignificant between years). The coefficients of variation (CV) were low (ranging 3.0 – 5.4% in the plots with the catch crops and 7.3% in the control plots). A strict correlation was confirmed between the ploughed-in catch crop biomass (incorporated into the soil) and soil organic carbon content. Particularly high (statistically significant) coefficients of correlation (r) were found in the following cases: white mustard, tansy phacelia, winter rye, and spring vetch + field pea mixture and oats + spring vetch + field pea mixture. This shows the particular suitability of these species as catch crops because they are characterized by large biomass production and high CO_2 sequestration (Table 3.) as well as they contribute to a high organic C content in the soil (Table 5).

Discussion

In agriculture, when plants produce yield, they reduce carbon dioxide. This means that a global increase in yields, among others through catch crops by skillfully using agronomic practices, will promote reduction in CO_2 emissions into the atmosphere [22-24]. As shown by the results of the present study, successfully grown catch crops (e.g. white mustard, phacelia, spring vetch + pea, rye) are able to fix substantial amounts of carbon (even up to 6t CO_2 $ha^{-1} \cdot yr^{-1}$), and this carbon is accumulated in soil together with ploughed-in biomass. Organic carbon contained in soils makes a significant contribution to the total balance of this element.

In Poland cereals are by far predominant in the crop structure. Therefore, the efficiency of cereals and the scale of CO_2 sequestration by these species is the most objective "background" for CO_2 sequestration by catch crops. Catch crops are most frequently grown in the crop rotation cycle cereal – catch crop – cereal. *L. Pawłowski et al*. [6] conducted a study on carbon dioxide sequestration by selected cereal crop species in Poland and in China. In Poland, such cereals as rye, wheat, triticale, oats, and barley, are grown on an area of 7.6 million hectares. These crops absorb about 23.8 million tonnes (Mt) of C, out of which 9.8Mt C yr^{-1} in grain, 9.4Mt C yr^{-1} in straw, and 4.7Mt C yr^{-1} in roots. In China, these cereals are grown on an area exceeding 24 million ha and absorb 98.9Mt C yr^{-1}, out of which 55Mt C yr^{-1} in grain, 36Mt C yr^{-1} in straw, and 7.9Mt C yr^{-1} in roots. These data indicate that a wider application of agro-engineering techniques for carbon dioxide sequestration would facilitate the reduction of carbon dioxide emissions [6]. The present study is the confirmation of the above presented findings. Cereal crops (especially maize, wheat, triticale, rye, barley, and oats) absorb from about 11 to 20t CO_2 $ha^{-1}\cdot yr^{-1}$. Successful catch crops, in turn, absorb from about 4.1 to nearly 7.0t CO_2 $ha^{-1}\cdot yr^{-1}$. The obtained results show that catch crops are an important factor in CO_2 sequestration. It is worth stressing that catch crops have a shorter growing season than the main crop plants. In spite of that, their biomass yield and the scale of CO_2 sequestration are high. This is confirmed by the results of other studies [25, 26]. A drawback of catch crops (particularly Fabaceae/Leguminosae species) is their vulnerability to rainfall deficit and drought [14, 18]. Under such conditions, their productivity and related CO_2 sequestration can be much lower than those presented in the results of this study.

There is a paucity of scientific studies on CO_2 sequestration by catch crops. Promotion of such crops would allow for an even greater contribution of widely understood agriculture to CO_2 sequestration. Studies of other authors [1, 4] demonstrate how important agricultural ecosystems are in CO_2 sequestration. The observed increase of CO_2 absorption by terrestrial ecosystems is caused by the fertilizing effect of the rising atmospheric concentration of CO_2 on the plant growth as well as the fertilizing effect of nitrogen compounds, mostly nitrogen oxides emitted from industrial plants. Globally, plants absorb approximately 123Gt C yr^{-1} in the photosynthesis process and at the same time emit 118.7Gt C yr^{-1} in the respiration and biomass decomposition processes [27]. The CO_2 sequestration of agricultural crops amounts ca. 103 million t CO_2 yr^{-1}. If combined with forests, the sum will total 187.5 million t CO_2 yr^{-1}, which roughly corresponds to 59% of the emissions from fossil fuel combustion and cement production. In other words, 59% of the CO_2 emissions from these two sources are absorbed by the agricultural crops and forests [4].

In the present study, catch crops were grown and their cut biomass was incorporated into the soil (ploughed in). In this way, carbon dioxide absorbed by the catch crop biomass entered the soil together with the biomass. Nonetheless, the so-called "soil CO_2 bank" is not stable and the scale of carbon retained in the soil depends on many factors. Carbon constitutes approximately 43% of the biomass in the above-ground parts of plants. This carbon can be retained in a soil ecosystem over a longer time, provided that the biomass is used as green manure. The amount of carbon that remains in soil permanently, and will not be released into the atmosphere in the form of CO_2, depends mainly on soil and climate conditions, such as porosity, humidity, temperature, etc.; these factors are also decisive in terms of what part of the root biomass remaining in the soil will be transformed into humic compounds [28-30].

This study proves that catch cropping contributes to a significantly higher amount of carbon in the soil compared to control plots (without catch crops). *C. Poeplau and A. Don* [31] also found a significantly higher carbon content in soils where catch crops were grown compared to soils without catch crops Due to their beneficial effects on the environment, catch crops have now become an instrument for developing environmentally friendly agriculture [10, 12, 32]. Productivity of catch crops largely depends on weather conditions and hence it is advisable to determine which species are best adapted to a specific region of the country [13, 18, 33-35]. The present study shows that white mustard, tansy phacelia, serradella, oats + spring vetch + field pea mixture, and winter rye are the least unreliable species that are adjusted to

Poland's climate and soil conditions. Temperature is closely related to soil CO_2 content. At higher temperatures, organic matter is mineralized more quickly in the soil, which in turn leads to increased soil CO_2 emissions [30]. In the opinion of some authors [36-39], increasing the retention of carbon in the biomass in soil will be possible through the intensification of the biomass production and slowing the rate of soil organic matter mineralization, for instance through the application of thick vegetation cover, mulching and no tillage practices.

Enhancement of carbon sequestration constitutes one of the main tasks of regenerative (sustainable) agriculture, also known as agroecological farming. The aim of regenerative farming systems is to increase the soil quality and biodiversity in farmland while ensuring the profitable production. It encompasses a range of techniques, i.e. non-tillage, avoidance of leaving soil uncovered, integrating livestock and cropping operations on the land. These actions aim at reconstructing and maintaining soil fertility as well as sequestering of carbon [40-42}. An IPCC report [43] estimates that the amount of carbon in organic compounds found in soil is 1580Gt. *R. Lal* [44] provides similar figures: 1550Gt of organic carbon and 950Gt of inorganic carbon.

Conclusions

As a result of mineralization of organic matter under aerobic conditions, carbon is oxidized and CO_2 is formed, which can be emitted into the atmosphere. Efforts should be made to ensure that organic matter accumulation processes predominate over mineralization processes. The following directions for action in this area can be distinguished:

- To prevent erosion processes (by maintaining plant cover on fields as long as possible, among others through catch crops, and preventing mineralization processes);
- To increase soil organic carbon resources by using natural fertilizers, including green ones (growing catch crops whose biomass affects the organic carbon content in soils);
- To increase yields and the carbon content in yields.

Moreover, future research in this area should be expanded to include the following aspects:

- To determine the optimal type of catch crops and catch crop species from the point of view of soil CO_2 sequestration timeframe;
- CO_2 accumulated in soil by ploughing under catch crop biomass is a 'soil CO_2 bank'. This allows, among others, methane fermentation processes and biogas production specifics to be investigated. As a result of the above processes, secondary fertilizer is created, the so-called bioferment, which can be used in agriculture.

The results of the present study show that the cultivation of catch crops in the following crop rotation: cereal – catch crop – cereal, allows about 30% higher CO_2 sequestration per year to be achieved compared to the cultivation of cereals without catch crops.

The results of the present study entitle us to suggest several catch cropping options in order to promote primary and secondary yield, carbon content in yield and in the soil as well as CO_2 sequestration.

Taking into account the above presented aspects of cultivation, yield, and CO_2 fixation by catch crops, it is proposed to include in further research catch crop species characterized by the highest biomass production (which is equivalent to the highest carbon dioxide sequestration) and to investigate the extent of CO_2 sequestration over the entire crop rotation cycle (main crops + a catch crop grown in a particular year/growing season in a field). The following catch crops are proposed to be studied over crop rotation cycles:

1. stubble crop (white mustard – a seeding rate of $20 kg \cdot ha^{-1}$) in the following crop rotation cycle: winter wheat – white mustard – spring barley;
2. stubble crop (lacy phacelia – a seeding rate of $10 kg \cdot ha^{-1}$) in the following crop rotation cycle: winter triticale – tansy phacelia – oats;

3. winter catch crop (winter rye – a seeding rate of 140kg·ha^{-1}) in the following crop rotation cycle: winter wheat – winter rye – maize.

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