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Evaluating the Effectiveness of Catch Crops and Tillage Systems for Carbon Farming

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Abstract. In modern agriculture, it is necessary to identify strategic steps that will reduce greenhouse gas emissions: on the one hand, reducing emissions by cutting down fuel consumption, reducing soil interference, limiting nitrogen losses when using fertilisers, and on the other hand – increasing the efficiency of carbon extraction from the atmosphere through plant photosynthesis and sequestration as organic matter of the soil. The purpose of this study is to figure out the influence on the carbon balance of such elements of the agricultural system as the system of tillage and the use of intermediate cover crops in a model 4-field crop rotation in the Steppe zone of Ukraine. This work was performed using the method of empirical calculations based on the online calculator of greenhouse gas emissions Cool Farm Tool. The influence of intermediate crops in two fields of crop rotation (after the early grain predecessors – wheat and winter barley) and tillage systems (traditional, reduced, and no-till) on the balance of carbon emissions and sequestration in the model 4-field crop rotation was analysed. According to the results, it was found that during the model 4-field crop rotation under the conditions of the classical system of tillage for sunflower and maize without intermediate crops and reduced processing for wheat and barley, the total greenhouse gas emissions amount to 4015 kg/ha of CO_2-eq. in 4 years. Switching to a reduced tillage system has been shown to reduce emissions by 30.1%. The addition of two intermediate crops in two crop rotation fields before spring crops allows obtaining a negative balance of greenhouse gas emissions of -377 kg/ha of CO_2-eq. during this period, and when switching to no-till for all crops -1221 kg/ha of CO_2-eq. for a 4-year rotation period. This study will help identify strategic steps and their potential contribution to the development and implementation of agricultural systems with minimal greenhouse gas emissions

Keywords: carbon farming, soil health, greenhouse gas emissions, intermediate crops, comprehensive quality assessment of intermediate crops, carbon balance

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INTRODUCTION

This paper is the first to consider the principal elements of the agricultural system in terms of reducing greenhouse gas emissions, and to estimate the potential impact of tillage systems and the use of intermediate crops on greenhouse gas emissions in the Southern Steppe of Ukraine.

Natural and anthropogenic factors in global terms are a constant source of emissions of greenhouse gases into the atmosphere, the main of which are CO_2 (carbon dioxide), CH_4 (methane) and N_2O (nitrogen oxide). Historically, for a prolonged period of time, these substances were in a safe ratio and humanity almost did not pay attention to the possibility of a violation of the balance and the emergence of threatening situations. But with the growing anthropogenic impact on the environment, already in the mid-20th century, there was a substantial increase in greenhouse gas emissions associated with the burning of fossil fuels, which over time led to the creation of a greenhouse effect and the threat of global warming (Sixth Assessment Report, 2021; Balyuk & Kucher, 2019; Bedernicek, 2017). Over the past 50 years, the concentration of CO2 increased from 0.03% to 0.042% (Carbon dioxide peaks..., 2021). The result was a noticeable increase in global air temperature by 1.5°C (Sixth Assessment Report, 2021). The average annual air temperature in Ukraine has increased by 1.4°C over 100 years (the average annual air..., 2020). This phenomenon has a global spread on all continents of the planet.

It is important to understand that agriculture also contributes substantially to greenhouse gas emissions. For instance, in 2019, the total emissions of greenhouse gases in Ukraine amounted to 332.1 million tonnes of CO_2-eq., of which the share of agriculture was 13% (Ukraine's greenhouse..., 2021). The main sources in the industries are animal husbandry and crop production. In the field of crop production, the main reasons for a substantial amount of greenhouse gas emissions are related to such reasons as considerable ploughing of land and conventional approaches in agriculture, which involve the desire to get rid of plant residues as soon as possible and substantial intervention in the soil upon its mechanical processing. Special attention should be paid to the increase in the use of nitrogen fertilisers and the associated increase in N_2O emissions, which has a 298-fold higher greenhouse effect (Boychenko, 2002).

Instead, implementing the principles of carbon farming can move it from emissions to carbon sequestration and will not become a source of emissions, but a powerful tool for extracting carbon from the atmosphere.

Research by scientists (Fiorini, 2020; Sauvadet, 2018, Tkachuk & Trofimenko, 2020) in different countries of the world has found that cover crops are an effective tool for carbon sequestration. All these data are summarised and used in various tools for calculating carbon balance, including the Cool Farm Tool (2022).

According to the studies by Poeplauab & Don (2015), the time since the introduction of cover crops into crop rotation was linearly correlated with the change in organic carbon reserves in the soil (R2=0.19) with an annual rate of change at 0.32±0.08 t/ha per year at an average soil depth of 22 cm, the observation period is 54 years.

A study by Tribouillois *et al.* (2018) showed that cover crops can improve the average direct GHG balance by 315 kg/ha CO_2-eq. per year in the long term compared to no cover crops, which could cause a reduction of 4.5-9% of annual greenhouse gas emissions in French agriculture and forestry.

In research by Brazilian scientists, Velosoa *et al.* (2018), the combination that provided the greatest increase in soil organic carbon was a no-till combination with two legume cover crops without nitrogen fertilisers (1.15 t/ha per year) compared to a conventional tillage system. Cover crops of the legume family were twice as efficient at storing organic carbon as nitrogen fertilisers, with 1 kg of applied residues converted to 0.15 kg of soil organic carbon. Changes in soil organic carbon reserves were mainly attributed to plant carbon intake (R2=80%).

The results of studies by Fiorini *et al.* (2020) showed that N_2O emissions under a no-till system were 40-55% lower than under a conventional tillage system. No-till technology also increased the organic carbon content of the soil (by 28%; 0-5 cm) and the number of earthworms (by 5 times) compared to the conventional tillage system. In no-till systems, N_2O emissions were 20-36% lower with rye cover crop than with vetch cover crop ($P<0.05$), which was a consequence of lower availability of mineral nitrogen in the soil under rye than under vetch due to high C/N ratio of rye residues. The combination of no-till and cover rye resulted in the lowest N_2O emissions and the highest yields and should be recommended in the Po Valley region of Italy.

The authors Ruis & Blanco-Canqui (2017) figured out the effect of cover crops and the removal of plant residues from the field of major crops when used for certain purposes. Thus, the removal of more than half of plant residues reduces soil organic carbon reserves by 0.87 t/ha per year, and less than half – by 0.31 t/ha per year. Cover crops increase the organic carbon content of the soil by 0.49 t/ha per year, which indicates that cover crops can compensate for at least some of the organic matter lost with the removal of residues.

The results of the research of Sauvadet *et al.* (2018) showed that the enzymatic efficiency of microorganisms in the soil under a reduced tillage system increased by 49% and 61% in the presence of residues of ripe and flowering wheat, respectively. These results showed that the soil with reduced cultivation benefited from both an increase in the number of residues included in microbial biomass and a decrease in soil carbon loss due to the priming effect, regardless of the degree of decomposition of residues.

In Ukraine, most studies on the effect of intermediate crops on improving soil health have been investigated on green manure. The results of Razanov's (2021) research show that the vegetative mass of green manure of winter wheat, spring barley, winter rapeseed, and peas, incorporated in the soil in post-harvest crops, contributes to an increase in humus content by 0.11-0.14%, alkaline hydrolysed nitrogen – by 1.7-7.1%, exchange potassium – by 27.4-32.2%. The larger the vegetative mass of green manure, the more the content of humus and essential nutrients in the soil.

Egorov (2021) notes that in sod-podzolic soils of Polissia, along with the introduction of manure, the use of straw, green manure, and the use of legumes in crop rotations (namely lupine for green mass and green manure) contributes to the preservation and reproduction of humus content in the soil, improves the balance of nutrients and increases the productivity of arable land in crop rotations, and in its effectiveness approaches the introduction of 10 t/ha of manure in the crop rotation area.

According to Tkachuk & Trofimenko (2020), over a 36-year research period, humus losses on the background of fertiliser-free ploughing annually amounted to 0.13 t/ha, while on non-soil cultivation – 0.11 t/ha. At an average CO_2 emission intensity of 6.3 kg/ha/h from the soil, during the day the volume of emissions is about 167 kg per 1 ha, and for the entire growing season about 20.1 t/ha of carbon dioxide. During the growing season of crops, on sod-podzolic sandy loam soil, non-productive losses of CO_2 range within 2.1-4.2 kg/ha/h.

The purpose of this study is to figure out the influence of soil cultivation and the use of catch cover crops on the carbon balance.

MATERIALS AND METHODS

The paper uses the methodology of empirical calculations for crops of a typical 4-field arable crop rotation in dry land conditions of the Steppe of Ukraine based on the Cool Farm Tool (CFT) greenhouse gas emissions calculator (2022), which is based on IPCC methods (Hansen *et al*., 2013) and is FAO-approved (Review of GHG calculators…, 2012).

The experimental plot is located near the village of Myrne in the Odesa District of the Odesa Oblast of Ukraine. The plot is located within the Dniester-Buh lowland region of the Black Sea region of the Middle-Steppe subzone of the Steppe zone (geographical coordinates: N 46.47444046488163, E30.40456107404692). According to agropedological zoning, the territory characterises the subzone of the southern Steppe, for which southern chernozems on forest rocks are typical. A strictly arid agroclimatic zone, where the hydrothermal coefficient (HTC) is about 0.7. The study was conducted based on data from 2021.

The crop rotation model and initial data for calculations based on information from standard technological maps of the farm and data on programmed yield for crop moisture availability are presented in Table 1.

Table 1*. Initial data for calculating greenhouse gas emissions*

Crop rotation culture	Planned yield, t/ha	Fertiliser system*	Plant protection system**	Diesel fuel consumption (excluding crop export), l/ha		
				CT	RT	NT***
Winter barley	4.3	$N_{76}P_{36}K_{18}$, CAM32 – 181 kg/ha, Superagro 12: 24:12 – 150 kg/ha	P – 0.04 l/ha (23.5%), H – 0.07 l/ha (17.5%), F – 0.75 l/ha (30%), I – 0.18 l/ha (24.7%)	–	41.1	26.6
Maize	5.4	$N_{78}P_{34}K_{17}$, Carbamide – 132 kg/ha, Supeagro 12:24:12 – 142 kg/ha	P – 0.05 l/ha (50%), H1 – 2 l/ha (48%), H2 – 2 l/ha (10.5%), I – 0.2 l/ha (15%)	61.0	50.6	33.7
Winter wheat	4.2	$N_{74}P_{33}K_{17}$, CAM32 – 180 kg/ha, DAP – 138 kg/ha	P – 0.04 l/ha (23.5%), H – 0.07 l/ha (17.5%), F – 0.75 l/ha (30%), I – 0.18 l/ha (24.7%)	–	41.1	26.6
Sunflower	2.4	$N_{71}P_{23}K_{12}$, Carbamide – 128 kg/ha, DAP – 96 kg/ha	P – 0.04 l/ha (50%), H1 – 2 l/ha (48%), H2 – 0.05 kg/ha (75%), F – 0.75 l/ha (25%), I – 0.18 l/ha (24.7%)	62.3	51.9	34.5

Note: **the rate of nitrogen is calculated for removal by the main part of the crop considering the nitrogen use efficiency approach (NUE) (Oenema, 2015), the rates of phosphorus and potassium fertilisers are calculated based on the law of returning – only for the removed part of the crop. **(P – protectant, H – herbicide, F – fungicide, I – insecticide), rate, l/ha, % a.s.). ***CT – classic tillage is prescribed for maize and sunflower, the main tillage is ploughing and added operations, RT – reduced tillage for wheat and barley – disk ploughing, cultivation, for sunflower and maize – deep tiller (chiselling), NT – no-till*

Source: *compiled by the authors*

Factors under study:

Factor A. Tillage systems: Variant 1. CT – classic tillage: for maize and sunflower, stubble scouring, ploughing, and cultivation. Variant 2. RT – reduced tillage: for maize and sunflower – deep tillage (chiselling), cultivation; for winter wheat and barley – disk ploughing, cultivation. Variant 3. NT – direct no-till sowing for all crops.

Factor B. Use of catch crops (Table 2):

***Table 2**. Scheme of field employment with main and catch crops in the model 4-field arable crop rotation of the farm*

Option 1 – no catch cover crops:

<table>
<tr><th rowspan="2">Crop rotation field</th><th colspan="12">Months of the year</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th></tr>
<tr><td>1</td><td colspan="6">Winter barley</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td></td><td></td><td></td><td colspan="5">Grain maize</td><td colspan="4">Winter wheat</td></tr>
<tr><td>3</td><td colspan="6">Winter wheat</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td><td colspan="5">Sunflower</td><td colspan="4">Winter barley</td></tr>
</table>

Option 2 – with catch cover crops:

<table>
<tr><th rowspan="2">Crop rotation field</th><th colspan="12">Months of the year</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th></tr>
<tr><td>1</td><td colspan="6">Winter barley</td><td colspan="6">Catch culture</td></tr>
<tr><td>2</td><td colspan="3">Catch culture</td><td colspan="5">Grain maize</td><td colspan="4">Winter wheat</td></tr>
<tr><td>3</td><td colspan="6">Winter barley</td><td colspan="6">Catch culture</td></tr>
<tr><td>4</td><td colspan="3">Catch culture</td><td colspan="5">Sunflower</td><td colspan="4">Winter barley</td></tr>
</table>

⬜ – no crops
▨ – main culture
🟦 – catch culture

***Source:** compiled by the authors*

In this study, only the absence or presence of a catch crop in crop rotation is important, regardless of its type, duration of the growing season and biological features, as per the CFT methods. The catch crop is provided here only to "fill in the pauses" between the main crops of crop rotation, continue to sequester carbon from the atmosphere and maintain soil health in the periods between the main crops. In Steppe conditions, one of the most common intermediate crops for this can be mustard, phacelia, spring vetch, millet, etc. These crops, sown in July after grain harvesting, overwinter and their remains stay until the next crop is sown, or are ploughed as green manure in case of a classic tillage system – in both cases, Cool Farm Tool standards make provision for a positive impact from their use.

RESULTS

One of the most principal issues is the correct definition of terms. According to DSTU 4691:2006 (2006), repeated (intermediate) crops are those grown in a crop rotation field when it is free from the main crop. In world standards, the concept of repeated crops intended specifically for preserving soil health is defined by the term "*cover crops*", green manure – "*manure crops*". According to the "Conservation practice standard 340" (2020) – this corresponds to the domestic term "intermediate crops", but with an important clarification that these crops are left in the field without harvesting any biomass of these crops and without burning this biomass. According to the EU definition, "cover crops" are crops sown on arable land specifically to reduce the loss of soil, nutrients, and plant protection products during winter or during other periods when the land would otherwise be exposed and prone to loss. They are usually ploughed in the spring before sowing the next main crop, not harvested, or used for grazing (Cover crop, 2018). In other words, the European policy is not categorical about banning the harvesting of catch crops.

According to DSTU 4691:2006 (2006), underplant, or inter row crop, is a crop sown in a crop rotation field under the cover of the main crop. Such approaches are well known when growing alfalfa or sainfoin under the cover of barley, millet, etc.

Green fertilisers (*green manure*) are plants that are temporarily grown on vacant plots of land to improve soil fertility (DSTU 4691:2006). The international definition of the term "*green manure*" is crops that are ploughed into the soil (using conventional or disc plough) while they are green (Adrian, 1927). Thus, these concepts are identical in Ukraine and the world.

Therefore, using the term "*cover crop*" in modern search engines and international scientific literature, one can find catch crops in the understanding of Ukrainian science as an essential element of carbon farming and restoring soil health. And it is this understanding of the term "catch crops" that is discussed in this paper.

Along with the concept of "soil fertility", a new one has emerged – "soil health". It is known that soil fertility is its ability to provide plants with a complex of conditions for harvest formation (DSTU 4362:2004, 2004). In contrast to fertility, the term "soil health" refers to its compliance with the spectral functions of an ecosystem according to its environment (Soil Health, 2022). This is the harmonious action of living and non-living components of the soil: microbiota, plants, and animals. Unfortunately, Ukrainian agrarian science does not identify or consider this important concept at all, which in its complex meaning defines that the soil is part of nature. Organic matter of the soil is the main factor of its health and fertility, and the primary source of organic matter in the soil is plants.

According to many studies (Fiorini *et al*., 2020; Sauvadet *et al*., 2018, Tkachuk & Trofimenko, 2020), perhaps the greatest contribution to greenhouse gas emissions in crop production is made by tillage through the activation of the processes of mineralisation of plant residues and organic matter. Previously, this was almost the key purpose of cultivation. But currently the views have changed. Therewith, the scientific community has determined that minimising tillage and switching to a no-till farming system substantially reduces emissions and switching to reduced tillage technologies, as defined in the international carbon farming standards (IPCC Assessment Report 6).

In the experiments of Reicosky (1997), in 19 days, as a result of mineralisation, emissions of carbon (C) were as follows: 249 g/m^2 after ploughing, 106.6 g/m^2 after disk ploughing, 99.8 g/m^2 after chiselling and 49.9 g/m^2 after no-till. Therewith, 185 g/m^2 of carbon was accumulated with the remains of the crop – spring wheat, which was harvested before processing. That is, after ploughing for 19 days, the amount of carbon lost was substantially higher than the amount accumulated by the harvested crop, which means the loss of organic carbon of the soil accumulated by previous crops in previous years. The highest amount of greenhouse gas emissions in agriculture occurs precisely because the fields are without plants in the off-season and conventional approaches to tillage.

The increase in the concentration of CO_2 from the standpoint of agronomic science also has positive consequences. The growth of plant biomass on the planet is noted due to the increase in the efficiency of photosynthesis caused by the increase in CO_2 concentration. By 2100, the yield of the main products is expected to increase by 10%, and the biomass of plants – by 12% (Terrer *et al*., 2019). This very phenomenon became the basis for the emergence of a new field in agriculture – carbon agriculture, which involves the effective extraction of CO_2 from the atmosphere due to plant photosynthesis and its preservation in the soil in the form of organic matter (sequestration). The potential for removing CO_2 from the air and sequestering it in the soil with the implementation of carbon farming approaches on the entire arable land of the world is estimated at 10% of current annual emissions, or 8-10 Gt/year (Hansen *et al*., 2013).

Therewith, carbon technology also makes provision for preserving the health of the soil. To some extent, it destroys conventional ideas about "scientifically sound" measures, which ultimately lead to the destruction of both fertility and soil health indicators. Presently, in the EU (Carbon farming, n.d.) identified the following components of carbon farming:

– plants (both the main and catch crops of crop rotation), as one of the main factors of soil formation, which should occupy the field for as long as possible during the year. This means that "rest" in the form of the absence of plants is harmful to soil health;

– tillage minimisation by introducing reduced tillage technologies: minimal, strip, vertical (mini-till, strip-till, verti-till, respectively) and no-till, which are energy-saving at the same time;

– accumulation and preservation of plant residues on the soil surface, which prevents their rapid mineralisation and risks of soil erosion;

– complete elimination of clean vapours as an element of technology that considerably accelerates the mineralisation of organic matter in the soil and increases greenhouse gas emissions;

– measures aimed at reducing N_2O emissions when applying nitrogen fertilisers: methods of applying nitrogen fertilisers with soil wrapping use of nitrification inhibitors to prevent nitrogen loss;

– harmonious management of fertiliser and plant protection systems.

Each of these links in carbon farming is a complex and multi-vector task that needs to be solved comprehensively. This paper analyses and highlights the role of such elements of the agricultural system as soil cultivation systems and the effectiveness of intermediate crops to reduce the time spent in the field without plants, as the main factor of soil formation.

If one analyses modern crop rotations by the periods of time when the field is occupied by the main crop, and when there are potential periods – intervals for catch crops, then often these intervals are longer than the time occupied by the main crops (Table 3).

***Table 2**. Scheme of field employment with main and catch crops in the model 4-field arable crop rotation of the farm*

Crop	Date		Duration of field occupancy, days	Duration of time suitable for growing repeated crops, days
	Sowing	Harvesting		
Winter wheat	25.09	05.07	283	82
Winter rapeseed	05.09	10.07	317	72
Winter barley	10.10	25.06	260	92
Maize	20.04	15.09	148	60 (autumn) 35 (spring)
Sunflower	15.04	05.09	143	70 (autumn) 25 (spring)
Peas	20.03	25.06	96	131
Buckwheat	20.04	20.08	107	103
Silage maize	20.04	20.08	120	85
Alfalfa (2 mowings)	–	20.06	176	136
Pea-oatmeal mixture	20.03	15.06	55	124

***Source:** compiled by the authors*

Therefore, only winter crops occupy the field for 70-85% of the time. Other crops occupy the field 20-37% of the entire year. And if there is black steam in the crop rotation, this figure is only 13%. This disrupts healthy soil processes, so it is recommended to abandon the specified precursor.

Any crop can be either basic or catch. For instance, if buckwheat is sown in the spring, and it is included in the crop alternation scheme, then this is the main crop, and if the same buckwheat is sown in the summer after winter barley, which was in the alternation scheme, then this buckwheat should be considered a repeated crop.

If one calculates the duration of all periods when the field is occupied by the main crop, the winter period when the conditions do not meet the requirements of crops, as well as the period when the field is free, but it is not used for growing repeated crops, then these three periods are 32-35% (Fig. 1).

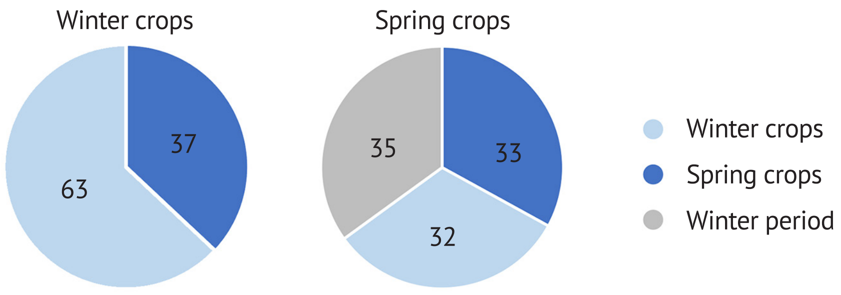

***Figure 1**. Ratio of field occupancy periods with winter and spring crops, %*
***Source:** compiled by the authors*

The above figure convinces of the extreme harmfulness of keeping a field without growing cultivated plants. And here attention is drawn not to the economic component (shortage of products), but to the negative environmental consequences discussed above. Depending on the place allocated for growing in crop rotation, intermediate crops are divided into the following groups (Fig. 2).

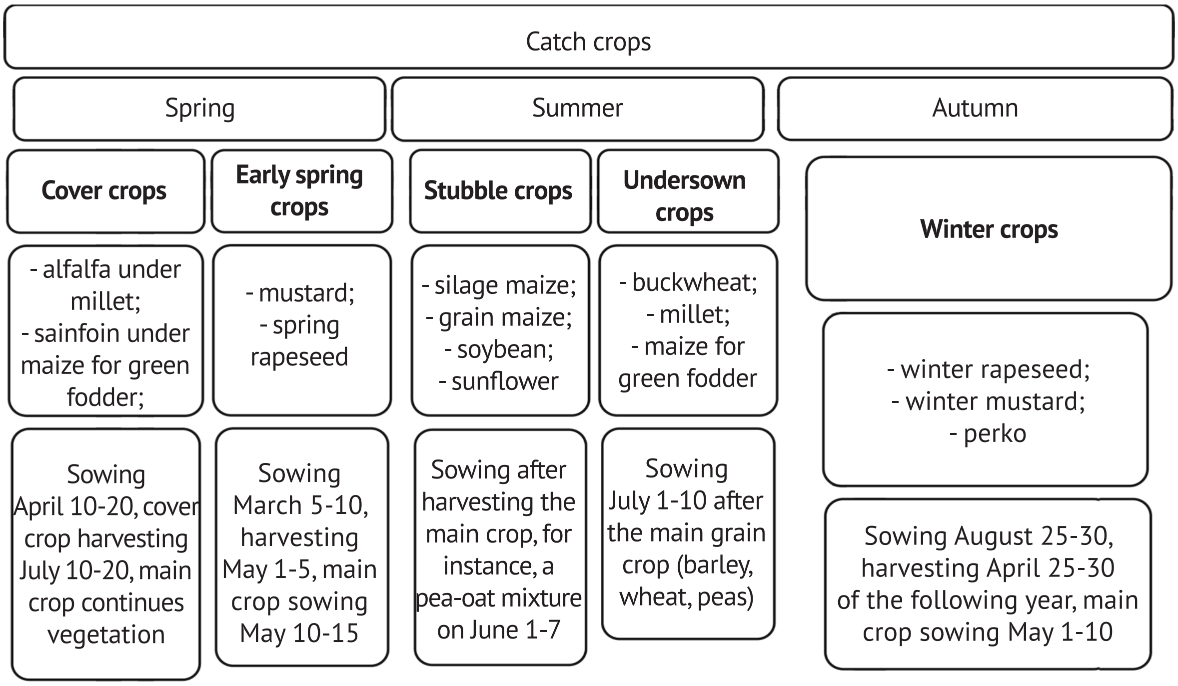

***Figure 2**. Classification of catch crops*

***Source:** compiled by the authors*

From an ecological standpoint, growing catch crops is always a positive measure. But for producers of agricultural products, it is also important to consider the economic feasibility and the possibility of including a catch crop without its adverse impact and the technology of the main crops of crop rotation (sowing dates, contamination, soil water regime, etc.).

Therefore, for an objective comprehensive assessment, it is necessary to evaluate each intermediate crop by as many indicators as possible, and then figure out the best ones by the sum of places that a particular crop will occupy. It is more appropriate to give an assessment not for the entire set of catch crops, but within their classification groups. For a comprehensive assessment, it is advisable to choose the widest possible range of indicators, but the following are crucial:

1. Duration of vegetation of the catch crop (days).
2. Crude biomass yield, t/ha, as the main indicator from the standpoint of economic activity.
3. Influence of the catch crop on the best parameters of the main crop. In most cases, when growing catch crops, the sowing time of the main crop may shift for a certain time (number of days).
4. Competitiveness of the catch crop in relation to weeds. The contamination is assessed on a 10-point scale. The higher the contamination – the higher the score.
5. Total greenhouse gas emissions during the growing season of the catch crop. The higher this indicator, the worse the quality of the catch crop (measured in t/ha of CO_2-eq.).
6. Direct production costs for growing catch crops, UAH/ha. The lower the cost, the better.

It is also important to consider the potential negative allelopathic effect of the catch crop as a precursor to the next main crop. Such influence should be excluded. The most widespread in the conditions of Ukrainian Steppe are catch crops of the post-harvest group. From the time of harvesting winter cereals (wheat, barley) to the transition of the average daily temperature through +5°C (November 5-16), there are about 90-97 days with the sum of temperatures of 2100°C. This resource ensures the cultivation of most field crops, but the limiting factor in this case is moisture, which is especially scarce in the second half of summer. Therefore, the possibilities of growing catch crops are significantly limited, and these calculations clearly prove this. Evidently, according to the comprehensive indicators, mustard has a substantial advantage, which has a reserve of vegetation and can be sown when the appropriate conditions for moisture supply appear. To increase grain production, millet and buckwheat are quite satisfactory, which as catch crops are not inferior to the main crops in terms of productivity, and often exceed them.

In the presence of intermediate crops with an ultra-short growing season, it is possible to obtain not only two, but three or more crops per year. This possibility is available in fodder and vegetable crop rotations. For instance, in a 4-field fodder crop rotation with alternating crops: 1. pea-oat mixture; 2. winter wheat; 3. fodder beet; 4. fodder pumpkin, it is allowed to grow several intermediate crops between the main ones (Table 4).

***Table 4**. Scheme of field occupancy by main and catch crops in a 4-field fodder crop rotation*

<table>
<tr><th colspan="12">Months</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th></tr>
<tr><td colspan="2">⬜</td><td colspan="3">▨ Peas and oats</td><td colspan="4">🟦 Silage maize</td><td colspan="3">▨ Winter wheat</td></tr>
<tr><td colspan="6">▨ Winter wheat</td><td colspan="3">🟦 Grain millet</td><td colspan="2">🟩 Mustard</td><td>⬜</td></tr>
<tr><td colspan="3">⬜</td><td colspan="5">▨ Fodder beet</td><td colspan="4">🟦 Winter rapeseed</td></tr>
<tr><td colspan="4">🟦 Winter rapeseed</td><td colspan="4">▨ Fodder pumpkin</td><td colspan="3">🟦 Peas and oats</td><td>⬜</td></tr>
</table>

⬜ – no crops
▨ – main culture
🟦 – catch culture first
🟩 – catch culture second

***Source:** compiled by the authors*

If one accurately calculates the duration of vegetation of the main and catch crops, as well as the time when the field was left without crops, then in total for the crop rotation, the results are as follows (Table 5).

***Table 5**. The specific weight of the occupation of the fields by main and catch crops for the 4-field forage crop rotation (1460 days)*

Field occupancy	No catch crops		With catch crops	
	Days	%	Days	%
With main crop	565	38.7	565	38.7
With catch crops	–	–	635	43.5
Duration of the no-sowing period	895	61.3	260	17.8

***Source:** compiled by the authors*

Without catch crops, the field is not covered with plants for 61.3% (almost 2/3 of the time). If one intensifies production, this figure is reduced to 17.8%, with all the resulting environmental consequences discussed above.

Vegetable crop rotations have even greater opportunities for multi-yielding fields, where certain crops have an ultra-short growing season and are grown under irrigation conditions. These crops include radishes, leafy vegetables, early cucumbers, early cabbage, early potatoes, vegetable peas, and many others. There is a lot of room for imagination based on yielding 3-5 crops a year. For instance:

1. radish – 35 days (15.03-25.04),
2. early ripe tomatoes – 75 days (05.05-20.07),
3. cucumbers – 50 days (25.07-15.09),
4. dill + parsley – 40 days (20.09-30.10)

In just 200 days, one can harvest 5 crops, which not only has a positive economic effect, but also radically optimises the carbon balance. Since the CFT tool has extensive capabilities for analysis, there is enough data to figure out the structure of greenhouse gas emissions and sequestration, as well as the influence of the factors under study in the authors' model (Figs. 3; 4).

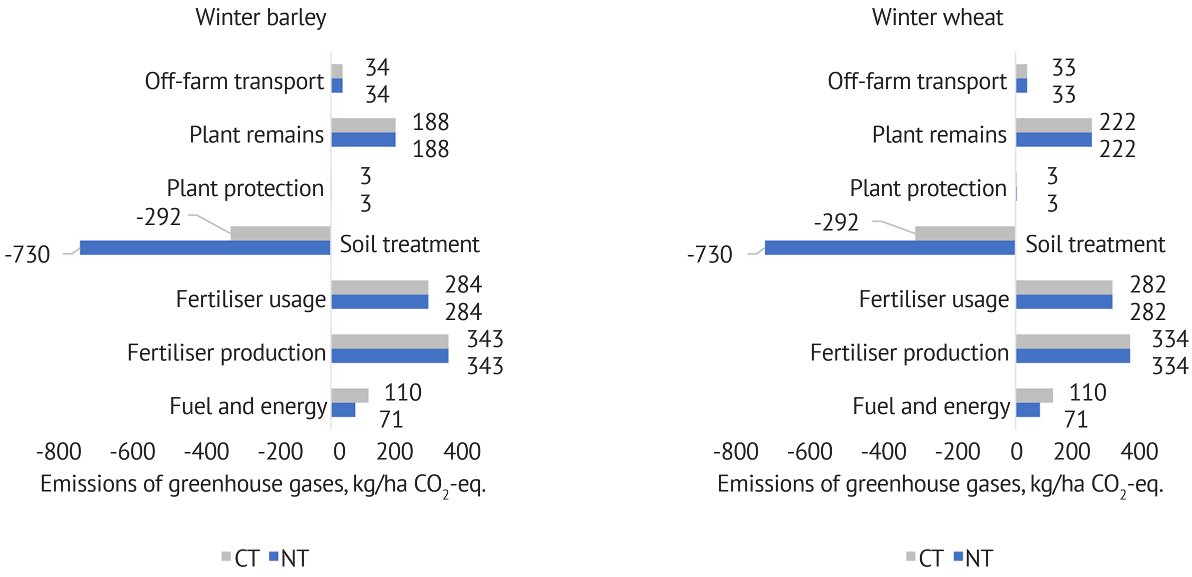

***Figure 3**. Balance of greenhouse gases during the cultivation of barley and winter wheat depending on soil cultivation systems, kg/ha CO_2-eq*

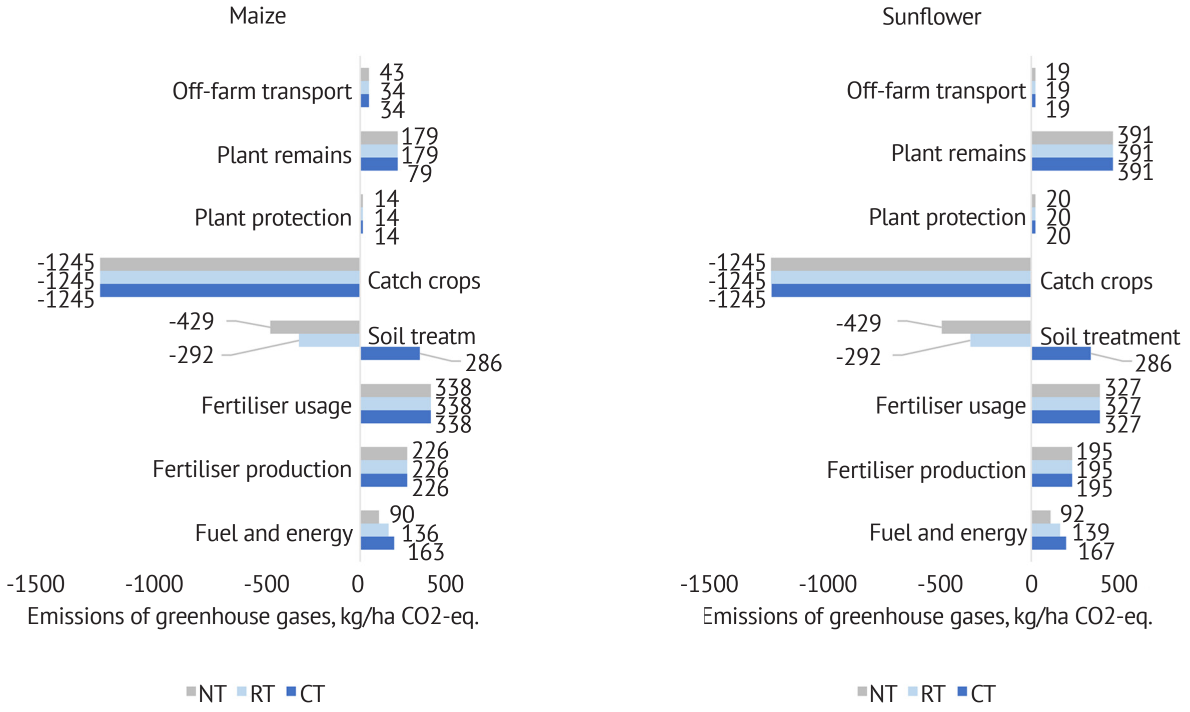

***Figure 4**. Balance of greenhouse gases during the cultivation of maize and sunflower depending on the systems of soil cultivation and catch crops, kg/ha CO_2-eq*

***Source:** compiled by the authors*

As the graphs show, in the structure of greenhouse gas emissions during the cultivation of winter wheat and barley, the largest share is occupied by emissions associated with the use of mineral fertilisers – about 29% and the management of plant residues – 22% – in both cases, the tool assumes that in the options under study they stay on the surface. Emissions associated with fertiliser production are transmitted from the producer (plant) to the farmer as indirect (Scope 3). Fuel use accounts for a small share of emissions – 11.2% with reduced tillage and decreases to 7.5% with no-till, while transport emissions account for about 3.5%. Emissions from plant protection products are only 0.3%. The greatest impact of tillage systems is on the level of sequestered carbon, which is clearly visible in the negative part of the graph related to tillage practices. It is clearly visible that upon reduced tillage, the sequestration reaches -292 kg/ha, with no-till it is almost twice as much – -730 kg/ha CO_2-eq., which compensates for greenhouse gas emissions from the entire technology. Thus, the transition from reduced tillage (mini-till) to no-till on winter grain crops can reduce greenhouse gas emissions by 69-71%, including by reducing fuel consumption – 5.6-5.8%.

Thus, catch crops, due to efficient carbon sequestration, allow obtaining a negative balance of greenhouse gas emissions with any tillage technology. For a 4-field crop rotation under the classical tillage system for sunflower and maize and without catch crops and reduced tillage for wheat and barley, the total emissions of greenhouse gases are 4015 kg/ha of CO_2-eq., under reduced tillage and without catch crops the total greenhouse gas emissions amount to 2805 kg/ha of CO_2-eq., when adding 2 catch crops between the winter grain predecessor before sowing late spring crops, it allows obtaining a negative balance of greenhouse gas emissions during this period – -377 kg/ha of CO_2-eq., and when switching to no-till for all crops – -1221 kg/ha of CO_2-eq. over 4 years (Table 6).

***Table 6**. Comparative characteristics of greenhouse gas emissions depending on the use of catch crops under different tillage systems, kg/ha per year*

Crop rotation culture	**Catch culture**	**Greenhouse gas emissions, kg/ha of CO_2-eq.**		
		CT	**RT**	**NT**
Winter barley	–	-*	669	192
Maize	No catch crops	1249	644	461
	With catch crops	7	-601	-784
Winter wheat	–	–*	692	215
Sunflower	No catch crops	1405	800	616
	With catch crops	163	-445	-629
Total per rotation	No catch crops	4015*	2805	1484
	With catch crops	839*	-377	-1221

***Note:** *to calculate the amount of emissions per rotation according to CT (classical tillage) for barley and winter wheat, data from RT (reduced tillage) were taken as the recommended and most common*
***Source:** compiled by the authors*

The use of catch crops allows reducing greenhouse gas emissions by 1245 kg/ha per year in the field where they are grown, and when using them twice in a 4-field crop rotation, by 794 kg/ha CO_2-eq. (79%) per year using classical tillage technology, by 795 kg/ha of CO_2-eq. (113%) per year with reduced tillage and by 676 kg/ha (181%) CO_2-eq. per year on the no-till farming system (Table 7).

***Table 7**. Greenhouse gas balance depending on the tillage system and the use of catch crops in the crop rotation under study, kg/ha CO_2-eq. for the year*

Catch crops	Tillage system		
	CT	RT	NT
No catch crops	1004	701	371
With catch crops	210	-94	-305

***Source:** compiled by the authors*

Reducing the intervention in the soil through tillage when growing maize and sunflower allows reducing greenhouse gas emissions when growing these crops upon switching from traditional ploughing with rotation to chiselling by 650 kg/ha of CO_2-eq. per year (43-48%), and when switching to no-till – by 788 kg/ha of CO_2-eq. (56-63%) compared to traditional ploughing, including as a result of reducing emissions from fuel – by 2-6%. This reduction in emissions is mainly explained by curbing the rate of mineralisation of organic matter and its more efficient sequestration in the soil. Cultivation of catch crops effectively improves the sequestration process – up to 1245 kg/ha of CO_2-eq. annually.

In calculations based on the Cool Farm Tool, the level of carbon sequestration from the use of catch crops is 1245 kg/ha of CO_2-eq. turned out to be substantially higher than in the studies of Poeplauab & Don (2015) – 0.32±0.08 t/ha and Tribouillois *et al.* (2018) – 315 kg/ha CO_2-eq. in a year. However, the indicator of this study is close to the results obtained by

Velosoa *et al.* (2018), where the combination of no-till with two cover legume crops showed a sequestration level of 1.15 t/ha of CO_2-eq. for a year.

Thus, such elements of the agricultural system as the system of tillage and the use of intermediate crops can substantially improve the carbon balance towards sequestration, which reduces greenhouse gas emissions into the atmosphere and increases the content of organic carbon in the soil.

CONCLUSIONS

Improving the carbon balance in agriculture is achieved by implementing a set of measures in two areas: reducing direct CO_2 emissions and improving its removal from the atmosphere through plant photosynthesis and sequestration in the form of organic matter in the soil. Reducing emissions involves measures to save fuel, reduce nitrogen losses from fertilisers, reduce soil interference through cultivation, and slow down the mineralisation of plant residues. The improvement of CO_2 extraction from the atmosphere is achieved by maximising the time the field is occupied by plants through the optimisation of crop rotation.

To improve the carbon balance in agrocenoses, it is important to reduce the field time in the state without plants by growing catch crops without harvesting them to avoid "pauses" in extracting carbon from the atmosphere and sequestering it in the soil as organic matter.

The use of catch crops allows reducing greenhouse gas emissions by 1245 kg/ha per year in the fields between winter grain predecessors before the summer crops in the year of cultivation, and when using them twice per a 4-field crop rotation – by an average of 794 kg/ha of CO_2-eq. (79%) per year using classical tillage technology, by 795 kg/ha of CO_2-eq. (113%) per year with reduced tillage and by 676 kg/ha (181%) CO_2-eq. per year on the no-till system.

Based on the results of calculations, it was found that the most substantial measures to improve the carbon balance are the transition to reduced tillage and no-till systems and the use of catch crops. Involvement of catch crops in a 4-field arable crop rotation in 2 seasons out of 4 allows reducing greenhouse gas emissions from 1004 kg/ha to 210 kg/ha CO_2-eq. a year. Switching from ploughing to a reduced tillage system for maize and sunflower allows reducing emissions by 303 kg/ha of CO_2-eq. a year. Switching to a no-till farming system for all crop rotations will reduce greenhouse gas emissions by an average of 633 kg/ha of CO_2-eq. a year. Switching to a no-till system for all crops and including catch crops in two crop rotation fields allows for a positive carbon balance – sequestration of an average of 305 kg/ha of CO_2-eq. a year.

REFERENCES

[1] Balyuk, S.A., & Kucher, A.V. (2019). Expansive features of the soil slope as the basis of the steel management of soils. *Ukrainian Geographic Journal,* 3, 3-14. doi: 10.15407/ugz2019.03.003.

[2] Bedernicek, T.Yu. (2017). Reservoirs and flows of carbon in terrestrial ecosystems of Ukraine. *Bulletin of the National Academy of Sciences of Ukraine*, 1, 98-106. doi: 10.15407/visn2017.01.098.

[3] Boychenko, S.G. (2002). Dynamics of nitrous oxide content in the Earth's atmosphere. *Scientific Works of the Ukrainian Research Hydrometeorological Institute*, 250, 124-137.

[4] Carbon dioxide peaks near 420 parts per million at Mauna Loa observatory. (2021). Retrieved from https://research.noaa.gov/article/ArtMID/587/ArticleID/2764/Coronavirus-response-barely-slows-rising-carbon-dioxide.

[5] Carbon farming. (n.d.). Retrieved from https://ec.europa.eu/clima/eu-action/forests-and-agriculture/sustainable-carbon-cycles/carbon-farming_en.

[6] Conservation practice standard 340-CPS. (2020). Retrieved from https://efotg.sc.egov.usda.gov/api/CPSFile/23444/340_NC_CPS_Cover_Crop_2020.

[7] Cool Farm Tool. (2022). Retrieved from https://app.coolfarmtool.org/.

[8] Cover crop. (2018). Retrieved from https://knowledge4policy.ec.europa.eu/glossary-item/cover-crop_en.

[9] DSTU 4362:2004 "On Soil Quality. Indicators of Soil Fertility". (2004, December). Retrieved from http://online.budstandart.com/ua/catalog/doc-page?id_doc=67099.

[10] DSTU 4691:2006 "On Agriculture. Terms and Definitions". (2006, December). Retrieved from http://online.budstandart.com/ru/catalog/doc-page?id_doc=54255.

[11] Egorov, O.V. (2021). The influence of fertilizers on the fertility indicators of sod-podzolic soils and the productivity of short-rotational crop rotations in Polissia. *Agroecological Journal*, 3, 119-126.

[12] Fiorini A., Maris, S.C., Abalos, D., Amaducci, S., & Tabaglio, V. (2020). Combining no-till with rye (Secale cereale L.) cover crop mitigates nitrous oxide emissions without decreasing yield. *Soil and Tillage Research*, 196, article number 104442. doi: 10.1016/j.still.2019.104442.

[13] Hansen, J., Kharecha, P., Sato, M., Masson-Delmotte, V., Ackerman, F., Beerling, D.J., Hearty, P.J., Hoegh-Guldberg, O., Hsu, Sh-L., Parmesan, C., Rockstrom, J., Rohling, E.J., Sachs, J., Smith, P., Steffen, K., van Susteren, L., von Schuckmann, K., & Zachos, J.C. (2013). Assessing "Dangerous Climate Change": Required reduction of carbon emissions to protect young people, future generations and nature. *PLoS ONE*, 8(12), article number e81648. doi: 10.1371/journal.pone.0081648.

[14] IPCC Assessment Report 6. (2022). Retrieved from https://www.ipcc.ch/assessment-report/ar6/.

[15] Nitrogen Use Efficiency (NUE) – an indicator for the utilisation of nitrogen in agriculture and food systems. (2015). Retrieved from http://www.eunep.com/wp-content/uploads/2017/03/Report-NUE-Indicator-Nitrogen-Expert-Panel-18-12-2015.pdf.

[16] Poeplauab, Ch., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, 200, 33-41. doi: 10.1016/j.agee.2014.10.024. doi: 10.1016/j.agee.2014.10.024.
[17] Razanov, S.F. (2021). The effect of siderates on soil fertility. *Balanced Nature Management*, 4, 144-152.
[18] Reicosky, D. (1997). Tillage-induced CO_2 emission from soil. *Nutrient Cycling in Agroecosystem*, 49(1), 273-285. doi: 10.1023/A:1009766510274.
[19] Review of GHG calculators in agriculture and forestry sectors. (2012). Retrieved from https://www.fao.org/fileadmin/templates/ex_act/pdf/ADEME/Review_existingGHGtool_VF_UK4.pdf.
[20] Ruis, S.J., & Blanco-Canqui, H. (2017). Cover crops could offset crop residue removal effects on soil carbon and other properties: A review. *Agronomy Journal*, 109(5), 1785-1805. doi: 10.2134/agronj2016.12.0735.
[21] Sauvadet, M., Lashermes, G., Alavoine, G., Recous, S., Chauvat, M., Maron, P-A., & Bertrand, I. (2018). High carbon use efficiency and low priming effect promote soil C stabilisation under reduced tillage. *Soil Biology and Biochemistry*, 123, 64-73. doi: 10.1016/j.soilbio.2018.04.026.
[22] Sixth Assessment Report. (2021). Retrieved from https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf.
[23] Soil Health. (2022). Retrieved from https://www.fs.usda.gov/nac/topics/soil-health.php.
[24] Terrer, C., et al. (2019). Nitrogen and phosphorus constrain the CO_2 fertilisation of global plant biomass. *Nature Climate Change*, 9, 684-689. doi: 10.1038/s41558-019-0545-2.
[25] The average annual air temperature in Ukraine is growing faster than the global temperature – Kulbida. (2020). Retrieved from https://www.unn.com.ua/uk/news/1883673-serednorichna-temperatura-povitrya-v-ukrayini-zrostaye-shvidshe-nizh-zagalnosvitova-kulbida.
[26] Tkachuk, V.P., & Trofimenko, P.I. (2020). Humus content for different use of sod-podzolic sandy soil and the amount of CO_2 emissions lost. *Scientific Reports of Nules of Ukraine*, 2(84). doi: 0.31548/dopovidi2020.02.007.
[27] Tribouillois, H., Constantin, J., & Justes, E. (2018). Cover crops mitigate direct greenhouse gases balance but reduce drainage under climate change scenarios in temperate climate with dry summers. *Global Change Biology*, 24, 2513-2529. doi: 10.1111/gcb.14091.
[28] Ukraine's greenhouse gas inventory 1990-2019. (2021). Retrieved from https://mepr.gov.ua/news/36912.html.
[29] Veloso, M.G., Angers, D.A., Tiecher, T., Giacomini, S., Dieckow, J., & Bayer, C. (2018). High carbon storage in a previously degraded subtropical soil under no-tillage with legume cover crops. *Agriculture, Ecosystems & Environment*, 268, 15-23. doi: 10.1016/j.agee.2018.08.024.

Оцінка ефективності проміжних культур і систем обробітку ґрунту для вуглецевого землеробства

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Анотація. В сучасному землеробстві необхідно визначити стратегічні кроки, що дозволять скоротити викиди парникових газів: з одного боку, скорочення викидів через зменшення витрат палива, зменшення втручання в ґрунт, обмеження втрат азоту при використанні добрив, а з іншого – підвищення ефективності вилучення вуглецю з атмосфери через фотосинтез рослин і секвестрацію його у вигляді органічної речовини ґрунту. Метою дослідження є визначення рівня впливу на баланс вуглецю таких елементів системи землеробства як система обробітку ґрунту і використання проміжних покривних культур у модельній 4-пільній польовій сівозміні в степовій зоні України. Дана робота була виконана за методикою емпіричних розрахунків на основі онлайн калькулятора викидів парникових газів Cool Farm Tool. Було проаналізовано вплив проміжних культур у двох полях сівозміни (після ранніх зернових попередників – пшениці і ячменю озимих) і систем обробітку ґрунту (традиційний, скорочений і no-till) на баланс викидів і секвестрації вуглецю в модельній 4-пільній польовій сівозміні. За результатами досліджень було встановлено, що за ротацію модельної 4-пільної сівозміни за умов класичної системи обробітку ґрунту для соняшнику і кукурудзи без проміжних культур і скороченої обробки для пшениці і ячменю, сумарні викиди парникових газів становлять 4015 кг/га CO_2-екв. за 4 роки. Було доведено, що перехід на систему скороченої обробки ґрунту зменшує викиди на 30.1%. Додавання двох проміжних культур у двох полях сівозміни перед ярими культурами дозволяє отримати за цей період від'ємний баланс викидів парникових газів -377 кг/га CO_2-екв., а при переході на no-till для всіх культур -1221 кг/га CO_2-екв. за 4 річній період ротації. Ця робота допоможе визначити стратегічні кроки та їхній потенційний внесок при розробці і впровадженні систем землеробства з мінімальними викидами парникових газів

Ключові слова: вуглецеве землеробство, здоров'я ґрунту, викиди парникових газів, проміжні культури, комплексна оцінка якості проміжних культур, вуглецевий баланс