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CHAPTER 3. OILSEED RADISH IN THE SYSTEM OF MULTI-SERVICE COVER CROP (MSCC) FOR REHABILITATION OF DEGRADED SOILS

3.1. Assessment of oilseed radish potential according to multi-service cover crop (MSCC) criteria

Modern processes of biologization of farming systems through diversification of classical approaches to crop rotation design and their saturation with intermediate crops are aimed at both preventing the degradation of agricultural land and realizing the goals of a significant reduction of anthropogenic impact on the environment (Waha et al., 2020). Usually, the use of intermediate crops in the basic links of crop rotations is considered from many perspectives, from optimizing organic fertilization to reducing the negative status of repeated crops, and in the complex of agroecological approaches guarantees a number of significant benefits that have a long-term positive effect on the overall ecological and productive potential of the soil (Couëdel et al., 2019; Dzvene et al., 2023). In the complex of the identified positive effects of intermediate crops, the paradigm of multi-service cover crop (MSCC) was formed, which is becoming more and more popular every year and gaining importance from the point of view of the system's ability to control negative soil degradation processes and agrochemical and biological transformations in it caused by the intensification of the impact of anthropogenic technological solutions (Justes & Richard, 2017). The very concept of MSCC from the beginning of its design envisaged the cultivation of specially selected crops capable of forming the appropriate biomass in a short period before sowing the main crop in different calendar terms for its green manure use or as a cover crop to control erosion and degradation processes (Couëdel et al., 2019; Lucadamo et al., 2022; Scavo et al., 2022). In the recent period, due to the actualization of such areas as greening and biologization of fertilizers, the development of green bioenergy, the MSCC list also includes the possibility of fodder and bioenergy use of relevant crops (Lavergne et al., 2021). A significant share in the MSCC system is played by the aspects of using intermediate crops to prevent the deficit of organic matter that enters the soil under different fertilization options, reduce the rate of its mineralization and optimize the accumulation of organic carbon (Lei et al., 2022; Lee et al., 2023). Green manure is considered from an ecological point of view as the most rational approach to balanced plant nutrition and guarantees appropriate optimized levels of macro and microelements recycling in assessing their balance in the use-return ratio (Wittwer et al., 2020; Guinet et al., 2023). It is important to investigate the potential of using varietal green manure under variant technological and calendar-term use against the background of widespread involvement of by-products left after harvesting the main crop (Couëdel et al., 2019; Boselli et al., 2020; Kenjaev & Davronova, 2023). This approach is in line with the defined strategy of the green course and adaptive soil conservation in view of the dynamic processes of soil degradation (dehumidification, over-compaction, loss of agronomically valuable structure and the proportion of moisture-resistant aggregates, and increased greenhouse gas emissions) (Ansari et al., 2022; Israt & Parimal, 2023).

Global trends in soil degradation, reduced availability of classic organic fertilizers, and intensive growth in mineral fertilizer prices against the background of a general rise in the cost of traditional energy resources lead to a constant search for alternatives in the agricultural sector of the economy (Kaletnik et al., 2020, 2020a; Honcharuk et al., 2023, 2023a; Tokarchuk et al., 2023). A widely recognized alternative for the formation of ecologically balanced soil use and soil conservation is the use of intermediate crops for multiple purposes in the scheme of classical crop rotations. These types of plants are used for various purposes: biologization of agrotechnologies, soil profile rehabilitation, source of organic recycling fertilization systems (green manure), source of biomass for fodder and bioenergy use, anti-erosion functions, etc. It should be noted that the market for such crops has a pronounced positive growth dynamics. Thus, the Green Manure Global Market Report 2024 (2023) notes that the green manure market size has grown strongly in recent years. It will grow from \$2.17 billion in 2023 to \$2.33 billion in 2024 at a compound annual growth rate (CAGR) of 7.6%. The green manure market size is expected to see strong growth in the next few years. It will grow to \$3.07 billion in 2028 at a compound annual growth rate (CAGR) of 7.1%. The growth in the forecast period can be attributed to climate change adaptation, soil health awareness, regenerative agriculture practices, consumer demand for sustainable agriculture, integration in precision agriculture, enhanced soil microbial activity, water quality management. Major trends in the forecast period include the integration of different cover crops, no-till and reduced-till farming systems, innovations in cover crops, integration of livestock in cover cropping.

Based on the above approaches, a systematic approach to an integrated bio-organic and ecologically oriented approach to soil use was formulated, taking into account the intensity of modern cultivation technologies. This led to the formation of the concept of multi-service cover crop (MSCC) (Justes & Richard, 2017). This concept involves the search, selection and combination in crop rotation of crops that have certain criteria, the main of which are unpretentiousness to the terms of use with the possibility of cultivation in a wide range of calendar dates, intensity and volume of accumulation of aboveground and underground biomass of a certain biochemical quality, intensity of the process of decomposition of their biomass in the soil and suitability for anaerobic fermentation processes (Couëdel et al, 2019; Lucadamo et al., 2022; Scavo et al., 2022). In this complex, the dominants characteristic of the respective soil and climatic zones are distinguished. Thus, a significant part of the MSCC system is played by the aspects of the use of intermediate crops to prevent the deficit of organic matter that enters the soil under different fertilization options (Boselli et al., 2020; Guinet et al., 2023). The relevance of the use of intermediate crops for green manure in the MSCC system is especially relevant in the context of the growing shortage of classical organic matter in fertilization due to changes in the keeping of farm animals and the transfer of modern livestock complexes to schemes for processing manure waste into biogas (Pan et al., 2021), as well as the transition to minimized and zero tillage technologies (Boselli et al., 2020). The positivity of the MSCC conceptual approach is also considered from the standpoint of an effective source of replenishment of soil organic matter with optimized modes of its subsequent humification and normalization of the positive ratio, taking into account the rate of humus mineralization (accumulation of organic carbon in general) (Lei et al, 2022; Lee et al., 2023) and from the point of view of a positive impact on the complex of soil properties (Couëdel et al., 2019; Chen et al., 2020; Ansari et al., 2022; Israt & Parimal, 2023). It has been noted (Justes & Richard, 2017) that MSCC contributes to the optimization of agro-ecological sustainability of agrocenosis and agro-landscapes in general through the optimized filling of ecological niches of fauna and flora of the territories. It is noted that the selection of potential candidate crops that possess the MSCC principle should be based on the study of basic compliance criteria, which for the optimal candidate are multiple in nature (Couëdel et al., 2019; Singh et al., 2023).

It has been noted that the selection of potential candidate crops that possess the MSCC criterion complex should be based on the study of their terms of use and response to soil and climatic resources without compromising the structure of agricultural production in the territories (Yadav et al., 2021; Pryshliak et al., 2022; Abdulraheem & Tobe, 2022; Honcharuk et al., 2023; Lohosha et al., 2023; Singh et al., 2023; Mazur et al., 2023; Tokarchuk et al., 2023). Considering the above arguments, the purpose of the ten-year research cycle was to find out the bioproductive potential of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) on gray forest soils from the point of view of compliance with MSCC requirements. It has been noted (Tsytsiura, 2019, 2020, 2020a, 2021, 2022; 2023, 2023a-b, 2024) that a number of important issues require scientific generalization, in particular, the level of adaptability to changes in sowing dates, patterns of formation of aboveground and underground biomass, its chemical composition, and the possibility of using both green manure and bioenergy options.

The research was carried out during 2014–2023 at the experimental field of Vinnytsia National Agrarian University (N 49°11′31″, E 28°22′16″.) on Grey and Dark Gray forest soils (Greyi-Luvic Phaeozems (Phaeozems Albic, Dark Gray Podzolic Soils) according to WRB (IUSS, 2015)) Haplic Greyzems according to FAO (IUSS, 2015)) of silty clay loamy texture (sicl) (fluctuations in the content of fractions for the horizon 0–30 cm: sand 12.03–14.32, silt 55.86–57.79 and clay 29.35–30.21). The agrochemical potential of the soil for layer 0–30 cm was determined with the standards for analytical laboratory methods (Sparks et al., 1996) and had the following average indicators for the research period: humus content: 2.68%, easily hydrolyzed nitrogen 81.5 mg kg^{-1} of soil, mobile phosphorus 176.1 mg kg^{-1} of soil, exchangeable potassium 110.8 mg kg^{-1} of soil, pH_{KCl} 5.8, hydrolytic acidity 3.29 mg-equivalent 100 g^{-1} of soil. The soil fertility potential based on the presented agrochemical properties was estimated as average (according to Sanchez et al., 1982).

The variety of oilseed radish 'Zhuravka' was used. Sowing was carried out on an unfertilized background with a seeding rate of 2.5 million seeds ha^{-1} using the conventional row method (row spacing of 15 cm). This sowing option corresponded to the variant of fodder–green manure use of oilseed radish (Tsytsiura, 2020). Two systems of using oilseed radish as an intermediate crop for multiple purposes in the recommended MSCC system in the study area were investigated:

I. System of early spring sowing after intermediate cultivation in the format of cultivation to a depth of 8–10 cm with leveling (first-second decade of April) against the background of autumn plowing at 20–22 cm at the date of phenological achievement of the optimal phase of multicomponent use of oilseed radish biomass (flowering stage (BBCH 64–67) in the second-third decade of June.

II. The system of intermediate (summer) use for sowing immediately after harvesting the predecessor with intermediate combined tillage (flat cutter + rotary loosening with leveling) to a depth of 12–14 cm in the second or third decade of July at the date of phenological achievement of the optimal phase of multicomponent use of oilseed radish biomass (flowering stage (BBCH 64–67) in the second or third decade of October. The sowing date of the first variant was determined at the early stage of physical ripeness of the soil.

For the second variant, the soil moisture indicator was used based on the date of the nearest precipitation with an intensity of at least 5 mm (according to the recommendations of Florentín et al. (2010)). The optimality of the phase of leaf mass use was determined taking into account the combination of maximum individual plant productivity and relevant quality indicators and corresponds to the recommended variant of biofumigant and green manure use of oilseed radish under conditions of unstable moisture in different soil zones against the background of general recommendations for the phases of cover crops use according to Alonso-Ayuso et al. (2014) and Duff et al. (2020).

A generalized assessment of the hydrothermal regimes of the oilseed radish vegetation period within the years of research is presented in Table 3.1. According to the general classification of the hydrothermal regime of the territories (Latief et al. (2017)), the study period was characterized as conditions of unstable moisture. Taking into account the optimal parameters for the growth processes of oilseed radish plants according to our previous long-term estimates (Tsytsiura, 2020) and the grouping classification by

De Martonne Aridity Index (IDM) and Vysotsky-Ivanov humidification coefficient (K_h), the years of research were placed in the following order of increasing favorability of growth processes for the conditions of spring sowing: 2017–2015–2016–2018–2021–2022–2023–2014–2020–2019. For the conditions of the summer sowing period, a similar series was as follows: 2015–2021–2019–2016–2023–2014–2020–2018–2017–2022.

The indicators of variation statistics were determined using the generally accepted calculation method in the statistical software Statistica 10 (StatSoft – Dell Software Company, USA) and Past 4.13 software (Øyvind Hammer, Norway). For statistical evaluation of the obtained average values were used arithmetic mean ($\bar{x}$), standard deviation (SD) and coefficient of variation (CV). Moreover, a Spearman correlation test was used for a statistical level of $p < 0.05^{*}$ and $p < 0.01^{**}$.

The data obtained were analyzed using the analysis of ANOVA (Wong, 2018). Tukey HSD Test in R (version R statistic i386 3.5.3) on the 95% family-wise confidence level were used.

To statistically assess the correlation in accordance with Snecdecor & Cochran (1991) was used the coefficient of determination (R^2) and adjusted coefficient of determination (R^2_{adj}). The Chaddock scale (1925) was used to estimate R^2 (R^2 of 0.1–0.3 indicated a weak relationship; 0.3–0.5 moderate; 0.5–0.7 significant; 0.7–0.9 high; 0.9–0.99 very high).

Both in spring (Table 3.2) and summer sowing (Table 3.3), oilseed radish showed a sensitive wide range of responses to changes in hydrothermal moisture conditions. This influence was realized through a significant difference and variability of biomass of both aboveground and underground parts of plants and the corresponding accompanying ratios. The highest level of aboveground biomass productivity on average during the study period was determined at the spring sowing date of 24.04 t ha^{-1} with a level of interannual variation of 30.55%.

For unstable moisture conditions, it has been established (Ramirez-Garcia et al. 2014; Ugrenović et al, 2019; Safaei et al. 2022; Ţiţei, 2022) the yield of aboveground biomass of such crops as white mustard, spring rape, *Tillage radish (Daikon radish)* in the range of 12–27 t ha^{-1}, winter rape (taking into account biomass in the early summer period) in the range of 25–60 t ha^{-1}. The formed underground (root) biomass for the same group of crops was 5–15 t ha^{-1} and 12–25 t ha^{-1}.

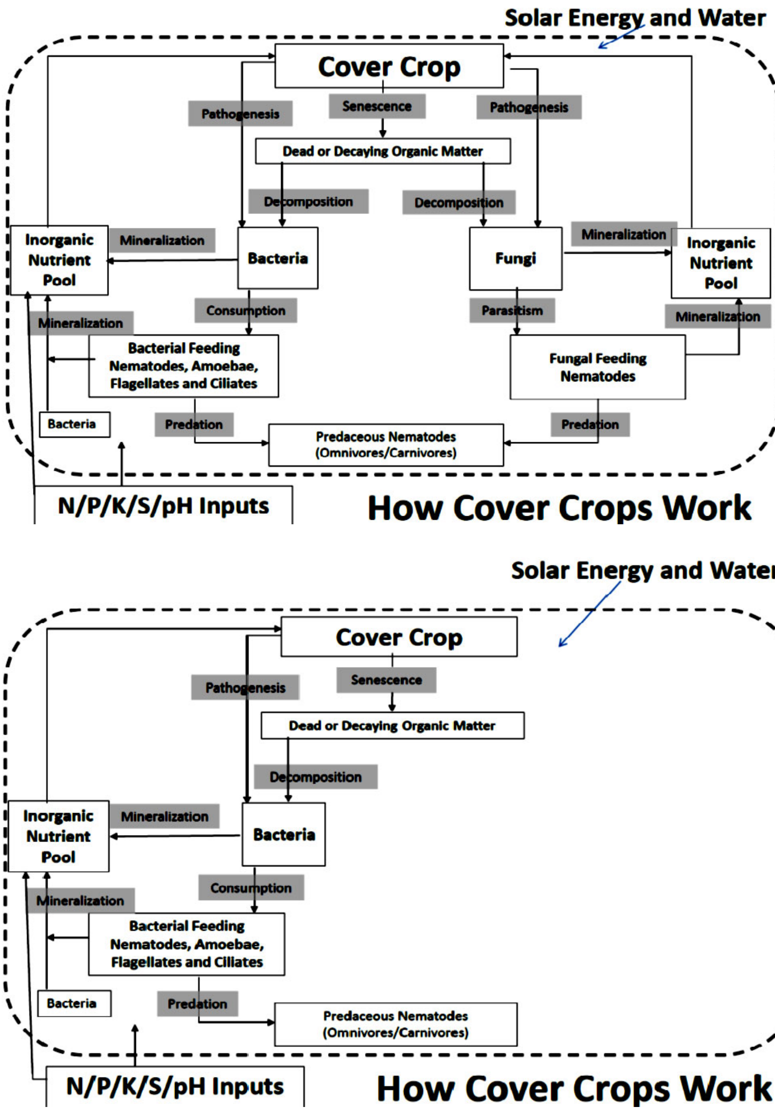

Figure 3.1 – How cover crops work (Warner et al., 2017)

Table 3.1

Estimation of the values of hydrothermal regimes of the period of active vegetation of oilseed radish for the variant of spring and summer sowing, 2014–2023

Year	Precipitation, mm (IV–VI)	$^*t_{aver}$, °C (IV–VI)	Months of the growing season								
			IV			V			VI		
			НТС	I_{DM}	$К_h$	НТС	I_{DM}	$К_h$	ГТК	I_{DM}	$К_h$
Spring sowing											
2014	339.6	13.84	0.725	45.7	1.18	3.928	88.9	2.11	1.545	34.8	0.83
2015	142.3	14.36	0.645	37.3	0.78	0.917	20.6	0.41	0.715	16.9	0.27
2016	193.4	15.06	0.296	21.6	0.44	0.489	40.4	0.99	1.265	29.9	0.75
2017	125.1	14.07	3.919	39.2	0.75	0.777	16.8	0.34	0.504	11.9	0.22
2018	170.8	16.38	0.290	10.8	0.19	0.308	7.2	0.12	4.404	103.7	2.31
2019	398.5	15.39	0.565	33.5	0.72	4.902	111.0	3.29	1.682	41.4	0.96
2020	343.8	13.67	0.091	36.4	0.50	5.327	106.4	3.18	1.548	37.3	0.89
2021	282.8	13.26	0.233	38.8	0.96	3.125	66.7	1.64	1.679	39.8	1.00
2022	242.1	14.30	0.563	57.4	2.33	1.430	31.3	0.79	1.496	36.1	0.85
2023	239.8	14.18	1.543	91.5	3.33	0.085	1.9	0.04	1.640	38.9	0.87

Year	Precipitation, mm (VII–X)	$^*t_{aver}$, °C (VII-X)	Months of the growing season												$^*t_{aver}$, °C	Precipitation amount mm**
			VII			VIII			IX			X				
			НТС	I_{DM}	$К_h$	НТС	I_{DM}	$К_h$	НТС	I_{DM}	$К_h$	НТС	I_{DM}	$К_h$		
Summer sowing																
2014	250.8	15.4	1.312	32.7	0.77	1.049	26.0	0.51	1.252	25.7	0.56	1.770	35.8	0.93	–	–
2015	160.8	16.6	0.321	8.1	0.14	0.124	3.1	0.05	1.184	26.8	0.63	3.039	49.4	1.25	0.2	245.5
2016	212.7	15.6	1.056	26.5	0.55	0.898	22.0	0.43	0.014	2.5	0.05	0.548	63.4	2.45	9.5	256.1
2017	318.0	16.0	1.524	37.5	0.72	0.819	20.7	0.38	3.100	61.2	1.57	1.065	30.0	1.26	-0.6	325.7
2018	273.4	16.4	2.158	53.4	1.63	0.585	14.6	0.30	1.378	27.2	0.71	0.873	27.6	0.95	-0.4	323.7
2019	161.7	16.0	1.013	24.4	0.56	0.237	5.9	0.11	0.994	20.7	0.42	0.383	27.4	0.93	0.0	271.0
2020	245.4	17.6	0.589	14.7	0.31	0.527	13.2	0.22	0.859	27.5	0.54	2.544	60.6	3.05	2.9	200.5
2021	176.9	15.4	0.782	20.1	0.45	1.459	35.7	0.91	0.705	17.6	0.51	0.000	1.7	0.04	-0.3	356.1
2022	436.6	16.0	0.900	22.4	0.58	1.712	43.1	1.06	4.960	98.1	2.60	3.167	51.4	1.50	1.2 2.2	216.9 278.0
2023	247.1	18.3	1.414	35.8	0.82	0.652	16.9	0.36	1.015	23.4	0.63	1.025	29.9	0.93	–	–

* – the average daily average temperature (°C) and ** – the amount of precipitation (mm) for the period November of the previous year – March of the following year.

Table 3.2

Indicators of bioproductivity of oilseed radish in spring sowing for flowering stage (BBCH 64–67), 2014–2023 (based on the results of the author's own research)

Basic and derived indicators of bioproductivity	Year of observation										*LSD$_{0.5}$
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	
Leaf and stem biomass yield, t ha^{-1}	33.49	20.11	21.29	15.22	13.89	35.75	30.88	24.12	21.18	24.48	1.39
Dry matter content of leaf and stem biomass, %	12.23	14.12	14.19	13.75	15.11	11.27	12.73	11.81	13.28	13.09	0.64
Leaf and stem biomass yield in dry matter, t ha^{-1}	4.10	2.84	3.02	2.09	2.10	4.03	3.93	2.85	2.81	3.20	0.24**
Root biomass yield, t ha^{-1}	13.28	7.88	6.22	4.47	3.39	14.85	13.02	9.57	7.44	6.87	1.15
Dry matter content in the biomass of root residues, %	20.42	23.12	21.73	22.84	23.95	20.68	19.84	19.09	21.47	21.11	0.88
Root biomass yield in dry matter, t ha^{-1}	2.71	1.82	1.35	1.02	0.81	3.07	2.58	1.83	1.60	1.45	0.26**
Total biomass produced (roots + aboveground biomass), t ha^{-1}	46.77	27.99	27.51	19.69	17.28	50.6	43.9	33.69	28.62	31.35	1.99
Total biomass produced (roots + aboveground part) in dry matter, t ha^{-1}	6.81	4.66	4.37	3.11	2.91	7.10	6.51	4.68	4.41	4.65	0.36
Root system productivity factor in raw weight	2.52	2.55	3.42	3.40	4.10	2.41	2.37	2.52	2.85	3.56	0,62
Root system productivity factor in dry matter	1.51	1.56	2.24	2.05	2.59	1.31	1.52	1.56	1.76	2.21	0.38
Share of root biomass in the crude total biomass of plants, %	28.39	28.15	22.61	22.70	19.62	29.35	29.66	28.41	26.00	21.91	1.05
Share of root biomass in dry total plant biomass, %	39.83	39.08	30.91	32.79	27.89	43.25	39.65	39.07	36.22	31.16	0.56
Leafiness of plants, %	43.91	40.84	41.27	38.22	40.81	48.78	46.77	38.29	43.92	43.26	2.89
Share of stem, %	47.77	49.81	45.08	47.44	46.87	42.89	42.42	51.68	44.72	46.31	2.56
Share of the generative part, %	8.32	9.35	13.65	14.34	12.32	7.33	9.81	10.03	11.36	10.43	0.98
Survival rate of plants, %	90.24	86.17	85.74	83.51	81.23	93.21	90.78	88.09	87.28	87.92	4.44
IVC	1.310	0.807	0.781	0.623	0.572	1.443	1.293	0.992	0.850	1.015	0.06

*LSD$_{05}$ for values in % in the expression of a fraction of the numerical value of the indicator according to Snecdecor & Cochran (1991); ** in combinatorial comparison of crude weight and dry matter content by repetitions according to Snecdecor & Cochran (1991).

Table 3.3

Indicators of bioproductivity oilseed radish in summer sowing for flowering stage (BBCH 64–67), 2014–2023 (based on the results of the author's own research)

Basic and derived indicators of bioproductivity	Year of observation										*$LSD_{0.5}$
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	
Leaf and stem biomass yield, t ha^{-1}	22.21	9.49	21.05	23.79	23.12	10.11	11.29	16.22	24.77	21.39	1.29
Dry matter content of leaf and stem biomass, %	15.17	17.52	15.97	14.27	14.91	17.15	16.08	16.83	13.43	15.75	1.11
Leaf and stem biomass yield in dry matter, t ha^{-1}	3.37	1.66	3.36	3.39	3.45	1.73	1.82	2.73	3.33	3.37	0.27**
Root biomass yield, t ha^{-1}	6.59	1.39	5.77	7.21	5.52	3.58	3.09	6.49	8.03	7.33	0.60
Dry matter content in the biomass of root residues, %	22.17	25.18	23.12	21.08	23.29	20.15	22.68	23.32	21.91	23.52	1.08
Root biomass yield in dry matter, t ha^{-1}	1.46	0.35	1.33	1.52	1.29	0.72	0.70	1.51	1.76	1.72	0.13**
Total biomass produced (roots + aboveground biomass), t ha^{-1}	28.8	10.88	26.82	31	28.64	13.69	14.38	22.71	32.8	28.72	2.19
Total biomass produced (roots + aboveground part) in dry matter, t ha^{-1}	4.83	2.01	4.70	4.91	4.73	2.46	2.52	4.24	5.09	5.09	0.27
Root system productivity factor in raw weight	3.37	6.83	3.65	3.30	4.19	2.82	3.65	2.50	3.08	2.92	0,48
Root system productivity factor in dry matter	2.31	4.75	2.52	2.23	2.68	2.40	2.59	1.80	1.89	1.95	0.32
Share of root biomass in the crude total biomass of plants, %	29.67	14.65	27.41	30.31	23.88	35.41	27.37	40.01	32.42	34.27	1.67
Share of root biomass in dry total plant biomass, %	43.36	21.05	39.68	44.77	37.29	41.60	38.60	55.44	52.89	51.17	3.56
Leafiness of plants, %	35.41	37.22	35.79	36.77	35.56	33.51	34.15	30.29	38.37	33.11	2.72
Share of stem, %	52.28	57.26	51.89	47.25	45.81	55.18	48.53	54.27	41.88	49.27	2.38
Share of the generative part, %	12.31	5.52	12.32	15.98	18.63	11.31	17.32	15.44	19.75	17.62	1.36
Survival rate of plants, %	80.28	70.29	80.17	81.08	81.52	71.17	70.14	77.37	82.31	78.79	3.09
IVC	0.780	0.334	0.763	0.971	0.876	0.333	0.479	0.481	1.027	0.781	0.08

*LSD_{05} for values in % in the expression of a fraction of the numerical value of the indicator according to Snecdecor & Cochran (1991); ** in combinatorial comparison of crude weight and dry matter content by repetitions according to Snecdecor & Cochran (1991).

Based on these results, oilseed radish can be attributed to highly productive crops with developed adaptive mechanisms of plant biomass formation. Such statements are also consistent with the results of the assessment of the dynamics of oilseed radish aboveground biomass formation with a focus on phenotypic resources of the growing season (Figure 3.2, Table 3.4). It should be noted that the models widely used in the practice of mathematical analysis of the formation of aboveground plant mass, such as the Gompertz model, Logistic model, Linear-exponential model (Tjørve & Tjørve, 2017), according to the results of statistical evaluation for adequacy, were ineffective for oilseed radish with a moderate closeness of dependence (R2<0.5) and were not included in Table 3.4. This indicates a certain species specificity of the formation of the indicator characteristic of cruciferous crops and is consistent with the findings of Ramirez-Garcia et al. (2014), who found, for example, that white mustard among the 5 species of cover crops (cereals, cruciferous and legumes) studied by them had the lowest statistical estimates of R^2 in the system of modeling its biomass growth in accordance with the above three models. Similar conclusions were reported by Tribouillois et al. (2016) and Snapp et al. (2005).

According to the correlation and statistical assessment of the curves of dynamic growth of aboveground biomass, with the dominance of power and exponential dependencies (Table 3.4), the Harris Model and Quadratic Fit for both sowing dates under the determination of the relationship (d_{xy}) were found in the range of 82.2–88.7% and 69.4–79.7%. Certain features of aboveground biomass formation have also been established. These are slow rates of its formation in the interval up to 1000 °C Day after sowing with intensive growth from the date of 1000 °C Day for spring and 1300 °C Day for summer sowing. That is, oilseed radish is characterized by a hyperbolic nature of biomass growth with the maximum intensity in the second half of the growing season. At the same time, the intensity of these processes in the spring sowing period was significantly more uniform than in the summer. This is proved by the level of determination of the dependence of the curve formation at the spring sowing date in such models as 'Exsponential Association' (d_{xy} = 78.0%) and ‘MMF Model’ (d_{xy} = 79.2%). In the case of summer sowing for these models, both the closeness of the relationship and the level of its adequate description by these models were significantly lower (47.4% and 65.7%, respectively).

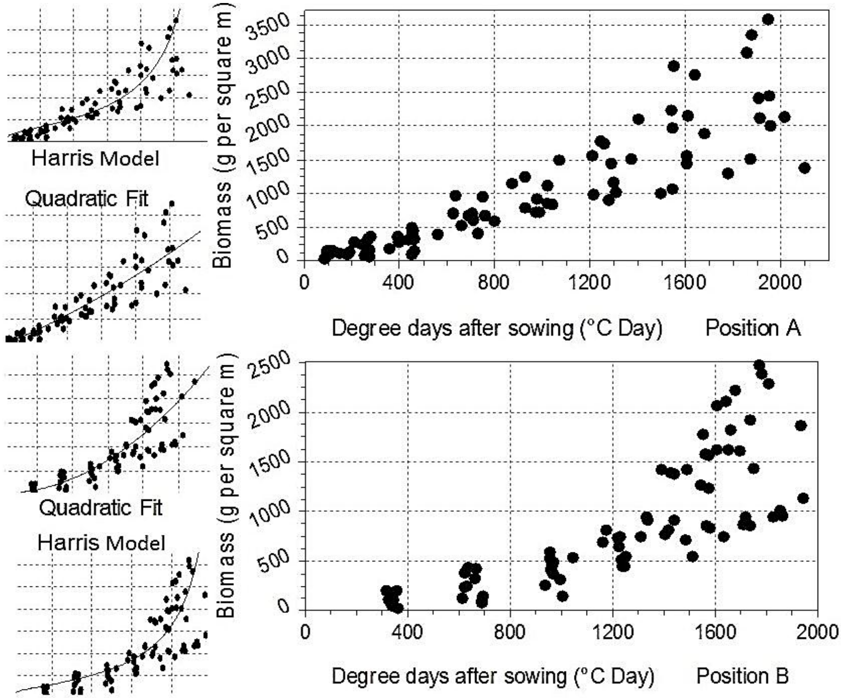

Figure 3.2 – Dynamics of formation of aboveground biomass of oilseed radish plants at different sowing dates in the total data set for 2014–2023 (g m^{-2}) (Position A – spring, position B – summer sowing dates) (based on the results of the author's own research)

For the same reasons, the closeness of the relationship in the 'Quadratic Fit' model in terms of R^2 for the spring sowing period was 14.8% higher than for the summer sowing period. As a result, taking into account the level of average daily temperatures (Table 3.4), an intensive period of growth of aboveground biomass from the stemming phase of oilseed radish plants for the spring sowing period (BBCH 30–32) and from the rosette phase (BBCH 24–26) for the summer sowing period should be expected with a high level of probability. That is, a steady-growing type of aboveground biomass formation was noted in the spring and unevenly growing for the summer sowing period. Taking into account the studies of Toom et al. (2019) and Konuntakiet (2020), the summer sowing period of oilseed radish will have more pronounced critical periods in terms of the need for hydrothermal resources than spring, which will require taking this factor into account when determining the possibility of sowing in summer for areas with unstable moisture or a characteristic deficit of atmospheric moisture against the background of an intensive increase in average daily temperatures. On the other hand, taking into account the analysis of aboveground biomass formation curves for a number of cover crops in the studies of Ramirez-Garcia et al. (2014, 2015), the parameters 'c' and 'd' in the models in Table 4 should be referred to as 'weighted mean relative growth'. Its value for different growth models in different types of intermediate-use cover crops ranges from 0.002–1.500 (Ramirez-Garcia et al., 2014; Bhogal et al., 2019; Wallander et al., 2021). The obtained values of this indicator in the presented models for oilseed radish confirmed the generalizations made about the uneven growth dynamics and intensive biomass growth in the second half of the growing season, taking into account the statement of Tjørve & Tjørve (2017) and the value of the parameter 'c' for individual applied models for oilseed radish with a dimensionality < 0.001.

According to Thorup-Kristensen & Kirkegaard (2016), the efficiency of multipurpose use of field crops is largely determined by the productivity of their root system, which can be used in different ways from the productivity coefficient to the share of root biomass in the formed plant biomass. According to the obtained indicators of bioproductivity of oilseed radish, the productivity coefficient of the root system in terms of the obtained crude biomass averaged 2.97 (20.33%) for the full period of study in spring and 3.63 (33.69%) in summer sowing. In terms of dry matter equivalent, these figures were 1.83 (22.82%) and 2.51 (33.53%). At the same time, the inverse ratio of root mass to aboveground mass for the spring sowing period was 0.35 in terms of wet weight and 0.57 in terms of dry matter at a level of interannual variation of 18.67–21.24%. For the summer sowing period, these indicators were at the level of 0.30 and 0.43 and 22.98–23.63%, respectively. Taking into account the statements of Thornley (1998) and Bláha (2021), this level of ratio on the one hand indicated the rapid growth rate of oilseed radish plants for both parts of the plants with parity development of aboveground mass and the presence of a sensitive stress response to deteriorating soil conditions in terms of moisture, aeration, etc. At the same time, the inertia of the growth of the aboveground part when the growth of the underground part is stopped has also been proven. This is confirmed by a decrease in the level of interannual variation of the ratio of root biomass to aboveground biomass with a coefficient of 1.88 for spring sowing and 1.54 for summer sowing, based on the studies of Fageria et al (1997) and Williams et al. (2013). This inertia, which determines the preservation of the intensity of growth processes due to the more pronounced stress resistance of the root system (noted in cruciferous species by Ahmad et al. (2012)) allows oilseed radish plants to adapt to possible medium-long periods of aridization and ensure the formation of aboveground plant biomass at the level of 50% of the long-term average in years with low values of the aridity index (I_{DM}) and moisture coefficient (K_h). For example, this is typical for the conditions of 2015 (Table 1) for both sowing dates of oilseed radish and for the conditions of 2017 for the spring sowing date. These processes of reducing the growth rate of oilseed radish plants are predicted to increase with a simultaneous increase in the significance of the deviation from the optimum of both aboveground and underground temperature and humidity conditions. Such conclusions are based on the studies of Williams et al. (2013), Feller et al. (2015), Agathokleous et al. (2019), Kul et al. (2021). At the same time, for oilseed radish, it is possible to have an intensive formation of root biomass at a minimum rate of aboveground biomass formation, which is possible already at a level ratio of the proportion of roots to the proportion of vegetative parts above 0.25 (according to Feller et al. (2015)) and was noted in the studies of Heuermann et al. (2019) on white mustard in a stressful year of vegetation. This is clearly confirmed by visualization of the correlation between underground and aboveground biomass in the total data set for the study period (Figure 3.3).

In particular, a positive numerical value of aboveground biomass was found at a zero value of root biomass, as well as the correspondence of the abscissa step of the graph to 4 units, which corresponds to a similar ordinal step of 15 units for the indicators of the formed crude plant biomass. For the same indicator in dry matter, 2 units of the abscissa of the graph account for 3.5 units of the ordinal position. That is, the strength of the relationship decreases in the case of biomass conversion to dry matter, which is confirmed by a significantly lower value of the correlation coefficient

(15.9% decrease in comparison with crude biomass) and is evidence of a pronounced asynchrony between the dry matter content in the aboveground and underground parts of plant biomass. This difference increases with the change in sowing dates from spring to summer (Table 3.2–3.3).

Table 3.4

Estimation of parameters of models of oilseed radish aboveground biomass formation (y) in the dynamics of Degree days after sowing (°C Day (x)) growth at two sowing dates, 2014–2023 (based on the results of the author's own research)

Model (model equation)	Parameters of the equation				Statistical evaluation of components				
	a	b	c	d	r	R^2	F	df1, df2	*p*
Spring sowing									
Quadratic Fit ($y=a+bx+cx^2$)	-42.35	-0.928	0.000158	–	0.893	0.797	22.012	2.170	*<0.001*
Exsponential Association ($y=a(1-exp^{-bx})$)	3093.9	0.0000237	–	–	0.883	0.780	18.156	2.170	*<0.001*
Logaritmth Fit ($y=a+blnx$)	-2071.3	524.7	–	–	0.700	0.490	3.599	2.170	*<0.05*
Harris Model ($y=(a+bx^c)^{-1}$)	0.025	-0.017	0.05	–	0.907	0.822	22.749	2.170	*<0.001*
MMF Model ($y=(ab+cx^d)(b+x^d)^{-1}$)	-91.60	44675.1	23808.5	1.12	0.890	0.792	21.708	2.170	*<0.001*
Summer sowing									
Quadratic Fit ($y=a+bx+cx^2$)	24.17	0.011	0.00048	–	0.833	0.694	14.599	2.170	*<0.001*
Exsponential ($y=a(b-exp^{-cx})$)	2477.0	1238.5	0.0019	–	0.689	0.474	4.188	2.170	*<0.05*
Exsponential Association ($y=a(1-exp^{-bx})$)	2322.3	0.0000287	–	–	0.775	0.600	8.569	2.170	*<0.001*
Logaritmth Fit ($y=a+blnx$)	-1768.3	380.7	–	–	0.543	0.295	1.926	2.170	*>0.05*
Harris Model ($y=(a+bx^c)^{-1}$)	0.049	-0.0034	0.05	–	0.942	0.887	23.293	2.170	*<0.001*
MMF Model ($y=(ab+cx^d)(b+x^d)^{-1}$)	-413.39	26215.5	22413.5	1.04	0.811	0.657	11.231	2.170	<0.001

Similar studies by Kemper et al. (2020) showed rapid rooting rates of oilseed radish with the formation of significant root biomass at higher rates of this process with a decrease in sowing rates when using oilseed radish as an intermediate cover or green manure crop with a fluctuation of the share of root biomass in the total phytomass from 18 to 50%. This is fully consistent with the results of our long-term research. The data obtained give grounds to assert that under optimal conditions of soil moisture and nutrition against the background of intensive increase in average daily temperatures and a certain duration of absence of precipitation, oilseed radish is able to maintain high rates of growth processes, which allows it to be used as an intermediate crop in the conditions of hot cycles of periods between the main crops of the crop rotation. This is based on both the high values of the direct and inverse ratio of aboveground and belowground biomass of oilseed radish plants in the experiment and is confirmed by a number of studies on other crops (Bacher et al., 2021; Kou et al., 2022). It should also be noted that the high proportion of root biomass in the total biomass of oilseed radish plants on average over the full cycle of research (25.68% in spring sowing (interannual variation of 14.19%) and 29.54% (23.63%) in summer sowing) indicates a high level of adaptation of oilseed radish to soil nutrition conditions from the point of view of the possibility of obtaining high levels of productivity on soils with low agrochemical potential.

This level of ratio, especially with an increase in the share of root biomass in the total dry biomass of plants by an average of 10.31–13.05% depending on the sowing date, also showed a high probable positive response of oilseed radish plants to additional mineral nutrition through the use of mineral fertilizers and a high intensity of accumulation of basic nutrients in the formed plant biomass. These conclusions are in line with the studies of Redin et al (2018), Lopez et al. (2023). Leafiness of oilseed radish plants, which is considered on the one hand as an indicator of potential overall plant compatibility, and on the other hand is an expression of the value of the crop in terms of soil surface coverage (Bhogal et al., 2019), biomass growth rate and faster rates of mass decomposition in the soil under green manure use (Quintarelli et al., 2022). In general, for optimized green manure options, plants should have a leaf cover of at least 30% (Liu et al., 2020). For a system of possible biogas utilization of biomass, this indicator should be in the range of 20-30%, which creates prerequisites for an optimal C/N ratio of 18-22 and provides sufficient starting levels of biomethane productivity in the first decade of anaerobic biofermentation of fresh, dried or pre-siloed cruciferous biomass (Herrmann et al., 2016; Tsytsiura Y. 2023a).

At the same time, the level of this indicator had significant differences in the spring and summer sowing dates of oilssed radish. Thus, on average, during the ten-year study period, the leaf area of plants was 42.61% (with an interannual variation of 8.03%) in the spring sowing period. In the summer sowing period, this figure was 7.59% lower, with a decrease in interannual variation of 1.35%. The presented data give grounds to assert the difference in the idiotypic structure of oilseed radish plants formation

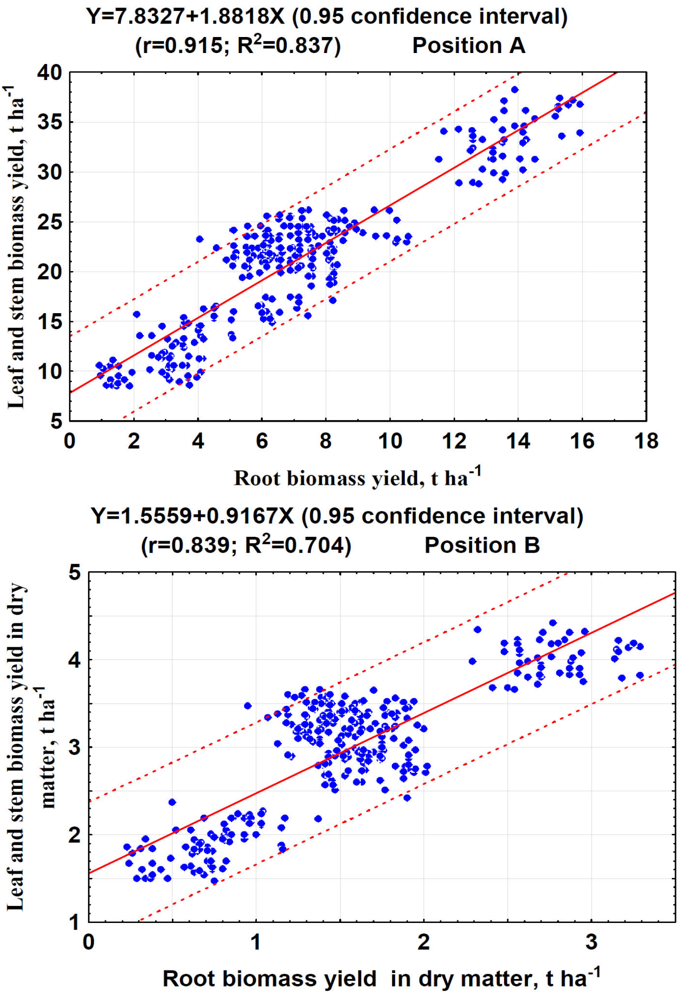

Figure 3.3 – Relationship between aboveground biomass yield and formed root biomass in oilseed radish, 2014-2023 (in a single data system of replication–year–sowing date for *N = 320;* position A – in raw mass, B – in dry matter) (based on the results of the author's own research) (based on the results of the author's own research)

when sowing dates are changed. In this case, the morphogenesis of plants is aimed at increasing the proportion of the stem from 46.50% on average for the variants of spring sowing to 50.36% for the variant of summer sowing. Another positive property of oilseed radish plants was confirmed to be the ability to maintain relatively constant levels of reproductive effort (proportion of the generative part (%)) with changes in sowing dates at the level of 10.69–14.62. This is in line with our previous findings (Tsytsiura, 2019; 2022) regarding the possibility of juvenile flowering of oilseed radish and accelerated growth rates in development during the period of stem formation and the beginning of the formation of the generative part of plants. This property is valuable from the point of view of growth rates under aridization of soil and climatic conditions of vegetation for the selection of a crop as a candidate for a group of intermediate crops in crop rotations of different rotation and the system of their green manure use.

It should be noted the sensitive response of oilseed radish plants to environmental conditions by changing their complex morphogenesis in terms of index vitality coefficient (IVC), which is consistent with our previous studies (Tsytsiura, 2020) and with the findings of Zlobin et al. (2021). This is confirmed by the high values of interannual variation of IVC under stressful growth and development conditions from the traditional spring start of the growing season (30.81%) to the more stressful (summer) one (37.54%).

At the same time, there was an increase in the general depression of plant morphogenesis in comparison of summer and spring terms of oilseed radish use with a growth coefficient of 1.42 in favor of summer terms. This led to the presence of IVC below 0.50 in a number of years with summer (intermediate) use of oilseed radish, which corresponds to the level of intense morphodepression. Under these conditions, the content of dry matter in the leaf and stem biomass of plants naturally increases and an idiotype of plants with higher leafiness is formed with a smaller proportion of the stem and a smaller proportion of the generative part. This character is consistented with the general life strategies of plants described by Zlobin et al. (2021) and differs from such cruciferous crops as white mustard, spring and winter rape. According to Heuermann et al. 2019 and Israt & Parimal (2023), the optimal moisture content of both soil and atmospheric moisture during the period of active growth is determined for mustard, and the period of stress response during summer sowing is quite short, which is determined by the level of vaporization of the leaves themselves and the rapid rate of decline in leafiness under conditions of high average daily temperatures. For spring rape, an intensive decrease in growth processes and the formation of aboveground biomass during sowing in summer against the background of increasing average daily temperatures was noted (Li et al., 2019) with subsequent optimization of growth processes at lower temperatures against the background of increasing precipitation with a shift in the timing of intermediate and green manure use to the autumn period. During the summer sowing period, higher levels of the formed underground biomass (roots) in comparison to the aboveground part of plants were studied (Ugrenović et al., 2019).

Taking into account the value of the survival rate of oilseed radish plants, significant differences in stress were found when using oilsed radish in the spring sowing period under the system of occupied fallow and in the summer period under the variants of intermediate (green manure) culture. Thus, the average survival rate for 10 years of our research (Tables 3.2, 3.3) was 87.42% for spring and 77.31% for summer sowing with interannual variation of 4.03% and 6.31%, respectively. A significantly lower level of variation of this indicator confirmed the useful mechanisms of adaptation of oilseed radish plants described by us in the system of its long-term and varied use.

The above analyzed features of oilseed radish growth processes allowed us to analyze another important indicator, namely 'ground cover' (GC), which is taken into account in the MSCC evaluation criteria in the case of using the crop as a 'cover crop' (integrated in the crop rotation between two cash crops) (Bodner et al., 2010). At the same time, it is noted that the main criterion is the duration of achieving a GC rate of at least 70% for the shortest possible period (Tixiera et al., 2010; Ramírez-García et al., 2015). The long-term evaluation of oilseed radish by GC is shown in Figure 2. For both sowing dates, a power-law exponential dependence was observed, which differs from the classical version of the Gompertz function, which assumes an asymptotic increase to maximum coverage and has the model function given in Bodner et al. (2010). In addition, the actual functional dependence is confirmed by the Chaddock (1925) scale as very close for both sowing dates and has a decline after reaching the peak value. This dynamics differs from the classical plateaued area or a curve with a small growth coefficient. Based on the established patterns of formation of the leaf apparatus of oilseed radish (Tsytsiura, 2020a) associated with a decrease in plant foliage from the beginning of flowering (BBCH 50–52) and intensive growth at the end of flowering (BBCH 68–69).

On 55–75 days after sowing, intensive leaf death was observed in oilseed radish. Based on this, it was found that the maximum soil coverage was observed on the 60th day after sowing in the spring sowing period (with a fluctuation in the range of 71.23–93.67 with an average value for the period of research of 83.69%) and on the 50th day in the summer sowing period (60.27–90.36% and 79.94%, respectively). Based on the study of Werker & Jaggard (1997), it was assumed that the ratio of the coefficients of the equation that most likely describes the mathematical regularity of the formation of the GC index of oilseed radish in the expression of the power $X2c^{-2}$ and $2bxc^{-2}$ for the spring sowing term and bx^{-1} for the summer sowing term (where X is days after sowing) is an indicator of the natural process of leaf death. These coefficients are the result of both the dynamic growth of the curves and the specifics of their decline (Figure 3.4).

It is also worth noting the peculiarities of growth dynamics. For the spring sowing period, the initiation of cover is characterized by the 15th day after sowing, and for the summer – by 20–25 days. At the same time, for the summer sowing period, both more intensive growth and more intensive decline in the dynamics on the dates of accounting were noted, which ultimately affected the final GC index on the 70th day after sowing: on average for the entire study period 73.77% for spring and 50.74% for summer sowing. The level of variability in the array of medium-term data in a number of accounting dates was also significantly different – 22.43% for spring and 29.93% for summer sowing dates. At the same time, for the summer sowing variant, the range of GC values had a pronounced upward trend from the 55th day of accounting (Figure 2, bottom position) to the date of accounting. Thus, with certain similarities in the formation of the GC index, which confirms the above features, the formation of biomass of oilseed radish plants, the intensity of achieving both the peak GC index and the decrease in leafiness is significantly less long in the summer sowing period. This reduces the duration of effective use of oilseed radish in the cover crop format during summer sowing under the regime of unstable moisture to 45–55 days after sowing. For the spring sowing variant, this indicator is prolonged to 70 days. If we analyze the GC index for a number of other cruciferous crops (according to the studies of Florentín et al., 2010;

Bodner et al., 2010; Ramírez-García et al, 2015; Couedel, 2019; Bhogal et al. (2019)), it should be noted that, given the common properties of leafiness reduction from the full flowering to maturation phase, the maximum GC level of more than 90% was achieved under optimal moisture in winter rape when used as a cover crop. For white mustard, spring rape in the system of their intercropping, this indicator in optimal years reached the level of 80–84% on 60–75 days after sowing. However, the duration of the 'cover crop' function in these crops is longer from 65 to 90 days after sowing at a slower rate of leaf decline in the process of physiological leaf death during maturation.

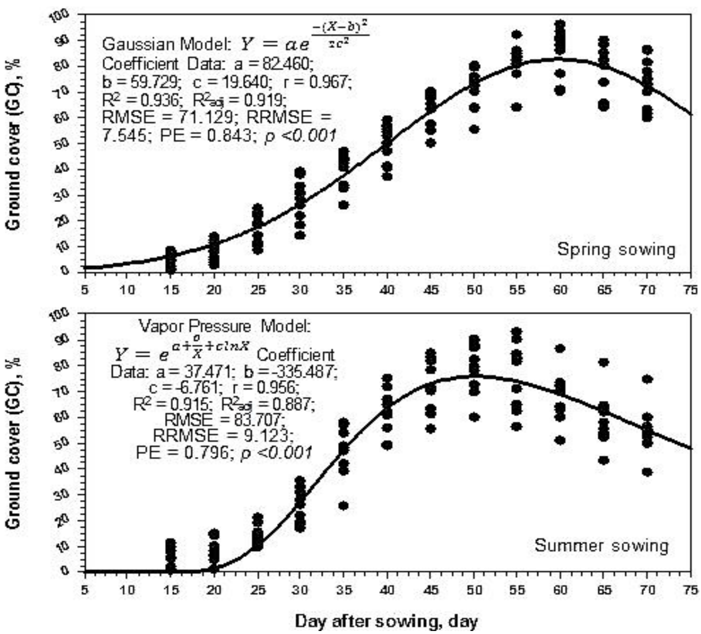

Figure 3.4 – Graphical model with statistical evaluation parameters for the indicator 'Ground cover' (GC) in oilseed radish (vertical marks on the dates of accounting – indicator values in the experimental interval 2014–2023) (based on the results of the author's own research)

The above features of oilseed radish have certain regularities of formation from the point of view of hydrothermal conditions of vegetation, confirmed by the results of correlation analysis (Table 3.4). According to the size of the correlation graph of the first type (Graf G), the formation of both aboveground and underground (root) biomass of oilseed radish plants had the highest total dependence of modular numerical values of correlation coefficients (12.60 and 12.59, respectively), and among the hydrothermal factors of the growing season, this indicator was maximum for hydrometeorological coefficients such as HTC, I_{DM}, K_h (on average >12). Among the parametric factors, the amount of precipitation played a more significant role in the system of formation of the total bioproductivity of plants than the level of average daily temperature (Graf G for the amount of precipitation was 27.4% higher). According to the values of the correlation graph of the second type (Graf G′), the coefficient of determination was 49% for the Aridity Index (I_{DM}), 46.2% for the hydrothermal coefficient (HTC), 47.6% for the humidification coefficient (K_h), 44.9% for the amount of precipitation, 28.1% for the average daily temperature and 13% for the relative humidity. At the same time, the level of correlating certainty for the value of the total formed plant biomass was 49%. Based on this, the determining factor in the formation of the total bioproductivity of oilseed radish plants will be the total moisture supply during their vegetation period due to atmospheric moisture and the processes of changing this indicator in relation to evaporation, temperature dynamics and their growth rates and changes over time. At the same time, a significantly lower dependence on the average daily temperature gives grounds to assert its adaptive resistance to low temperatures and the ability to initiate growth processes in the early and very early stages. In this case, the direction of the dependence established that the level of total biomass of oilseed radish plants with a high level of predicted probability will increase with increasing precipitation (d_{yx}=92.2%), decreasing average daily temperature (d_{yx}=23.0%), increasing relative humidity (d_{yx}=24.0%) and high values of hydrothermal coefficients and ratios (d_{yx}=81.0–88.4%). If we compare the obtained dependencies with the model parameters that were included in the predictive models of biomass formation for such species as spring and winter rape, white mustard in variants of its multiple use (Dorsainvil et al., 2005; Saseendran et al., 2010; Deligios et al., 2013; Jing et al., 2016; Asgari et al., 2021), it should be noted that oilseed radish has certain advantages in terms of climate adaptation indicators.

Table 3.4

Pearson's correlation coefficients of dependence of oilseed radish bioproductivity parameters on hydrothermal parameters of the growing season (for a joint system of matching sowing dates–repetitions–years (*N=160*)) (based on the results of the author's own research)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	-0.40	0.49	0.91	0.96	0.91	0.95	0.95	0.96	-0.76	-0.64	-0.51	0.52	0.59	-0.46	-0.55	0.77	0.72
2		-0.02	-0.71	-0.62	-0.71	-0.44	-0.53	-0.48	0.77	0.54	0.51	-0.54	-0.43	-0.57	0.72	-0.80	0.68
3			0.29	0.37	0.29	0.52	0.36	0.49	-0.43	-0.32	-0.35	0.28	0.55	0.34	0.33	0.53	0.46
4				0.99	1.00	0.87	0.93	0.90	-0.86	-0.73	-0.57	0.61	0.65	-0.07	-0.70	0.86	0.62
5					0.99	0.91	0.96	0.94	-0.85	-0.71	-0.56	0.60	0.65	-0.10	-0.66	0.85	0.84
6						0.87	0.93	0.90	-0.86	-0.73	-0.57	0.61	0.65	-0.07	-0.69	0.86	0.72
7							0.94	0.99	-0.82	-0.57	-0.41	0.40	0.68	0.48	-0.64	0.86	0.76
8								0.97	-0.81	-0.65	-0.63	0.66	0.62	0.54	-0.68	0.83	0.61
9									-0.83	-0.61	-0.49	0.49	0.67	0.63	-0.66	0.86	0.72
10										0.66	0.52	-0.51	-0.62	0.45	0.75	-0.92	-0.40
11											0.62	-0.58	-0.35	-0.15	0.52	-0.55	-0.38
12												-0.96	-0.06	0.47	0.37	-0.51	0.61
13													0.13	0.44	-0.44	0.50	0.44
14														-0.53	-0.72	0.61	0.58
15															-0.41	0.31	0.44
16																-0.69	0.57
17																	0.62
**12.05	9.47	6.42	12.27	12.56	12.36	12.11	12.60	12.59	11.82	9.31	8.72	8.71	9.09	6.46	10.10	11.93	10.17
***0.67	0.53	0.36	0.68	0.70	0.69	0.67	0.70	0.70	0.66	0.52	0.48	0.48	0.51	0.36	0.56	0.66	0.57

r = |0|–|0.4| No or weak correlation; r = |0.4|–|0.7| Moderate correlation; r = |0.7|–|1.0| Strong correlation. 1=Precipitation (mm); 2=Average daily temperature (°C); 3=Air humidity (%); 4=HTC; 5=I_{DM}; 6=K_h; 7=Leaf and stem biomass yield (t ha^{-1}); 8=Root biomass yield (t ha^{-1}); 9=Total plant biomass (t ha^{-1}); 10=Dry matter content of aboveground biomass (%); 11=Dry matter content of root residue biomass (%); 12=Root system productivity coefficient (in dry matter); 13=Share of root residues in total dry biomass of plants (%); 14=Leafiness of plants (%); 15=Share of stem part in plant biomass (%); 16=Share of generative part in plant biomass (%); 17=Survival rate of plants, (%); 18=IVC; ** Graf G; *** Graf G′. Significance level of $p < 0.05$, the interval r = 0.15–0.19, for $p < 0.01$ r = 0.20–0.25, for $p < 0.001$ r > 0.25.

In particular, the ability to intensive growth processes at lower temperatures during the growing season has already been noted. This is especially true for the early spring sowing of oilseed radish and the summer use of its biomass.

This level of temperature for white mustard and spring rape will already contribute to a decrease in the rate of growth processes and the size of the formed generative part of plants (Ahmad et al., 2012). At the same time, given the higher levels of dependence for relational quantities (ratios, coefficients) in comparison with the basic climatic parameters based on the generalizations of Agarwal et al. (2015), a more complex hierarchy of dependencies between the bioproductivity of oilseed radish plants and the climatic parameters of its growing season should be expected. With this in mind, we additionally applied multiple regression analysis to the data set (Table 3.5). According to the results of this regression assessment, a complex power law (second order) nature of the formation of bioproductivity of oilseed radish plants for both basic and derived parameters of the hydrothermal regime during the growing season was established by R^2_{adj} in the range of 0.800–0.951, which corresponds to a high tightness of the complex regression relationship according to the Chaddock scale. Based on the studies of Rameeh (2014), Han et al. (2020), Rajković et al. (2022) and by modeling the dynamic series of components x and y, their values were determined to obtain adequate maximum levels of the resulting indicators of plant bioproductivity that correspond to the long-term achievable level of climatic resources of the study area. This made it possible to determine the long-term optimum of the hydrothermal regime of oil radish vegetation in an array of two sowing dates. For the formation of above-ground biomass, the amount of precipitation for the period from sowing to flowering (BBCH 64–67) should be 240–255 mm at an average daily temperature of 18–20 °C with the formation of I_{DM} and K_h indicators at the level of 21–22 and 1.00–1.14, respectively.

For the formation of root biomass, on average, these indicators are 7.2% lower in terms of precipitation, 15.8% higher in terms of average daily temperature, and 15.8% and 14.7% lower in terms of$_{IDM}$ and$_{Kh}$, respectively. This difference is explained by the peculiarity of the root system formation in the soil substrate with the corresponding hydrothermal regime and physiological features of the delayed growth response of root systems to

Table 3.5

Regression models of dependence of oilseed radish bioproductivity on basic parameters of hydrothermal vegetation regime (in the total data set (sowing dates–repetitions–years of growth) for 2014–2023 (*N = 160*)) (based on the results of the author's own research)

Resulting indicator	Components of the equation: x	Components of the equation: y	Regression equation of dependence	Multiple regression coefficient R/R^2_{adj}	Statistical significance criteria R
Leaf and stem biomass yield, t ha^{-1} (LSBY)	Precipitation, mm	Average daily temperature, °C	$LSBY=13{,}4158-0.0037x+0.2923y+9.7657E\text{-}5x^2+0{,}0048xy-0.0334y^2$ **** *For the* $LSBY_{ma}$: *x=240.1; y=18.7°C*	0.951^{***} /0.893	$F/SS_{total} = 80.789$ (p = 0.000000), $t_{05} = 7.35$ (p = 0.00182)
Root biomass yield, t ha^{-1} (RBY)	Precipitation, mm	Average daily temperature, °C	$RBY=14.8153-0{,}0076x-1.2633y+9.7858E\text{-}5x^2+0.0014xy+0.0294y^2$ *For the* RBY_{max}: *x=228.5; y=20.9°C*	0.972^{***} /0.930	$F/SS_{total} = 116.460$ (p = 0.00000), $t_{05} = 13.20$ (p = 0.000000)
Leaf and stem biomass yield, t ha^{-1} in dry matter ($LSBY_{DM}$)	Precipitation, mm	Average daily temperature, °C	$LSBY_{DM}= 0.7987+0.0041x+0.1289y-5.9224E\text{-}6x^2+0.0006xy-0.0057y^2$ *For the* $LSBY_{DM\,max}$: *x=216.3; y=18.2°C*	0.938^{***} /0.846	$F/SS_{total} = 25.719$ (p = .0000595), $t_{05} = 6.72$ (p = 0.00682)
Root biomass yield, t ha^{-1} in dry matter (RBY_{DM})	Precipitation, mm	Average daily temperature, °C	$RBY_{DM} = 4.7469-0.0107x-0.3982y+2.9518E\text{-}5x^2+0.0007xy+0.0089y^2$ *For the* $RBY_{DM\,max}$: *x=208.9; y=21.8°C*	0.950^{***} /0.891	$F/SS_{total} = 36.690$ (p = .0000195), $t_{05} = 9.43$ (p = 0.00217)
Leaf and stem biomass yield, t ha^{-1} (LSBY)	Aridity Index (I_{DM})	Humidity coefficient (K_h)	$LSBY=7.6847+9.9413x-57.782y-1.0575x^2+11.7904xy-31.9372y^2$ *For the* $LSBY_{ma}$: *x=22.9; y=1.14*	0.981^{***} /0.951	$F/SS_{total} = 88.485$ (p = 0.000000), $t_{05} = 7.942$ (p = 0.0000)
Root biomass yield, t ha^{-1} (RBY)	Aridity Index (I_{DM})	Humidity coefficient (K_h)	$RBY=2{,}5733+0{,}6683x-2.6161y+0.6215x^2-7.9348xy+25.5887y^2$ *For the* RBY_{max}: *x=20.7; y=1.32*	0.967^{***} /0.925	$F/SS_{total} = 57.730$ (p = 0.00004), $t_{05} = 5/488$ (p = 0.00193)
Leaf and stem biomass yield, t ha^{-1} in dry matter ($LSBY_{DM}$)	Aridity Index (I_{DM})	Humidity coefficient (K_h)	$LSBY_{DM}=1.0683+0.676x-3.3215y-0.0293x^2+0.2705xy-0.6023y^2$ *For the* $LSBY_{DM\,max}$: *x=21.1; y=1.02*	0.906^{***} /0.800	$F/SS_{total} = 39.000$ (p = 0.00000), $t_{05} = 7.611$ (p = 0.0000)
Root biomass yield, t ha^{-1} in dry matter (RBY_{DM})	Aridity Index (I_{DM})	Humidity coefficient (K_h)	$RBY_{DM} = 0.2148+0.3391x-1.5257y-0.0411x^2+0.5154xy-1.6147y^2$ *For the* $RBY_{DM\,max}$: *x=19.5; y=1.17*	0.949^{***} /0.888	$F/SS_{total} = 76.451$ (p = 0.00000), $t_{05} = 9.177$ (p = 0.00098)

*, **, *** Significant at 5%, 1%, 0.1% level probability, respectively; **** components of the equations at the maximum achievable level of plant bioproductivity.

the increase in weather stress noted in the studies of Williams et al. (2013) and Kul et al. (2021), as well as the peculiarities of the morphometry and anatomy of the root system of oilseed radish noted in our previous studies (Tsytsiura, 2020).

The results of a long-term comprehensive evaluation of oilseed radish by the criterion of plant bioproductivity and related derivative indicators that determine the possibility of adequate accumulation of both aboveground and underground mass allowed us to classify this crop as strategically valuable for use in the multi-service cover crop (MSCC) system. The determined statistically reliable system of correlation and regression dependencies of both basic indicators of biomass accumulation and important indicators of growth rates, leafiness, plant survival while maintaining the appropriate vitality tactics according to the criterion of vitality index for radically different sowing dates proved the effectiveness of using oil radish in the system of such MSCC components as 'cover crop', 'catch crop', 'green manure' and potentially 'biogas resource'.

The above statements are based on certain levels of bioproductivity, which, even in extremely stressful years in terms of moisture and hydrothermal conditions, ensure the formation of at least 2.5 t ha^{-1} of dry matter and in optimal years exceed the mark of 7.0 t ha^{-1}. Limiting its use in the MSCC system is moisture, which productively in the form of precipitation should reach the level of 150–200 mm with an optimum of 205–250 mm during the period from sowing to flowering (BBCH 64–67). The level of average daily temperature had a wide range from 14 to 22 °C. Based on this, the most appropriate option for using oil radish in the system of intermediate and green manure use is the option of early spring sowing, as well as the option of summer intermediate use with a shift in sowing time to late July-early August for areas of unstable and moderate moisture.

The correlation analysis confirmed the above conclusions about the role of hydrothermal conditions in the possible level of achievement of the total bioproductivity of oilseed radish plants (Table 3.6). According to the value of the correlation graph of the first type (Graf G), the formation of both aboveground and underground (root) biomass of oilseed radish plants had the highest total dependence of modular numerical values of correlation coefficients from the position of plant weight characteristics (interval 7.30–7.61). Among the hydrothermal factors of the growing season, this indicator was maximum for hydrometeorological coefficients such as HTC, I_{DM}, K_h (average >7.70). Among the parametric factors, the amount of precipitation played a more significant role in the system of formation of the total bioproductivity of plants than the level of average daily temperature (correlation coefficient 1.52) and relative humidity (correlation coefficient 2.18). According to the values of the correlation graph of the second type (Graf G′), the coefficient of determination was 51.84% for the Aridity Index (I_{DM}), 50.41% for the hydrothermal coefficient (HTC) and the humidification coefficient (K_h), 47.6% for the amount of precipitation, 20.3% for the average daily temperature and 9.6% for the relative humidity. On this basis, the determining factor in the formation of the total bioproductivity of oilseed radish plants was the total moisture supply during their vegetation period due to atmospheric moisture and the processes of change of this indicator in relation to evaporation, temperature dynamics and the rate of their growth and change over time. The determined lower dependence on the average daily temperature gives grounds to assert its adaptive resistance to low temperatures and the possibility of initiating growth processes in the early and ultra-early periods according to the sowing dates. At the same time, the direction of the dependence showed that the level of total biomass of oilseed radish plants with a high level of predicted probability will increase with increasing precipitation (dyx=92.2%) and high values of hydrothermal coefficients and ratios (dyx=81.0–88.4%). If we compare the obtained dependencies with the model parameters that were included in the predictive models of biomass formation for such species as spring and winter rape, white mustard in variants of their multiple use (Dorsainvil et al., 2005; Jing et al., 2016; Asgari et al., 2021), it should be noted that oilseed radish has certain advantages in terms of climate adaptation indicators.

In particular, the ability to intensive growth processes at lower temperatures during the growing season has already been noted. This is especially true for early spring sowing of oilseed radish. Thus, on average, over the 10-year period of research, the average daily air temperature was 14.5 °C for the period April-June (Table 3.1). Such a level of temperature for white mustard and spring rape will already contribute to a decrease in the rate of growth processes and the size of the formed generative part of plants (Ahmad et al., 2017). At the same time, taking into account the higher levels of dependence for relational quantities (ratios, coefficients) in comparison with the basic climatic parameters, based on the generalizations of Akbarzadeh A & Katsikas (2021), a more complex hierarchy of dependencies between the bioproductivity of oilseed radish plants and the climatic parameters of its growing season should be expected. That is, oilseed radish has a rather flexible adaptive mechanism that distinguishes it from other cruciferous plants in terms of the possibility of using it in the MSCC system. From the point of view of assessing the value of the respective crop for its use in green manure, reclamation (rehabilitation of degraded soils) and biogas potential, it is important to assess the biochemical composition of the formed biomass. The results of such an assessment for aboveground biomass for the studied sowing dates as of the date of the phenological optimal period of use are presented in Tables 3.7 and 3.8. To estimate and determine the average biochemical portfolio of oilseed radish, gradations of estimates of a number of cruciferous crops were applied in the studies of Ayres & Clements (2002), Azam et al. (2013), Villalobos & Brummer (2013), Winkler (2017), Bell et al. (2020), Keim et al. (2020), Castillo-Umaña et al. (2020), Bakker et al. (2021), Omokanye et al. (2023), Sánchez et al. (2023). Based on these studies, the formed aboveground biomass of oilseed radish plants should be attributed to high-protein with a range of crude protein content at the level of 12–23$\%_{DM}$ with an increase in the indicator when changing the sowing dates from spring to summer with a ratio of 1.23. The high fat content of more than 3.0 $\%_{DM}$ also actualizes the leaf and stem mass of oilseed radish from the point of view of its fodder value and high ash content of more than 12$\%_{DM}$ against the background of high phosphorus, potassium, calcium and sulfur (based on the approaches of evaluation by Abe (1984), Justes & Richard, 2017), the effective possibility of using leaf mass simultaneously for fodder and green manure purposes has been proved in view of the recycling of nutrients through the system of their return to the soil through the use of plant residues and green fertilizers in the form of oilseed radish biomass. The relatively high cellulose content at the flowering stage of more than 18$\%_{DM}$ in spring and more than 23$\%_{DM}$ in summer sowing against the background of the previously noted features of accelerated plant development (‘biological aging’) in summer sowing and high overall rates of phenostage formation of plants indicates a steady trend of reducing the quality biochemical parameters of plant mass when used in later phases of the growing season. This is confirmed by comparing the content of not only cellulose but also the constituent derivatives NDF, ADF and ADL and is consistent with the findings of Azam et al. (2013), Herrmann et al. (2016) and Bell et al. (2020) on other cruciferous plant species. This is also indicated by a 1.5-fold increase in lignin content in plant mass (in the form of ADL) when comparing summer and spring sowing dates. Such a stable trend allowed us to determine the peculiarities of oilseed radish biomass formation at different sowing dates under study. Thus, for the spring sowing date, against the background of lower average daily temperatures and slow growth rates, the process of protein complex formation takes place under lower stressful temperature conditions, which, according to the studies of Sharma & Dubey (2019) and Zhou et al. (2023), contributes to the formation of plant tissues with a higher level of organic matter, higher water content with lower fiber and cellulose content, lower protein content and lower ash content.

Table 3.6

Pearson's correlation coefficients of dependence of oilseed radish bioproductivity parameters on hydrothermal parameters of the growing season (for a joint system of matching sowing dates–repetitions–years (*N=160*)) (based on the results of the author's own research)

1	2	3	4	5	6	7	8	9	10	11
1	-0.40	0.49	0.91	0.96	0.91	0.95	0.95	0.96	-0.51	0.52
2		-0.02	-0.71	-0.62	-0.71	-0.44	-0.53	-0.48	0.51	-0.54
3			0.29	0.37	0.29	0.52	0.36	0.49	-0.35	0.28
4				0.99	1.00	0.87	0.93	0.90	-0.57	0.61
5					0.99	0.91	0.96	0.94	-0.56	0.60
6						0.87	0.93	0.90	-0.57	0.61
7							0.94	0.99	-0.41	0.40
8								0.97	-0.63	0.66
9									-0.49	0.49
10										-0.96
** 7.56	4.96	3.46	7.78	7.90	7.78	7.30	7.86	7.61	5.56	5.67
*** 0.69	0.45	0.31	0.71	0.72	0.71	0.66	0.71	0.69	0.51	0.52

r = |0|–|0.4| No or weak correlation; r = |0.4|–|0.7| Moderate correlation; r = |0.7|–|1.0| Strong correlation. 1=Precipitation (mm); 2=Average daily temperature (°C); 3=Air humidity (%); 4=HTC; 5=I_{DM}; 6=K_h; 7=Leaf and stem biomass yield (t ha^{-1}); 8=Root biomass yield (t ha^{-1}); 9=Total plant biomass (t ha^{-1}); 10=Root system productivity coefficient (in dry matter); 11=Share of root residues in total dry biomass of plants (%); ** Graf G; *** Graf G´. Significance level of $p < 0.05$, the interval r = 0.15–0.19, for $p < 0.01$ r = 0.20–0.25, for $p < 0.001$ r > 0.25.

Table 3.7

Chemical composition of oilseed radish leaf and stem mass in spring sowing for flowering stage (BBCH 64–67), 2014–2023 (based on the results of the author's own research)

Year	Organic dry matter (ODM) ($\%_{DM}$)*		Crude protein (CP) ($\%_{DM}$)		Crude fat (CF) ($\%_{DM}$)		Crude fibre (CFb) ($\%_{DM}$)		Crude ash (CA) ($\%_{DM}$)		NDF ($\%_{DM}$)		ADF ($\%_{DM}$)		ADL ($\%_{DM}$)	
	$\bar{x}$	**SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	87.29	2.50	17.55	2.78	3.02	0.24	19.22	0.64	12.71	0.59	36.91	0.52	24.12	0.42	5.85	0.12
2015	85.41	1.82	15.08	1.91	5.55	0.40	23.07	0.65	14.59	0.45	40.12	0.29	31.24	0.59	4.77	0.14
2016	86.72	1.74	14.29	1.29	3.89	0.16	21.75	0.42	13.28	0.57	36.88	0.42	25.09	0.51	3.89	0.21
2017	84.89	2.47	15.91	1.85	5.09	0.49	23.24	0.30	15.11	0.19	38.09	0.35	28.57	0.57	4.05	0.12
2018	85.95	1.88	15.12	0.56	4.53	0.10	21.52	1.00	14.05	0.27	36.17	0.28	26.62	0.39	3.35	0.09
2019	87.48	1.59	19.17	0.84	3.01	0.31	19.17	0.87	12.52	0.76	34.02	0.19	22.19	0.25	3.58	0.11
2020	87.12	2.13	14.19	1.25	3.28	0.12	20.97	0.83	12.88	0.24	35.39	0.44	24.97	0.39	3.37	0.15
2021	87.39	1.72	12.75	0.83	3.59	0.45	21.83	0.43	12.61	0.34	36.41	0.25	25.17	0.47	4.02	0.07
2022	87.73	0.81	14.56	1.27	3.87	0.66	22.19	0.58	12.27	0.81	37.58	0.57	25.91	0.21	3.81	0.18
2023	86.32	1.49	17.02	1.01	3.94	0.20	22.29	0.87	13.68	0.54	35.89	0.39	24.11	0.33	3.96	0.13
$\bar{x}$	86.63	0.96	15.56	1.89	3.98	0.85	21.53	1.40	13.37	0.96	36.75	1.65	25.80	2.54	4.07	0.75
***R_{min}	1.17-1.33	–	0.55-1.08	–	0.47-0.58	–	0.81-1.09	–	0.63-0.82	–	0.81-0.97	–	0.88-1.05	–	0.13-0.21	–
LSD_{05}	1.29	–	0.87	–	0.52	–	1.00	–	0.75	–	0.90	–	0.93	–	0.16	–

(End of Table 3.7)

Year	Cellulose ($\%_{DM}$)	Hemicellulose ($\%_{DM}$)	TKN (%DM)		TOC ($\%_{DM}$)		Phosphorus ($\%_{DM}$)		Potassium ($\%_{DM}$)		Calcium ($\%_{DM}$)		Sulfur ($\%_{DM}$)		GSL µmol g^{-1} DM	
	$\bar{x}$	$\bar{x}$	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	18.27	12.79	2.81	0.44	38.25	0.57	0.54	0.06	2.71	0.11	1.07	0.14	0.32	0.06	12.08	0.45
2015	26.47	8.88	2.41	0.31	40.22	0.81	0.62	0.05	3.96	0.19	0.97	0.12	0.42	0.09	13.52	0.43
2016	21.20	11.79	2.29	0.21	39.14	0.48	0.77	0.17	4.74	0.24	1.00	0.10	0.50	0.10	14.51	0.37
2017	24.52	9.52	2.55	0.30	41.12	0.65	0.85	0.08	5.72	0.38	1.15	0.15	0.59	0.11	16.08	0.87
2018	23.27	9.55	2.42	0.09	39.77	0.78	0.69	0.07	3.74	0.20	1.03	0.08	0.52	0.06	15.56	0.57
2019	18.61	11.83	3.07	0.13	37.14	1.14	0.52	0.05	2.25	0.11	0.81	0.18	0.35	0.12	11.89	0.44
2020	21.60	10.42	2.27	0.20	40.09	0.43	0.63	0.08	4.08	0.16	0.92	0.07	0.35	0.05	12.44	0.60
2021	21.15	11.24	2.04	0.13	37.95	0.73	0.48	0.09	2.87	0.37	0.93	0.17	0.39	0.05	12.77	0.40
2022	22.10	11.67	2.33	0.20	38.44	0.46	0.51	0.03	3.03	0.10	0.89	0.10	0.41	0.08	13.84	0.52
2023	20.15	11.78	2.72	0.16	38.89	0.42	0.61	0.06	3.19	0.31	0.82	0.07	0.34	0.09	12.97	0.59
$\bar{\bar{X}}$	21.73	10.95	2.49	0.30	39.10	1.21	0.62	0.12	3.63	1.04	0.96	0.11	0.42	0.09	13.57	1.44
R_{min}	–	–	0.20-0.39	–	0.89-1.05	–	0.09-0.14	–	0.25-0.39	–	0.15-0.20	–	0.10-0.14	–	0.19-0.36	–
LSD_{05}	–	–	0.34	–	0.98	–	0.12	–	0.34	–	0.18	–	0.12	–	0.23	–

*The indicator of transformation between %DM and g kg^{-1}_{DM} = %DM x 10. **SD – standard deviation; ***Tukey‘s test (R_{min} for $p_{adj} < 0.05$).

For the summer sowing period, when plants are formed at significantly higher levels of average daily temperature and more stressful conditions of hydrothermal vegetation regime (Table 3.1), biochemical processes of the reverse nature occur. A similar system of correlations was noted for white mustard at different periods of its use (Ţiţei (2022)) and some representatives of the radish genus (Ayres & Clements, 2002). This is also confirmed by the results of comparing the main biochemical components of the spring sowing period with similar long-term averages of the summer one. The obtained coefficients of this ratio in the interval of research years for ODM 1.03-1.11, CP 0.77-0.85, CF 0.74-0.88, CFb 0.79–0.89, ADL 0.59–0.71, Cellulose 0.81–0.89, Hemicellulose 0.73–0.85, TNC 0.74–0.85, TOC 0.91–0.99, P 0.89–0.98, K 0.85–0.94, Ca 0.87–0.95, S 0.79–0.90, GSL 0.82–0.88. As a result, taking into account a number of studies (Clark 2008; Hansen et al., 2021, 2022; Jauhiainen 2022; Launay et al., 2022; Fajobi et al., 2023; Lallement et al., 2023; Lymperatou et al., 2023; Manyi-Lohn & Lues, 2023), the leaf mass of oilseed radish of different sowing dates will have different criterion evaluation in the MSCC system.

At the same time, due to the increasing stress of general environmental factors (Latief et al. (2017)), the overall variability of the obtained average values in terms of years of research is also increasing. According to the results of the presented estimates, the coefficient of variation (CV) of the average for the general data set for the summer sowing period of oilseed radish had an average growth coefficient of 1.21 compared to the indicators of the spring sowing period. Such features lead to an increase in the variable component in assessing the effectiveness of the use of the obtained oilseed radish biomass for the criterion goals of the MSCC system.

It should also be noted that based on studies that have studied oilseed radish in the management system of cover crops for different purposes (Herrmann et al., 2016; Blume et al., 2020; Gamba et al., 2021; Hansen et al. 2021; Lövgren, 2022; Olofsson & Ernfors, 2022; Kemper et al., 2023), the results of biochemical evaluation presented in Tables 3–4 have certain differences. Thus, the crude protein content at the spring sowing date was 0.9–1.5% $_{DM}$ lower than the value, and at the summer sowing date it did not reach the value of 25–27%$_{DM}$ noted in the above studies. The content of lignin, cellulose and its derivatives is 3.8–7.7%$_{DM}$ higher than in the estimates of Herrmann et al. (2016) and Hansen et al. (2021). The total organic carbon (TOC) content according to our estimates had a relatively stable value with fluctuations in the range of 38–42%$_{DM}$, although in the study by Hansen et al. (2021) this value had a narrower interval of 39–40%$_{DM}$, and in the study by Gamba et al. (2021) for the radish genus, the possibility of its value at the level of 35–44%$_{DM}$ was noted. The detail of the content of the main elements (nitrogen, phosphorus and potassium) was estimated for two seasons with different weather conditions in the study by Hansen et al. 2021. In comparison with the data of this study, for oilseed radish on gray forest soils under conditions of unstable moisture, the phosphorus content was found to be 0.13–0.33%$_{DM}$ higher, the potassium content was 0.72–1.12%$_{DM}$ lower, and the calcium content was 0.15–0.24%$_{DM}$ higher.

The nitrogen content was lower by 0.18–0.35%DM. Regarding the comparison of the biochemical profile of oilseed radish with other cruciferous crops such as white mustard, spring and winter rape, and radish (according to Swarcewicz et al. (2013), Li et al. (2019), Abdallah et al. (2020), Liu et al. (2020), Tian & Deng (2020), Wang et al. (2022), Jacob et al. (2022), Rajković et al. (2022), Ţiţei (2022), Oliveira & Słomka (2021), Shitophyta et al. (2023), Israt & Parimal (2023)) was determined to be 3.4–8% lower. 7 %DM crude protein content, at or above 1.3–2.4%DM crude fat content, at or below 1.7–2.2%DM ash content, at or below 0.7–2.5%DM lignin content, below 1.9–6.1%DM crude fiber content, higher potassium content by 1.8–3.7%DM, equal or lower by 0.12–0.22%DM phosphorus content, equal calcium content and equal or lower by 0.27–0.35%DM sulfur content.

The presented comparison confirms the value of oilseed radish leaf mass as a potential candidate for use in green manure system and possible use for anaerobic fermentation for biogas production. For conditions of unstable moisture on soils with medium fertility potential, which include Grey forest soils (Greyi-Luvic Phaeozems (IUSS, 2015)).

Table 3.8

Chemical composition of oilseed radish leaf and stem mass in summer sowing for flowering stage (BBCH 64–67), 2014–2023 (based on the results of the author's own research)

Year	Organic dry matter (ODM) ($\%_{DM}$)*		Crude protein (CP) ($\%_{DM}$)		Crude fat (CF) ($\%_{DM}$)		Crude fibre (CFb) ($\%_{DM}$)		Crude ash (CA) ($\%_{DM}$)		NDF ($\%_{DM}$)		ADF ($\%_{DM}$)		ADL ($\%_{DM}$)	
	$\bar{x}$	**SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	85.08	0.99	17.44	1.31	4.17	0.82	23.32	0.82	14.92	0.90	42.31	0.52	29.89	0.42	6.12	0.12
2015	83.79	0.87	14.88	1.61	5.82	0.62	26.72	0.70	16.21	0.72	46.12	0.29	33.17	0.59	6.61	0.14
2016	84.08	1.78	18.38	2.15	4.40	0.40	23.89	0.61	15.92	0.33	42.87	0.42	30.05	0.51	6.18	0.21
2017	85.36	3.32	19.88	2.00	4.29	0.33	22.97	0.75	14.64	0.60	41.92	0.35	29.19	0.57	5.74	0.12
2018	84.80	1.71	20.75	2.42	4.78	1.09	23.69	0.99	15.20	0.63	42.30	0.28	29.68	0.39	5.92	0.09
2019	83.21	1.13	16.13	1.65	5.02	0.48	25.33	1.03	16.79	0.35	44.35	0.19	31.87	0.25	6.48	0.11
2020	84.63	0.74	20.44	1.39	4.55	0.79	24.17	0.85	15.37	1.11	44.11	0.44	31.05	0.39	6.25	0.15
2021	83.56	1.93	19.31	1.52	4.72	0.28	24.85	0.64	16.44	0.86	44.55	0.25	31.27	0.47	6.29	0.07
2022	85.03	0.67	22.94	3.26	4.08	0.65	22.51	0.79	14.97	0.44	42.37	0.57	28.97	0.21	5.52	0.18
2023	84.42	0.54	21.44	3.13	4.27	0.32	23.92	0.64	15.58	0.92	43.09	0.39	30.34	0.33	6.09	0.13
$\bar{x}$	84.40	0.71	19.16	2.48	4.61	0.52	24.14	1.23	15.60	0.71	43.40	1.34	30.55	1.30	6.12	0.33
***R_{min}	0.81-0.96	–	1.05-1.28	–	0.82-0.96	–	0.92-1.19	–	0.88-1,12	–	0.99-1.36	–	1.53-1.81	–	0.32-0.48	–
LSD_{05}	0.92	–	1.14	–	0.91	–	1.14	–	1.05	–	1.24	–	1.64	–	0.37	–

(End of Table 3.8)

Year	Cellulose ($\%_{DM}$)	Hemicellulose ($\%_{DM}$)	TKN (%DM)		TOC ($\%_{DM}$)		Phosphorus ($\%_{DM}$)		Potassium ($\%_{DM}$)		Calcium ($\%_{DM}$)		Sulfur ($\%_{DM}$)		GSL µmol g^{-1} DM	
	$\bar{x}$	$\bar{x}$	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	23.77	12.42	2.79	0.21	41.03	1.34	0.57	0.09	3.52	0.36	1.07	0.17	0.41	0.11	18.55	1.04
2015	26.56	12.95	2.38	0.26	39.82	1.31	0.71	0.10	4.71	0.20	1.13	0.26	0.68	0.06	21.58	1.56
2016	23.87	12.82	2.94	0.34	40.59	1.78	0.67	0.07	3.89	0.14	1.09	0.29	0.39	0.04	18.19	1.09
2017	23.45	12.73	3.18	0.32	38.51	0.79	0.59	0.09	3.33	0.46	0.92	0.18	0.35	0.06	17.92	0.60
2018	23.76	12.62	3.32	0.39	38.09	1.71	0.65	0.07	4.35	0.16	0.85	0.09	0.53	0.04	21.02	0.53
2019	25.39	12.48	2.58	0.26	40.87	0.82	0.78	0.07	4.98	0.15	1.28	0.23	0.56	0.17	21.19	0.56
2020	24.80	13.06	3.27	0.22	38.44	0.85	0.54	0.06	3.39	0.23	1.09	0.15	0.47	0.05	19.75	0.52
2021	24.98	13.28	3.09	0.24	41.29	0.76	0.64	0.09	3.57	0.34	1.05	0.09	0.59	0.07	21.53	0.70
2022	23.45	13.40	3.67	0.52	38.98	1.73	0.52	0.03	3.05	0.20	0.67	0.18	0.31	0.09	17.17	0.63
2023	24.25	12.75	3.43	0.50	39.15	0.89	0.59	0.08	3.82	0.40	0.95	0.11	0.49	0.09	20.09	0.47
$\bar{x}$	24.43	12.85	3.07	0.40	39.68	1.20	0.63	0.08	3.86	0.63	1.01	0.17	0.48	0.12	19.70	1.64
***R_{min}	–	–	0.41-0.53	–	1.73-1.95	–	0.07-0.15	–	0.32-0.44	–	0.21-0.32	–	0.08-0.15	–	0.31-0..54	–
LSD_{05}	–	–	0.49	–	1.82	–	0.11	–	0.41	–	0.27	–	0.12	–	0.43	–

*The indicator of transformation between %DM and g kg^{-1}_{DM} = %DM x 10. **SD – standard deviation; ***Tukey's test (R_{min} for $p_{adj} < 0.05$).

Regarding the content of glucosinolates, this indicator is important in the MSCC criterion system from the point of view of providing the appropriate crop with a broad spectrum biofumigation effect due to the incorporation of the formed plant biomass into the soil, which helps to reduce the germination of weed seeds, soil fungicidal effect against a number of harmful pathogens and reduction of soil pests, in particular, various species of nematodes and pests of the polyphagous group with a soil development cycle at the larval stage due to soil transformation of glucosinolates into isothiocyanates (ITC) (Śmiechowska et al., 2010; Edwards & Ploeg, 2014), which are commercially used to control numerous crop pests, including nematodes, pathogens, and weeds (Sang et al., 1984; Kirkegaard & Sarwar, 1998; Sarıkamıs et al., 2017; Blažević et al., 2020; Yan et al., 2023; Redha et al., 2023). Additionally, the presence of glucosinolates at certain concentration levels is desirable for intermediate cover crops, especially in summer sowing, to control a number of entomophages and diseases, which guarantees the necessary level of plant survival and guaranteeing the appropriate technological planting density and the desired bioproductivity (Zachariah, 2011; Bhandari et al, 2015; Perniola et al., 2019; Andini, 2020; Ait Kaci Ahmed et al., 2022; Abdel-Massih et al., 2023). It is especially relevant for the control of cruciferous fleas, the harmfulness of which in the agrocenosis of oilseed radish causes a significant decrease in plant survival already at the germination stage (up to 20–60% reduction). As a result, this significantly reduces the indicators of the formed aboveground biomass, worsens its quality and forms a reduced soil cover, especially during summer sowing, in conditions of a more favorable temperature regime for intensive feeding of this pest (Tsytsiura, 2024). In this regard, it was proved that the glucosinolate content had a high direct correlation with the level of harmfulness of various cruciferous pests, including cruciferous fleas (Bohinc et al., 2013). In view of these facts, the content of glucosinolates in aboveground biomass is of paramount importance in the criterion evaluation of crops in the MSCC system in such areas as 'cover crop', 'catch crop', 'green manure' for the formation of an agrocenosis of a sufficient level of bioproductivity while maintaining the appropriate biochemical quality indicators.

At the same time, the high concentration of these compounds significantly narrows the use of this species in the MSCC system as a ‘fodder crop’, reducing the feed value of the plant and can cause poor compatibility and a number of disorders in animals (Prieto et al, 2019) and also reduces the efficiency of such a direction as 'biogas crop' due to the formation of certain processes of inhibition of the intensity of anaerobic fermentation of the resulting leaf-stem mass (Cleemput, 2011; Al Seadi et al., 2013; Herrmann et al., 2016; Tsytsiura 2023b). The content of glucosinolates is also important for cruciferous crops used as 'catch crops', since it has been established that these compounds are involved in the formation of plant stress responses to abiotic factors, and their intensive growth has high levels of significant correlation with the increase in the overall stress of the growing season by climatic parameters, which is especially important for intermediate crops that are often grown in the summer-autumn period with increasingly stressful environmental conditions (Chowdhury, 2022; Lei et al. , 2022; Zhang et al., 2022).

Long-term assessment of the direct and derived glucosinolate potential of cruciferous plants (Sang et al., 1984; Kirkegaard & Sarwar, 1998; Bellostas et al., 2004; Ciska et al., 2008; Velasco et al., 2008; Edwards & Ploeg, 2014; Bhandari et al., 2015; Yi et al., 2016; Ricardo et al., 2018; Liu et al., 2020; Wu et al, 2021; Mocniak et al., 2023; Iwar et al., 2024) proved high interspecific variability of their content as well as high variability of concentration in the aboveground parts of the plant depending on the phenological phase of development and abiotic environmental conditions. Thus, the total content of glucosinolates and different cruciferous plant species ranged from 1.97 to 140.9 μmol g^{-1} DM with a maximum concentration in seeds and generative parts and a minimum in the early stages of vegetation in leaves and roots. At the same time, it was noted (Velasco et al., 2008) that the concentration of glucosinolates among the cruciferous groups was maximum for leafy cruciferous plants (up to 26 μmol g^{-1} DM), lower values were noted for the group of fodder cruciferous plants (up to 24 μmol g^{-1} DM) and classical oilseed cruciferous plants had the lowest level of the indicator (12-16 μmol g^{-1} DM). In the study by Bhandari et al. (2015), the lowest GSL concentrations were observed in representatives of the genus radish across all tissues examined (18-40 μmol g^{-1} DM).

The long-term average content of glucosinolates in the aboveground biomass of oilseed radish was 13.57 μmol g^{-1} DM (CV 8.32%) in spring and 19.70 μmol g^{-1} DM (CV 10.58%) in summer sowing, which confirms the increase in their concentration with an increase in the overall stress of the growing season, taking into account the level of average daily temperatures (Table 1). Regarding the assessment of the level of the obtained values, in various studies on oilseed radish at the flowering stage, the level of glucosinolates was in the range of 9–41 μmol g^{-1} DM and was 1.2–1.5 times higher in inflorescences compared to leaves and stem (Gimsing & Kirkegaard, 2006; Bohinc et al., 2013; Duff et al., 2020). At the same time, as for other cruciferous crops recommended for use in the MSCC system, for white mustard the average glucosinolate content (on average per plant) for the flowering phase was in the range of 11-56 μmol g-1 DM (Sang et al, 1984; Kirkegaard & Sarwar, 1999; Bohinc et al., 2013; Ciska et al., 2008; Tian & Deng, 2020), spring rape 9-44 μmol g-1 DM (Sang et al., 1984; Birch et al, 1992), winter rape 8-51 μmol g^{-1} DM (Sang et al., 1984; Milford & Evans, 1991; Kirkegaard & Sarwar, 1999; Ciska et al., 2008; Yasumoto et al., 2010; Bohinc et al., 2013; Salisbury et al., 2018). Thus, long-term data on the content of glucosinolates in oilseed radish (Table 3–4) give grounds to attribute it to cruciferous crops with high biofumigation potential for both spring and summer use.

It is noted (Couëdel et al., 2018a, 2019) that the biochemical assessment of the leaf mass of plants used as cover crops for multipurpose use requires a system of appropriate ratios that determine the processes of decomposition, mineralization, accumulation and the predicted intensity of anaerobic fermentation. These ratios are widely used by the scientific community and proposed in the analysis of Hansen et al. (2021, 2022), Thiébeau et al. (2021), Quintarelli et al. (2022), Allam et al. (2023), Yousefi et al. (2024). The results of this assessment are presented in Table 3.9. According to a number of studies (Kriaučiūnienė et al., 2012; Jahanzad et al., 2016; Sousa et al., 2019; Liu et al., 2020; Toleikiene et al., 2020; Dorissant et al., 2022; Silva et al., 2023), the C/N ratio is decisive in the decomposition rate of green biomass that is incorporated into the soil.

From the point of view of these criteria, the biomass of oilseed radish at the interval value of C/N ratio, taking into account the SD value in the context of research years 8.73-20.11 with interannual variation of 12.3% for spring sowing and 15.4% for summer sowing (Table 5) fully meets the criteria of 'fodder crop' and 'green manure' and is predicted to ensure rapid decomposition of fresh biomass in the soil, especially under conditions of sufficient moisture supply against the background of high average daily temperatures. These values also indicate a significant proportion of leaves and inflorescences in the total biomass of oilseed radish, especially at the summer sowing date, which is consistent with the findings of Kriaučiūnienė et al. (2012) on the decomposition rates of different parts of cruciferous plant species.

It should also be noted that in the case of summer sowing of oilseed radish , according to a number of studies (Wadman & de Haan, 1997; Hadas et al., 2004; Flores-Sánchez et al., 2016; Drost et al., 2019; Salume et al, 2020) decomposition rates, despite the 17% lower average C/N ratio over the entire evaluation period, will have predictably slower decomposition rates due to the significantly lower temperature level during the period of direct use of biomass in the form of green manure (Table 1). Taking into account that the optimal value is a certain balance C/N value, which provides a positive ratio between the rate of decomposition and subsequent humus accumulation and immobilization of mineral nutrients, which is in the range from 13 to 25 depending on weather conditions, soil type and the nature of the use of the corresponding cover crop (according to Wadman & de Haan, 1997) and positively correlates with this ratio in classical cattle manure 16.6-25.0 (according to Pan et al, 2021) – the biomass formed during spring sowing had a higher degree of compliance with these intervals for green manure use. However, according to the recommendations of Couëdel et al. (2019) and Hansen et al. (2021), its use can be optimized by using oilseed radish in mixed crops with cereals and legumes, as well as using additional plant materials for combined green manure (e.g. straw).

The determined long-term average C/N ratio allowed us to classify oilseed radish as a candidate for the 'fodder crop' in the MSCC system, since in this case the value of the indicator is considered from the standpoint of increased protein content, i.e. higher total nitrogen content with optimization of fiber and non-nitrogenous compounds (lower carbon content). As a result, the optimal value of the C/N ratio is in the range of 8–15 (Li & Zhou, 2002). It has been noted (Guarino et al., 2016; Herrmann et al., 2016; Dębowski et al., 2022; Manyi-Loh. & Lues, 2023; Tsytsiura, 2023a) that the optimal C/N value for anaerobic biomass dehydration in biogas production technologies is in the range of 20-30 with an interval of possible technological deviations in the range of 10 to 30. At low values of the C/N ratio, the concentration of the ammonium form of nitrogen increases significantly and the microbial process of anaerobic fermentation is inhibited (Cerón-Vivas et al., 2019; Choi et al., 2020).

Table 3.9

The main indicators of quality of oilseed radish aboveground biomass for different terms of sowing, 2014–2023 (based on the results of the author's own research)

Year	C/N ratio				C/P ratio				C/S ratio				Carbohydrates (CH) ($\%_{DM}$)			
	*SprS		SumS		SprS		SumS		SprS		SumS		SprS		SumS	
	$\bar{x}$	**SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	13.94	2.80	14.77	1.18	71.41	7.27	73.59	13.45	122.24	19.90	106.69	34.14	66.71	3.37	64.43	1.33
2015	16.86	1.81	16.86	1.60	65.12	4.58	57.06	9.16	98.68	18.50	58.94	5.65	64.80	2.05	65.01	1.98
2016	17.20	1.67	13.99	2.18	53.27	14.66	61.25	8.23	80.55	15.57	105.36	15.79	68.52	1.90	62.44	1.95
2017	16.28	1.83	12.21	1.35	48.70	4.49	66.25	9.09	71.71	14.05	112.41	18.62	63.86	2.49	62.45	2.22
2018	16.45	0.71	11.58	1.41	58.20	7.29	59.08	6.73	77.13	7.97	72.27	7.92	66.30	0.83	60.60	1.90
2019	12.12	0.86	15.97	1.73	72.13	8.98	52.73	4.93	115.31	35.43	80.62	33.69	65.28	1.71	63.31	1.97
2020	17.75	1.37	11.81	1.03	64.30	7.13	71.70	6.70	116.73	19.14	82.29	6.68	69.65	1.37	61.08	1.45
2021	18.67	1.44	13.42	1.06	80.82	12.41	65.64	10.32	98.56	14.00	70.80	9.22	71.05	0.81	60.88	1.57
2022	16.59	1.48	10.84	2.11	75.56	4.00	75.03	2.14	96.60	18.90	134.31	40.91	69.30	1.00	59.18	2.97
2023	14.34	0.96	11.58	1.51	64.24	6.67	67.15	8.31	120.76	31.85	82.23	17.63	65.38	1.71	59.93	3.24
$\bar{x}$	16.02	2.36	13.30	2.40	65.37	12.13	64.95	10.23	99.83	25.78	90.59	29.80	67.08	2.83	61.93	2.63
LSD_{05}	2.30	–	2.05	–	5.79	–	3.89	–	12.81	–	10.55	–	2.71	–	3.08	–

(End of Table 3.9)

Year	Residue quality (RQ) ($\%_{DM}$)				Accumulation in aboveground biomass (kg ha^{-1})											
					Nitrogen***				Phosphorus				Potassium			
	SprS		SumS		SprS		SumS		SprS		SumS		SprS		SumS	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	81.36	0.82	81.46	0.88	114.6	15.27	93.94	11.22	22.14	2.70	19.50	5.27	111.15	9.64	118.21	12.98
2015	86.35	0.84	80.44	0.72	68.34	8.05	39.51	4.58	17.62	1.71	11.88	2.50	112.56	9.22	78.38	7.71
2016	84.32	0.98	81.00	1.33	69.32	8.38	98.71	14.96	23.19	4.95	22.32	0.16	143.27	10.32	130.87	15.65
2017	86.43	0.65	81.53	1.84	53.28	6.04	108.00	12.61	17.76	1.65	20.04	3.26	119.68	10.73	113.53	20.25
2018	87.10	1.15	81.46	0.78	51.08	9.02	114.45	14.26	14.58	3.01	22.42	2.64	78.54	10.69	150.09	11.32
2019	84.59	0.88	81.04	0.78	123.8	10.91	44.75	5.09	21.05	3.56	13.56	1.81	90.61	5.69	86.49	7.42
2020	86.21	1.08	80.69	0.68	89.21	8.25	59.46	6.82	24.79	3.46	9.77	0.74	160.26	4.34	61.51	5.40
2021	84.74	1.33	80.43	0.52	58.03	4.48	84.48	10.67	13.88	4.07	17.56	3.53	81.32	8.28	97.64	13.52
2022	84.52	1.07	81.08	0.71	65.62	7.09	122.58	21.80	14.35	1.12	17.28	1.17	85.26	4.59	101.62	10.79
2023	84.26	1.39	81.16	0.98	87.14	5.89	115.51	17.38	19.50	1.36	19.79	1.68	101.96	6.37	129.07	18.97
$\bar{x}$	84.99	1.83	81.03	0.95	78.04	25.40	88.14	31.25	18.88	4.57	17.41	4.80	108.46	25.52	106.74	22.25
LSD_{05}	1.50	–	2.17	–	8.69		9.73		4.33		3.86		8.77		10.72	

Year		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	$\bar{x}$	LSD_{05}
Ca accumulation (kg ha^{-1})	SprS	44.05	27.48	30.27	24.04	21.75	32.28	36.17	26.79	25.05	26.31	29.42	3.69
	SumS	36.27	18.69	36.90	31.04	29.24	22.09	19.72	28.81	22.10	32.03	27.69	4.27
S accumulation (kg ha^{-1})	SprS	13.18	11.89	15.15	12.31	11.00	14.29	13.78	11.10	11.52	10.82	12.50	2.34
	SumS	14.09	11.32	13.02	11.87	18.24	9.75	8.51	16.19	10.36	16.53	12.99	3.82
GSL productivity (mol ha^{-1})	SprS	49.5	38.4	43.8	33.6	32.7	47.9	48.9	36.4	38.9	41.5	41.2	0.17
	SumS	62.5	35.8	61.1	60.8	72.5	36.7	36.0	58.8	57.2	67.7	54.9	0.35
Equivalent cattle manure, t ha^{-1}	SprS	23.0	18.9	22.8	18.9	13.7	21.7	26.1	13.9	15.2	19.6	23.0	–
	SumS	22.0	12.6	24.3	23.1	28.1	14.2	12.5	19.2	23.1	25.6	22.0	–

*SprS – Spring sowing; SumS – Summer sowing. **SD – standard deviation; *** transformation from kg ha^{-1} to g m^{-2} by dividing the value by 10.

Based on this, the most appropriate option for oilseed radish would be the use of pre-prepared biomass both through silage and through co-fermentation of fresh mass with other plant or organic resources (according to the technological solutions proposed by Wang et al, 2012), as well as the use of cofermentation and inoculum to guarantee an optimal start of the process, according to a ssuch technological applications in the application to other cruciferous crops (Carvalho et al., 2011; Herrmann et al., 2016; Oliveira & Słomka, 2021) and the results of our previous studies. We proved (Tsytsiura, 2023c) that silage fermentation of oilseed radish leaf mass allows to increase the C/N ratio by 3-6 units depending on the phenological phase of plants during the formation of silage mass, and the use of inoculum starter helps to optimize the accumulation curve of the generated biomethane and intensifies the digestion process.

Regarding the obtained C/N ratio in our studies compared to the data for other cruciferous crops used in MSCC variants, it should be noted that for most cruciferous species this indicator in different years at the flowering stage was in the range of 12–23 for spring sowing and 10–18 for summer sowing (Herrmann et al, 2016; Li et al., 2019; Blume et al., 2020; Keim et al., 2020; Liu et al., 2020; Hansen et al., 2021; Ţiţei, 2022). Such results confirm the high potential of oilseed radish in the MSCC criterion system in comparison with the already widely used cruciferous crops.

It is also important to evaluate the C/P ratio, which, according to Ngatia et al. (2014), is a certain expression of the relationship between soil immobilization of mobile phosphorus forms and the efficiency of its replenishment by biomass introduced into the soil. This ratio affects the nature of the microbiological decomposition of green manure, especially in soils depleted in mobile phosphorus forms. According to Rinasoa et al. (2022), the optimal option for green manure application of the formed biomass is its high phosphorus content and low C/P ratio.

This ensures the maintenance of intensive rates of biomass decomposition in the soil with a positive balance of phosphorus release (Amy et al., 2024). According to this criterion, the leaf and stem mass of oilseed radish meets the required disparity between the phosphorus content and its ratio to organic carbon with a long-term average value not exceeding 70 with an interannual variation of 15.3% in spring and 11.34% in summer sowing. For example, in cereal green manure, this figure was 115–140, and in legumes

110–125 (Hansen et al., 2021). At the same time, the difference between the average long-term value for both sowing dates was not significant. Taking into account the above, oilseed radish will be effective for green manuring of soils poor in mobile phosphorus and in options for restoring a positive phosphorus balance in soils under organic fertilization systems. It should also be noted that in comparison with other cruciferous crops, oilseed radish is characterized by a high phosphorus content in terms of dry matter (average long-term level of 0.62–0.63 $\%_{DM}$ (Table 34)). In particular, for white mustard, this indicator ranges from 0.24–0.70 $\%_{DM}$ (Swarcewicz et al., 2013; Tian & Deng, 2020; Ţiţei, 2022; Israt & Parimal, 2023), for spring and winter rape in the range of 0.36–0.82 $\%_{DM}$ (Nobile et al., 2019; Amy et al., 2024).

Important for assessing the biofumigation potential of plants is the C/S ratio, which is a relative indicator of the presence of glucosinolates in plant biomass, since the biochemical composition of some chemical compounds belonging to this group of substances are sulfur-containing (De Kok et al., 2012; Pekarek et al., 2013; Galaup, 2018; Couëdel et al., 2019; Duff et al., 2020). It has been established that an effective green manure option with an overall biofumigation effect is possible at a C/S ratio of no more than 120 (Kirkegaard & Sarwar, 1998; Zachariah, 2011). According to our estimates, it was in the range from 71 to 122 for spring sowing and from 59 to 134 for summer sowing, which meets the requirements of an effective biofumigation process for green manure use of the formed biomass. During the summer sowing period, this indicator had a 1.36 times higher level of interannual variation than during the spring sowing period (25.6%) and significantly lower than its long-term average value by 9.24 units. This character of the formation of the indicator, in addition to the hydrothermal features of the growing season in the summer sowing period, is also explained by the lower proportion of the generative part and the larger proportion of leaves, which, given the data on the content of glucosinolates in different parts of cruciferous plants (Bohinc et al., 2013; Perniola et al., 2019), naturally reduces the content of sulfur-containing compounds in the formed biomass. This is confirmed by comparing the maximum C/S value of 134.31 for the conditions of summer sowing in 2022, for which the highest amount of precipitation of 436.6 mm at moderate temperature was recorded in the cycle of years of research of this period

(Table 3.1), which contributed to intensive growth vegetative processes in accordance with the previously described features of the formation of oilseed radish biomass and the lowest percentage of the generative part of plants. The biofumigation potential of oilseed radish was also confirmed by the value of glucosinolate productivity for both sowing dates (Table 5). The obtained values in the range of 32.7–49.5 mol ha^{-1} (with an interannual CV of 15.1%) for spring sowing and 36.0–72.5 mol ha^{-1} (24.9%) for summer sowing are in line with the study of Duff et al. (2020), who noted the effective level of this indicator for achieving multiple goals of soil biofumigation by green manure in the case of spring and summer sowing, depending on the type of cruciferous plants in the range of 30–105 mol ha^{-1}. At the same time, the interval of 60–105 mol ha^{-1} was achieved by using different types of mustard (White mustard (*Sinapis alba*), Ethiopian mustard (*Brassica carinata*), Indian mustard (*Brassica juncea*), Fodder mustard (*Brassica napus*), Black mustard (*Brassica nigra*)) in pure sowings or in various mixtures with radishes (such species-specific trademarks as 'Tillage Radish', 'Terranova Radish', 'Black Jack Radish'). Thus, at the achieved level of glucosinolate accumulation, the studied species of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) can be effectively used at both sowing dates in the soil rehabilitation system through the process of green manure biofumigation. At the same time, the issue of combining oilseed radish with other cruciferous species under conditions of unstable moisture should be further investigated in the future.

The criterion value of the leaf-stem aboveground mass of oilseed radish in the MSCC system is also confirmed by the level of carbohydrates, which determine the dynamics of mass decomposition and the nature of such decomposition in terms of released substances and their subsequent positive effect on the microbiological activity of the soil and the promotion of its self-aggregation. From this point of view, the value of this indicator in the range of 55-60 %DM fully meets the requirements for the effective green manure utilization of the biomass of this plant species (Liu et al., 2020; Israt & Parimal, 2023).

In addition, it has been proven that carbohydrates are energy-providing feed components composed of carbon, hydrogen, and oxygen. They should make up about $75\%_{DM}$ of an animal's diet (Navarro et al., 2019). Accordingly, according to this indicator, the biomass of oilseed radish with a carbonate content of up to 50–70 $\%_{DM}$ needs to be improved in terms of the desired compatible use, in particular with cereals and legumes, which is confirmed in a number of studies (Ayres & Clements, 2002; Mbambalala et al., 2023; Sánchez et al., 2023).

It is argued that biomass, particularly agricultural residues and biomass rich in structural carbohydrates, offers significant potential for sustainable biogas production (Venslauskas et al., 2024). At the same time, for most crops with high biogas production potential, the carbohydrate content should reach 65–75$\%_{DM}$ (Herrmann et al., 2016). Based on these statements, the leaf mass of oilseed radish formed by the plant during the spring sowing period with an average long-term carbonate content of 67.08$\%_{DM}$ was technologically more suitable for biogas production than the same during the summer sowing period, which is consistent with the results of our previous studies (Tsytsiura, 2023a).

To evaluate the possibility of effective use of oilseed radish leaf mass in the form of mulching with spreading of the chopped mass on the soil surface (Duff et al. 2020), the residue quality (RQ) index in the traditional variation (Quemada and Cabrera, 1995) was adapted. The obtained long-term average of 84.99$\%_{DM}$ for spring and 81.03$\%_{DM}$ for summer sowing, in line with similar estimates in Bajgai et al. (2014), Thiébeau et al. (2021) and Sharma et al. (2022), prove the potential use of oilseed radish biomass for green mulching (according to Nithisha et al. 2022) in the system of creating a protective mulching layer in the variants of bioconservation agriculture. This type of technological solution is predicted to be more efficient when using plant biomass grown in the spring sowing period.

The study of the indicators of accumulation of the main nutrients in the formed biomass of oilseed radish is comparable to their concentration noted in Tables 3.8–3.10. The average long-term ratio of content and accumulation in the aboveground biomass of N:P:K:Ca:S was established in the following expression (with indication of the range of values) 1.00(0.65–1.59):0.24(0.18–0.40):1.39(1.04–2.05):0.38(0.28–0.56):0.16(0.14–0.19) for spring sowing and 1.00 (0.51–1.39):0.20 (0.11–0.25):1.21 (0.70–1.70):0.31(0.21–0.42):(0.70–1.70):0.31(0.21–0.42):0.15(0.10–0.21) for the summer sowing period. To compare the intensity of accumulation of individual elements for different mustard species 0.8–1.2:0.3–0.6:1.2–1.6: 0.40–0.65:0.24–0.60 for other types of cruciferous plants used in the system of intermediate green manure use (for example, Barbarea vulgaris L.) – 0.6–1.1:0.2–0.6:1.1–1.3:0.25–0.50:0.18–0.32. That is, oilseed radish is characterized by similar features in the accumulation of basic nutrients as for widely used rapeseed and mustard in the MSCC system. Based on the determined ratios, the intensity of growth processes for the formation of oilseed radish leaf mass will be predicted to be high with sufficient soil supply of available forms of nitrogen and potassium. As for phosphorus, according to the findings of Weih et al. (2018), at a low level of accumulation of the element, the critical period in relation to the need for it shifts to the early stages of the growing season. At the same time, in terms of the direction and use of 'catch crop' in the MSCC system, according to the ‘N uptake’ indicator, oilseed radish showed significantly lower levels of nitrogen removal over the ten-year evaluation period compared to the predicted levels of this indicator for already noted widely used crops such as rapeseed and mustard. The determined nature of accumulation also showed a high positive response of oilseed radish to additional mineral nutrition, especially during the period of active growth of vegetative mass, which according to our studies corresponds to 30-35 days after sowing for spring and 25 days after sowing for summer sowing (Figure 3.4). According to the accumulation of phosphorus and calcium in comparison with niche cruciferous crops, oilseed radish is classified as a species with intensive accumulation of these elements (based on the gradation assessment of Wallace & Mueller, 1980). Based on the above, the established high levels of productivity of oilseed radish at lower levels of consumption of the main elements to ensure this productivity allow us to recommend it for the system of saturating multi-term crops in the links of typical crop rotations with the criterion of ‘catch crop’ and ‘green manure’. This statement is consistent with the findings of Grzebisz et al. (2022, 2023). This is also confirmed by the results of equivalent transformation of the formed aboveground mass of oilseed radish in terms of the content of organic and dry matter in cattle manure. Such conversion, which provided an average perennial rate of more than 20 tons per hectare and taking into account the study by Carr et al. (2020), proved the effectiveness of using oilseed radish at both sowing dates in the system of bioorganic fertilization technologies and rehabilitation of degraded soils with the direct use of green manure.

It is important to note that the characterized basic indicators and correlations (according to Ramírez-García et al. (2015)) that determine the belonging to different niche areas in the MSCC system for oilseed radish formed a regression system of dependencies (the most significant of which) are presented in Table 6. According to the regression equations, it was found that the quality of plant residues (RQ) decreased with both an increase in precipitation and an increase in temperature. This is explained by the intensification of vegetative growth processes with a slowdown in qualitative biochemical transformations characteristic of natural physiological aging. At the same time, an increase in temperature will ensure an increase in the content of lignin derivatives and an increase in precipitation will cause a general decrease in the components of NDF and ADL (this is consistent with the similar nature of the regression relationships for the indicative indicator of fiber content (CFb)). In interaction, this will form plant residues with rapid rates of aerobic decay and reduce their quality in terms of bio-cycling of their components. This character is consistent with the determined dependencies between RQ and hydrothermal ratios – the aridity coefficient I_{DM} and the moisture coefficient K_h and is confirmed by the analysis in Bajgai et al. (2014).

The C/N ratio also decreased with an increase in both precipitation and average daily temperature. This is due to the already mentioned theory of stress proteins and an increase in the content of nitrogenous compounds, and in the case of precipitation due to the extension of the growing season and a decrease in the rate of physiological aging with the formation of an increased nitrogen content in late phenostages.

In the case of temperature, a stress response system is formed in the form of an increased content of stress proteins and, accordingly, a higher concentration of nitrogen in biomass. Against the background of the previously mentioned stable organic carbon content, this ultimately reduces the value of the C/N ratio. At the same time, the negative forming direction in the equation of the aridity index (I_{DM}) and the positive forming direction for the moisture coefficient (K_h) indicates a more important role of the precipitation to evapotranspiration ratio than precipitation to the sum of temperatures. In the first case, this contributes to the accumulation of both organic carbon and nitrogen compounds and is consistent with the estimates of Agren & Weih (2012) and is confirmed by the presented results of regression dependencies on the resultant component Nupt. For the indicator of soil coverage ‘GC’, the peculiarities of the formation of the indicator for oilseed radish were confirmed: an increase in its value with an increase in precipitation and a decrease in evaporation in terms of the value of the moisture coefficient (K_h) and a decrease in the average daily air temperature. This is consistent with all the dependencies that determine the intensity of growth processes and the analysis of the formation of the indicator in the dynamics (Figure 3.3) and with the conclusions of a number of studies (Ramirez-Garcia et al., 2012; Ugrenović et al., 2019; Kashyap et al., 2023).

Table 3.10

Multiple regression dependence between hydrothermal conditions of vegetation and indicators of value of vegetative mass of oilseed radish according to the criteria of multi-service cover crop (MSCC) (average data for 2014–2023) (based on the results of the author’s own research)

Qualitative indicator	**Equation of dependence**	**Parameters of the equation**		**Statistical evaluation of components**				
		x	**y**	**Multiple R**	**Multiple $R^2_{(adj.)}$**	**F**	**df1, df2**	***p***
RQ	RQ = 92.503-0.00995x-0.4975y	Precipitation (mm)	Average daily temperature (°C)	0.873	0.735	27.334	2.170	*<0.001*
C/N	C/N = 24.5149-0.0189x-0.4478y			0.788	0.576	13.891	2.170	*<0.001*
N_{upt}	N_{upt} = -7.040+0.1394x+1.3556y			0.850	0.689	22.058	2.170	*<0.001*
CFb	CFb = 21.851-0.0152x-0.1937y			0.862	0.713	24.599	2.170	*<0.001*
GC	GC = 84.205+0.0934x-1.343y			0.821	0.636	17.625	2.170	*<0.001*
GSL	GSL = 12.918-0.0147x+0.1731y			0.806	0.609	15.773	2.170	*<0.001*
RQ	RQ = 84.268-1.5649x+10.285y	I_{DM}	K_h	0.738	0.545	10.188	2.170	*<0.05*
C/N	C/N = 17.569-2.151x+13.344y			0.854	0.729	22.823	2.170	<0.001
N_{upt}	N_{upt} = 13.420+9.622x-54.875y			0.921	0.831	47.785	2.170	*<0.001*
CFb	CFb = 25.222-0.1074x-0.7081y			0.815	0.625	16.785	2.170	*<0.001*
GC	GC = 62.557-1.1471x+16.155y			0.895	0.707	21.789	2.170	*<0.001*
GSL	GSL = 15.779-0.0079x-1.2605y			0.783	0.612	19.446	2.170	<0.001

The regression analysis proved a positive formative effect of the increase in average daily temperatures and a negative formative effect of precipitation on the accumulation of glucosinolates (GSL), which is consistent with a significantly higher concentration of them in the biomass of oilseed radish during the summer sowing period, especially under conditions of moisture deficit against the background of intensively increasing average daily temperatures and positively correlates with similar studies on other cruciferous crops (Milford & Evans, 1991; del Carmen Martínez-Ballesta et al., 2013, Bellec et al., 2023; Ben Ammar et al., 2023).

An important component in assessing the belonging of oilseed radish to the MSCC system is an attribute assessment of the component coefficients of the resulting equations of the corresponding conceptual direction of use. For scientific detailing and substantiation of the selected attributes, a scientific systematization of a number of studies that directly or indirectly relate to the issues of MSCC formation was applied. The results of this generalization in terms of the coefficients of the equations in accordance with the fundamental scale (Saaty & Vargas, 2012) and the resulting direction of formation of the selected method of use by sign at the attribute coefficient are presented in Table 7.

To update the analysis for the direction of use ‘fodder crop’, the fiber content indicator (CFb) was replaced by the indicator ‘dietary fiber content’ (DFb) in accordance with the feed assessment system (FOSS. 2018). The formed array of initial data on the importance of the studied attributes in the formation of the direction of use of oilseed radish allowed us to obtain their normalized matrix (Table 3.11–3.13).

Accordingly, the conditions of 2014 and 2023 were recognized as ensuring the maximum realization of the possibility of multicomponent use of aboveground biomass of oilseed radish in all defined areas. In contrast, the conditions of 2015 and 2017 had a significant lowest level of criterion realization. In the system of evaluation of individual attributes, their importance was confirmed on the basis of the systematization of the results of long-term studies, according to which the indicator of the amount of formed aboveground biomass is dominant in the context of all studied areas of use of oilseed radish, and the fiber content or its dietary form is in the last ranking place. At the same time, the significance of the difference within the years of evaluation was minimal for the attributes ‘GSL’, ‘CFb’ and ‘RQ’, which is associated with the different directions of the identified trends of their formation for different uses in the MSCC system and is positively consistent with the data of Ramírez-García et al. As a result, the results of the multicriteria analysis within different sowing dates established the final sums of normalized and weight-adjusted attributes (Table 3.12). Accordingly, it was determined that different sowing dates of oilseed radish have different years of optimality for a particular use. The maximum number of maximum values of the adjusted coefficients was observed for the conditions of 2019 for the spring sowing period and for the conditions of 2022 for the summer sowing period. On this basis and based on the research of Ramirez-Garcia et al. (2015), El Amine et al. (2016), the possibility of involving oilseed radish as an effective candidate for crops of the MSCC system was determined. The sowing dates influenced the assessment of the efficiency of use, which is confirmed by the average normalized index for this attribute in the array of years of study. Shifting the sowing dates of oilseed radish from spring to summer increased the efficiency of its use in the such criterion area as 'Green manure', 'Fodder' and 'Catch crop' (increase in the rating position by 1–2 levels).

Table 3.11

Intensity of importance of the normalized attributes on fundamental scale in oilseed radish as the multi-service cover crop (MSCC) utility functions assigned by the decision makers based on analysis of publications for both sowing dates (based on the results of the author's own research)

<table>
<tr><th>Use</th><th>GC*</th><th>BM</th><th>C/N</th><th>N_{upt}</th><th>RQ</th><th>GSL</th><th>CFb</th><th>Attributes selected based on the analysis of publications</th></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td></tr>
<tr><td rowspan="2">Cover crop</td><td>5</td><td>2</td><td>1</td><td>1</td><td>3</td><td>3</td><td>1</td><td rowspan="2">Snapp et al., 2005; Clark, 2008; Bodner et al., 2010; Tixier et al., 2010; Bangarwa et al., 2011; Zachariah, 2011; Justes et al., 2012; Gieske, 2013; Ramírez-García et al., 2015a; White et al., 2016; Wendling et al., 2016; Wollford & Jarvis, 2017; Warren, 2017; Couedel et al., 2018, 2019; Tribouillois et al., 2018; Bhogal et al., 2019; Toom et al., 2019; Ugrenović et al., 2019; Chapagain et al., 2020; Duff et al., 2020; Norberg & Aronsson, 2020; Hansen et al., 2021; Lövgren, 2022; Quintarelli et al., 2022; Ait Kaci Ahmed et al., 2022; Restovich et al., 2022</td></tr>
<tr><td>**+</td><td>+</td><td>+</td><td>-</td><td>+</td><td>+</td><td>+</td></tr>
</table>

(End of Table 2.36)

1	2	3	4	5	6	7	8	9
Catch crop	2	2	1	2	2	3	1	Snapp et al., 2005; Molinuevo-Salces et al., 2014; Gieske, 2013; Alonso-Ayuso et al., 2014; Ramírez-García et al., 2015, 2015a; White et al., 2016; Wendling et al., 2016; Wollford & Jarvis, 2017; Warren, 2017; Couedel et al., 2018, 2019; Bhogal et al., 2019; Sieling et al., 2019; Toom et al., 2019; Chapagain et al., 2020; Duff et al., 2020; Hansen et al., 2021; Lövgren, 2022; Restovich et al., 2022
	+	+	-	-	+	+	+	
Green manure	3	5	2	3	5	7	3	Kirkegaard & Sarwar, 1998; Eberlein et al., 1998; Gimsing & Kirkegaard, 2006; Clark, 2008; Florentín, 2010; Bangarwa et al., 2011; Zachariah, 2011; Ramírez-García et al., 2015; Flores-Sánchez et al., 2016; Stubbs & Kennedy, 2017; Galaup, 2018; Hu et al., 2018; Heuermann et a., 2019; Li et al., 2019; Liu et al., 2020; Salume et al., 2020; Lövgren, 2022; Ait Kaci Ahmed et al., 2022; Lei et al., 2022; Jie, 2022; Jauhiainen, 2022; Wang et al., 2022; Israt & Parimal, 2023; Källén, 2023;
	+	+	-	-	+	+	-	
Fodder	3	5	3	3	1	7	5	Gustine & Jung, 1985; Capecka & Libik, 1998; Westwood & Mulcock, 2012; Ramírez-García et al., 2015, 2015a; Winkler, 2017; FOSS. 2018; Duff et al., 2020; Kılıç et al., 2021; Olofsson & Ernfors, 2022; Abdelrahman et al., 2022; Safaei et al., 2022; Jie, 2022; Ţiţei, 2022
	+	+	-	+	+	-	+	
Biogas	3	5	5	3	5	5	3	Cleemput, 2011; Herout et al., 2011; Murphy et al., 2011; Carvalho et al., 2011; Herrmann et al., 2011, 2014; Al Seadi et al., 2013; Molinuevo-Salces et al., 2013; Dandikas et al., 2014; Guarino et al., 2016; Herrmann et al., 2016; Einarsson & Persson, 2017; Maier et al., 2017; Martínez-Gutiérrez, 2018; Cerón-Vivas et al., 2019; Choi et al., 2020; Liu et al., 2020; Oliveira et al., 2021; Launay et al., 2022; Jauhiainen, 2022; Fajobi et al., 2023; Lallement et al., 2023; Lymperatou et al., 2023; Manyi-Lohn & Lues, 2023; Shitophyta et al., 2023
	+	+	+	+	+	-	-	

Equations with attribute for uses (desirable trend of formation: growth '+', decline '-')	
Cover crop	$5GC + 2BM + C/N - N_{upt} + 3RQ + 3GSL + CFb$
Catch crop	$2GC + 2BM - C/N - 2N_{upt} + 2RQ + 3GSL + CFb$
Green manure	$3GC + 5BM - 2C/N - 3N_{upt} + 5RQ + 7GSL - 3CFb$
Fodder	$3GC + 5BM - 3C/N + 3N_{upt} + RQ - 7GSL + 5DFb^{***}$
Biogas	$3GC + 5BM + 5C/N + 3N_{upt} + 5RQ - 5GSL - 4CFb$

*GC: ground cover (% на 60 добу після сівби); BM: biomass reached at the end of the experiment (kg m^{-2}); CN: C/N ratio; N_{upt}: N uptake (g m^{-2}); RQ: residue quality (g kg^{-1}_{DM}); CFb: fiber content (g kg^{-1}_{DM}); DFb: dietary fibre content (g kg^{-1}_{DM}); GSL: glucosinolate productivity (mmol m^{-2}). **desirable trend of formation: growth '+', decline '-' ***DFb only for the 'fodder crop' direction.

Table 3.12

Average of normalized values for 7 attributes of oilseed radish evaluation as multi-service cover crop functions (MSCC), 2014–2023 (averaged for the complete data set, directions of use–sowing dates) (based on the results of the author's own research)

Year	GC*	BM	C/N	N_{upt}	RQ	GSL	CFb (DFb**)	Amount	Rating
2014	0.213^a	0.268^b	0.129^c	0.069^b	0.072^b	0.086^b	0.057^c	0.897	1
2015	0.128^f	0.196^h	0.118^e	0.064^d	0.075^a	0.089^a	0.061^b	0.730	9
2016	0.179^c	0.231^e	0.120^e	0.069^b	0.075^a	0.088^a	0.062^a	0.824	6
2017	0.151^h	0.208^g	0.123^d	0.070^b	0.076^a	0.089^a	0.064^a	0.782	8
2018	0.154^g	0.214^f	0.125^d	0.075^a	0.075^a	0.089^a	0.064^a	0.796	7
2019	0.168^e	0.278^a	0.136^a	0.067^c	0.073^b	0.088^a	0.057^c	0.868	3
2020	0.167^e	0.262^c	0.120^e	0.063^d	0.074^a	0.088^a	0.060^b	0.834	5
2021	0.159^f	0.263^c	0.117^f	0.069^b	0.076^a	0.089^a	0.060^b	0.834	5
2022	0.172^d	0.270^b	0.127^c	0.073^a	0.076^a	0.088^a	0.061^b	0.867	4
2023	0.185^b	0.262^c	0.132^b	0.071^b	0.076^a	0.088^a	0.060^b	0.873	2
Average	0.168	0.245^d	0.125^d	0.069^b	0.075^a	0.088^a	0.061^b	–	–
Rating	2	1	3	6	5	4	7	–	–

* GC: ground cover (% at 60 days after sowing); BM: biomass reached at the end of the experiment (kg m^{-2}); CN: C/N ratio; N_{upt}: N uptake (g m^{-2}); RQ: residue quality (g kg^{-1}_{DM}); CFb: fiber content (g kg^{-1}_{DM}); DFb: dietary fibre content (g kg^{-1}_{DM}); GSL: glucosinolate productivity (mmol m^{-2}). **DFb for the direction use only for 'fodder crop' direction.

At the same time, the positions in the criterion of 'Biogas' use remained unchanged. However, the direction of its use in the direction of 'Cover crop' is significantly lower (decrease in the rating by 4 positions). Such changes, taking into account the saturating and intermediate nature of the summer sowing of oilseed radish, prove the technological potential of its use in a wide period of time in the MSCC system. It was also found that the rating by the direction of use depended on the conditions of the year. For example, for the conditions of 2018 and 2023, the direction 'Biogas' during the summer sowing period had the first rating among other directions of use with an average fourth position in the consolidated data set. Similar trends were found for other uses. This confirms our conclusions about the role of hydrothermal regimes of the growing season in shaping compliance with MSCC criteria.

Table 3.13

Sum of normalized values multiplied by the weighting coefficients for 7 attributes attained by each use oilseed radish as multi-service cover crop functions (MSCC), 2014–2023 (based on the results of the author's own research)

Year of research	Direction of use in the concept of MSCC										Rating by MSCC
	Cover crop		Catch crop		Green manure		Fodder		Biogas		
	*SprS	SumS	SprS	SumS	SprS	SumS	SprS	SumS	SprS	SumS	
2014	0.82^{d}	0.86^{b}	0.95^{b}	0.85^{d}	0.88^{b}	0.91^{c}	0.96^{b}	0.91^{c}	0.95^{b}	0.88^{c}	1
2015	0.82^{d}	0.84^{c}	0.73^{g}	*0.72f*	*0.75*^{f}	*0.62*^{h}	0.76^{g}	*0.60*^{g}	0.75^{g}	*0.59*^{g}	10
2016	0.83^{d}	0.82^{d}	0.76^{d}	0.83^{e}	0.80^{e}	0.89^{d}	0.79^{f}	0.89^{c}	0.78^{f}	0.87^{c}	7
2017	0.82^{d}	*0.73*^{g}	0.68^{h}	0.83^{e}	0.80^{e}	0.87^{e}	*0.65*^{i}	0.87^{d}	*0.65*^{i}	0.87^{c}	9
2018	0.83^{d}	0.79^{e}	*0.63*^{i}	0.87^{c}	0.80^{e}	0.89^{d}	0.70^{h}	0.88^{c}	0.69^{h}	0.93^{b}	8
2019	*0.79*^{e}	**0.89**^{a}	**0.98**^{a}	0.82^{e}	**0.91**^{a}	0.76^{g}	**0.99**^{a}	0.73^{f}	**0.99**^{a}	0.72^{f}	4
2020	0.87^{b}	0.78^{f}	0.86^{c}	0.82^{e}	0.85^{c}	0.79^{f}	0.90^{c}	0.80^{e}	0.90^{c}	0.76^{e}	6
2021	**0.93**^{a}	0.84^{c}	0.74^{g}	0.86^{d}	0.82^{d}	0.87^{e}	0.80^{e}	0.87^{d}	0.80^{e}	0.85^{d}	5
2022	0.85^{c}	0.80^{e}	0.77^{f}	0.90^{b}	0.83^{d}	**0.99**^{a}	0.82^{e}	**0.99**^{a}	0.81^{e}	**0.98**^{a}	3
2023	0.82^{d}	0.81^{d}	0.84^{c}	**0.93**^{a}	0.85^{c}	0.93^{b}	0.88^{d}	0.94^{b}	0.87^{d}	0.94^{b}	2
Average	0.838^{a}		0.794^{d}		0.829^{b}		0.825^{b}		0.819^{c}		–
		0.816^{d}		0.843^{b}		0.852^{a}		0.849^{a}		0.839^{b}	–
Rating by use	1		5		2		3		4		–
		5		3		1		2		4	–
Consistensy index (CI)*	0.431		0.188		0.340		0.370		0.226		–
		0.244		0.357		0.415		0.407		0.305	

*SprS – Spring sowing; SumS – Summer sowing. In bold, the maximum values, and in italics, the minimum. Case letters indicate statistical differences ($p < 0.05$); *the indicator is a component of the scheme of Analytic Hierarchy Process (AHP) according to Saaty & Vargas (2012).

According to the results of a multi-year study cycle, oilseed radish showed high productivity and adaptability. This is confirmed by the average indicators of its long-term productive and biochemical portfolio, which for the spring sowing period had the following parameters: formed aboveground biomass (BM) 24.04 t ha^{-1}, formed root biomass (RBM) 8.7 t ha^{-1}, soil coverage index on the 70th day after sowing (GC_{70}) 73.77%, crude protein content (CP) 15.56%$_{DM}$, crude fat (CF) 3.98%$_{DM}$, cellulose 21.73%$_{DM}$, hemicellulose 10.95%$_{DM}$, phosphorus 0.62%$_{DM}$, potassium 3.63%$_{DM}$, calcium 0.96%$_{DM}$, sulfur 0.42%$_{DM}$, glucosinolates (GSL) 13.57 μmol g^{-1} DM, C/N ratio 16.02, Residue quality (RQ) 84.99%$_{DM}$, Carbohydrates (CH) 67.08%$_{DM}$, GSL productivity 41.2 mol ha^{-1}. For the summer sowing period, similar parameters were as follows: BM 18.34 t ha^{-1}, RBM 5.50 t ha^{-1}, GC$_{70}$ 50.74%, CP 19.16%$_{DM}$, CF 4.61%$_{DM}$, cellulose 24.43 %$_{DM}$, hemicellulose 12.85%$_{DM}$, phosphorus 0.63%$_{DM}$, potassium 3.96%$_{DM}$, calcium 1.01%$_{DM}$, sulfur 0.48%$_{DM}$, GSL 19.70 μmol g^{-1} DM, C/N ratio 13.30, Residue quality (RQ) 81.03%$_{DM}$, CH 61.93%$_{DM}$, GSL productivity 54.90 mol ha^{-1}.

Using the above data block with the application of Multi-criteria decision aiding (MCDA), the possibility of multi-purpose use of oilseed radish in the criterion system of multi-service cover crop (MSCC) was proved in the following order of decreasing technological significance for the conditions of unstable hydrothermal regime of its vegetation period on soils with an average level of soil fertility potential (averaged for both sowing dates): ‘Green manure’ – ‘Fodder’ – ‘Cover crop’ – ‘Biogas’ – ‘Catch crop’.

3.2. Potential of oilseed radish as a green manure crop

It is noted (Gadzalo, 2016) that the choice of green manure form is determined by the soil, climatic and economic conditions of the agricultural producer (Figure 3.5).

The forms of green manure are determined by the choice of the method of sowing or underplanting green manure crops. The following forms of green manure are distinguished:

– basic (independent) – involves the use of perennial and annual grasses for green fertilizer and the replacement of black manure with green manure. The fallow crops are sown in the fall or spring using the entire green mass as fertilizer, and if necessary, the flocks;

– Sowing – green manure seeds are sown along the rows immediately after sowing the cover crop. After the main crop is harvested, green manure is built up on a high cut, which is plowed under the next crop;

– intermediate green manure is divided into stubble and stubble;

– pre-harvest green manure is carried out in the first half of the growing season after the field is cleared of annual grasses or corn for silage;

– post-harvest green manure is carried out in the second half of the growing season after harvesting early grain crops – winter crops, barley; early vegetables – radishes, early cabbage, early cucumbers, etc.

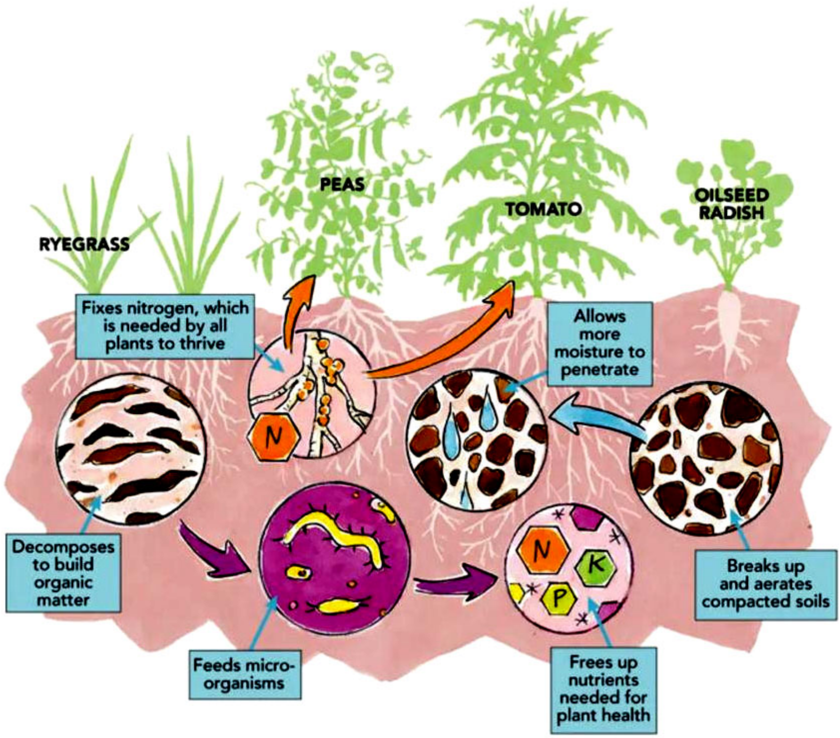

Figure 3.5 – Positive aspects of green manure in the soil

Independent and flock green manure. Traditionally, an independent form of green manure in the form of flocks of annual and perennial grasses is available for farms in any soil and climatic zone of Ukraine if they grow perennial and annual grasses that can grow green mass by the end of the growing season. This form of green manure is most promising for areas of unstable and insufficient moisture.

It is generally accepted that green manure fallowing is most appropriate as a temporary measure on infertile, depleted sandy soils, especially those remote from farms. Due to changing climatic conditions and increased rainy periods in areas of unstable moisture, green manure is being introduced to the Left Bank Forest-Steppe and southern Ukraine, not only on irrigated lands but also on rainfed lands.

Post-cutting green manure. Post-cutting green manure is carried out immediately after harvesting the main crop – winter or annual grasses and corn for green fodder. Post-harvest crops accumulate more green mass due to the long duration of the growing season. The green mass is used for winter cereals and spring row crops such as potatoes, corn, sugar beets and fodder.

Crops from the cruciferous family, such as oil radish, spring rape, percoche, and legumes such as lupine, sweet clover, and seradella, are effective for post-mowing green manure. For sowing, the field is cultivated immediately after it is freed from the main crop. With the gradual harvesting of green mass for fodder, the field is then cultivated with a heavy disk harrow or shallow plowing.

Intermediate green manure. Intermediate green manure can be either post-mowing or post-harvest, depending on the timing of sowing. This is the most common method of green manure, especially in areas of sufficient moisture and on irrigated land.

Features of growing crops for green manure in intercrops:

1. After harvesting the predecessor (mainly cereal spiked crops), the field is immediately (to prevent moisture evaporation from the soil) disked in two tracks, followed by leveling and rolling with any combined unit such as "Europak". It is advisable to leave high stubble or straw chopped during harvesting on the field.

2. When growing cruciferous and cereal crops (oil radish, winter rye and others) for green manure, it is recommended to apply nitrogen fertilizers in the rate of N30-45 for regenerative agriculture. When growing legumes on green manure, no fertilizer is required.

3. Seeding rates should be calculated 25–30% higher than those recommended for technologies of growing crops for economic needs.

4. It is necessary to carry out post-sowing rolling.

5. When growing green manure, all phosphorus and potassium fertilizers and half of the nitrogen fertilizers intended for the main crop should be

applied under "pioneer plants" (green fertilizers); this makes it possible to increase the return on mineral fertilizers by 1.5-2 times.

6. When applying manure in crop rotation, it is advisable to combine it with green manure cultivation, which will increase the aboveground and root mass of green manure by 2–3 times, reduce the loss of nutrients from manure by 2–2.5 times, and, accordingly, increase the coefficient of organic fertilizer use by 1.6–1.8 times.

7. The mass of intermediate green manure crops is incorporated into the soil with one pass of disks (October-November); with high and dense grass (yield over 35 t/ha) – with two passes.

8. Pre-sowing tillage for the following early spring crops consists of harrowing (which levels the surface) and rolling. The soil surface remains lumpy after the autumn disk harrowing of green mass. Snow is well retained on it, which ensures the emergence of full sprouts 3–4 days after sowing.

9. Early incorporation of a large mass of green fertilizer into the soil in the intermediate sowing can have a negative impact on the yield of the subsequent crop. In this case, fresh organic matter is intensively mineralized and there are significant losses of nitrogen and humus. Therefore, it is advisable to plow green manure in late fall, and for spring crops in spring. Sowing is carried out with a seeder with disc coulters equipped with furrows.

Post-harvest green manure is the most common form of green manure due to the sufficient amount of vacant land after harvesting early crops. The effectiveness of growing post-harvest green manure depends on the efficiency of agrotechnical work immediately after harvesting the predecessor, clearing the field of straw or after shredding it and applying and cultivating the soil to obtain friendly and complete green manure emergence. For this purpose, soil cultivation is carried out with a BDT-7 disk harrow with harrowing with a BIG-3 needle harrow or other tools at an increased speed and rolling on soils of medium and heavy granulometric composition. With sufficient moisture, the green manure seeds are sown into the stubble, followed by disking to a depth of 6–8 cm. Resource- and moisture-saving surface tillage is highly effective, reducing the time required to prepare the soil for sowing.

For post-harvest green manure of cruciferous crops such as oilseed radish, spring and winter rape, and rape, it is advisable to apply nitrogen fertilizers at the rate of 60–90 kg/ha for regenerative agriculture, as the soil reserves of assimilable nitrogen compounds are sharply reduced at the time of sowing. In the Polissya, Northern and Western Forest-Steppe regions, mustard, oil radish, fodder cabbage, and rapeseed are sown no later than August 5–10. At the end of July, lupine, peas, oats, vetch and their mixtures are sown. It is important to note that high-quality seeds of large fractions are chosen for green manure. The preferred methods of sowing are conventional row or narrow-row, or scattered sowing. In case of late sowing, the seeds are planted by shallow disking, with a seeding depth of 2–3 cm.

Ushkarenko et al. (2000) note that cruciferous crops are characterized by a short growing season, high cold resistance, and the presence of high protein content in the green mass. Being good predecessors for all crops in the crop rotation, cabbage crops leave 120–200 c/ha of crop residues in the soil, which are quickly mineralized, improve the mechanical composition and fertility of the soil (Table 3.14).

Table 3.14

Yield of green mass of cabbage crops depending on the nutritional background, c/ha

Growing crops	Nutrition background	Research periods			Ave-rage	Dry matter harvest, c/ha
		1998	1999	2000		
Camelina	No fertilizers	96	118	107	107	21.9
	$N_{60}P_{45}$	186	228	192	202	47.9
	$N_{120}P_{90}$	254	246	251	250	51.2
White mustard	No fertilizers	137	208	190	178	37.7
	$N_{60}P_{45}$	279	302	265	282	64.3
	$N_{120}P_{90}$	311	369	292	324	59.0
Rapeseed	No fertilizers	177	252	219	216	40.8
	$N_{60}P_{45}$	360	334	305	333	67.9
	$N_{120}P_{90}$	445	370	372	396	70.9
Oilseed radish	No fertilizers	256	252	220	243	33.0
	$N_{60}P_{45}$	460	371	336	389	40.3
	$N_{120}P_{90}$	533	422	390	448	59.1

LSD_{05}, c/ha: for culture 30.7 21.8 18.5; for the power supply background 26.6 19.0 16.0; for the interaction of factors 53.1 37.9 32.0

When growing cabbage crops, the soil was enriched with organic matter due to their root system by 22.2–45.5 c/ha.

As a result of the research by Ushkarenko et al. (2000), the following conclusions were made:

1. The highest yield of green mass was provided by oil radish on all nutrition backgrounds.

2. The maximum dry matter yield (67.9–70.9 c/ha) was obtained when growing oilseed rape with fertilizers in doses of $N_{60}P_{45}$ and $N_{120}P_{90}$.

3. The lowest coefficient of water consumption (61–106 m^3/t) was recorded on all nutrition backgrounds in oilseed radish.

In another study (Hansen et al., 2020) six different species of green manure, white lupin (Lupinus albus), winter vetch (*Vicia villosa*), crimson clover (*Trifolium incarnatum*), buckwheat (*Fagopyrum esculentum*), oilseed radish (*Raphanus sativus*) and winter rye (*Secale cereale*)) were sown after harvest of oilseed rape in plots with either low or moderate soil fertility with 6 and 16 mg Olsen-P kg $soil^{-1}$, respectively. According to the results of the research, oil radish demonstrated high efficiency and biological and agrochemical productivity in comparison with other green manure crops studied (Figures 3.6–3.8).

Figure 3.6 – Biomass sampling in autumn revealed that biomass production of winter vetch, crimson clover, oilseed radish and winter rye were significantly decreased when growing at low soil fertility whereas white lupin and buckwheat showed the same growth at both fertility levels

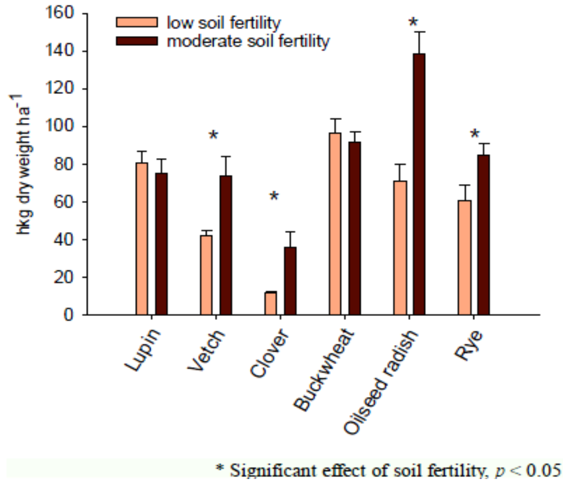

Figure 3.7 – After 80 days of incubation, the treatments receiving sorrel and oil seed radish revealed the highest P mobilization, with an increase of water-extractable P (WEP) corresponding to 50 and 31%, respectively, of the added P.

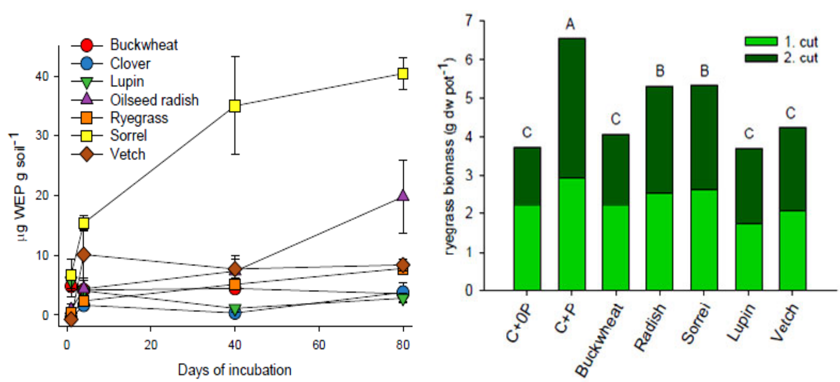

Figure 3.8 – After 40 days of ryegrass growth, the addition of oilseed radish and sorrel significantly increased the growth of ryegrass by 43 and 44 % compared to the 0P control, respectively, confirming their value as green manure plants for crop P nutrition

In general, according to the results of long-term studies, oil radish is included in the list of cover crops for different soil and climatic zones of the USA and Canada (Table 3.15).

Table 3.15

Cover crops/green manures at various planting times

Early Spring	Early Summer	Early autumn
Buckwheat	Buckwheat	Buckwheat
Canola (Rapeseed)	Canola (Rapeseed)	Canola (Rapeseed)
Red, white or crimson clover	Red, white or crimson clover	Red, white or crimson clover
Oilseed Radish	Oilseed Radish	Oilseed Radish
Mustards	Mustards	Mustards
Daikon Radish	Daikon Radish	Daikon Radish
Spring cereal crops	Hairy Vetch	Hairy Vetch
Austrian winter pea	Chickling Vetch	Winter cereal crops
Austrian Winter Pea/cereal	Sorghum	Austrian Winter Pea
Purple Top Turnips	Sorghum Sudangrass	Austrian Winter Pea/cereal
	Teff	Purple Top Turnips
	Pearl Millet	
	Spring Peas	
	Oats	

The research by Kemper et al. (2020) noted that in mixtures, oilseed radish was dominant in shoot and root underlining the importance of species identity in cover crop mixtures. Positive mixture effects for RLD and RMD were more frequent in the subsoil due to a strong rooting of oil radish if integrated as a mixture partner. Consistently positive mixture effects were found for SRL, i.e. mixing makes roots thinner. Root mass complementarity, vertical root niche differentiation and mixture effects in topsoil might have not occurred pronouncedly because partners were not sufficiently balanced in mixtures. Thus, future research should focus on the balance when mixing different cover crop species. More conceptual planning of seed density ratios and mixture composition is advised to design well-balanced cover crop mixtures to exploit mixture effects above and belowground more effectively. Mixture effects seem to be more prominent for morphological than architectural root traits. Enhanced SRL in mixtures might be linked to higher root turnover and rhizodeposition which would influence cover crop functions such as carbon storage and microbial activity. Future research on roots of cover crop mixtures should consider root turnover, rhizodeposition, microbial processes as well as other acquisitive root traits such as root tips, branching and root N content (Figure 3.9–3.11).

Kemper et al. (2020) have given first insights into belowground interactions of mixed cover crops and mixture effects on their root traits in autumn. Future root research will profit from methods that allow an understanding of belowground interaction throughout the crop growth period.

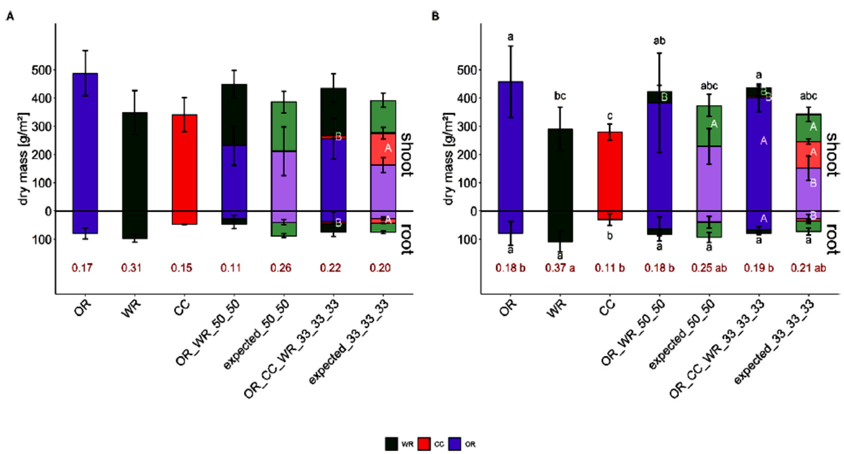

Figure 3.9 – Mean values ± standard deviation of shoot (n = 4) and root (n = 3) dry mass [g/m2] and mean values of root-shoot-ratio (n = 3) of sole cover crops oil radish (OR), winter rye (WR), crimson clover (CC), 50:50 cover crop mixtures of oil radish and winter rye (0R_WR_50_50), 33:33:33 cover crop mixtures of oil radish, crimson clover and winter rye (0R_ CC_WR_33_33_33) and of expected mixtures (corresponding proportions of sole crops) in 2018 (A) and 2019 (B). Bars above 0 represent shoot dry mass, bars below 0 show root dry (Kemper et al., 2020)

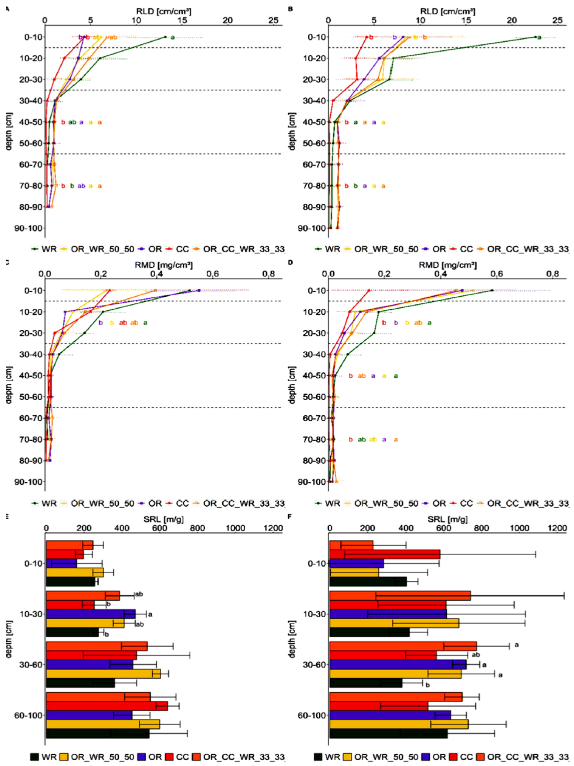

Figure 3.10 – Mean values ± standard deviation (n = 3) of root length density [cm/cm3] (RLD) (A, B), root mass density [mg/cm3] (RMD) (C, D) and specific root length [m/g] (SRL) (E, F) of sole cover crops oil radish (OR), winter rye (WR), crimson clover (CC), 50:50-cover crop mixtures of radish and rye (OR_WR_50_50), 33:33:33-cover crop mixtures of radish and rye (OR_CC_WR_33_33_33) in 2018 (A, C, E) and 2019 (B, D, F) at different soil depth levels. Colours refer to cover crops: green for rye, yellow for 50:50-mixture, orange for 33:33:33-mixture, red for clover and violet for radish. Different lowercase letters indicate significant differences (p < 0.05, HSD Tukey-test) between different cover crops within the different soil depth layers (0-10 cm, 10-30 cm, 30-60 cm and 60-100 cm) within one year (Kemper et al., 2020)

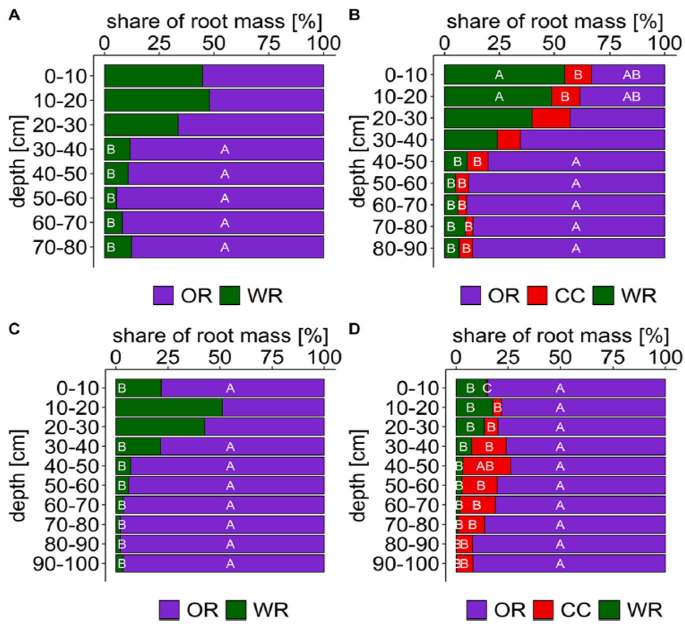

Figure 3.11 – Mean values (n = 3) of root mass share [%] of oil radish (violet), crimson clover (red) and winter rye (green) at different soil depth in 2018 (A, B) and 2019 (C, D) in a 50:50 cover crop mixture of oil radish and winter rye (A, C) and in a 33:33:33 cover crop mixture of oil radish, crimson clover and winter rye (B, D). Different uppercase letters indicate significant differences ($p < 0.05$, t-Test) between proportions of root mass of mixture partners within one soil depth layer (Kemper et al., 2020)

In Ukraine, according to Pisarenko et al. (2012), legumes (sainfoin, alfalfa, spring vetch, sweet clover, lupine, seradella) are mostly sown as green manure and green manure, which are more useful for enriching the soil with nutrients. Oil radish, mustard, buckwheat, phacelia, and others are widely used. Mixtures are also sown, such as spring vetch and spring oats, oil radish and spring oats, etc.

Under the influence of legume green manure, the number of nodule bacteria increases by 4–7 times, the enzymatic activity of the soil increases significantly, its phytosanitary and water-physical properties improve, and conditions are created for the intensive development of microorganisms and microfauna that determine the fertility of a given field. The positive effect of green manure lasts for 3–4 years.

The widespread introduction of green manure helps to incorporate unused reserves of phosphorus, potassium, calcium, magnesium and other plant nutrients from deeper soil genetic horizons into the small cycle.

Green manure crops are grown with a cover crop, in a row crop and a harvest crop. In the first case, in the year of cultivation, green manure is sown under a cover crop (spring barley, corn for green fodder, etc.) or sown directly after harvesting the main crop (stubble, harvest). In the process of growing green manure crops with a cover crop, the field is cultivated using the technology of soil preparation for the cover crop. For the purpose of growing green manure after mowing or harvesting, the soil is prepared with the recommended aggregates to a depth of 6–8 centimeters. The main thing is to prevent a gap between harvesting the predecessor and sowing the green manure, as this leads to significant moisture loss and, as a result, poorer development of the green manure crop. It is also important to ensure that the seeds are planted in moist soil. Sowing is carried out immediately after tillage or simultaneously with it. The main method of sowing is conventional row sowing; seeding rates for post-mowing or stubble sowing are increased by 20–25% compared to optimal conditions (when sowing in spring) and seed is planted 1–2 cm deeper. After sowing, rolling, pre-emergence and post-emergence harrowing with light sowing harrows is carried out, and inter-row cultivation is also carried out on wide-row crops. The best results for friendly germination and subsequent growth of green manure are obtained by surface tillage: moisture is retained, the negative effects of erosion are minimized, weeds are reduced and the number of passes of the machines is reduced, and the soil is not compacted. In combination with green manure, surface tillage provides the most effective way to preserve and improve soil fertility. Growing green manure crops improves the fertility of the soil created by the plants themselves. This property has even been calculated mathematically. During its lifetime, a plant takes only 10 percent of its «material» from the soil to form biomass, and 90 percent comes from the air and the energy of the sun's rays (Pisarenko et al., 2012).

Thus, for each ton of dry matter harvest (main and by-products), perennial legumes (alfalfa, sainfoin, clover) fix about 30–38 kg of nitrogen from the air, lupine and fodder beans – 20–27 kg, peas – 10–15 kg. Surface tillage and residues on the surface of plant residues significantly increase nitrogen fixation by legumes. The best results for friendly germination and subsequent growth of green manure are obtained by surface tillage: moisture is preserved, the negative effects of erosion are minimized, weeds and weeds are reduced, and the amount of At the same time, it is important to replenish the soil with basic nutrients, which improves the mineral nutrition of plants. The data obtained by the author are presented in Table 3.16 (Pisarenko et al., 2012).

Thus, increasing the specific mass of biological nitrogen and other nutrients in agroecosystems by increasing the area of green manure (primarily legume green manure crops) is the main lever for stabilizing the productivity, energy and economic efficiency of agriculture.

The author concludes that green manure is one of the main factors of the organic farming system. This measure is mandatory in transitional (rehabilitation) farming, as well as in intensive farming. Its use enriches the soil with organic matter, increases the amount of nutrients, and generally improves soil fertility and profitability. The use of green manure virtually eliminates the need for additional mineral fertilizers, which is an environmentally and economically sound measure.

All of this ensures an increase in production profitability, contributes to the ecological rehabilitation of the soil, improves its fertility based on biological principles of farming, and protects the environment. The widespread introduction of green manure contributes to the transition to a resource-saving and, in the future, organic farming system.

The choice of green manure is determined by the biological characteristics of the plant, including its relation to the level of soil fertility, taking into account the content of humus and nutrients, and the reaction of the soil solution is also important. Cereal crops such as winter rye and its varieties (green rye and perennial rye), oats, and ryegrass can tolerate high soil acidity and low nutrient content. Legumes, unlike cereals, grow better on fertile soils (except for perennial lupine), do not require additional nitrogen, but do not tolerate weeds and cannot grow significant biomass in a short growing season. Cabbage crops grow better on fertile soils, are suppressed by weeds, and react negatively to lack of moisture and nitrogen deficiency. They require a high level of farming culture, with the exception of oil radish, which differs from other cabbage crops in its need for soil conditions by its relative unpretentiousness. For post-harvest sowing, regardless of its purpose, only those crops are suitable that are primarily early maturing, insensitive to low air and soil temperatures and to a decrease in solar radiation and daylight hours, and cold and frost resistant. Plants from the cabbage family are such early maturing and heat-resistant crops, the best of which are spring and winter rape, white mustard, oil radish, winter and spring rape. Forms of green manure. The choice of green manure form is dictated by the soil, climatic and economic conditions of the agricultural producer. The form of green manure is determined by the choice of sowing or underplanting method of green manure crops.

Table 3.16

Agrochemical characterization of green manure plants by the calculation-equivalent method (Pisarenko et al., 2012)

Green manure	Green mass yield, c/ha	Accumulated nutrients in total biomass, kg/ha			Total, kg/ha	In stock, kg/ha 1*
		N	P_2O_5	K_2O		
Sainfoin	275	145	25	75	245	510.4
Winter vetch	250	160	75	200	435	906.3
Vetch-oat mixture	275	120	35	80	235	489.6
Fodder peas	350	80	70	90	240	500
White sweet clover	200	110	45	140	295	614.6
Annual lupine	520	230	60	200	490	1020.8
Buckwheat for two earnings	650	200	135	305	640	1333.3
White mustard	250	60	40	90	190	395.8
Ragweed	340	135	55	240	430	895.8
Oilseed radish	450	85	65	245	395	822.9
Phacelia	300	80	50	200	330	687.5

Advantages of green fertilizers (Advantages and disadvantages of green fertilizers, 2022):

1. *Nitrogen (N) accumulation*. Legume green manure enriches the soil with nitrogen, which is "taken" from the air by nodule bacteria located on their roots. The accumulated nitrogen is enough for both the green manure crop and the next one after it. With a green manure crop yield

of 350-400 c/ha, 150–250 kg/ha of total nitrogen is released into the soil, which is equal to the application of about 30-40 tons/ha of manure.

2. *Accumulation of humus*. Green manure is an important source of organic matter replenishment. Crops grown on green manure have different effects on humus accumulation. It depends on whether the ground mass of the green manure is used for fertilization, whether it is plowed into the soil at the place of growth with the root system, or whether only crop and root residues are plowed into the soil. The accumulation of humus also depends on the time of plowing the green manure. Spring plowing creates better conditions for the preservation and accumulation of organic matter. As pointed out by OM. Berdnikov points out, the green mass of a legume plowed in late autumn (150–200 kg) is equivalent to the application of 20 tons of manure per hectare, annual lupine gives 80–160 kg/ha of root and crop residues with a humification coefficient of 0.15–0.25, cruciferous plants, when used for green fertilization, leave 1.0–1.5 t/ha of plant residues or more than 200 kg/ha of humus in the soil (humification coefficient 0.15–0.20).

3. *Improvement of air and water regimes of the soil*. After plowing green mass of green manure along the passages of dead roots, aeration is good and the water regime improves.

4. *Less leaching of nutrients (N + Ca + K)*. On the sandy soils of Polissya, intermediate sowings of green manure during autumn rains delay the leaching of easily soluble forms of nutrients, especially nitrogen.

5. *More efficient use of nutrients from the lower soil layers for crop formation*. Rainwater in the upper layers of the soil dissolves nutrients and carries them to the lower horizons, but crops cannot use them from there. The roots of green manure absorb these nutrients from the groundwater and use them to form the mass, so the nutrients remain in the topsoil.

6. *Reducing erosion (soil consolidation)*. During the summer and autumn period, the soil under green manure is less eroded and less compacted by rain, water does not run off the surface, does not wash away its fertile layer, but is absorbed, replenishing moisture reserves. Therefore, green fertilizers should be considered as a measure to reduce water and wind erosion.

7. *Soil shading (soil protection).* The soil under green manure does not overheat or dry out, and microorganisms and earthworms are active in it, which also work to enrich the topsoil with organic matter. The soil surface is

protected by the vegetation cover and, for a short period of time, conditions close to natural are created to restore soil fertility.

8. *Soil structuring (biological tillage).* K.I. Dovban found that the widespread introduction of green manure in Polissya crop rotations on sod-podzolic soil increases the content of not only the total number of water-resistant aggregates, but also its most valuable fraction – aggregates with a diameter of more than 1 mm.

9. *Loosening of arable and subsoil layers*. When growing green manure, the bulk of the plant roots are located in the arable and subsoil layers, which loosens the soil well.

10. *Reducing soil salinity*. Sweet clover is one of the salt-resistant crops, so it can be grown on saline soils as a phytomeliorant. After plowing sweet clover, salts from the saline horizons are washed out into the deeper soil layers through the passages of its dead roots. Its powerful root system also extracts calcium from deep soil layers, and after plowing and mineralization of the mass, it releases and displaces sodium from the soil-absorbing complex of the soil.

11. *Improving soil biological activity*. The use of green manure in crop rotations stimulates an increase in the number of soil microorganisms, enriches their quantitative composition and helps to increase the biological activity of the soil. As a result, soil fertility and crop yields improve.

12. *Weed control* by shading them with green manure and antagonistic action.

13. *Disease control*. When plowing the green mass of green fertilizer, the activity of a large group of saprophytic soil microorganisms, which are antagonists of many pathogens, increases.

14. *Pest control* (reducing the number of nematodes). When growing main crops, it is recommended to introduce green manure crops that repel nematodes into the crop rotation.

15. *Increase in the yield of the next crop with less nitrogen application* or greater efficiency of the impact of measures (fertilization, tillage). Widespread use of green manure helps to restore soil fertility and increase crop yields. The increase in yields from green manure is 1.7-4.3 cwt/ha for wheat, 50-90 cwt/ha for potatoes, 50-140 cwt/ha for sugar beet, 70-130 cwt/ha for corn, 9-13 cwt/ha for corn kernels, and 6-10 cwt/ha for buckwheat.

Disadvantages of green manure (Advantages and disadvantages of green fertilizers, 2022):

1. Some green manures have a narrow C:N ratio, which can lead to a decrease in soil organic matter. To prevent this, it is advisable to apply green fertilizer together with low rates of bedding manure (up to 10 t/ha) or with straw that remains on the field.

2. Lupine does not tolerate high soil calcium content, and therefore it is unprofitable to grow it on carbonate black soil. Therefore, other green manure should be used on these soils.

3. One of the disadvantages of green manure is the drying of the soil during the growing season. In dry periods, plowing them may be ineffective. This is often observed in green manure pairs when green manure is plowed late (shortly before sowing winter crops).

4. Loss of humus during very intensive cultivation in the warm season (for sowing winter intermediate or stubble crops).

5. High water consumption in arid areas with improper crop selection or high doses of nitrogen (possible absence or thinning of seedlings due to lack of water).

6. Widespread diseases (cereals, clover) or pests (nematodes) due to mistakes (wrong choice of crop or duration of its cultivation).

In agriculture, all technical and economic considerations and the accumulated experience of specialists culminate in the implemented crop rotation. Therefore, it is advisable to conduct experiments with green manure on every farm. However, the results obtained may vary greatly and should not be used on other farms.

The number of types of green manure crops that can be grown is very large. It is limited by the growing season of the crop, the type of soil (the possibility of cultivating it) and the climatic conditions of cultivation, especially the amount of precipitation, as well as the technical support of the farm and the cost of seed.

Green manure can be grown when:

– increasing the yield of the next crop;

– improving pre-sowing or main soil cultivation;

– reducing the amount of mineral nitrogen applied to the next crop;

– a large supply of available moisture in the soil due to the large depth of root penetration after green manure cultivation;

– reduction in the number of pathogens or pests when growing subsequent crops.

Green manure crops are an integral part of any farming system. Existing classical forms of green manure, due to climate change, are becoming ineffective due to the instability of precipitation at the time of sowing green manure crops, even in areas of sufficient moisture.

Depending on the type and purpose of growing crops, green manure can occupy the field for one or more growing seasons (independent crops), be grown together with another main crop or in its inter-rows (intercrops), as well as during a short period from harvesting one crop to sowing another (intermediate crops) or after the stubble of perennial grasses has grown back (fallow crops).

The green manure system must be identified with the crop production system, which is determined by soil and climatic conditions and the structure of sown areas.

In the green manure system, the initial determination of the possible volumes and methods of growing green manure crops is made taking into account the state of soil fertility, planned yields and the level of organic and mineral fertilizers. At the same time, green manure production is usually carried out without changing the existing structure of sown areas under the main food, fodder and industrial crops. An exception is allowed for green manure on completely degraded soils, during the reclamation of abandoned and new land development (Degodyuk et al., 2020):

There are 5 forms of green manure:

1. Independent and flocked form.
2. Under-sowing green manure, post-mowing.
3. Post-cutting (post-cutting).
4. Post-harvest.
5. Backstage form of green manure (annual or perennial and, in turn, mowing and non-mowing).

The main (independent) one consists in the use of perennial and annual grasses for green fertilizer and in the replacement of black manure with green manure. The fallow crops are sown in the fall or spring, using the entire green mass for fertilization, and, if necessary, the flocks. This form of green manure is possible for farms in any soil and climatic zone of Ukraine when growing annual and perennial grasses. It is promising for areas of unstable and insufficient moisture.

Sowing green manure – green manure seeds are sown along the rows immediately after sowing the cover crop. After the main crop is harvested, green manure mass is built up on a high cut, which is plowed under the next crop. Perennial lupine, seradella, and perennial legumes (clover, alfalfa, sainfoin) are sown under winter grain crops. The main types of fertilizers in organic farming are sown under the cover of winter crops in late autumn or winter on snow or in early spring with a seeding rate of 55–60 kg ha^{-1}. The effectiveness of lupine as a green manure increases when combined with winter crop straw. This form of green manure is suitable for all soil and climatic zones of Ukraine.

Intermediate green manure can be either post-mowing or post-harvest, depending on the timing of sowing. This is the most common method of green manure, especially when there is sufficient moisture and on irrigated land.

Post-cutting green manure is applied in the first half of the growing season after the field is cleared of annual grasses or corn for silage. With a longer growing season, post-mowing grasses accumulate more green mass, which is applied to winter cereals and spring row crops such as potatoes, corn, sugar beets and fodder. Crops such as oil radish, spring rape, and legumes such as lupine, sweet clover, and seradella are selected for this form of green manure. Part of the green mass of these crops can be used for livestock feed. This form of green manure, as well as the following post-harvest green manure, can be consistently guaranteed in areas of sufficient rainfall or on irrigated land.

Post-harvest green manure is carried out in the second half of the growing season after harvesting early grain crops – winter crops, barley; early vegetables – radishes, early cabbage, early cucumbers, etc. For this form of green manure, high-yielding crops with a short growing season are selected – mustard, oil radish, fodder cabbage, rapeseed, or mixtures of lupine, peas, vetch and oats.

The most effective application of green manure, according to the results of research by Ukrainian scientists, is observed in the cultivation of potatoes, fodder and sugar beets, corn, winter cereals, vegetables and fruit and berry crops (Nosenko, 2011).

According to Nosenko (2011), depending on the place in the crop rotation, an intermediate (insertion) form of green manure is most appropriate, which is divided into under-sowing (sowing under the main crop) and post-harvest and post-harvest (sowing after harvesting the main crop) forms. In this case, the green manure is plowed in during autumn plowing for the next year's harvest. The independent form of green manure should be used only in the form of green manure pairs for winter crops. For other crops, independent green manure is unprofitable, as the field remains unproductive for a year.

According to the method of green manure use, there are full use (the entire green manure mass is plowed), mowing (the aboveground mass of green manure grown outside the crop rotation is plowed), and flocking (combined). The latter is divided into two types: two mowings for green fodder and plowing of crop and root residues; the first mowing for green fodder and plowing of the flock of the second mowing (used as flock-siderata pairs under winter crops). Intermediate green manure is more profitable than the main one, so the timing of sowing is very important, as it determines the biomass yield and the reliability of green manure in general. Under production conditions, immediately after harvesting the main crop, surface tillage is carried out and green manure is sown. In dry conditions, pre- and post-sowing soil rolling is mandatory.

According to Likhochvor (2008), growing crops for green fertilizers is of great agronomic and economic importance. From the economic point of view, it is more expedient to grow them as intermediate crops, occupying the field with the main crop that will provide profit. They can be divided into three groups according to the length of the growing season:

– short growing season (45–60 days) – phacelia, white mustard, oil radish;

– medium growing season (60–80 days) – peas, narrow-leaved lupine, seradella, sunflower, etc;

– long growing season (more than 80 days) – yellow lupine, fodder beans, etc.

Two groups of crops are most suitable for green manure: legumes, which produce green mass rich in nutrients, especially nitrogen; cabbage, which is characterized by rapid growth and high yields of green mass.

When using cruciferous crops for green manure, it should be borne in mind that the biomass of oil radish, rapeseed, switchgrass and other crops is determined by the presence of nitrogen in the soil and the level of soil fertility. With low nitrogen reserves on poor soils, cruciferous green manure does not grow at all.

The Chernihiv Institute of Agricultural Research has identified the most suitable crops for green manure in the Polissya and Forest-Steppe zones in intermediate sowings: pre-sowing, post-mowing, and post-harvest forms (Table 3.17).

Table 3.17

Suitability of plants for green manure in intercrops (Nosenko, 2011)

Crops	Requirements for growing conditions	Seeding rate of seeds, kg ha^{-1}	Reproduction rate	Biomass accumulation (a/mass + roots), c ha^{-1}	Degree of suitability for green manure
Narrow-leaved lupine	Undemanding	200	15	240	XXX
Yellow lupine	Undemanding	200	4	200	X
Lupine perennial	Relatively demanding	60	10	200	XX
Red clover	Demanding	20	10	140	X
Seradella	Undemanding	50	12	180	XX
White sweet clover	Relatively demanding	20	30	150	XX
Peas	Demanding	300	5	120	X
Diaper pea	Demanding	250	6	120	X
Winter vetch	Demanding	60	7	160	X
Spring vetch	Demanding	150	10	110	X
Phacelia	Undemanding	15	20	120	X
Oat	Undemanding	180	11	80	X
Barley	Demanding	200	10	70	X
Winter rye	Undemanding	200	10	200	XX
Green rye	Undemanding	75	26	250	XXX
Perennial rye	Undemanding	100	20	250	XXX
White mustard	Demanding	20	50	100	XX
Winter rape	Demanding	15	67	130	XX
Percot	Demanding	15	53	150	XX
Oilseed radish	Relatively demanding	40	25	230	XXX
Annual ryegrass	Relatively demanding	40	15	210	XXX
Pasture ryegrass	Relatively demanding	30	16	180	XXX

Notes. The degree of suitability of the intermediate crop for green manure: XXX – high, XX – medium, X – weak, n – undemanding, c – demanding, r.d. – relatively demanding.

Possible options for growing green manure crops are presented in Tables 3.18–3.20.

Thanks to their well-developed root system, green manure improves the fertility of not only the topsoil but also the deeper subsoil and subsoil horizons: the nitrogen regime improves, the content of phosphorus and potassium available to plants increases, and positive changes in the physical and chemical state of the soil occur, while the fertilizing effect of manure is limited to the topsoil.

Table 3.18

Cultivation of crops for green manure in post-harvest crops (Shuvar, 1997)

Crops	Sowing period	Seeding rate of seeds, kg ha^{-1}
Spring vetch	July 1–31	120–140
Fodder peas (diaper peas)	July 1–31	180–230
Yellow lupine	July 1–31	170–200
Spring vetch + diaper + yellow lupine	July 1–31	40 + 120 + 60
Seradella	July 1–31	50–70
Yellow lupine + seradella	July 1–31	130 + 30
Spring vetch + yellow lupine	July 1–31	40 + 100
Fodder beans	July 1–31	250–300
Buckwheat	July 1–31	60–70
Sunflower	until August 10	30–40
Fodder beans + diaper + sunflower	until August 5	100 + 100 + 15
Phacelia	until August 15	8–10
Seradella + phacelia	until August 5	30 + 5
Winter vetch + phacelia	until August 5	40 + 6
Seradella + buckwheat	until August 5	40 + 40
Diaper + sunflower	until August 5	150 + 15
White mustard	until August 15	15–20
Oilseed radish	until August 15	15–25
White mustard + phacelia	until August 15	15 + 5

Peculiarities of growing crops for green manure in intercrops:

After harvesting the predecessor (mainly cereal spiked crops), the field is immediately disked in two tracks to prevent moisture evaporation from the soil, followed by leveling and rolling with any combined unit such as the Europak. It is advisable to leave tall stubble or straw chopped during harvesting on the field. When applying manure in crop rotation under organic and other fertilization systems, it is advisable to combine it with green manure cultivation, which will increase the aboveground and root mass of green manure by 2–3 times, reduce the loss of nutrients from manure by 2.0–2.5 times and, accordingly, increase the utilization rate of organic fertilizers by 1.6–1.8 times. The mass of intermediate green manure crops is incorporated into the soil with one pass of disks (October-November); with high and dense grass (yield over 35 t ha^{-1}) – with two passes. Pre-sowing tillage for the following early spring crops consists of harrowing (which levels the surface) and rolling. The soil surface remains lumpy after the autumn disk harrowing of green mass. Snow is well retained on it, which ensures the emergence of full sprouts 3-4 days after sowing. Green manure is a powerful factor in the interaction of biotic and abiotic processes that transform substances into forms assimilable by plants with the help of microflora. Green manure accumulates in the soil about the same amount of root residues as aboveground mass – 15–45 t ha^{-1}. The decomposition of organic matter in green manure occurs much faster in the soil than in fiber-rich crop residues.

Methods of green manure application according to Gospodarenko (2013):

The following methods of green manure application are distinguished: undercover, independent, intermediate (or insertion), mowing, felling, mowing and felling.

Undercover application. Sainfoin, lupine, clover, and sweet clover are sown as green manure.

It is self-sufficient. The crop occupies the entire field during the growing season or even for several years in a row (green manure or green manure). Under certain conditions, green manure should be used to replace pure fallow land, where the field remains unproductive for a year.

Intermediate or intercropping – a crop occupies the field between harvesting one crop and sowing another. Depending on the timing of sowing the green manure, it can be a subsowing crop (for example, lupine is sown under winter rye for green fodder in spring, and after mowing the rye, the green manure grows back and is then plowed) or a stubble crop (lupine is sown after harvesting spring or winter crops). This is the most common way to use green manure. The criterion for the possible use of green manure crops in stubble crops is the temperature at which vegetation stops. The most commonly used crops in this case are peas, vetch, white mustard, ryegrass, phacelia, rapeseed, and switchgrass.

Sowing of stubble crops is carried out immediately after harvesting the main crop. In these cases, the soil is not tilled, but direct sowing is used. A sufficient amount of green mass (10–20 t ha^{-1}) is usually accumulated before the temperature drops to +5 °C, which is plowed under.

Mowing green fertilizer. Green manure is grown on one field and used on another in the form of a mowed, chopped mass that is scattered across the field and plowed. Most often, perennial lupine is used for this purpose, which is grown in fallow wedges.

Mowing, or mowing and mowing, green fertilizer. The first mowing of green manure is used for livestock feed, and the growing crop is plowed into the soil.

The depth of plowing green manure affects crop yields and the humus condition of the soil. For example, shallow plowing of green manure significantly increases the yield but has little effect on the accumulation of humus in the soil; deep plowing, on the contrary. Deep plowing is especially important on light soils. After plowing peat or straw together with green manure, the decomposition of the former slows down, while adding manure or slurry, on the contrary, accelerates the decomposition of green manure.

It is especially important to know at what stage of growth and development the plants are plowed. Plowing them before legumes bloom or cereals spike activates microbiological processes in the soil, increases the yield of subsequent crops, but does not affect the quantity and quality of humus. This is because the delicate green mass of green manure is poor in lignin, mineralizes quickly and is not fixed into humus compounds.

It should be noted that plowing green manure in the early stages can provoke mineralization of soil organic matter and dry out the topsoil. Therefore, the green manure crop is chopped and covered before the soil freezes in the fall. In addition, it is possible to carry out backstage green manure for snow retention in winter with the mass of plants being incorporated in the spring with disk harrows and then plowed.

It is advisable to “destroy” weeded green manure crops with any continuous herbicide, taking into account the aftereffects on the next crop. In this case, the cost of green manure increases, and the mineralization of plant residues is slower.

In terms of their impact on crop yields, green manures are close to bedding manure in the amount of 20–30 t ha^{-1}, and the costs of their production and application are 2–4 times lower.

The use of green manure has positive effects, in particular, it prevents soil erosion and degradation; regulates soil and microbiological processes by stimulating the reproduction of microorganisms; improves soil structure and water properties; reduces plant disease; mobilizes soil nutrients; and reduces weed infestation.

Table 3.19

Fertilizer value of green manure crops (Novikov et al., 2013)

Crops	Applied to the soil (biomass, organic matter, c/ha, NPK, kg ha^{-1})									
	green manure				occupied field				recycling with manure	
	biomass	organic matter	NPK	N biological	root and crop residues	organic matter	NPK	N biological	organic matter	NPK
Lupine perennial	640	91	563	187	–	–	–	–	31	181
Narrow-leaved lupine	550	78	453	153	75	13	49	17	48	262
White sweet clover	540	119	655	176	165	49	160	43	44	247
Yellow sweet clover	506	109	617	163	152	46	148	39	24	141
Seradella	370	60	353	110	65	11	50	16	24	137
Fodder peas	450	59	343	97	45	8	27	8	27	234
Red clover	400	68	584	148	135	23	158	40	26	222
Pink clover	380	64	555	141	125	21	146	37	29	232
Oriental goat's fescue	450	72	580	160	110	19	113	31	22	107
Fodder beans	350	56	268	99	40	7	25	9	26	208
Horned lambsquarters	400	65	520	165	120	31	125	40	27	144
Spring vetch	330	53	359	109	33	6	29	6	26	162
Oilseed radish	450	65	404	–	45	7	32	–	23	134
Spring melilot	350	57	334	–	35	5	27	–	27	127
Spring rape	450	68	317	–	45	7	25	–	26	156
White mustad	410	66	391	–	40	6	30	–		

Table 3.20

Characteristics and fodder properties of green manure crops (Novikov et al., 2013)

Crops	**Duration of vegetation** *(period of mowing ripeness), days*	**Number of mowings**	**Resistance to**			**Optimal soil pH**	**Harvest, c ha^{-1}**		**In 100 kg of green mass**	
			frosts	**droughts**	**waterlogging**		**green mass**	**seed**	**feed units**	**digestible protein, kg**
1	2	3	4	5	6	7	8	9	10	11
Red clover	2–3/*50–70*	2–3	medium resistant	medium resistant	medium resistant	5–6	300–400	1.5–3.5	21.0	2.7
White clover	10/*55–60*	2	resilient	resilient	resilient	4.5–5.0	150–200	1.5–2.0	22.0	2.8
Horned bent grass	4–6/*50–60*	2–3	resilient	resilient	medium resistant	4.5–5.5	180–300	3–4	23.0	3.8
Blue-horned alfalfa	4–6/*50–60*	3–4	resilient	resilient	unstable	6–6.5	250–400	3–5	21.3	4.0
Goat grass	6–10/*40–50*	2	resilient	resilient	medium resistant	6–6.5	280–500	5–10	20.3	3.5
Sweet clover	*2/80–90*	2	resilient	resilient	resilient	5.5–6.0	300–500	5–10	18.2	3.4
Sainfoin	3–5/*55–70*	2	resilient	resilient	medium resistant	5.5–6.0	200–350	6–7	20.6	3.8
Timothy	*6–8/60–70*	2	resilient	medium resistant	resilient	4.5–5.5	250–500	4–8	28.8	1.7
Bindweed	8–10/*40–50*	2	medium resistant	medium resistant	unstable	5.5–6.0	200–500	1.5–3.5	20.3	3.2

(End of Table 3.20)

1	2	3	4	5	6	7	8	9	10	11
Awnless bromegrass	*12–14/50–60*	3–4	resilient	resilient	resilient	5.0–5.5	280–500	5–6	29.0	2.9
Tall ryegrass	*4–5/50–60*	2–3	unstable	medium resistant	unstable	5.5–6.0	150–300	2–4	18.4	1.8
Meadow fescue	*6–8/50–60*	2	resilient	resilient	resilient	5.0–6.0	150–250	2–3	27.5	3.0
Meadow bluegrass	15–20/*45–55*	1–2	resilient	medium resistant	medium resistant	5.5–6.0	100–150	1.7–4	24.5	3.2
Meadow foxtail	10–20/*50–60*	2	resilient	unstable	resilient	5.0–6.0	150–250	2–5	28.3	2.3
Festalolium	*3–5/50–60*	2–3	resilient	resilient	resilient	4.5–6.5	250–400	5–8	26.5	2.7
Winter rye	*2/55–60*	2	resilient	resilient	medium resistant	4.5–5.5	200–400	25–50	25.3	2.0
Lupine perennial	*4–6/80–90*	2–3	resilient	resilient	resilient	4.0–5.0	250–450	4–8	–	–
Annual lupine	1/*70–80*	1	medium resistant	medium resistant	medium resistant	4.5–5.5	200–500	10–30	19.7	3.5
Seradella	1/*75–85*	2	resilient	resilient	medium resistant	4.5–5.5	200–250	5–10	17.1	2.4
Spring vetch	1/*70–80*	1	resilient	medium resistant	medium resistant	5.5–6.0	150–250	8–15	20.0	3.8
Pea	1/*70–80*	1	resilient	medium resistant	medium resistant	5.5–6.0	150–300	10–30	19.2	3.1
Oilseed radish	1/*50–55*	1	resilient	medium resistant	medium resistant	5.0–6.0	300–600	6–10	14.6	1.9
White mustard	1/*55–60*	1	resilient	medium resistant	medium resistant	5.0–6.0	250–500	5–10	14.1	1.8

Post-harvest residues. Post-harvest plant residues (non-marketable part of the crop, stubble and roots) are an important input item in the balance of organic matter and the transformation of nutrients in the soil. Therefore, they can be considered a type of green manure.

The quantity and quality of post-harvest residues depends on the crop, variety and yield and varies within a fairly wide range, t/ha: perennial lupine – 2–3, clover – 3–7, alfalfa – 4–9, peas – 1.5–3, winter rye and wheat – 2.2–6.5, barley – 2–4.5, corn – 1.5–6, potatoes – 1–1.2, sugar beets – 1–1.5, rye for green fodder – 1–2, mustard – 0.4–1, perennial grasses – 5–11.

Intermediate crops of green manure can be used in three ways:

a) spring, when the green manure crop is sown and grown before the fertilized crop is sown;

b) autumn, when the green manure crop is sown and grown in the fall after the main crop is harvested until the onset of winter;

c) winter, when the green manure crop is sown before winter and uses the late autumn and early spring periods for its development.

Rapid climate dynamics towards warming significantly changes the conventional wisdom about the diversity of biological set and technological capabilities of some long-known crops. Previously well-known crops can show themselves under these conditions from previously unknown sides and demonstrate excellent productivity. It is advisable to test new crops that tolerate dry periods well, are undemanding to the soil, and are adapted to growing in deserts. These are plants from the legume family (woolly astragalus; naked, rough and Ural licorice; small, mouse and thin-leaved peas; tuberous and meadow chinu; Don and large sainfoin; large-flowered rue; false or common camel thorn), thin-leaved plants (Karelin reed, multi-stemmed and giant hairstalk, swollen sedge and colchicum) and many other crops. The main thing is that the land should not be empty, but covered with a green cover.

The roots of green manure loosen and structure the soil, improve its water and air regime. In this regard, cereal green manure plays a leading role. Cereal plants have a widely branched root system that divides the soil into small clods. This effect of green fertilizer is especially useful for heavy, compacted soils that are poorly penetrated by water and air. Therefore, in the crop rotation or crop rotation that should be used in the garden, it is very important to set aside a place for green manure so that the soil is exposed to the structuring and healing effects of green manure, approximately once every few years (Table 3.21).

Table 3.21

Features of different green manure and their soil requirements (Trofimenko, 2009)

Root system	**Plant species**	**Removal of slumping substances from the soil***	**Speed of develop-ment****	**Desired soil type from – to**	**Desired pH from – to**
1	2	3	4	5	6
Nitrogen fixers					
Deep, 150–200 cm	Lupine blue	+++	XX	Light to medium	Dougher acidic-neutral
	Lupine yellow	+++	X	Light	Acidic
	White lupine	+++	XX	Medium–heavy	Acidic–slightly alkaline
	Sweet clover	++	X	All kinds	Weakly acidic–alkaline
Medium, 80–150 cm	Fodder beans	+	X	Medium–heavy	Weakly acidic–alkaline
	Sowing vetch	++	X	Light–heavy	Weakly acidic–alkaline
	Sowing pea	+	X	Light–heavy	Weakly acidic–alkaline
	Seradella	+++	XX	Light	Very acidic–alkaline
Shallow, 0–80 cm	Mossy vetch	++	Wintering	All kinds	Very acidic–alkaline
	Field pea	++	X	All kinds	Very acidic–alkaline
	Incarnate clover	++	Wintering	All kinds	Very acidic–alkaline
	Hybrid clover	+	XX	All kinds	Very acidic–alkaline
Non-legumes					
Deep, 150–200 cm	Mustard	+	XXX	All kinds	Very acidic–alkaline
	Buck-wheat	+++	XXX	Poor	Acidic–neutral

(End of Table 3.21)

1	2	3	4	5	6
Medium, 80–150 cm	Rape	+	Wintering	Light–heavy	Acidic–neutral
	Melilot	+	Wintering	Light–heavy	Acidic–slightly alkaline
	Oilseed radish	+	XX	Light–heavy	Acidic–slightly alkaline
	Phacelia	++	XXX	Light–heavy	Acidic–alkaline

* Nutrient removal from the soil: + weak; ++ medium; +++ high.

** Development: slow X; fast XX; very fast XXX.

On light soils, the positive effect of green manure is to increase the water-holding capacity by enriching the soil with organic matter. On heavy soils, cereals and legumes with deep root systems, such as lupine, alfalfa, rye, barley, loosen deep layers of the soil, and this is important for facilitating water penetration into the soil and improving its water and air regime. Crops grown for green fertilizer do not produce any products in the year of cultivation, but improve soil health for 3–6 years.

It is necessary to keep in mind the sanitary gap between the predecessors of green manure plants and subsequent crops. For example, cabbage green manure should not be placed after other crops of this family, rapeseed, sugar beets and oil flax, which have common pests and diseases, as well as after sunflower. Legumes should not be included in crop rotations with peas and soybeans, perennial grasses with spiked and tilled crops (taking into account the effects of soil drying). However, grain-intensive crop rotations should be broken up with sweet clover or white mustard to combat root rot and improve biodiversity in the crop structure. Green manure is of great importance for the cultivation of newly developed areas. They help to restore the fertility of soils destroyed by construction and other works, where machines and people have completely destroyed or compacted the top layer. In addition, the roots of green manure plants secrete organic acids, which, interacting with soil minerals, convert phosphorus into a soluble state. Legumes and mustard are particularly active in this regard. In addition, some legumes and mustard absorb phosphorus from deep soil layers with their deeply penetrating roots. Phosphorus accumulates in the aboveground part of these plants and in their root system. After plant residues are embedded in the soil and decomposed, the topsoil is enriched with organic phosphorus compounds contained in them, which are transformed into a form accessible to plants by microorganisms. So the crop following this green fertilizer grows on soil enriched with available phosphorus.

The soil and climatic conditions in Ukraine allow a large number of crops to be sown with green manure (Table 3.22–3.23).

Table 3.22

Suitability of crops for green manure in intercrops (M. Shevchuk et al., 2012)

Crops	Requirements for growing conditions	Seeding rate, kg ha^{-1}	Reproduction rate	Green mass yield, c ha^{-1}	Suitability for green manure
Narrow-leaved lupine	U	200	5	240	XXX
Yellow lupine	U	200	4	200	X
Perennial lupine	R	60	10	200	XX
Meadow clover	D	20	10	140	X
Seradella	U	50	12	180	XX
White sweet clover	R	20	30	150	XX
Pea	D	300	6	120	X
Diaper peas	D	250	6	150	X
Winter rye	U	200	10	200	X
White mustard	D	20	50	100	XX
Winter rape	D	15	67	130	XX
Oilseed radish	D	25	50	250	XXX

Notes.

1. The degree of suitability of the crop for green manure. XXX – high, XX – medium, X – low. 2. Requirements of the crop to growing conditions: U – undemanding, R – relatively demanding, D – demanding.

At the same time, it is emphasized (Shuvar, 2014) that in the context of modern global climate change, which humanity has been experiencing in recent years, including in Ukraine, the task of protecting soil fertility, and with it, increasing the productivity and sustainability of agrophytocenoses, taking into account the soil and climatic characteristics of the zone, must be addressed in a comprehensive manner, within the framework of adaptive landscape energy and resource-saving farming systems, which, along with fertility restoration and soil erosion protection, ensure the preservation of agricultural landscapes and the environmental cleanliness of the human environment. The development and implementation of green manure farming systems is of great practical importance in modern agriculture in Ukraine. Being cheap, effective and widely available, green manure is an inexhaustible, constantly renewable source of organic matter in the soil.

It has been noted (Gospodarenko and Lysianskyi, 2018) that one of the main constraints to the widespread introduction of cover crops is the problem of soil moisture availability. The negative role of green fertilizers can be manifested by the fact that if intermediate crops use too much moisture, it may not be enough for the main crop, which negatively affects the yield of the latter. Therefore, it is recommended to use post-harvest green manure crops in regions with less than 600 mm of precipitation per year.

The most difficult conditions for green manure crops are when they are grown in the post-harvest period (July-August), which is characterized by the greatest moisture deficit in Ukraine. Its reserves in the 0–10 cm layer on the black soils of the Central Forest-Steppe are 3–8 mm. To prevent the complete evaporation of water from the soil intended for green manure, it is necessary to apply surface tillage, consisting of disking the soil by 5–6 cm, harrowing and rolling the surface with ring rollers, together with harvesting winter crops, and, as an exception, one day after harvesting.

Such cultivation, especially at night, destroys the capillaries between the upper cultivated and lower untreated layers with more moisture (from which water rises up through the capillaries). This stops its evaporation and helps to gradually moisturize the upper layer. Dew is especially important for young green manure plants in case of insufficient soil moisture, because it is the only thing that saves plants from dying in dry, hot weather, and falling from the plants, it improves the moisture content of the soil surface and the soil air.

Table 3.23

Characteristics of certain types of green manure plants (Shuvar, 2014)

Crops	Preferred soil type	Nitrogen storage	Vegetation period / sowing period
Blue alfalfa (*Medicago sativa*)	Except for acid and moisture	Yes	From one year
Hop alfalfa (*Medicago lupilina*)	Except for acidic	Yes	From 3 months
Horse beans (*Vicia faba*)	Heavy	Yes	Before the winter
Vetch, pea (*Vicia sativa*)	Except acidic and dry	Yes	2–3 months
Incarnate clover (*Trifolium incarnatum*)	Light	Yes	2–3 months, before winter
Meadow clover (*Trifolium pratense*)	Rich loams	Yes	3–18 months
Narrow-leaved lupine (*Lupinus angustifolius*)	Light acidic moist	Yes	2–4 months
White sweet clover (*Melilotus albus*)	Any, including poor	No	Before winter
Sandy sainfoin (*Onobrychis arenaria*)	Any, including poor	Yes	From the year
Horned loosestrife* (*Lotus corniculatus*)	All types	Yes	From the year
Seradella (*Ornythopus sativus*)	Any moist	Yes	2–4 months
Buckwheat (*Fagopyrum esculentum*)	Any, including poor	No	1–3 months
Tansy phacelia (*Phaceba tanacetjfoha*)	All types	No	1–3 months
Rye (*Secale cereale*)	All types	No	Before winter
White mustard (*Sinapis alba*)	Any, including poor	No	1–2 months
Oilseed radish (*Raphanus sativus*)	Heavy clay soils	No	2–3 months
Comfrey (*Symphytum*)	All types	No	From the year

The amount of water formed from dew overnight reaches 0.1–0.5 mm. And in a year, it falls up to 40 mm, which is the amount that corresponds to the monthly precipitation rate in the Central Forest-Steppe in April or

August-November. Dew is formed mostly on a flat but rough soil surface, which is the case with the technology of direct tillage for green manure. This technology helps to preserve the remaining water in the soil that was not used by the predecessor, promotes the accumulation of water in the surface layer of the soil due to its rise from the lower layers. This ensures that the plants germinate fully 3–4 days after sowing, and their dense grass stand is an environment for the formation of a large amount of dew, which saves the plants from death in the first days of the growing season. Even the smallest rains (3-5 mm), which are considered ineffective in agronomy, are very useful for post-harvest green manure. More abundant rains (up to 10 mm or more) moisten the soil first to a depth of 15 cm, and then to the full depth of the root layer. Such conditions, combined with warm weather in July-September, contribute to the intensive growth of green manure, prevent the reproduction of weeds and pests.

Research conducted at the Khmelnytsky State Agricultural Research Station made it possible to develop a way to reduce the impact of weather conditions on the productivity of crops in a five-field grain rotation by post-harvest sowing of white mustard for green fertilizer. In extremely dry periods of grain cultivation in this crop rotation, under the influence of green manure, the reserves of productive moisture in the upper layer (0–40 cm) of the soil were 15–25% higher.

Nitrogen in the green mass of plants plowed into the soil is contained mainly in the form of protein compounds. In the process of its mineralization, ammonification and nitrification occur first, and the nitrogen in green manure is converted into compounds available for plant nutrition.

The rate of decomposition of the earned sidereal mass depends on a number of conditions. The type and age of the siderate, the granulometric composition and soil moisture, and the depth of cultivation are important. The older the plant, the heavier the granulometric composition and the greater the depth of the fertilizer, the slower it decomposes.

It is indicated (Gospodarenko and Lysyanskyi, 2018) that in order to speed up decomposition and obtain nutrients in a form available to plants, the depth of siderate must be less. And vice versa, if the goal is to increase the content of humus in the soil, it is necessary to earn it more deeply, since the humification coefficient increases with slow decomposition. Deep plowing is especially important on soils of light granulometric composition. Slows down the decomposition of siderates of earning together with legumes relatively inert materials that decompose slowly (peat, straw). The same effect is obtained when mixing in sowing for sideration of leguminous and cereal crops. Adding manure or slurry, on the contrary, accelerates the decomposition of green manure.

In the first year of operation, the nitrogen utilization rate of green manure is usually higher than that of manure. In addition, leguminous siderates have a well-developed root system that penetrates deep into the soil, so they absorb nutrients from the lower layers of the soil, as well as phosphorus and other nutrients from poorly soluble compounds. In this regard, during the decomposition of the earned plant mass, the upper layer of the soil is enriched not only with organic substances and mobile nitrogen compounds, but also with phosphorus, potassium, calcium and other elements.

The phase of growth and development of plowed plants is of particular importance. Cultivation of side crops in the phase before flowering of legumes or earing of cereals activates microbiological processes in the soil, increases the yield of subsequent crops, but does not affect the quantity and quality of humus. This is explained by the fact that the tender green mass of siderate is poor in lignin, is quickly mineralized and is not fixed in humus compounds.

When the biomass yield of sideral culture is up to 150 t ha^{-1}, it is plowed into the soil, and when the yield is more than 150 t ha^{-1}, it is first rolled with rollers or crushed with disc harrows or mulchers, and only then plowed. Continuous action herbicides can also be used to stop the growth of siderates.

Additional grinding of plant biomass into green fertilizer increases the costs of their application, however, longitudinal grinding of siderable mass accelerates biochemical processes due to the increase in the surface area of these materials and the improvement of the contact of microorganisms with the substrate. In addition, crushed cider mass is more evenly moistened, supplied with oxygen, and therefore decomposes faster. It retains moisture well due to a violation of the capillary system and prevents heat loss through organic mass. As a result of the acceleration of the processes of destruction of organic substances due to grinding, their consumption for the vital activity of cellulose-destroying microorganisms increases.

Generalized long-term research by German scientists (Gospodarenko and Lysyanskyi, 2018) showed that in order to achieve a balance of humus in the soil without a deficit, depending on the crops grown in crop rotation, it is necessary to earn the following amount of green fertilizer: for the cultivation of grain crops – 38 t/ha of green mass, and row crops – 75–100 t ha^{-1}. In terms of the degree of influence on the yield of crops, siderates are close to litter manure at the rate of 20–30 t ha^{-1}, and the costs of their production and application are 2–4 times lower.

Each sideral culture has its own characteristics of use for fertilizer. Thus, it is advisable to chop the green mass of cabbage for winter grain crops, disk it and after 14 days to earn, leguminous crops – to chop and earn without prior exposure in the upper layer of the soil. These features are related to the chemical composition of sider crops and, first of all, the C:N ratio in the mass, which determines the rate of its mineralization and the availability of nutrients for fertilizing crops.

Positive from the point of view of the potential of green manure use of oilseed radish in comparison with other traditional crops is the depth of rooting of oil radish plants, which sometimes reaches the level of rooting of sunflower (AHDB Horticulture, 2020) (Figures 3.12–3.13).

Extensive research has systematized and classified a set of sideral crops according to the directions and terms of their possible application. This summary information according to a number of studies (Rosenfeld and Rayns, 2010, 2010a, b, 2012) is presented in Table 3.25.

For South America, the list of effective cover and green manure crops is as follows: black oats (Avena strigosa Schreb), rye (*Secale cereale* L.), triticale (Tritico-cereale), oilseed radish (*Raphanus sativus* var. *oleiferus* Metzg), white bitter lupins (*Lupinus albus* L.), blue bitter lupins (*Lupinus angus*tifolius L.) common vetch (*Vicia sativa* L.), hairy vetch (*Vicia villosa* Roth), forage peas (*Pisum sati*vum subspecies *arvense*), chick peas (*Lathyrus sativus* L.), serradela (*Ornitophus sativus* Brot.), sunflower (*Helinthus annuus* L.), rygrass (*Lollium multiflorum* L.) etc. The most commonly used summer cover crops are millets (*Penisetum americanum* L., *Sorghum bicolor* L etc), foxtail or German millet (*Setaria italica* L.), sunnhemp (*Crotalaria juncea* L.), lab-lab (*Dolichos lablab* L.), pigeon pea (*Cajanus cajan* L.).

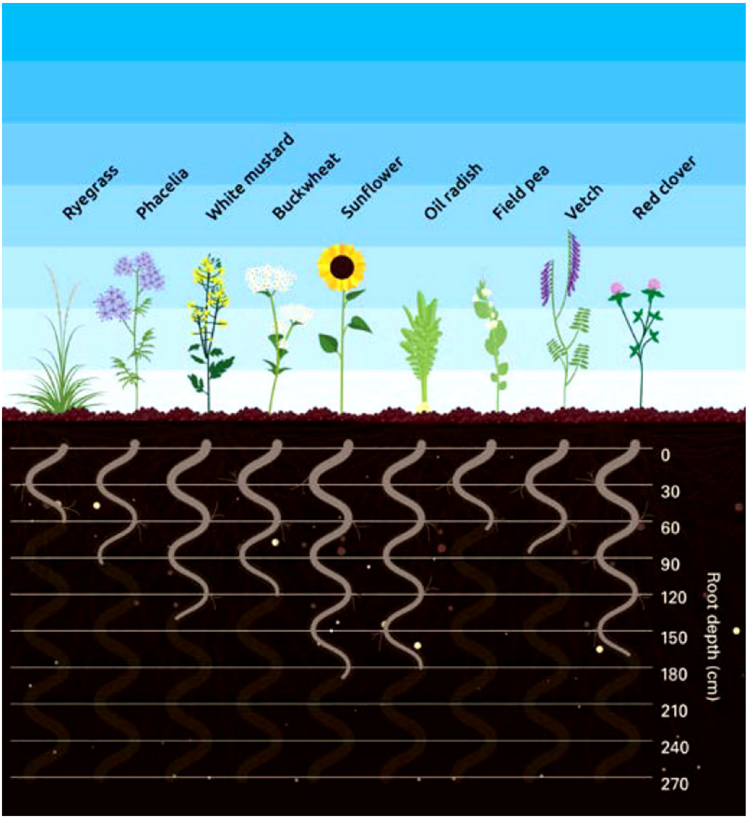

Figure 3.12 – Green manure species have different attributes, e.g. deep-rooted species can bring up nutrients, including trace elements, from the deep (AHDB Horticulture, 2020)

The following nomenclature and agrotechnological grouping is given for cruciferous plants of the Radish tribes in terms of their use in the green manure system (Radishes, 2021, 2022; Forage Radish, 2021; Forage Radishes, 2022):

Forage radishes (Raphanus sativus var. longipinnatus) are members of the Brassica family, which also includes arugula, mustard, and cabbage, to name just a few. Forage radishes are also known as Tillage radishes, Daikon radishes, and Japanese radishes. They are marketed under various cultivar names such as 'GroundHog', 'Nitro', 'Sodbuster', and 'Bio-till'.

Figure 3.13 – Process of root formation and rooting of oil radish plants

Oilseed radishes (*Raphanus sativus* var. *Oleiformis* Pers) are another type of radish grown as a cover crop. They are related to the forage radish but have a stubbier taproot, more branches, and tend to be somewhat more winter hardy than the forage radish. Oilseed radishes are marketed under cultivar names such as 'Adagio' and 'Colonel'. As the name implies, oilseed radishes were originally grown for oil. Often the names oilseed and forage ('Daikon') are used interchangeably, and that can be confusing because they are different. However, most of the traits and growing recommendations are the same for both types of radishes.

Forage radishes are excellent at breaking up compacted soils, and have earned the nickname "bio-drills." Planted in the early fall, 3 to 10 weeks before the first freeze, the roots of forage radishes can penetrate compacted soils more deeply than other cover crops such as cereal rye. Under ideal conditions, the thinner part of the taproot can grow to a depth of 6 feet or more during the fall! The thick fleshy part of the taproot can grow 12 to 20 inches (including 2 to 6 inches protruding above ground), creating vertical holes and zones of weakness that tend to break up surface soil compaction. After the plants die in the winter and the roots decompose, the open root channels can be used by the roots of your vegetable crops to grow through the compacted layers of soil. The channels created by the roots tend to remain open at the surface, improving water infiltration and soil warming in the spring. The channels also provide an access route for subsequent roots to reach subsoil moisture, resulting in greater plant resilience under drought conditions. The decomposed roots of the forage radishes improve the soil's porosity (air spaces) and the general physical soil condition (tilth).

Weed Suppression. A good stand of radishes – more than 5 plants per square foot – has been shown to eliminate nearly all winter annual weeds. Weed suppression from fall-planted radishes typically lasts into April but does not extend much further into the summer planting season.

Nutrient Scavenger. The deep root system, the rapid root growth, and the heavy feeding of forage radishes combine to make them an excellent scavenger of residual nitrogen after the summer growing season. Radishes take up nitrogen from both the topsoil and from deeper soil layers and then store the nitrogen in their shoots and in their root biomass. Because radishes do an excellent job of cleaning up nitrogen left over in the soil from summer crops, they help prevent nitrogen from leaching into groundwater during fall, winter, and spring.

Unlike cereal rye (annual winter rye), whose residues decompose slowly and continue to hang on to nitrogen for extended periods (thus immobilizing the nitrogen), radish roots decompose and release nitrogen rapidly. This means that early spring crops can get an early boost from the nitrogen captured by the radish crop.

In addition, forage radishes have also been shown to be excellent scavengers of potassium (K) and phosphorus (P) left over from the past growing season.

Effects on Nematodes. Research has provided evidence that the residues from radishes reduce the number of plant parasitic nematodes such as root knot nematodes.

Seeding. It is difficult for the home gardener to determine the ideal seeding rate, but several seed packets I reviewed suggested rates of ¾ lb. to 1 lb. per 1,000 square feet. Follow the seed company's recommendation listed on the seed packet and adjust the sow rate after a season or two of experience.

Table 3.25

Overview of the main green species and mixtures which have potential as short-term green manures in UK vegetable and salad production (Radishes, 2021, 2022; Forage Radish, 2021; Forage Radishes, 2022)

Species	Plant type	Annual/ perennial / biennial	Approximate ideal duration	N fixer	Speed of N release on cultivation	Good nutrient lifter	Best for soil structure improvement	Good for organic matter	Good for very short summer terms (<2 months)
Red clover	legume	perennial	1–4 years	√	fast	√	√	√	
Crimson clover	legume	annual	6–9 months	√	fast	√	√	√	
Persian clover	legume	annual	5–12 months	√	fast	√	√	√	√
Sweet clover	legume	biennial	6–18 months	√	fast	√	√		
Yellow trefoil	legume	annual	6–18 months	√	fast	√	√		
Vetch	legume	annual	6–10 months	√	fast				
Grazing rye	cereal	annual	6 months	X	slow	√		√	
Mustard	brass i ca	annual	2–4 months	X	slow			√	
Tillage (oilseed) radish	brassica	annual	3–6 months	X	slow	√	√	√	√
Buckwheat	polygo-naceae	annual	4–6 months	X	moderate				√
Phacelia	borage	annual	4-6 months	X	slow				
Chicory	composite	perennial	1–5 years	X	moderate		√	√	
Perennial ryegrass	grass	perennial	1–5 years	X	slow			√	
Cocksfoot	grass	perennial	2–5 years	X	slow			√	
Italian ryegrass	grass	perennial	1–2 years	X	slow			√	
Westerwolds	grass	annual	6–12 months	X	slow			√	
Red clover & ryegrass	mixture	perennial	1–3 years	√	slow			√	
Rye & vetch	mixture	perennial	6 months	√	slow	√			
Ryegrass & vetch	mixture	perennial	6 months	√	slow			√	
Mustard & mixed clovers	mixture	perennial	4–6 months	√	fast				
Oats, peas and vetch	mixture	annual	3–6 months	√	fast			√	
Yellow trefoil & white clover	mixture	perennial	6–18 months	√	fast				

The recommended depth for seed planting is ¼ to ½ inch, however, seed can be broadcast (remember my brother in-law's air plane method?) and left uncovered. The recommendation is to sow uncovered seeds about 50 per cent more thickly. So, if the recommendation is to sow 1 lb., sow about 1½ lbs. if the seeds will not be covered with soil.

Radishes germinate rapidly, emerging within 3-4 days when environmental conditions are favorable. Seed broadcasted on the soil's surface can establish well if followed by a timely rain. Forage radishes do not tolerate very wet soil, so low spots that collect standing water should be avoided. The radishes are tolerant of frost until temperatures dip below 25ºF. It takes several nights of temperatures in the low 20s to kill forage radishes.

Cautions. Deer will be attracted to your forage radish crop. Also, during warm spells in winter and in early spring, decomposing radishes may release a pungent rotten-egg odor.

Since forage radishes are in the Brassica family, it's best to avoid planting them in areas where you will be planting other Brassica members such as cabbage, cauliflower, broccoli, kale, kohlrabi, turnip, or mustard.

Another great tool in the cover-crop tool box, forage radishes can provide multiple benefits including: alleviation of soil compaction, weed suppression, nutrient capture (N, P &K), and erosion control. They can also be mixed with other cover crops such cereal rye to add more organic material to your soil.

An important aspect is the use of green manure crops in the system of modern approaches to surface tillage and various crop rotation systems in terms of the duration of their rotation.

Thus, in studies (Derpsch, 2020) it was noted that it is not possible to talk about green manure cover crops without talking about crop rotation. In a no-till system we can not talk about crop rotation without talking about cover crops. Maximum diversification of the system should always be a goal when applying no-tillage techniques. Mixtures of cover crops should be preferred over the use of a single species. Green manure cover crops are the cornerstone of sustainable agriculture and should always be included in sound crop rotations. Green manure's and cover crops are used as synonyms in this paper. In a no-till system cover crops are incorporated biologically and not by tillage implements.

Green manure cover crops should:

– be of low cost (seeds);

– be easy to seed and manage;

– provide good weed control and shading;

– produce a positive residual fertilizer effect on following cash crops;

– they should not compete in area, labor, time and space with cash crops.

Monoculture, that means the continuous seeding of the same crop, in the same place during many years has only been possible in the case of rice. This crop has been cultivated as the only crop sometimes for centuries in highly populated areas in Asia. In general monoculture results in diminishing productivity per unit area, the maintenance of low productivity's, or in extreme cases the complete loss of production. In general the following factors are responsible for this situation (Derpsch, 2020):

– Increase of specific diseases and pests.

– Increase of specific weeds.

– Reduced availability of nutrients due to changes in biological activity and physical degradation of the soil.

– Reduced root development.

Accumulation of specific toxic substances that inhibit growth. The principles and fundamentals of crop rotation are:

– To alternate plant species;

– with different rooting depth;

– with different ability to absorb nutrients that are susceptible to diseases with those that are resistant;

– taking into account positive & negative effects of one crop on the next;

– that tend to mine with those that tend to increase soil fertility;

– with different needs in terms of labor peaks, machines & implements, water, etc. (Derpsch, 2020).

In a no-till system the use of crop rotation is much more important than in conventional tillage systems. Experience has shown, that tillage negates cover crops. Also cover crops are essential for producing the mulch needed in the no-tillage system. Cover crops have to be integrated in the agricultural system of each farm and show their beneficial effects.

The main functions of green manure and cover crops are as follows:

Provide soil cover for:
– no -tillage;
– increasing water infiltration into the soil;
– reducing water evaporation;
– reducing soil temperature;
– protection against erosion reducing weed infestation;
– accumulation of organic matter in the soil;
– adding and recycling nutrients;
– improve soil structure;
– promotion of biological soil preparation.

Adding of organic matter in the soil is often mentioned in the literature as one of the main objectives of cover crops, but this can in general and (especially in warmer climates) only be achieved in the no-tillage system.

Benefits of Green Manure Cover Crops

Cover crops are a key element to make sustainable agriculture possible and have shown the following benefits in Latin America:
– Higher economic returns when appropriately chosen.
– Reduce the need for herbicides and pesticides.
– Improve yields of following cash crops.
– Conserve soil moisture (when properly managed).
– Prevent soil erosion.
– Enhance organic matter content of the soil.
– Provide nitrogen.
– Avoid leaching of nutrients and improve soil fertility.
– Reduce fertilizer costs.

Possibilities of Reducing Weeds and Herbicides Costs with the Use of Cover Crops in No-Tillage:

One of the most recent and fruitful lessons we have learned n the no-tillage system is that farmers should, if possible, never leave the land in fallow. In general fallow periods of only a few weeks will result in weed proliferation, seeding of weeds, reduction of soil cover, soil erosion as well as lixiviation (le aching) of nutrients. The old farmers rule is still true, «one years seeding means seven years weeding». If instead of leaving the land in fallow, farmers seed any crop immediately or as soon as possible after harvest of the previous crop, they will reduce weed proliferation, avoid that weeds produce viable seeds, increase soil cover and the biomass returned to the soil, increase organic matter content of the soil, avoid soil erosion as well as washing out of nutrients, and improve biological conditions of the soil.

Generalizations were also made regarding the use of oil radish in the system of multifunctional use as a universal cover crop. In particular, Chammoun (2009) noted that oilseed radish (Raphanus sativus) is a cover crop that has been used in sugar beet production to aid in soil pest control. (Hafez, 1998) Nematodes are plant pathogens that live in the soil and cause yield losses on a wide range of crops. In a study done by Saad Hafez of The University of Idaho's Cooperative Extension, an average level of 92% in nematode population reduction was observed when oilseed radish was used in rotation with sugar beets. (Hafez, 1998) Assuming oilseed radish could yield similar results on nematode populations in Georgia when used as a cover crop, a reduction of input costs could be achieved when economic crops were grown in the warm season. Six pounds of aldicarb per acre is the recommended rate of insecticide to apply on Georgia cotton when nematode populations are problem in the field. (Baird et al., 1995) Oilseed radish appears to have the potential to save this application of pesticide when used in a rotation with cotton in Georgia. Oilseed radish has also been observed providing additional benefits of soil compaction reduction, soil aeration, weed suppression, and nitrogen trapping. (Ngouajio and Mutch, 2004, Sundermeier, 2008) A reduction in soil nitrogen leaching during the cool season has also been observed. (Justes et al., 1999) With these benefits in mind, oilseed radish is commonly referred to as a green manure crop (Hafez et al., 1998).

In the study of Chammoun (2009) noted that the seed of the oilseed radish contains 40% oil by weight. (Eckey, 1954). A high oil value makes this crop a good candidate for biodiesel production also. Assuming a cover crop of oilseed radish could be grown and harvested as seed, leaving other crop residues in the field, could allow for added value in growing the crop in Georgia. In order to provide and estimate of the value of the co-products of oilseed radish we obtained assessments through personal communications from collaborators for three cases, cover crop, meal, and biodiesel. In the first case, viability as a Georgia cover crop was estimated by planting five plots totaling one acre were planted at the USDA National Peanut Research Laboratory in Dawson, GA in late September 2008 after peanut harvest.

Excellent germination was achieved and the crop has grown well with minimal inputs. Harvest is planned for May 2009 and yield data will be recorded (personal communication with Wilson Faircloth).

In the second case, value of the meal was estimated by crushing 200 pounds of seed, and the meal analyzed for its potential as poultry feed in Georgia. A feeding trial was done by Dr. Michael Azain of the University of Georgia's Department of Animal and Dairy Science (personal communication with Dr. Michael Azain). Results from the study confirm that oilseed radish has the potential to be used as a partial replacement in poultry feed in Georgia's poultry industry. More detailed and replicated studies will be needed to establish proper diets and levels of oilseed radish meal. Assuming the results from Dr. Azain's study will be replicated, a potential value for oilseed radish meal can be calculated based on the composition of the meal. To aid in the characterization of the meal, the following tests were reported: the fatty acid profile of oilseed radish meal, the plant tissue analysis, the proximate analysis, and the amino acid profile of oilseed radish meal (Table 3.26–3.27). The fatty acid profile provides a detailed description of the different carbon molecules that comprise the meal and oil. It is important to note the high level of erucic acid (22:1) similar to rapeseed. Also the fat content in the meal is typically higher than soybean meal (fat content of 1%) because this meal was extracted with only a screw type press, and not using solvents which would be typical in industrial uses. The proximate were found to vary from soybean meal. For comparison, soybean has 48¬49% crude protein, 3.9% crude fiber, and 1% fat. (Chammoun, 2009).

Previously made conclusions about oil radish are also confirmed by Frank (2015) who noted (with reference to other authors in the author's statement) that the practice of using cover crops in corn-soybean rotations is relatively new and becoming of great interest to many producers in the Corn Belt region of the United States. However, the concept of using plants to cover soil and recycle nutrients has been practiced historically by many. Farmers essentially replicated most natural ecosystems, realizing that having plants actively growing, covering the soil, transpiring water, taking up nutrients, fixing carbon, and supporting soil fauna benefited the environment (Kaspar and Singer, 2011). As a first priority, cover crops were traditionally used by farmers to cover bare soil and reduce erosion. Many cover crop species were also used for grazing livestock to save costs on additional feed sources, suppress pests, and provide nitrogen to a succeeding crop. Even with many traditional farmers using cover crops, farmers may not have completely understood the benefits and effectiveness of cover crops.

Table 3.26

Fatty Acid Profile of Oilseed Radish Meal (Chammoun, 2009)

Fatty Acid (n=3)	Percent (%)
16:0	6.13
16:1	0.05
18:0	1.68
18:1	23.87
18:2	13.46
18:3	10.34
20:0	0.68
20:1	8.58
22:0	1.64
22:1	31.76
24:0	0.61
24:1	1.26
Saturated	10.74
Monounsaturated	65.51
Polyunsaturated	23.75
Fat Content in Meal	18.48

Current research is now starting to show the true successes and efficiency of cover cropping, and therefore creating an interest amongst producers, conservation tillage, including no-tillage systems (Blevins et al., 1983). Researchers and producers have recognized that conservation tillage systems increase residues on the soil surface and reduce mechanical manipulation and mixing of soil (Blevins et al., 1983). Cover crops can be an effective means of increasing surface residues, and are often implemented when using conservation tillage practices. This is especially true in the Corn Belt, where cover crops are grown in the fallow period after cash crop harvest which lasts six to eight months out of a year (Kaspar and Singer, 2011). Based on their function within a given system, cover crops are also classified as «green manures,» «catch crops,» or «living mulch» (Kaspar and Singer, 2011). Magdoff and Van Es (2009) define each of these terms individually and further describe how the term «cover crop» is most widely used because farmers usually have multiple goals when planting these crops and many species fit into more than one of the classifications.

Table 3.27

Plant Tissue Analysis of Oilseed Radish Meal (Chammoun, 2009)

Element	Average Value (n=5)
Ca	0.33%
K	1.31%
Mg	0.46%
N	5.41%
P	1.27%
S	2.35%
Al	24.32 ppm
B	8.8 ppm
Cd	< 0.4 ppm
Cr	< 1 ppm
Cu	5.72 ppm
Fe	75.65 ppm
Mn	28.28 ppm
Mo	1.72 ppm
Na	44.28 ppm
Ni	< 2 ppm
Pb	< 5 ppm
Zn	44.52 ppm
Moisture	7.35 %
Crude Protein	35.04 %
Fat	17.97 %
Crude Fiber	5.42 %
Ash	6.28 %

Despite recent movements to protect their valuable water and soil resources, cover crops have had limited adoption in the Midwestern U.S. Singer (2008) reported that only 11% of Corn Belt farmers planted cover crops between 2001 and 2005, and therefore he concluded that farmer surveys were needed to understand how cover crops fit into farmer expectations and farming systems. Singer et. al. (2007) found that 18% of Corn Belt farmers have used or tried cover crops on their farms, primarily for reducing soil erosion and increasing soil organic matter. The authors determined that most farmers in the Corn Belt are aware of cover crop benefits, but educational programs focused on cost, selection and management need to be initiated to fill information gaps between the researcher and producer. Arbuckle et. al. (2014) took a distinctive approach when surveying farmers based on their belief that climate change is or is not occurring. Results indicated that 63% of farmers tend to believe that climate change is occurring and would likely respond by using adaptation and mitigation strategies against extreme weather events. Ultimately, cover crops could be used as one adaptation and mitigation strategy in conservation farming practices; however, effective communication between researchers and producers regarding cover crops needs further improvement.

Frank (2015) also noted that many state and governmental agencies have more recently developed subsidy programs for timely planting and management of cover crops. Weil and Kremen (2007) stated that despite the state of Maryland having paid subsidy programs, cover crop adoption has been low, with only 20–25% of cropland hectares being planted to cover crops. Weil and Kremen (2007) also suggest most farmers are either unaware of direct benefits offered by cover crops or simply cannot afford the cost and trouble of cover crop implementation, even though most desire to improve the environment and cropland. Through extensive research and collaboration, Weil and Kremen (2007) hypothesized that when farmers are able to see multiple benefits of specific cover crops, farmers will realize that cover crops are a profitable farming practice worth integrating into their production systems. For example, when using a five-state Corn Belt regional assessment model, Kladivko et. al. (2014a) found that if producers with acreage using corn-soybean rotational systems incorporated a cereal rye cover crop where suitable, the region as a whole could reduce nitrate leaching loss to the Mississippi River by approximately 20%. Ultimately, a main goal of most cover crop research today is to create a larger awareness of cover crops and the multiple benefits that can be generated through adaptation of cover cropping practices.

Recently, there has been much concern about cash crop growth under extreme weather events such as drought, large rainfall events, fewer rainfall events, floods, and severe heat stress. Variable climate presents uncertainty and challenges to managing soil and water resources in agricultural regions (Morton, 2014). Highly productive and intensely managed cropping systems such as corn and soybean in the Midwestern U.S. «often represent low diversity of land use and have a history of unintended consequences on soil and water quality» (Morton, 2014). As global issues such as increasing soil erosion, off-farm nutrient losses, and pollution of limited water supplies occur, on-farm adaptation strategies must occur to successfully address these issues (Morton, 2014). Cover crops could serve as a promising adaptation and mitigation strategy when it comes to increased climate variability. Using the upper Mississippi River Basin as a model, researchers found that implementing a rye cover crop reduced impact of N pollution, reduced erosion potential and nutrient losses, and would continue to be more effective if grown every winter fallow period as compared to production systems with tillage and no cover crop present (Panagopoulos et. al., 2014). Additionally, researchers concluded that the use of cover crops as a mitigation strategy would positively affect environmental and economic sustainability during future decades of adverse climatic conditions (Panagopoulos et. al., 2014). Therefore, implementing cover crops in the Midwestern Corn Belt region could potentially serve as a sustainability approach both economically and environmentally during periods of climatic variability and uncertainty.

More recently, along with a sparked interest in cover crops, many farmers in the Midwest have needed to address the issue of protecting and conserving our soil resources. As a result, many producers are shifting from conventional tillage.

Benefits of cover crops As mentioned previously, cover crops provide multiple potential benefits to soil and subsequent cash crops, while also improving the environment. Actual benefits of a cover crop depend on the species and productivity of the crop (Magdoff and Van Es, 2009) as well as its management, such as timing of planting and termination. Additionally, benefits from cover crops may require several growing seasons before benefits are noticeable (Kaspar and Singer, 2011). Therefore, it is important to research and quantify the benefits of cover crops to gain further insight on when and how benefits may occur.

Perhaps the greatest benefit of introducing a cover crop into rotations with a fallow period is implementation of a beneficial soil management practice (Kaspar and Singer, 2011). Cover crops enhance nutrient cycling through scavenging in fall and release in spring, protect topsoil from erosion and runoff, support soil microorganisms, increase organic matter, and suppress cash crop pests. Even though yield benefits may not be detectable right away, improvement of land, soil and water resources are possible as well as cash crop growth and yield improvements.

A fall brassica species such as oilseed radish (OSR) *(Raphanus sativus* L.) grow faster in the fall and accumulate more N in its large, fleshy taproot as compared to oats. Due to its deep-penetrating taproot, OSR can scavenge N from deeper soil layers that is quickly transported beyond the rooting zone of most plants, further aiding in decreasing N leaching losses and increasing N conservation (Dean and Weil, 2009). In addition, OSR is excellent at creating soil macropores and penetrating through compacted layers because of its large taproot (Horton, 2013). In addition to the large taproot, OSR can accumulate large amounts of leafy aboveground biomass which contributes to accumulation of soil N. The amount of N scavenged by OSR depends largely on amount of biomass growth, timing of fall establishment, residual N in the soil profile, and optimum environmental conditions for fall growth (Horton, 2013).

In Maryland, forage radish and OSR were more efficient than rape and rye cover crops at scavenging N during fall growth and further depleting the soil profile of NO3-N and contributing to soil N conservation in the fall (Dean and Weil, 2009). However, the researchers concluded that OSR may have been releasing NO_3-N too early for the succeeding corn crop based on large amounts of available spring soil NO3-N concentrations. Justes et. al. (1999) found less spring nitrate concentrations in drained water from fields grown with an OSR cover crop as compared to no cover crop; 45 and 91 mg NO_3- L^{-1}, respectively. When monitoring fodder radish, winter rye, and ryegrass ^{15}N uptake after a growing season of bare soil, only 18 kg N ha^{-1} was left under radish treatments, as compared to 59 and 87 kg N ha^{-1} under winter rye and ryegrass treatments, respectively (Kristensen and Thorup-Kristensen 2004). In addition to N cycling, OSR can also aid in providing surface soil P availability in the spring in the vicinity of radish root holes left behind after decomposition of residues (White and Weil 2011). The OSR may be able to survive several frosts before complete winter-kill occurs, more so than forage radish, making OSR a popular cover crop choice for simple management and great N scavenging capabilities (Clark 2007).

According to the results of research by Frank (2015), the following aspects of the efficiency of using oil radish as a covered and green manure crop were established:

– Results indicate that OSR bicultures have potential for rapid fall growth and N scavenging. There was reduced potential for fall N losses in all OSR treatments at DTC as compared to the no cover crop control treatment. Therefore, OSR-based cover crops have great potential to reduce soil-N losses (approximately 10 kg N ha^{-1}) in the fall by scavenging N and storing N in aboveground biomass tissues and can serve as a valuable conservation tool in Midwestern cropping systems to reduce N leaching and runoff losses.

– Rigorous soil sampling in the spring (March-June) allowed for multiple snapshots of soil-N concentrations throughout the period of cover crop residue decomposition and corn establishment. When OSR and oat residues started to decompose in early spring, N was released back into the soil profile and was highest in the uppermost layer of the soil profile (0–15 cm) throughout the duration of this study. In general, soil NO_3-N concentrations increased with time in the spring, and soil NH_4-N concentrations increased with time in early spring, and then decreased with time in late spring. Spring soil-N concentrations tended to be highest at position B (2.5 cm away from cover crop row) as compared to position C (7.6 cm away from cover crop drilled row). Due to cover crop decomposing in the spring, NH_4-N and NO_3-N concentrations were highest closest to decomposing surface residues.

– The OSR/rye treatment greatly reduced soil-N concentrations in spring and results suggested fairly little N leaching in this treatment due to rye actively growing in the beginning of spring during the first two sampling times and residues not decomposing until later in the season as compared to OSR and oat residues decomposing earlier. Therefore, it is important to realize N will most likely not be readily available at corn establishment from cereal rye. Rye needs to be terminated approximately two weeks before corn planting to initiate residue decomposition and to avoid a prolonged period of N tie-up in residues. These results show that OSR bicultures can have large impacts on soil N concentrations during the spring, with

OSR/oat providing additional N and OSR/rye providing less N as compared to the OSR alone treatment, in general. Cover crop treatment did not have an effect on soil PSNT concentrations in June of 2014.

– All OSR treatments most likely reduced the amount of N leaching during the fallow period as compared to the no cover crop control treatment. Without a cover crop, a considerable amount of N could have been lost in the off-season, prior to corn establishment in spring. However, decomposing cover crop residues did start releasing large amounts of N early in the spring, indicating the importance of timely corn planting in order to benefit from N released in spring following a winter-killed cover crop.

– Corn still received the recommended fertilizer rates following the OSR cover crop treatments as to not hinder corn growth and achieve reasonable yields. In order to fully understand N contributions from OSR cover crop systems, it would be optimal to perform an N-15 study to monitor N scavenged and released from cover crop residues and utilization of that N in corn plants starting at establishment in spring.

This experiment demonstrates that cover crops can be an effective way to protect the soil and scavenge excess nutrients during the fallow period, even with smaller amounts of growth and variability in fall temperatures. Sampling OSR root tissues to determine N content in those tissues would have had a positive impact on this research. Horton (2013) was able to sample OSR taproots and oat and rye fibrous roots and concluded that a significant amount of N was scavenged and stored in the belowground tissues. Further research is necessary to determine exactly when OSR and OSR biculture cover crop residues have peaks in N release throughout the spring. As mentioned previously, N-15 may be one valuable technique to monitor N cycling in cover crop systems. In addition, soil sampling should extend through the entire spring season and begin as early as possible in the spring. Soil sampling throughout the entire corn growing season would also help determine soil-N patterns. This study, as well as a study by Horton (2013) were one year studies. Therefore, multi-year studies would be beneficial to determine effectiveness of OSR and OSR bicultures at reducing N leaching and increasing inorganic-N concentrations during the spring for use of the following cash crop.

Similar conclusions, especially regarding the positive impact of oil radish on nitrogen biorecycling, were made in the study of Lövgren (2022), where it was noted potential in decreasing N_2O emissions from OSR, but the results need to be confirmed through further studies. More broadly, research is also needed to determine the economic and practical feasability. The results for treatments 2 and 4 were not as expected, but raised questions and impulses for further research, eg. the question of whether the cutting of biomass made more intense, thereby increasing N_2O emissions.

There are many processes that produce N_2O in soils, but the main N_2O producing process during winter in temperate climates can often be assumed to be denitrification. There are three main parameters that need to coincide for denitrification to occur, that is 1. Microbially available NO^{3-} 2. Microbially available C, and 3. Oxygen limited conditions. Cover crops contain both NO^{3-} and C, so when frost sensitive cover crops are left in the field over winter, and therefore die and wither during frost, they release NO^{3-} and C, which becomes available for microbes to decompose. This in itself doesn't create nitrous oxide, but, if conditions are also oxygen limited, which it often is during winter when the soils and plants freeze and thaw, repeatedly, conditions become favourable for denitrification, and nitrous oxide production. One of these frost sensitive species is oilseed radish (*Raphanus sativus* var. *oleiformis*) (OSR). It has been seen to emit high levels of N_2O winter emissions, emissions that are in many cases higher than those from other cover crop species. At the same time, it is a species with several valuble characteristics as a cover crop. Therefore, further research is needed on how the high N_2O emissions from OSR could be mitigated (Lövgren, 2022).

The aim of this thesis was to identify management methods for decreasing N_2O emissions from the frost sensitive cover crop OSR. This was done by performing a field trial with four different treatments of OSR, including control. If the crop biomass is removed before the first frost, a large part of the C and N needed for the denitrification is not present when the soil starts to freeze and thaw, which should decrease N_2O emissions. Therefore, two treatments of OSR were 1. Harvest by cutting the plant material at a height of 2–3 cm, which meant that root and stubble were left in the soil, and 2. Harvest by pulling the plants up with the roots, removing both aboveground biomass and coarse roots. If soil denitrification is nitrogen limited, adding a C rich material, with a high level of C in relation to N, could decrease the N_2O emissions. This is due to the fact that when microbes decompose C rich materials they scavenge the surrounding soil for N, which limits substrate availability for nitrification and denitrification (Lövgren, 2022).

The field experiment was performed at the SITES Lonnstorp research station. 13 gas measurements were carried out about once a week between the 20 December and 3 March in field plots of OSR. Finally, the samples from the gas measurements were analysed on a gas chromatograph, so that gas fluxes could be calculated from the change in N2O concentration over time. 774.3 g ha^{-1} was the highest cumlative emission and it came from untreated OSR. Emissions from the uprooted plots were significantly lower than all other plots. During the first half of the study period, emissions from uprooted and cut were significantly smaller than those from the immobilisation treatment and untreated oilseed radish. These were expected results, indicating that N_2O emissions in period 1 were mainly related to the decomposition of organic material. During the second half of the study period, there were no significant differences between any of the treatments. It was surprising that the immobilisation and untreated did not emit higher levels of N_2O since no biomass had been removed from these treatments. One possible explanation for this is that the biomass that was left in the immobilisation and control plots could have had an insulating effect, while the removal of biomass in the cut treatment led to more intense freezing and thawing, and therefore larger N_2O emissions from the small amount of biomass left. Since uprooted was the only treatment that was significantly lower than the other treatments over the whole study period, removing all of the OSR biomass seems to be a better solution than the cutting of aboveground biomass (Lövgren, 2022).

The immobilisation did not significantly lower nitrous oxide emissions compared to control. This could be a result of that wood chips were not incorporated into the soil, that not enough material was added or that the particles were too large. Another possible explanation is that the N_2O emissions might not even be of soil origin. High emissions peaks from immobilisation and untreated OSR were registred already in the beginning of the study period; a time when the plants were still pretty upright standing and no considerable amount of withered biomass was present at the soil surface. This could imply that emissions have possibly originated from the aerial parts of the plant (Lövgren, 2022).

3.3. The effectiveness of the use of oilseed radish green manure in different variants of the technology of growing agricultural crops

Modern trends in the development of adaptive technologies for growing the main agricultural crops are based on a number of basic directions that take into account both the features of innovative changes and the technological renewal of mechanization, and the main trends in the development of agricultural production aimed at ensuring the environmental friendliness of the products obtained, soil conservation while ensuring the appropriate levels of economic and energy efficiency. One of the ways to ensure sufficient levels of environmental friendliness of final products for the cultivation of any crop is an appropriate system of using agrochemicals of various nature – pesticides, mineral fertilizers, growth-stimulating substances, etc. The use of the specified components in agrotechnologies of different levels and their ratio determines the actual level of biologicalization of the technology of growing a certain agricultural crop. There are, to some extent, two main approaches to assessing the level of biologization of the technology precisely according to the criterion of the fertilization system. One of them is based on the use of the fertilizer greening index, which is defined as the ratio of the amount of applied mineral fertilizers in the active substance per 1 ton of applied organic fertilizers. The other is defined as the ratio of the share of dosed fertilizer for the corresponding nutrient element, which is absorbed from mineral fertilizers to the total share of dosed fertilizer, absorbed from the full set of application forms of all mineral and organic fertilizers. At the same time, it is emphasized that the most expedient option of fertilizer for the majority of rural areas.crops should have a combined, namely, organo-mineral fertilizer character as the closest to the natural processes of plant nutrition and aimed at ensuring the conditions of ecologically oriented (organic) agro-technological production. Unfortunately, it should be stated that the modern realities of providing classical organo-mineral fertilizer are problematic, since they provide for the presence of a correspondingly sufficient amount of classic organic fertilizers and, in particular, semi-rotted manure. However, the degree of provision of this type of organic fertilizer for most regions of Ukraine is included in the rate of application at the level of 0.27-0.52 t/ha, which is significantly lower than the determined agrochemical rate of organic fertilizers in the system of regenerative agriculture at the level of 8-12 t/ha of arable land.

These aspects lead to an intensive search for effective alternative substitutes for classic organic fertilizers. Among these substitutes in agricultural practice, a permanent niche is occupied by sidereal crops. Sideration is considered as the most potentially capable means to ensure the necessary share of introduced organic matter in the general fertilization system and ensures the appropriate level of biologization of this fertilizer. Among the many plants that are traditionally used as siderates in the conditions of the research region, mainly white mustard, lupine, and annual mixtures are used. Oily radish should be added to this list, which, according to recent studies, demonstrates the multi-purpose nature of its own use and is a potential alternative to other sidereal crops for the use of sideral-mineral fertilization systems of agricultural crops.These conclusions are confirmed by a system of numerous studies on the use of oil radish as a siderate, emphasizing its significance and agrotechnological value summarized by the author of this monograph (Tsitsyura and Tsitsyura, 2015) (Table 3.28).

Table 3.28

Characteristics of oil radish as a green manure crop in case of systematic use during crop rotation (according to the summary data of literature sources for 1960–2014 (generalized by Tsytsyura and Tsytsyura, 2015)

Indicators	Significance
1	2
Options for green manure	All are possible: main, post-cutting, post-harvest, intermediate, winter stubble, etc.
Competitiveness	Very high, in combined crops it occupies mainly the middle and upper tiers, especially with an increase in the individual feeding area
Accumulation of plant biomass, t ha^{-1}	25–50
Reaction to additional mineral fertilizer	Positive in a wide range, especially for nitrogen forms of fertilizers: increase from 20 to 180%, depending on the fertilizer dose
Decomposition rate of green manure biomass	Intensive for aboveground leaf mass and slow for root residues
Intensive for aboveground leaf mass and slow for root residues	0.35–0.70

(End of Table 3.28)

1	2
Acidity reduction by pH value, units.	0.1–0.3
Volume of carbon dioxide emissions from soil, %.	Increase by 18–60 %
Soil structure coefficient	Increase by 1.15-1.23 times
Topsoil density, g cm^{-3}	Reduced by 12–28%.
Total soil porosity, %	Increase by 10–30 %.
Capillary porosity of the soil, %	Decrease by 8–20 %
Number of water-resistant soil aggregates, %	Increases by 3–14% over a 3–5 year cycle of use
Availability of hardly soluble salts and hardly digestible salts of soil minerals	Increases by at least 10–15% over a three-year cycle of use
Microbiological activity of the soil	Increase by 1.25–1.60 times, positive mobilization of organic matter increases, decomposition of straw and other post-harvest residues is accelerated
Soil heat balance, ^0C	General optimization with reduced amplitude (night – day)
Reduction in the number of soil nematodes, cysts m^{-3} of soil	Overall reduction by 1.3–2.0 times
Reducing the total weed infestation of the field, pcs. m^{-2}	Overall reduction from 30 to 95%.
Reduction in the number of wheatgrass, pcs. m^{-2}	Overall reduction from 40 to 78%
Type of field weediness	Changes towards the predominance of weeds of the late spring annual group
Accumulation of amino acids and active biological chemicals in soils	Increased content of sulfur-containing amino acids, increased concentration of brassinoteroids, inhibitors, antioxidants, a number of allopathic substances, etc.
Soil redox potential balance	Normalization towards a slightly acidic – neutral reaction
The rate of onset of physical maturity of the soil	Acceleration by 1 to 3 days depending on soil type
Macronutrient balance, kg ha^{-1}	Increase in balance sheet positivity by 15–40%
Nitrate accumulation in the soil, mg kg^{-1}	Reduction by 35–70% with regular green manure in crop rotation

(End of Table 3.28)

1	2
Nitrate accumulation in groundwater, mg l^{-1}	Reduction by 10 times with regular green manure in crop rotation
Accumulation of radioactive isotopes (Cesium-137) during greening of radioactively contaminated areas	A reduced isotope transfer coefficient from the soil is characteristic even on sandy and sandy loam soils
Increase in yields of spring and winter cereals, c ha^{-1}	Overall increase in the range of 15–60%.
Increase in sugar beet yield, c ha^{-1}	Overall increase in the range of 8–25%.
Increase in potato yield, c ha^{-1}	Overall increase in the range of 20–45 %
Increase in hop yields, c ha^{-1}	Overall increase in the range of 20–35 %
Phytopathological situation of the field	General improvement with a decrease of 1 – 3 points in the overall phytopathological assessment)
Costs of green manure	Relatively low in comparison with other green manure crops
The optimal soil and climate zone for green manure	Zones of sufficient and unstable moisture are optimal, with early or late autumn sowing dates, as well as southern and even arid zones. Ground cover – the widest range of options
The cost price as green manure	Lower than other crops from the cruciferous family by 22–35%.
Availability of soil moisture for the decomposition of green manure	Mandatory requirement of at least 55–70% field moisture content

The analyzed bibliography notes that oil radish is particularly effective as a green manure on poor and heavy soils: it improves the physical properties of the soil, reduces the risk of disease (reduces the number of soil pests and pathogens, such as root rot pathogens and nematodes, by 1.5–2 times), increases the yield of subsequent crops, and improves the overall health of the soil.

The intensity of decomposition of oil radish green manure has its own characteristics. Its plant mass mostly consists of leaves, which have a higher nitrogen content and a narrower carbon-to-nitrogen ratio, so that the aboveground mass decomposes faster in the soil and is the first priority soil nutrition for the next crop, while the roots, on the contrary, are thickened and decay last, rhythmically and gradually providing the soil and plant with nutrients. In addition, the green mass, when incorporated into the soil, deoxidizes it, acting similarly to lime, as it has an alkaline reaction of cell sap (Figure 3.14).

Sometimes oil radish plants are called "biological plows" because they have a powerful taproot system that penetrates deep into the subsoil (Figures 3.14–3.16). This is very important in the current trends of zero and minimal tillage. Due to its root secretions, it promotes the absorption of hard-to-reach phosphorus, potassium, calcium, and sulfur compounds from the soil-absorbing complex, which are utilized by the next crop in the crop rotation. The diameter of its root collar is 2–2.5 cm (about 1 cm for mustard), which allows it to penetrate much deeper than mustard roots, even on soils with heavy mechanical composition. The degree of drainage of the soil by radish plants increases, excess moisture goes to the lower horizons of the soil, and therefore in spring it reaches physical ripeness faster, which facilitates sowing at the optimal time. Radish performs especially well in a mixture with legumes that can fix atmospheric nitrogen, so in a mixture with spring vetch, this grass mixture accumulates up to 200 kilograms of biological nitrogen per 1 hectare.

Accounting for the amount of plant residues and the yield of aboveground mass of oil radish showed that their share in fertilized variants in spring crops is 30.4%, in post-mowing – 41.1%, and in post-harvest – 47.6% of the total biomass. The highest coefficient of root system productivity in oil radish is observed in spring crops 4.4–4.6. In post-mowing and post-harvest crops, it decreased significantly and amounted to 2.6–3.0 and 1.8–2.0, respectively (Moiseev and Mishurov, 1976). The coefficient of productivity of oil radish roots in spring crops can reach a value of 5.66, and in summer 1.3–1.9. It is also important that oil radish roots are a valuable component of biological fertilizer due to their chemical composition. In post-harvest oil radish crops, the ratio of plant residues to yield was 1.31–1.81:1.0 (Table 3.29). Due to this ratio, oil radish is an effective component of the positive biological cycle of nutrients during the rotation period of crop rotation) (Tables 3.30–3.31).

Thus, the amount of organic matter that enters the soil with root and post-harvest residues of oil radish depends on the timing of sowing, seeding rates, doses of mineral fertilizers and meteorological conditions. The largest amount of root plant residues is formed in intermediate crops of oilseed radish.

Table 3.29

Biomass accumulation (dry matter) by a number of intercrops, t ha^{-1} (average for an 8-year rotation) (Nikonchik and Vostrova, 1980)

Crops	All biomass	Biomass harvested from the field	Plant residues			Ratio of post-harvest residues to crop
			stubble	roots	in total	
Winter rye for green mass	62.3	35.0	8.6	18.7	27.3	0.78 : 1
Oilseed radish (post-harvest)	42.1	18.3	8.3	15.5	23.8	1.81 : 1
White mustard (post-harvest)	40.3	19.5	6.9	13.9	20.8	1.07 : 1
Winter rape (post-harvest)	39.9	16.0	8.5	15.4	23.9	1.49 : 1
Seradella (under-sowing)	25.0	12.4	4.4	8.2	12.6	1.02 : 1
Perennial fodder lupine (under-sowing)	25.4	8.9	3.4	13.1	16.5	1.85 : 1
Perennial bitter lupine (for green manure)	48.2	–	25.3	23.4	48.7	1.92 : 1

Table 3.30

Comparative chemical composition of the root system of a number of crops in the Northern region (Nosenko, 2011)

Crops	Chemical composition of roots, % on absolutely dry matter			
	N	P_2O_5	K_2O	Ca
Spring vetch	1.92	0.62	1.48	0.97
Oilsed radish	1.65	0.76	2.15	1.54
Silage mallow	1.28	0.30	2.35	0.92
Spring rape	1.52	1.00	2.08	0.36
Fodder beans	1.81	0.35	1.06	0.92
Sunflower for milling	1.15	0.27	2.97	0.72

It was also found (Pysarenko et al., 2013) that its green mass contains the same amount of nutrients as cow manure: nitrogen – 0.5%; phosphorus – 0.25%; potassium – 0.6%. The mass of plant residues grown on an area of 100 m^2 contains the following amount of mineral fertilizers (in terms of chemical composition): mineral fertilizers (in terms of chemical composition) 3–5 kg of ammonium nitrate; 2.5–3.5 kg of superphosphate;

3.5–5.0 kg of potassium salt. In the Forest-Steppe zone, plants of oil radish sowing accumulate on average 65–85 kg ha^{-1} of nitrogen, 24–30 kg ha^{-1} of phosphorus and 87–100 kg ha^{-1} of potassium, which confirms the high ability of this crop to accumulate the main mineral compounds and their further use by the main field crops (Table 3.32). According to M. Nowakowski (1996), with oil radish yields above 400 c ha^{-1}, N 75–120 P 40–50 K 210–240 remain in the soil, and with a yield of 462 c ha^{-1}, N86 P66 K248 accumulate in the soil.

Figure 3.14 – Harvesting of oil radish as a green manure in the budding phase for sowing buckwheat on the experimental field of VNAU (top position – the state of the field after disking with John Deere 637 disk harrows, bottom position – the state of oil radish plant residues on the 5th day after harvesting in the layer of cultivated soil) (Tsytsiura and Tsytsiura, 2015)

Figure 3.15 – Harvest residues of oil radish harvested as green manure after cultivation of the green manure plot on day 35 (emphasizing the value of oil radish as an effective green manure for rapid immobilization of macro- and microelements of green manure mass and slow root decomposition. In the lower photo, the undecomposed remains of the root system and the lower part of the stems of oil radish are clearly visible) (Tsytsiura and Tsytsiura, 2015)

According to Drinch (2011), due to the bulky mass of roots and low carbon to nitrogen ratio, the leaf mass of oil radish decomposes quickly and the nutrients contained in it are easily available for subsequent crops (Table 3.33). Based on the data presented in the table and taking into account the rate of availability of nutrients for subsequent crops at 10%, they will be absorbed at least 68 kg of nitrogen, 14 kg of phosphorus and 119 kg/t of potassium.

Figure 3.16 – Root system of oil radish at different seeding rates (top position) and white mustard at different seeding rates (bottom position) (Tsytsiura and Tsytsiura, 2015)

Antonets et al. (2010) indicates that at yields of oil radish leaf mass over 40 t ha^{-1}, N75–90 P20–30 K50–70 remain in the soil. According to Pysarenko et al. (2013), oil radish used as a green manure at high yields provides up to 395 kg ha^{-1} of NPK (Table 78), according to Dovban (2009), N30–45 P10–15 K30–50 per 10 t of leaf mass (Table 3.34), and at average productivity, even on poor soils, oil radish is able to accumulate, in general, 220–270 kg ha^{-1} of nitrogen (Tables 3.35–3.38).

Table 3.31

Amount of nutrients involved in the biological cycle by intermediate crops (for an 8-year crop rotation), kg ha^{-1}

Crops	Total used			Including						The ratio of nutrients left in the soil with plant residues to their removal with the harvest, %.		
				taken out with the harvest			returns to the soil with plant residues					
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Winter rye for green mass	110.0	30.30	113.0	77.40	19.60	90.30	32.40	10.70	23.10	41.90	54.60	25.60
Oilseed radish	92.80	37.40	113.0	59.30	22.90	70.10	33.50	14.50	43.30	56.50	63.30	61.80
White mustard	89.50	27.40	98.90	64.00	18.10	64.50	25.50	9.26	34.40	39.80	51.20	53.30
Winter rape	88.10	30.20	92.20	48.30	15.50	50.60	39.80	14.70	41.40	82.40	94.80	82.20
Seradella	60.30	17.80	40.70	40.40	12.00	29.90	21.30	5.80	10.80	53.00	48.30	36.10
Perennial fodder lupine	65.90	13.30	33.10	28.20	6.05	17.70	32.90	6.81	13.30	117.00	112.00	75.10
Perennial bitter lupine	144.0	29.00	66.60	–	–	–	144.00	29.00	66.60	–	–	–

Table 3.32

Amount of macronutrients in the aboveground mass of green manure crops at average yield levels of leaf and stem mass (in the flowering phase – beginning of fruiting), kg ha^{-1} (Pysarenko et al., 2013)

Green manure	N	P_2O_5	K_2O	CaO
Oilseed radish (all biomass)	69.08	29.87	93.35	33.61
Oilseed radish (post-harvest residues)	64.49	27.89	87.15	30.37
Spring rape (all biomass)	58.21	19.85	64.83	19.85
Spring rape (post-harvest residues)	56.63	19.31	63.06	19.31
Small mallow (all biomass)	160.39	36.22	168.16	124.18
Small mallow (post-harvest residues)	157.29	35.52	164.91	121.78

Table 3.33

Nutrient content in dry matter of oil radish (Drinch, 2011)

Nutrients	Concentration, %		Amount of nutrients, kg ha^{-1}		
	plants	roots	plants	roots	total
Nitrogen	3.8	2.5	371	305	676
Phosphorus	0.7	0.6	68	73	141
Potassium	5.8	5.1	566	622	1188

Table 3.34

Agrochemical characteristics of green manure plants (calculated by the equivalent method) (Pysarenko et al., 2013)

Green Manure	Green mass yield, c ha^{-1}	Accumulation of post-harvest residues in the total biomass, kg ha^{-1}			Total, kg ha^{-1}
		N	P_2O_5	K_2O	
Sainfoin	275	145	25	75	245
Winter vetch	250	160	75	200	435
Vetch-oat mixture	275	120	35	80	235
Fodder pea	350	80	70	90	240
White sweet clover	200	110	45	140	295
Annual lupine	520	230	60	200	490
Buckwheat for two earnings	650	200	135	305	640
White mustard	250	60	40	90	190
Barbaréa vulgáris	340	135	55	240	430
Oilseed radish	450	85	65	245	395
Phacelia	300	80	50	200	330

Table 3.35

Macronutrient content in the leaf and stem mass of different green manure crops and litter-based manure (Dovban, 2009)

Green manure, manure	In % of raw weight			Kg in 10 tons		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Manure	0.44 – 0.60	0.25 – 0.30	0.50 – 0.70	44 – 60	25 – 30	50 – 70
Lupine perennial	0.46 – 0.50	0.08 – 0.095	0.25 – 0.34	40 – 50	8 – 9.5	25 – 34
Narrow-leaved lupine	0.40 – 0.42	0.10 – 0.12	0.20 – 0.25	40 – 42	10 – 12	20 – 25
White sweet clover	0.60 – 0.70	0.05 – 0.08	0.18 – 0.23	60 – 70	5 – 8	18 – 23
Winter rye	0.30 – 0.35	0.10 – 0.12	0.25 – 0.30	30 – 35	10 – 12	25 – 30
Annual ryegrass	0.35 – 0.40	0.11 – 0.13	0.25 – 0.30	35 – 40	11 – 13	25 – 30
Seradella	0.40 – 0.50	0.10 – 0.15	0.30 – 0.40	40 – 50	10 – 15	30 – 40
Diaper	0.45 – 0.50	0.12 – 0.15	0.40 – 0.45	45 – 50	12 – 15	40 – 45
Cruciferous (rapeseed, rape, oil radish)	0.30 – 0.45	0.10 – 0.15	0.30 – 0.50	30 – 45	10 – 15	30 – 50
Phacelia	0.32 – 0.40	0.10 – 0.13	0.40 – 0.48	32 – 40	10 – 13	40 – 48

Table 3.36

Comparison of a number of fodder crops by nitrogen accumulation on sod-podzolic soils, kg/ha (Dovban, 2009)

Crops	Nitrogen content		Total nitrogen content	Ratio C:N
	nitrogen content	in post-harvest and root residues		
White sweet clover	150–200	50–70	200–270	12–15:1
Meadow clover	140–180	40–80	180–260	11–13:1
Oriental goat's milkweed	200–250	80–100	280–350	12–15:1
White mustard	100–120	60–70	160–190	11–13:1
Oilseed radish	150–180	70–90	220–270	11–12:1

A positive factor that emphasizes the importance of oil radish as a green manure is the high ash content of oil radish leaf mass. Thus, Melnychuk and Stelmakh (1996) reported that the highest accumulation of ash elements in the leaf mass of oil radish during summer sowing was observed in the phase of early flowering, and then decreased to 20–22% in the phase of pod formation. According to this indicator, oil radish is ahead of all green manure crops: fodder lupine and meadow clover by

2.6 times, white sweet clover by 2.14 times, spring rape by 2.0 times, white mustard by 1.86 times, and a mixture of spring rape and vetch by 1.5 times (Figure 3.18).

Table 3.37

Amount of organic matter and mineral nutrients entering the soil during plowing of post-harvest green manure (Feshchun, 2011)

Crops	Leaf and stem weight, t/ha	Dry matter		Content in dry matter							
				$N-NO_3$		Phosphorus		Potassium		Calcium	
		mass, %	t ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}
Beans	20.71	19.0	3.94	2.82	107.7	0.37	14.13	1.40	53.48	1.12	42.78
Lupine	19.50	19.2	3.74	3.14	117.4	0.36	13.50	1.53	57.22	1.15	43.01
Peas	18.22	20.4	3.72	2.65	98.6	0.36	13.4	1.36	50.59	1.16	43.15
Oilseed radish	20.62	18.3	3.77	2.56	96.5	0.64	24.1	1.25	47.13	0.96	36.19
White mustard	18.97	18.9	3.59	2.41	85.5	0.62	22.3	1.27	45.59	1.04	37.34
Beans + lupine + peas	20.28	19.7	4.00	2.87	114.8	0.37	14.8	1.44	57.60	1.14	45.60
Radish + mustard	20.51	18.7	3.84	2.44	93.7	0.63	24.2	1.27	48.80	1.00	38.40
Manure (control)	30.00	22.0	6.60	2.25	148.5	0.34	22.4	1.60	105.6	1.10	72.60

Table 3.38

Nutrient content in green manure biomass (Feshchun, 2011)

Crops	In % of dry matter		
	N	P_2O_5	K_2O
Sweet clover	1.95	0.33	1.07
Sainfoin	1.81	0.34	0.95
Winter vetch	1.86	0.31	0.93
Oilseed radish	1.49	0.24	0.81
White mustard	1.55	0.25	0.78
Rape	1.55	0.27	0.82
Vetch + oats	1.27	1.23	0.75

Figure 3.17 – Root system of oilseed radish variety Zhuravka at the flowering stage (Excavation was carried out to a depth of 20 cm to the level of sharp narrowing of the main root. It is noticeable that the bulk of the roots is concentrated in a soil layer 25-30 cm thin. The diametric branching of the roots (lateral lateral roots of different orders) ranges from 5–8 to 12–15 cm. The taproot penetrates the soil to a depth of 50-80 cm and is a thin cylindrical structure up to 1.5–3.5 mm thick, depending on the technological parameters of the formation of the stem with small lateral roots. The diameter of the root thickening in our studies ranged from 0.5 cm to 5.5 cm. We have noticed that there is a certain relationship between the diameter of the root thickening and the length of the root system in the main direction of its growth) (Tsytsiura and Tsytsiura, 2015)

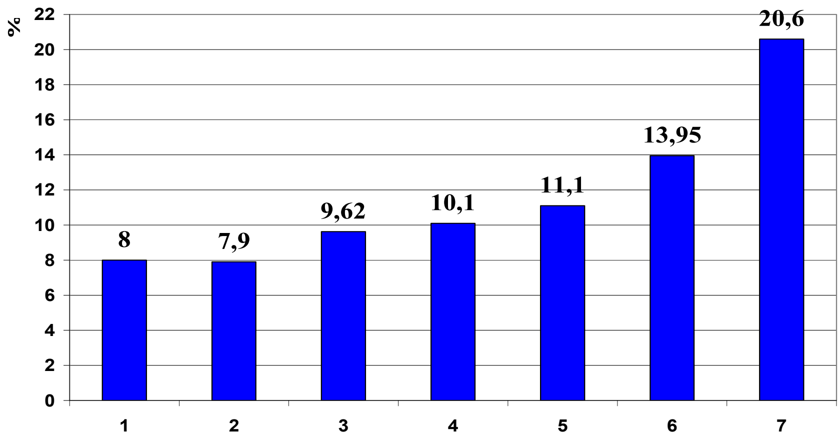

Figure 3.18 – Content of ash elements in the leaf and stem mass of green manure crops (full flowering stage): 1 – fodder lupine; 2 – meadow clover; 3 – white sweet clover; 4 – spring rape; 5 – white mustard; 6 – spring rape + vetch; 7 – oilseed radish (Melnychuk and Stelmakh, 1996)

It is also noted that even with summer and late summer sowing dates, oil radish under conditions of moderate moisture during the period of germination – pod formation is able to form at least 12–18 t ha^{-1} of leaf-stem mass, and under conditions of moisture of the period of full germination – pod formation at the level of 100–120 mm, even with these sowing dates, it is able to form up to 35 t ha^{-1} of leaf mass and 5.33 t ha^{-1} of dry matter at the beginning of pod formation, which can be successfully used for green manure or for other economic purposes starting from the budding phase (and even earlier). At the same time, the moisture content of the leaf-stem mass will be quite high, up to 95% (Table 3.39).

Dovban (2009) notes that the use of oil radish as a green manure not only has a positive effect on the accumulation of organic matter in the soil, ensuring a positive balance of macro and microelements, but also helps to improve the water and physical properties of soils. Thus, the use of oil radish for green manure reduced the density of the topsoil by 22% and the total porosity by 15% compared to the control. Under these conditions, capillary porosity decreased and non-capillary porosity increased. The decrease in soil volume was at least 15-18%. The author also notes that one of the disadvantages of green manure is the drying of the soil during the green manure growing season, and plowing it under other crops during dry periods reduces the efficiency of green manure. This is often observed in green manure pairs when, for some reason, green manure is plowed late, shortly before sowing winter crops. To avoid this, oil radish green manure in pairs should be plowed, depending on meteorological conditions, no later than 25–30 days before sowing the main crop. It is better to plow green manure for spring crops in late fall or spring. During the autumn-winter and early spring periods, soil moisture is restored to the optimum level for germination and development of spring crops. Observance of such conditions contributes to moisture conservation in the variants of green manure use – soil moisture in the layer of 0–40 cm was 6–12% higher than in the variant without green manure radish.

Table 3.39

Biological yield of oilseed radish by stages of organogenesis (Melnychuk and Stelmakh, 1996)

Stages of organogenesis	Moisture content of the leaf-stem mass, %	Dry weight, %	Yield, t ha^{-1}		Note
			leaf-stem mass	dry mass	
The budding of the flower	94.68	5.32	28.2	1.50	
The beginning of flowering	88.40	11.60	31.0	3.60	
Full flowering	86.30	13.70	34.6	4.74	Partial lodging
Pod formation	84.80	15.20	35.1	5.33	Full lodging

Kovalev V. P. et al. (1990) noted that the systematic use of oil radish as a green manure improves the overall soil structure. Thus, in the green manure plots, the number of water-resistant soil aggregates (0.25–0.50 mm) increased by 3–5% over 2–3 years, and the total clay content of the soil decreased by 2.5–6% in the first year of its use to 18–22% and 16–24%, respectively, in the 3rd–4th year of systematic green manure application.

The value of oil radish as a green manure is also in the fact that it grows rapidly, develops a large amount of leaf and root mass in a short period of 25 to 40 days, which opens up the possibility of its use in arid growing conditions and, in particular, at very early sowing dates.

For example, in recent years, the Central Experimental Farm of the Sumy Institute of Plant Industry has widely used oil radish as a post-harvest green manure for sugar beet cultivation. With the introduction of moderate doses of nitrogen, oilseed radish increased the amount of organic matter contained in 30–35 tons of manure in two months on one hectare. The use of green manure in combination with chopped straw made it possible to plow an amount of organic matter per 1 ha for sugar beet equivalent to the use of 45–50 tons of cattle bedding manure. In this case, the sugar beet yield was not inferior to the application of 40 t/ha of manure. The costs of all operations related to fertilization were reduced by 50–55% compared to the use of manure (Nosenko, 2011).

It has also been proven that post-harvest sowing of oil radish helps to reduce soil pollution with nitrate forms of nitrogen. The concentration of soil nitrates after oil radish was on average 70% lower than when sowing crops without using oil radish as a cover crop and as an intermediate green manure.

Oil radish also has a positive effect on the microbiological activity of the soil and improves the agrophysical and agrochemical properties of the soil and has a positive effect on the growth, development and productivity of subsequent crops in the rotation.

It is known that anthropogenic impact on agrophytocenosis significantly affects the structure of soil microbiocenosis and the total number of bacteria. In the studies of Rakhmetov (2000, 2012), the microbiological features of the soil rhizosphere were studied using different cruciferous green manure crops in comparison with the introduction of unhumified organic matter (Table). In general, the root secretions of oil radish were slightly inferior to mallow and contributed to the improvement of the rhizosphere zone, as indicated by the data on the colonization of parts of the soil by nitrogen bacteria. Compared to the control, when growing oil radish as a green manure, the phytotoxicity of the soil decreased by 1.5-2.0 times. Thus, the cultivation of oil radish is an important environmental lever for the formation of positive microbial communities in the soil rhizosphere.

Oil radish can be effectively used as an intermediate crop in short rotation crop rotations to improve the predecessor as an intermediate crop between the two main crops. In the conditions of agricultural production, especially taking into account the market orientation of specialization of many farms, it is not always possible to concentrate the main crops on the optimal predecessors. For these reasons, cruciferous intermediate crops, having intensive growth rates with the accumulation of high levels of biomass, allopathic properties due to the high content of sulfur-containing compounds, mustard oils, glucosinolates, indole substances and other physiologically active compounds, are an important reserve for optimizing crop rotations, reducing the negative impact of adjacent crops in the crop rotation through intermediate cultivation of the latter.

Under the influence of these substances, the virulence of some pathogenic bacteria in the soil is reduced. Root secretions of cruciferous plants reduce the germination of spores of pathogens and inhibit the length of their growth tubes.

At the same time, the content of microspore cells is also compressed, which leads to their destruction and death. Sowing of cruciferous plants also restrains the development of weeds, as their root secretions inhibit the germination of seeds of some weed species (Rakhmetov, 2012). Due to the rapid development of oil radish, the density of creeping wheatgrass weeds decreases. Scientists explain the death of creeping wheatgrass by the allopathic effect of cruciferous crops, which adversely affect the physiological and biochemical processes of acceptor plants, leading to inhibition of their growth and development and, as a result, death.

Allelopathically active substances enter the soil with root secretions during the life of the plant, as well as with crop residues of field crops, on which certain microflora settle. Gradually, the natural ratio between certain types of microorganisms shifts: the number of some decreases sharply, while others increase. In this regard, biologically active compounds are not involved in the cycle of substances and accumulate in the soil, having a harmful effect on certain crops. It is known that different green manure crops have different effects on the integrity of soil "breathing." Soil "breathing" is considered an indicator of its biological activity, the end result of which is the release of CO2, which is carried out by the entire soil biota and is an important indicator of the intensity of organic matter decomposition.

The intensity of carbon dioxide emission is an indicator of the rate of destruction of organic material. Determining the intensity of "breathing" of soils of different types when assessing agrotechnical measures establishes a link between this indicator and the biological potential of the soil.

Table 3.40

Microbiological activity of the soil rhizosphere under the use of cruciferous crops as green manure (Rakhmetov, 2000, 2012)

Variant	Spore bacteria on Mishustin medium, thousand/g abs. dry soil			CA nonspore bacteria, mln/g of abs. dry soil		
	timeframe for sampling (month)					
	May	June	July	May	June	July
No fertilizer (control)	94.2	81.8	11.6	3.6	2.5	2.9
Winter block						
Manure 20 t ha^{-1} (control)	130.4	51.0	90.4	8.3	4.0	5.7
Winter rape (total biomass)	82.4	99.1	129.2	10.1	3.3	1.6
Typhon (all biomass)	105.4	102.0	107.4	11.4	3.5	4.6
Spring block						
Manure 20 t ha^{-1} (control)	84.9	83.3	96.1	4.9	3.1	6.3
Oilseed radish (all biomass)	74.3	82.0	97.1	17.2	4.5	9.7
Barbaréa vulgáris (all biomass)	67.0	59.6	77.4	12.7	3.0	2.3
Small mallow (all biomass)	112.6	78.8	88.9	9.5	3.4	3.5
Variant	**Number of streptomycetes on cabbage agar. thousand /g abs. dry soil**			**Development of nitrogen bacteria. %**		
	May	**June**	**July**	**May**	**June**	**July**
No fertilizer (control)	254.6	943.2	138.7	48	78	38
Winter block						
Manure 20 t ha^{-1} (control)	294.0	1528.8	424.9	86	98	72
Winter rape (total biomass)	400.7	1288.0	184.6	98	90	77
Typhon (all biomass)	58.6	800.4	185.2	92	98	83
Spring block						
Manure 20 t ha^{-1} (control)	358.8	973.6	365.1	96	90	40
Oilseed radish (all biomass)	406.7	713.4	567.3	82	96	77
Barbaréa vulgáris (all biomass)	289.5	759.8	323.0	98	96	49
Small mallow (all biomass)	1138.1	1253.7	417.9	90	100	99

Oil radish is a fairly powerful emitter of CO_2 in the process of its decomposition in the soil after harvesting. Research conducted by Trofymenko and Bilan (2014) showed that different green manure crops are decisive in the value of CO_2 concentration with a directly proportional character depending on exposure. The studied green manure crops in terms of soil respiration (mg m^{-2} min^{-1}) in the same studies can be ranked in the following order: oil radish 73.7 – field diaper 42.0 – multiflorous ryegrass 39.2 – narrow-leaved lupine 35.6. Thus, the highest intensity of soil respiration is observed under oil radish. In the course of research by Trofymenko and Bilan (2014), it was also found that there is a high and medium degree of dependence between the yield of leaf-stem mass of green manure in the flowering phase and the intensity of soil respiration according to the correlation coefficient (r): oil radish and diaper 0.62, fenugreek 0.46 (medium degree), lupine 0.93 (very high degree).

Oil radish leaf mass can be successfully used to prepare multicomponent straw-based composts. The goal is achieved by adding to the straw, as a stimulant of the intensity of microbiological processes, easily hydrolyzable organic matter in the form of green mass of green manure crops in a certain amount (wet weight) per 1 ton of straw.

The green manure is applied to straw moistened with a solution of mineral salts – ammonium nitrate, superphosphate and potassium chloride, which are commonly used as NPK fertilizer. The amount of moisture in relation to the weight of the straw is 1:4 to 1:5. The concentration of mineral additives per 100 kg of straw is 2.8 kg of ammonium nitrate (1 kg of nitrogen active ingredient); 5.0 kg of superphosphate (1.09 kg of P_2O_5); 4.0 kg of potassium chloride (2.4 kg of K_2O). One of the recipes for this composting involves the use of enamel buckets with a capacity of 10 liters. The straw is chopped into 3 to 5 cm pieces, moistened with NPK solution at the above concentration, and mixed with the green mass of the green manure. It has been proven that the decomposition of such compost in the soil leads to an active reproduction of microorganisms. Thus, the content of bacteria in the soil (thousand grams of soil) was 6400 without green manure, 25000 with lupine, 24600 with rape, 19800 with oil radish, and 20300 with clover. Siderates are added in the amount of 0.2–0.3 dry weight, which corresponds to 80–120 kg of raw weight per 1 ton of straw. Composting is carried out without stirring at room temperature of 18–20 ^{o}C.

The results of using the proposed method of activating the straw composting process are presented in Tables 3.41–3.43.

Table 3.41

Influence of oil radish green manure on microbial growth in composted straw after 7 months, million g

Composting option	Types of microorganisms					General bio-geneticity
	cellulose-degrading	oil-sour	pectin-degrading	actino-mycetes	mushrooms	
NPK	5,88	79	12	11	2,5	563
NPK + green manure oilseed radish	15.88	277	22	66	7.6	3734

Table 3.42

Influence of oil radish green manure on mineralization processes during straw composting (after 7 months)

Composting option	Weight reduction, %					Ratio C: N
	total	cellulose	hemic-ellulose	pectin substances	lignin	
NPK	44.9	52.7	31.7	70.2	20.4	60
NPK + green manure oilseed radish	64.1	70.2	65.9	91.5	23.5	22

The obtained results confirm that the enrichment of straw with plant material that is easily hydrolyzed by microorganisms significantly stimulates the reproduction of all major physiological groups of microorganisms, as a result of which the processes of mineralization of hardly hydrolyzable components that make up straw are activated, which in turn contains on average (%): lignin 18 – 22; cellulose 33 – 35; hemicellulose 21 – 22; protein 3 – 5; mineral nitrogen 4 – 6. Compared to straw, green manure is enriched with water-soluble and easily hydrolyzable fractions of carbon-containing substances used by microorganisms as a source of food and energy.

The positive effect of oil radish on the microbiological activity of the soil and the nature of physical and chemical reactions was confirmed in the research of Rakhmetov (2012). He found that the introduction of green manure crops, including oil radish, affects redox processes in the soil by intensifying them (Table 3.43). This indicates an increase in the level of mobile substances released during the decomposition of plant mass.

The results of biochemical studies showed that the decomposition of green manure released organic substances that were in the soil in a free state, which is why their content is higher when using green manure. It should be noted that oil radish is one of the most active components of the studied green manure system in this regard, both in terms of free phenolic substances (for oil radish their concentration was 55 – 67 mg/kg, and in the control – 49–60 mg kg^{-1}), and especially in terms of the concentration of free amino acids in the soil (Table 3.44), which is evidence of its positive role in increasing the biological activity of the soil.

Table 3.43

Influence of green manure crops on redox potentials in soil depending on the developmental stages of spring barley, tV (average for two years) (Rakhmetov, 2012)

Variant	Bushing	Stemming	Before harvesting
Control – without fertilizers and green manure	262	265	331
Winter block (plowing in spring)			
Manure (20 tons ha^{-1})	301	280	250
Winter rocket-cress (all biomass)	276	285	322
Typhon (all biomass)	285	292	316
Spring block (plowing in the fall)			
Manure (20 tons ha^{-1})	268	272	279
Oilseed radish (all biomass)	275	272	307
Mallow (all biomass)	271	260	309
Spring rocket-cress (all biomass)	275	267	291

It is also noted (Rakhmetov, 2009) that plowing green mass of cruciferous and other intermediate crops also has a healing effect on the soil. In this case, the number of actinomycetes, which are antagonists of root rot pathogens, increases in the soil.

After harvesting the green mass, along with crop residues, plant growth and development stimulants from the brassinosteroid class remain in the soil, increasing yields and improving the quality of the marketable products of subsequent crops. All of the above suggests that growing cruciferous crops in intercrops will help reduce the use of chemical plant protection products in agriculture.

Table 3.44

The effect of green manure on the qualitative composition of free amino acids in the soil in the second decade of May, mg/kg (average of three years) (Rakhmetov, 2012)

Variant	Cystine	Lysine	Histidine	Aspartic acid	Glycine	Glutamic acid	Valine	Isoleucine	Leucine	Total
Control – without fertilizers and green manure	0.88	1.13	4.37	10.46	4.65	0.53	0.99	1.21	1.19	25.41
Winter block (plowing in spring)										
Manure (20 tons ha^{-1})	0.81	1.64	4.71	11.28	5.57	0.64	1.72	1.21	1.29	28.47
Winter rocket-cress (all biomass)	0.81	2.65	6.58	12.82	6.49	0.61	1.29	0.68	1.27	32.71
Typhon (all biomass)	0.84	1.30	5.75	12.92	6.43	0.86	2.01	0.61	1.21	31.93
Spring block (plowing in the fall)										
Manure (20 tons ha^{-1})	0.93	2.90	6.92	15.95	6.12	1.07	1.77	0.78	1.55	38.09
Oilseed radish (all biomass)	1.45	2.71	6.27	20.00	6.60	2.06	1.51	1.27	1.14	43.01
Mallow (all biomass)	1.84	2.41	6.30	18.75	6.24	0.83	1.87	0.72	0.74	39.70
Spring rocket-cress (all biomass)	0.96	1.69	5.02	11.61	5.04	1.69	1.24	0.78	0.64	28.67

Many studies have also emphasized the positive effect of oil radish as a green manure on the water and physical properties of the soil. Rubin (1985) found that the use of cruciferous green manure in the general block of spring green manure under different systems of garden row spacing contributed, on average, to an increase of more than 20% in the number of water-resistant aggregates (> 0.25 mm) (Table 3.45).

Zubets (2004) found that the use of cruciferous green manure has a multifaceted and complex effect on the change of agrophysical, agrochemical and biological parameters of different soil types and, in particular, leached chernozem in the Volga region: Increase in the amount of valuable water-resistant aggregates from 0.8 to 8.3% (2.0 to 3.2% for oil radish in particular); improvement of the soil profile structure within 1 to 3 years after green manure, reduction of soil density by 0.05 to 0.08 g/cm^3 (0.06 for oil radish); reduction of nutrient migration to deeper horizons from arable soil; restoration of the normal cycle of organic matter and nitrogen in the soil, etc.

Table 3.45

Effect of different soil containment systems on the amount of water-resistant aggregates > 0.25 mm, % (Rubin, 1985)

Soil retention option	Soil layer, cm	Average for the research period	
		absolute value	in relation to control
Black field	0 – 20	42.5	100
	20 – 40	55.7	100
	0 – 40	49.1	100
Spring green manure (oil radish, white mustard, peas)	0 – 20	54.1	127.3
	20 – 40	64.0	114.9
	0 – 40	59.0	120.2
Sowing grasses	0 – 20	60.0	141.2
	20 – 40	68.7	123.3
	0 – 40	64.4	140.9

Oilseed radish, together with white sweet clover and spring rape, provided 59-63% of agronomically valuable aggregates and 33–40% of water-resistant aggregates, which is close to the optimal parameters of these indicators for chernozem soils (Table 3.46).

Table 3.46

Influence of different green manure crops on the composition of soil aggregates in the 0-30 cm layer at the end of buckwheat growing season, % (Zubets, 2004)

Variant	Вид аналізу	Fraction size, mm									10 – 0,25 mm %
		>10	10-7	7-5	5-3	3-2	2-1	1-0,5	0,5-0,25	<0,25	
Without green manure (control)	Dry sieving (A)	28	8	7	8	6	14	6	7	16	56
	Wet sieving (B)			2.4	2.0	1.8	2.3	6.6	15.6	69.3	30,7
Phacelia	Dry sieving (A)	26	9	8	8	8	11	6	8	16	58
	Wet sieving (B)			1.1	1.9	1.9	2.1	9.8	14.7	68.5	31,5
White sweet clover	Dry sieving (A)	24	10	9	8	7	14	7	8	13	63
	Wet sieving (B)			1.2	1.0	1.6	6.9	10.0	18.3	61.0	39,0
Spring rape	Dry sieving (A)	23	9	9	9	7	15	7	8	13	64
	Wet sieving (B)			1.5	1.2	1.6	7.7	10.2	17.4	60.4	39,6
White mustard	Dry sieving (A)	25	9	8	9	8	12	6	7	16	59
	Wet sieving (B)			1.5	1.2	1.8	5.4	7.0	17.0	66.1	33,9
Oilseed radish	Dry sieving (A)	24	10	8	9	7	12	6	8	16	60
	Wet sieving (B)			1.7	1.5	1.7	3.4	7.2	17.2	67.3	32,7
F_f(A)		87.5*								60.9*	172.1*
LSD_{05} (A)		0.74								0.43	1.67
F_f (B)										123.7*	98.6*
LSD_{05} (B)										1.74	0.98

* $F_f > F_{table}$

Research by Narusheva (2018) also showed that green manure increased the activity of ammonifying and nitrifying groups of microorganisms, resulting in an increase in the concentration of available forms of ammonium and nitrate nitrogen in the soil. The green mass of the studied green manure is rich in nitrogen and has a narrow carbon to nitrogen ratio of 10:1–12:1, which contributed to the mobilization of nutrients in the topsoil. The use of green manure, in addition, increased the content of nitrate ($N–NO_3$) and ammonium ($N–NH_4$) nitrogen in the soil, respectively, by

0.8–4.6 and 7.5–15.2 mg kg^{-1} (oil radish in particular by 3.1 and 9.6 mg kg^{-1} (Table 3.47). Moreover, a positive trend in the concentration of these forms of nitrogen was observed in the third year after the application of these green manure.

Table 3.47

Effect of green manure on the content of nitrate and ammonium nitrogen in the layer 0 – 30 cm at the end of the growing season (Narusheva, 2018)

Variant	Nitrogen content in the 0–30 cm layer, mg kg^{-1} soil		
	$N\text{-}NO_3$	$N\text{-}NH_4$	Nitrogen amount
Without green manure (control)	6.1	11.2	17.3
Phacelia	6.9	18.7	25.6
White sweet clover	10.7	26.4	37.1
Spring rape	10.4	25.6	36.0
White mustard	9.5	25.3	34.8
Oilseed radish	9.2	20.8	30.0
LSD_{05}	0.24	0.61	0.86

The content of mobile forms of phosphorus and potassium in the soil also tended to increase with the use of green manure due to organic acids – root secretions of green manure. The use of oil radish contributed to an increase in phosphorus availability by 2.5–3.5% and potassium by 1.5–1.8% over a three-year cycle. The indicators of soil “breathing” also increased – the release of carbon dioxide was 15–18% higher when oil radish was planted than in the variant without green manure. Under the same conditions of the study, the water regime improved when plowing green manure, in particular, water retention and water-raising capacity, and the enzymatic activity of the soil increased (Table 3.48)

Karpenko (2002) found that the use of oil radish as a green manure for corn under different tillage systems had a positive effect on the dynamics of Nitrogenobacterium, as well as non-spore bacteria, actinomycetes and fungi. The presence of Azotobacter in the soil is an indicator of its fertility, as it is an indicator of the presence of phosphorus, potassium, calcium, pH, etc. in the soil. This microorganism has the ability to fix atmospheric nitrogen and synthesize plant growth stimulants such as auxin and vitamins. The author's experiments have shown that the use of oil radish increases the number of nitrogenase in the phase of 6-8 leaves of corn, which indicates its high biological activity. Under these conditions, a higher amount of nitrogen bacteria is observed in shelf cultivation than in chisel cultivation. This dependence was observed before harvesting corn in the variant with manure application and the use of oil radish for green manure and green fodder, while the amount of nitrogen bacteria decreased under chisel tillage (Table 3.49).

Table 3.48

Effect of green manure on the activity of soil enzymes under buckwheat sowing (Narusheva, 2018)

Variants of the experiment	Enzyme activity			
	urease, mg urea/ 10 g soil/day	amylase, mg maltose/ 10 g soil/day	xylanase, mg/1 ml of reaction mixture	invertase, mg glucose/ 1 g soil/4 h
Without green manure (control)	107	12.2	7.26	16.0
Phacelia	128	21.4	7.74	24.2
White sweet clover	151	25.0	8.80	18.8
Spring rape	144	28.5	9.10	32.8
White mustard	135	23.8	8.40	28.6
Oilseed radish	135	26.9	8.10	27.2
LSD_{05}	3.4	0.5	0.2	0.6

It has also been found that the use of oil radish as a green manure contributes to an increase in glycine, aspartic and glutamic acids in the soil, which is evidence of an increase in soil biological activity and the intensification of positive microbiological processes, especially expressed in the background of chiseling. The positive effect of oil radish on the soil bulk was also noted. Its use as a green manure provided the lowest soil density among all studied variants 1.05 –1.22 g cm^{-3} with lower values on the background of plowing (Table 3.50).

Table 3.49

Influence of non-humified organic matter and different tillage methods on the allelopathic activity of soil under maize (% fouling of soil lumps with Azotobacter culture), % (Karpenko, 2002)

Variants	Plowing by 28 to 30 cm			Chisel cultivation by 28 to 30 cm		
	before sowing	phase 6 leaves	before the harvest	before sowing	phase 6 leaves	before the harvest
Control (root and stubble residues of winter wheat)	98	96	98	96	94	98
Manure, 40 t ha^{-1}	100	100	100	94	98	98
Winter rape for green manure	92	100	94	98	96	96
Winter rape for green fodder	96	100	98	100	100	96
Oilseed radish for green manure	96	100	100	96	100	98
Oilseed radish for green fodder	96	100	100	96	100	98

Oil radish also had a positive effect on the soil nutrient regime: the amount of hydrolyzed nitrogen in the soil and the content of mobile forms of phosphorus and potassium increased, especially under chisel cultivation (Table 3.51).

The conclusions of various researchers were confirmed by Perchuk (2008). The author argues that oilseed rape plays a leading role in terms of its impact on density reduction. This crop can be attributed to crops that can contribute to the loosening of the topsoil, which is an obstacle to the active penetration of moisture, air and plant roots (Table 3.52).

Thus, the introduction of green manure and green manure under the main tillage leads to a tendency to reduce the volume mass of the soil, both before sowing crops and during harvesting. The decrease in soil density due to the use of green manure is associated with a faster decomposition of the organic mass of green fertilizers.

Table 3.50

Influence of primary tillage and post-harvest crops on the dynamics of active soil layer density in corn crops, g cm^{-3} (Karpenko, 2002)

Variants	Soil cultivation					
	Plowing by 28 to 30 cm			Chisel cultivation by 28 to 30 cm		
	before sowing	phase 6 leaves	before the harvest	before sowing	phase 6 leaves	before the harvest
Control (root and stubble residues of winter wheat)	1.07	1.15	1.20	1.10	1.22	1.27
Manure, 40 t ha^{-1}	1.06	1.14	1.18	1.08	1.22	1.25
Winter rape for green manure	1.05	1.12	1.18	1.08	1.20	1.24
Winter rape for green fodder	1.06	1.15	1.18	1.09	1.21	1.25
Oilseed radish for green manure	1.05	1.11	1.17	1.06	1.17	1.22
Oilseed radish for green fodder	1.06	1.14	1.18	1.08	1.19	1.22

The author (Perchuk, 2008) notes that the application of different types of organic fertilizers reduced the degree of soil fracture, which thereby depended on the amount of organic matter supplied with fertilizers. The highest value of this indicator was observed in variants using green mass of post-harvest oil radish crops. The peculiar and quite useful work of its vertical-taproot systems is that penetrating with powerful roots deep into the depths, beyond the arable layer, it leaves behind a network of corresponding passages that carry out vertical soil drainage. As a result, favorable water and air regimes are created not only in the topsoil, but also in the subsoil. These moves facilitate the penetration of gravity water into the depths and accelerate the process of enriching the subsoil layers with humus.

The use of oil radish increased the slotting of the topsoil by 2–6%. The best slotting is created with the use of shelf cultivation with a general positive trend of green manure influence on the change of this physical indicator.

The moisture availability of the topsoil in the variants using different types of organic fertilizers was on average 1.0–2.5% higher than in the control variant within the tilth layer, which is explained by the general improvement of the main agrophysical parameters of the soil, as well as the influence of the green mass of oil radish as a mulching material and organic matter, which reduces unproductive moisture losses.

Table 3.51

Influence of non-humified organic matter and different methods of basic tillage on the dynamics of exchangeable phosphorus and potassium content in soil under maize crops, mg per 100 g of dry soil (Perchuk, 2008)

Variants	Plowing by 28 to 30 cm						Chisel cultivation by 28 to 30 cm					
	before sowing		phase 6 leaves		before the harvest		before sowing		phase 6 leaves		before the harvest	
	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
Control (root and stubble residues of winter wheat)	17.07	2.07	17.14	17.3	17.02	13.3	17.70	20.2	17.40	17.1	17.53	13.9
Manure, 40 t ha^{-1}	18.52	23.8	19.37	19.3	20.07	14.8	19.00	23.2	19.60	18.0	19.26	15.7
Winter rape for green manure	17.23	23.0	17.66	17.3	17.85	14.6	18.43	21.8	19.25	18.3	17.82	16.7
Winter rape for green fodder	16.18	21.8	16.96	14.7	16.72	13.5	15.7	21.2	16.78	17.5	16.12	15.1
Oilseed radish for green manure	18.82	22.5	17.38	18.7	17.66	14.7	-	21.9	20.96	19.1	20.05	17.1
Oilseed radish for green fodder	14.71	20.5	16.78	15.7	16.98	14.0	15.94	21.5	17.15	17.2	16.90	15.3

The data indicate that the best conditions for moisture availability were formed in variants with shelf basic tillage at 25-27 cm against the background of the use of oil radish green manure (Table 3.53). Plowing oil radish into the soil increases the content of water-resistant aggregates and the slit content in the tilth layer of the soil, which leads to a more even distribution of precipitation profile and better water absorption.

The results of the research by Perchuk (2008) showed that the content of phenolic compounds in the soil depends on the type of organic green manure and the main soil tillage (Table 3.54).

Table 3.52

Influence of green manure and basic tillage on the volume mass of topsoil 0-30 cm, g/cm3 (Perchuk, 2008)

Variant	Observation period					
	during sowing		6 to 8 leaves		during harvesting	
	g cm^3	%	g cm^3	%	g cm^3	%
Plowing by 25 to 27 cm						
Root and stubble residues of winter wheat (control)	1.18	100	1.27	100	1.35	100
Manure – 40 t ha^{-1}	1.13	96	1.18	93	1.21	90
Oilseed radish	1.10	93	1.17	92	1.20	89
Oats + peas	1.12	95	1.19	94	1.20	89
Straw – 4 t ha^{-1}	1.15	97	1.22	96	1.24	92
Chisel cultivation by 25 to 27 cm						
Root and stubble residues of winter wheat (control)	1.19	100	1.25	100	1.34	100
Manure – 40 t ha^{-1}	1.15	97	1.20	96	1.22	91
Oilseed radish	1.12	94	1.18	94	1.20	89
Oats + peas	1.15	97	1.20	96	1.21	90
Straw – 4 t ha^{-1}	1.18	99	1.20	96	1.25	93
LSD_{05}	0,03		0,03		0,06	

The total content of phenolic compounds in the soil depended solely on the amount of green manure applied and the degree of its decomposition. The mass of oil radish plants underwent the process of decomposition most actively during the second term of determination – in the phase of formation of 6–8 leaves of corn.

When assessing the shelf and non-shelf tillage, and, accordingly, the method of green manure and green manure, almost the same tendency of decomposition of non-humified organic matter and release of phenolic compounds was noted. However, their amount is higher when using the shelf method of basic tillage with the simultaneous introduction of oil radish as a post-harvest green manure.

The study of methods of soil cultivation and green manure cultivation in the aisles of the orchard, as well as their impact on the physical and biological properties of the soil and productivity of apple trees was carried out in the educational and research garden of Podilsky State Agrarian and

Technical University (Table 3.55), it was found that the best option for maintaining the soil of an apple orchard of an intensive type of plantations for the conditions of the southwestern part of the Forest-Steppe of Ukraine is tillage to a depth of 5–6 cm in combination with the cultivation of oil radish, which increases soil fertility with simultaneous improvement of its agrophysical properties and ensures high productivity of apple plantations (Pecheniuk et al, 2017).

Table 3.53

Influence of green manure and main tillage on moisture content of 0-100 cm soil layer, % (Perchuk, 2008)

Variant	Observation period					
	during sowing		6 to 8 leaves		during harvesting	
	%	% to control	%	% to control	%	% % to control
Plowing by 25 to 27 cm						
Root and stubble residues of winter wheat (control)	23.5	100	22.1	100	19.7	100
Manure – 40 t ha^{-1}	24.2	103	23.0	104	20.2	103
Oilseed radish	25.8	109	23.7	107	21.5	109
Oats + peas	24.0	102	22.5	102	20.8	105
Straw – 4 t ha^{-1}	23.8	101	21.5	97	20.0	101
Chisel cultivation by 25 to 27 cm						
Root and stubble residues of winter wheat (control)	22.6	100	21.3	100	18.5	100
Manure – 40 t ha^{-1}	23.3	103	22.2	104	19.3	104
Oilseed radish	24.6	109	22.8	107	19.8	107
Oats + peas	23.0	102	21.5	101	18.8	101
Straw – 4 t ha^{-1}	22.8	101	21.2	100	18.2	98

In the studies of Gudzia et al. (2011), it was proved that the use of post-harvest oil radish green manure, as well as the main tillage, directly affected the soil density under potato crops (Table 3.56). Thus, against the background of oil radish green manure, the volume mass of the tilthy soil layer decreased significantly – on average by 0.04 g cm^{-3} under both moldboardless tillage and plowing. And the share of green manure influence on soil moisture availability in potato cultivation was 41.2% (Table 3.57).

Under these conditions, the factor of green manure in the value of total potato productivity was 15.3%, and the yield on the background with green manure radish was 5.3 t ha^{-1} higher compared to the background without its use.

Table 3.54

Effect of green manure and main tillage on the content of phenolic compounds in the soil, mg/kg (Perchuk, 2008)

Variant	Observation period								
	during sowing			6 to 8 leaves			during harvesting		
	alcohol	water-acetone	total	alcohol	water-acetone	total	alcohol	water-acetone	total
Plowing by 25 to 27 cm									
Root and stubble residues of winter wheat (control)	5.7	25.7	31,4	4,5	30,5	35,0	10,0	26,5	36,5
Manure – 40 t ha^{-1}	8.4	31.5	39,9	6,0	34,3	40,3	15,0	30,1	45,1
Oilseed radish	7.4	36.7	44,1	7,0	37,7	44,7	17,3	38,0	55,3
Oats + peas	6.0	26.6	32,6	5,1	30,8	35,9	11,0	31,0	42,0
Straw – 4 t ha^{-1}	6.5	26.5	33,0	4,1	29,0	33,1	10,3	27,0	37,3
Chisel cultivation by 25 to 27 cm									
Root and stubble residues of winter wheat (control)	4.9	20.3	25,1	5,0	26,4	31,4	8,7	23,3	32,0
Manure – 40 t ha^{-1}	7.0	26.5	33,5	6,3	33,2	39,5	11,4	25,8	37,2
Oilseed radish	8.2	28.5	36,7	7,7	36,7	44,4	15,5	32,5	48,0
Oats + peas	5.1	11.7	26,8	5,3	27,0	32,3	10,3	24,7	35,0
Straw – 4 t ha^{-1}	5.4	20.5	25,9	4,7	25,5	30,2	7,8	24,0	31,8
LSD_{05}	1.2	6.7		1,1	4,5		3,1	4,5	

There is a high positive role of oil radish as a component of biological compatibility when grown together with most vegetable crops (Table 3.58), and as a green manure for growing vegetable crops in comparison with other green manure crops and mulching. For example, according to Bublik (2013), carrot yields after oil radish green manure were twice as high as when mulch was used as a control and significantly higher than when vetch and phacelia were used as green manure.

Table 3.55

Structural composition of soil depending on the methods of its cultivation in the garden aisles and green manure cultivation (Pechenyuk et al., 2017)

Methods of soil cultivation	Greem manure	Soil layer 0–60 cm			
		> 10	10 – 0,25	< 0,25	structural coefficient
Plowing 20–22 cm	Without green manure (control)	21.11	75.06	3.8	3.01
	Spring rape	18.94	79.38	2.9	3.63
	Oilseed radish	17.77	79.31	2.9	3.83
Disking 10–12 cm	Without green manure (control)	20.78	75.01	4.2	3.00
	Spring rape	18.92	77.57	3.5	3.46
	Oilseed radish	19.13	77.76	3.1	3.50
Milling 5–10 cm	Without green manure (control)	19.51	77.02	3.4	3.36
	Spring rape	18.09	79.16	2.8	3.78
	Oilseed radish	17.15	80.06	2.7	4.03

Table 3.56

Influence of main tillage methods and green manure background on bulk mass in 0-30 cm soil layer during potato cultivation, g cm^{-3} (Gudz et al., 2011)

Organic fertilizers (factor A)	Methods of primary tillage (factor B)			
	plowing 28 –30 cm	shelfless 28–30 cm	shelfless 13–15 cm	shelfless 6–8 cm
Without green manure	1.20	1.18	1.21	1.21
Post-harvest green manure (oilseed radish)	1.15	1.13	1.17	1.18
LSD_{05} 0.017. factor A 0.009. factor B 0.012				

Table 3.57

Influence of methods of main tillage and green manure on productive moisture reserves in 0-30 cm soil layer during potato cultivation, mm (Gudz et al., 2011)

Organic fertilizers (factor A)	Methods of primary tillage (factor B)			
	plowing 28 –30 cm	shelfless 28–30 cm	shelfless 13–15 cm	shelfless 6–8 cm
Without green manure	30.4	32.2	31.7	32.5
Post-harvest green manure (oilseed radish)	32.7	34.7	33.4	34.8
$LSD_{05\ зас}$ 1.02. factor A 0.51. factor B 0.72				

Table 3.58

Compatibility of oilseed radish with main vegetable and berry crops (Bublyk, 2013)

Crops	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. Eggplant																			+		
2. Vegetable bean						*		*	–		+		*							–	*
3. Grape					–	+			–				+						+		
4. Pea									–	+	+	*	*	*			–		–		
5. Cabbage			–			*			*		*	–	–	+	*	+	*		+		*
6. Potatoes		+			*			*					*	*		–			+		+
7. Strawberries					*	*			*			+	*	*	*				+	*	+
8. Corn		+									+			+	–	–	+	*	+		
9. Onion		–		–			*			+			*	*	*				–		*
10. Carrot				+					+				*	*			*			*	+
11. Cucumber		+			*			*	*				*	*	*	*			*	*	*
12. Parsley				*			*						*	*		*	+				
13. Radish, radish, oilseed radish, daikon, lobo				*	–	*	*		*	*		*	–	+	*		*		+	*	*
14. Lettuce				*	+		*		*		*		+				*		*	*	*
15. Beetroot					*		*		+		*		*	*	+	+			+	*	+
16. Celery					+	–		–	*	–		–		*	*		*			+	*
17. Tomato					*				*	*		+	*	*	*	*			*	*	*
18. Pumpkin								*													
19. Beans				–	+	+	*	+	–		+		+	*	+	+	+			–	+
20. Garlic				–	–		*			*	*				*		*		–		
21. Spinach					*	+	*		*	*		*	*	*	+	*	+		+		

+ – very good compatibility; * – good compatibility; – - poor compatibility.

Today, oil radish is also an active component of biological farming. Thus, according to Shuvar (1994, 1997, 2003, 2005, 2014), green manure crops can compensate for the negative impact of intensive agricultural production on its quality and the environment, and provide a deficit-free balance of humus in soils, acting as an alternative to organic fertilizers. In his proposed scheme – a model of biological farming (organic fertilization system), presented below, green manure from three crops – oil radish, white mustard and winter rape – are the key components.

Organic fertilization system (model of biological farming) for rotational crop rotations:

1) vetch–oat mixture – $N_{20}P_{30}K_{30}$ + post–harvest oil radish – N_{30} (during sowing); 2) winter wheat – 20 t ha^{-1} of oil radish green manure + $N_{15}P_{40}$; post–harvest white mustard – 3 t ha^{-1} of straw + N_{15} (for wrapping with straw) + N_{40} (during sowing); 3) potatoes – 55 t ha^{-1} of manure + 20 t ha^{-1} of white mustard or oil radish green manure + $N_{20}P_{40}K_{40}$; 4) spring barley – P40 + post–harvest winter rape – 3 t ha^{-1} of straw + N_{15} (for hilling with straw) + $N_{20}P_{30}K_{30}$ + N_{30} (spring fertilization); 5) corn for silage – 55 t ha^{-1} of manure + 30 t ha^{-1} of winter rape green manure + $N_{30}P_{60}$.

Confirmation of the effective role of oil radish in the system of biological farming, even on relatively poor soils, is a study that examined the effectiveness of the use of oil radish green manure on their impact on the yield of a number of crops (potatoes, spring barley) and on soil quality and fertility (Table 3.59). It was found that biological indicators of soil fertility are closely related to the amount of green mass of plowed oil radish green manure, which is not inferior to narrow–leaved lupine and is close to increased doses of cattle manure. Both oil radish and white mustard green manure increase yields and improve crop quality both in the first crop of the rotation and in the first year afterwards, with oil radish being more effective than white mustard.

The research studied the variants of oil radish without fertilizers, oil radish + background ($P_{90}K_{90}$), oil radish + background + N_{60}, oil radish + background + N_{120}, oil radish + background + N_{180}. In all the studied variants of the experiment, a close direct correlation was observed between the yield of potatoes and barley (r = 0.929–0.996), the intensity of soil respiration and the amount of green manure incorporated into the soil (r = 0.835–0.920). Moreover, this relationship is manifested both by the effect of green manure and its aftereffect.

The intensity of soil respiration, which was estimated by the amount of CO_2 released from the soil in terms of kg/ha per hour. Depending on the variant of oil radish use, this indicator was in the range of 2.0–3.3 kg ha^{-1} per hour and was significantly higher than that of mustard, approaching the equivalent of using 20 t ha^{-1} of cattle manure. The respiration intensity of direct use of oil radish green manure was 25–40% higher.

The analysis of the conditional balance of mineral nutrients in the crop rotation link, both with direct and combined use of oil radish, showed that the studied variants have a positive balance of all three macronutrients under study – nitrogen, phosphorus and potassium. Moreover, the relative balance before the removal of mineral nutrients for three years was: N – 148 – 155 %, P_2O_5 – 256 – 283 %, K_2O – 160 – 165 % with combined and N – 147 – 159 %, P_2O_5 – 270 – 331 %, K_2O – 163 – 171 % with direct use of green manure. At the same time, the calculations showed that when using oil radish as a green manure (combined use), depending on the variant of the experiment, N – 30–70, P_2O_5 – 10–30, K_2O – 40–70 kg ha^{-1} were introduced into the soil. With direct use, these values were higher and amounted to N – 50–110, P_2O_5 – 30–50, K_2O – 60–150 kg ha^{-1}, which is equivalent to the application of 10–22 t ha^{-1} of cattle manure. The conditional balance of nutrients (N, P, K) was higher with the direct use of green manure compared to the combined application by an average of 10–20%.

The balance of humus in the green manure-potato-barley crop rotation was negative in all variants. However, with the direct use of oil radish, it was close to deficit-free. A positive humus balance was observed only in the variant with cattle manure of 40 t/ha. With the combined use of green manure, the humus balance indicators for all crops were lower than with its direct use. This is due to both lower doses of plowed green mass than with single mowing and the use of the first mowing crop for fodder purposes.

The maximum yield of potatoes with direct use of green manure was in the variant "oil radish + Fon + N_{180}" and amounted to 29.5 t ha^{-1}, while with the combined use of the same variant it was 23.2 t ha^{-1}. In general, the yield of potatoes with direct use of green manure was higher than with the combined one by an average of 2.0–5.0 t ha^{-1} or by 5–15%.

Table 3.59

Dependence of yield and soil respiration rate on the amount of plowed green manure – oilseed radish (Kiselev, 2012)

Indicators	Direct use of green manure		Use of the 1st mowing for fodder, the second for green manure (combined)	
	regression equation	correlation coefficient	regression equation	correlation coefficient
The amount of plowed green manure and potato yield after its application	y = 0.209x + 177.7	0.996	y = 0.088x + 206.8	0.920
The amount of plowed green manure and the yield of spring barley in the aftermath of its application	y = 0.006x + 20.85	0.946	y = 0.012x + 19.19	0.893
The intensity of soil respiration under potatoes and the amount of green manure plowed (direct effect)	y = 0.002x + 1.452	0.929	y = 0.006x + 0.962	0.906
The intensity of soil respiration under spring barley and the amount of green manure plowed (aftereffect)	y = 0.002x + 1.266	0.974	y = 0.007x + 0.3	0.835

The same studies (Kiselev, 2012) found that starting from a nitrogen dose above N_{60}, the yield of oil radish green mass exceeded the MPC for nitrates by 2.5–3 times. Therefore, the dose of nitrogen for fodder purposes and in the combined use of oil radish as a green manure should not exceed 60 kg ha^{-1}, which confirms our conclusions about the peculiarities of fertilizing oil radish when it is grown for fodder purposes.

It is important to note that the experience of the so-called "green mulching" is widely used, especially in European countries. Most often, lupine, oil radish, white mustard, alfalfa, horse beans, sainfoin, clover are used. As mulch, the mowed green mass is scattered on the soil surface, but a greater effect can be obtained by mixing it with the topsoil with disk tools.

Another important factor in the importance of oil radish as a phytomeliorant is its use as a green manure on radioactively contaminated soils. Chernilevsky et al. (2003) note that oil radish can be effectively used even on sod-podzolic soils with a cesium contamination density of more than 5 Ci km^{-2} due to low values of radioactive isotope transfer coefficients into the plant (Table 3.60).

Table 3.60

Transition coefficients (TC) of Cesium-137 from sod-podzolic soil to different types of fodder crops (Chernilevsky et al., 2003)

Fodder crops (leaf and stem mass)	Conversion rate (CR)*	Fodder crops	Conversion rate (CR)
Kostrytsa	0.02	Barley	0.10
Visianytsia	0.05	Oats	0.10
Tymofiivka	0.05	Paisa	0.20
Collective bentgrass	0.20	Mallow	0.30
Meadow foxtail	0.32	Vetch	0.21
Fierce	0.10	Vetch	0.30
Oilseed radish - green mass	0.20	Alfalfa	0.50
- seeds	0.30	Clover	0.50
Rapeseed	0.40	Sweet clover	1.20
Fodder cabbage	0.70	Amaranth	1.50

PC* – proportionality (transition) coefficient, (Bq kg^{-1})/(kBq m^{-2}).

Due to the low values of the conversion coefficient, oil radish is recommended as an annual organic ameliorant to reduce the accumulation of radioactive isotopes (in particular, cesium) in crop products by 1.2–1.5 times.

Thus, oil radish should be recommended in biological systems of technologies aimed at restoring the fertility of disturbed lands, providing green manure fertilization systems in various cultivation systems, and as an active and effective phytosanitary of the field.

According to the research of Klymenko et al. (2001), the biological activity of soils largely depends on the application of fertilizers, primarily organic fertilizers. The use of mineral fertilizers does not lead to an increase in most indicators of soil biological activity, and also negatively affects the development of microorganisms. Only an organic-mineral fertilizer system provides a sustainable increase in soil biogenicity and positive changes in the species composition of microorganisms: the number of nitrogen-fixing bacteria increases. Physical processes in the soil are extremely important for soil fertility. Mineral fertilizers have been shown to stimulate crop development by increasing the content of organic matter in the soil and thus indirectly affecting its physical properties. Organic fertilizers have a direct effect on soil physical properties, improving them

It has been established that green manure affects the allopathic activity of the soil. Thus, the study of the allopathic activity of the soil revealed that in the process of decomposition of the green mass of oil radish and white mustard in both concentrations, there is a stimulation of biotics, especially during the 2nd growing season. The joint use of green manure improved the allopathic state of the soil in the 2nd year of the experiment (Table 3.61).

Among the nonspecific organic substances of the soil, an important place is occupied by phenolic carboxylic acids, which can be formed during the decomposition of plant tissues by microbial degradation of lignin. They determine the degree of soil humification and are allopathically active substances (Grodzinsky, 1991; Blum, 2004). An increase in the content of phenolic carboxylic acids in the soil of the experimental variants by 1.2–1.7 times compared to the control 6 months after the introduction of unhumified organic matter was observed, mainly due to ferulic and coumaric acids (Pavliuchenko, 2011) (Table 3.62).

Table 3.61

Allelopathic activity of the soil at different doses of non-humified organic matter (watercress root growth, % to control) (M ± m) (Pavlyuchenko, 2011)

Variant	Number of months after application of organic matter					
	1	3	6	12	14	17
Soil + white mustard (5%)	117.9 ± 3.54	113.2 ± 3.40	84.3 ± 2.53	115.1 ± 3.45	116.1 ± 3.48	137.9 ± 4.14
Soil + white mustard (2,5%)	102.0 ± 3.06	112.6 ± 3.38	76.7 ± 2.30	120.8 ± 3.62	105.4 ± 3.16	137.9 ± 4.14
Soil + oilseed radish (5%)	112.6 ± 3.38	103.4 ± 3.10	89.9 ± 2.70	134.9 ± 4.05	154.4 ± 4.63	147.7 ± 4.43
Soil + oilseed radish (2,5%)	101.3 ± 3.04	107.5 ± 3.22	87.4 ± 2.62	131.1 ± 3.93	149.0 ± 4.47	134.1 ± 4.02
Soil + white mustard (2,5%) oilseed radish (2,5%)	93.4 ± 2.80	98.9 ± 2.97	86.2 ± 2.59	121.7 ± 3.65	127.5 ± 3.82	130.3 ± 3.91

Table 3.62

Phenolic carboxylic acids content in soil 6 months after application of non-humified organic matter, mg/kg (M ± m) (Pavlyuchenko, 2011)

Acid	Variant					
	Control (syringaria soil)	**Soil + white mustard (5%)**	**Soil + white mustard (5%)**	**Soil + white mustard (5%)**	**Soil + white mustard (5%)**	**Soil + white mustard (5%)**
Ferulova	6.4 ± 0.26	9.0 ± 0.36	8.6 ± 0.34	9.7 ± 0.39	10.1 ± 0.40	7.8 ± 0.31
p-Kumarova (trans-)	9.0 ± 0.36	14.0 ± 0.56	13.6 ± 0.54	14.5 ± 0.58	12.9 ± 0.52	11.3 ± 0.45
p-Coumarova (cis-)	5.3 ± 0.21	10.7 ± 0.43	10.1 ± 0.40	13.3 ± 0.53	9.8 ± 0.39	8.0 ± 0.32
o-Kumarova	7.0 ± 0.28	11.7 ± 0.47	9.0 ± 0.35	12.1 ± 0.48	10.8 ± 0.43	9.1 ± 0.36
Syringic	3.2 ± 0.13	5.8 ± 0.23	5.0 ± 0.20	4.7 ± 0.19	6.0 ± 0.24	4.0 ± 0.16
Vanillin	4.9 ± 0.20	6.6 ± 0.26	6.2 ± 0.25	7.1 ± 0.28	5.5 ± 0.22	5.1 ± 0.20
p-Oxybenzoic	4.7 ± 0.19	5.5 ± 0.22	5.7 ± 0.23	6.5 ± 0.26	6.4 ± 0.26	5.2 ± 0.21
Total	40.5 ± 1.62	63.3 ± 2.53	58.2 ± 2.33	67.9 ± 2.72	61.5 ± 2.46	50.5 ± 2.02

After 17 months of green mass decomposition, the amount of phenolic carboxylic acids in the soil decreased by 1.7–2.0 times. The content of coumaric acids decreased significantly. At the same time, the concentration of phenolic carboxylic acids in the control variant remained almost unchanged, which indicates the important role of green manure crops in the intensification of humus formation processes (Table 3.63).

This conclusion is confirmed by the results obtained in determining the humus content. The introduction of unhumified organic matter of white mustard and oil radish in different doses contributed to a gradual increase in its content by 10-40% compared to the control.

Reducing the phytotoxicity of syringaria soil under the influence of green manure affected the physiological state of plants, in particular the content of the main photosynthetic pigments, and growth processes.

An increase in the content of chlorophylls a and b and carotenoids in the leaves of seedlings was noted a month after the introduction of organic matter. After 17 months, the best results were obtained in variants with separate application of oil radish plant mass in doses of 2.5% and 5%.

The concentration of carotenoids in the leaves of seedlings in all experimental variants during the experiment significantly increased compared to the control (Table 3.64). Since carotenoids play an important role in the formation of protective mechanisms of the photosynthetic apparatus of plants (Taran, 1999; Vasyl'yeva, 1997), the increase in their content with the introduction of organic matter of green manure contributed to the increase of adaptive capacity of lilac to the action of the allopathic factor.

The growth of lilac seedlings was the highest in the variants with oil radish (2.5% and 5%) and exceeded the control values by 36–48%.

Table 3.63

Content of phenolic carboxylic acids in soil 17 months after application of unhumified organic matter, mg/kg (M ± m) (Pavlyuchenko, 2011)

Acid	Variant					
	Control (syringaria soil)	Soil + white mustard (5%)	Soil + white mustard (5%)	Soil + white mustard (5%)	Soil + white mustard (5%)	Soil + white mustard (5%)
Ferulova	7.5 ± 0.30	5.8 ± 0.23	6.5 ± 0.26	5.7 ± 0.23	7.1 ± 0.28	5.7 ± 0.23
p-Kumarova (trans-)	10.0 ± 0.40	9.0 ± 0.36	7.2 ± 0.29	9.1 ± 0.36	8.0 ± 0.32	6.2 ± 0.25
p-Coumarova (cis-)	4.4 ± 0.18	4.4 ± 0.18	3.1 ± 0.12	3.3 ± 0.13	3.8 ± 0.15	2.6 ± 0.10
o-Kumarova	6.0 ± 0.24	6.8 ± 0.27	5.0 ± 0.20	4.8 ± 0.19	5.6 ± 0.22	4.3 ± 0.17
Syringic	4.0 ± 0.16	2.8 ± 0.11	2.5 ± 0.10	3.1 ± 0.12	3.1 ± 0.12	2.5 ± 0.10
Vanillin	5.6 ± 0.22	4.5 ± 0.18	3.2 ± 0.13	4.5 ± 0.18	4.6 ± 0.18	3.2 ± 0.13
p-Oxybenzoic	3.6 ± 0.14	3.4 ± 0.14	2.7 ± 0.11	3.8 ± 0.15	3.6 ± 0.14	2.7 ± 0.11
Total	41.1 ± 1.64	36.7 ± 1.47	30.2 ± 1.21	34.3 ± 1.37	35.8 ± 1.43	27.2 ± 1.09

The use of non-humified organic matter of green manure crops, such as oil radish and white mustard, can be recommended as a means of improving the root soil and increasing the adaptive capacity of lilac plants in continuous long-term cultivation. The introduction of green mass of green manure helped to reduce the intensity of the allopathic soil regime during long-term lilac culture, which had a positive effect on the physiological processes of plants. The highest efficiency was found when applying oil radish in doses of 2.5% and 5% by weight of soil.

Table 3.64

Content of main photosynthetic pigments in leaves of lilac seedlings, mg% of crude matter (M ± m) (Pavlyuchenko, 2011)

Variant	Number of months after application of organic matter					
	1		6		17	
	chlorophyll	carotenoids	chlorophyll	carotenoids	chlorophyll	carotenoids
Control (syringaria soil)	242.0 ± 7.3	44.8 ± 1.3	248.0 ± 7.4	43.1 ± 1.3	239.7 ± 7.2	42.2 ± 1.3
Control (syringaria soil)	261.4 ± 7.8	52.0 ± 1.6	280.1 ± 8.4	51.8 ± 1.6	325.3 ± 9.8	55.4 ± 1.7
Control (syringaria soil)	249.5 ± 7.5	50.2 ± 1.5	275.2 ± 8.3	53.0 ± 1.6	306.9 ± 9.2	57.5 ± 1.7
Control (syringaria soil)	280.9 ± 8.4	55.2 ± 1.7	310.5 ± 9.3	59.0 ± 1.8	326.8 ± 9.8	61.7 ± 1.85
Control (syringaria soil)	253.0 ± 7.6	51.6 ± 1.6	300.2 ± 9.0	54.1 ± 1.6	311.8 ± 9.3	55.5 ± 1.66
Control (syringaria soil)	248.5 ± 7.5	47.3 ± 1.4	265.5 ± 8.0	49.0 ± 1.5	308.7 ± 9.3	50.4 ± 1.5

The positive formative role of different types of green manure on soil microbiological activity has been proven (Slavkina, 2019). The variants of the experiment in which the microbiological analysis was carried out were as follows: 1) no fertilizer (control); 2) white mustard + winter vetch; 3) oats + rapeseed + barley; 4) annual lupine; 5) oil radish; 6) oil radish + lupine.

Plowing green manure changed the content of soil organic matter, which, in turn, led to a change in the structure of the soil microorganism complex. The introduction of fresh organic matter into the soil increased its biogenicity by 15–40% (Table 3.65). Microorganisms that reproduce in the soil at the expense of organic matter of dead plant residues largely determine soil microbiological conditions for plant growth. Their activity determines the course of agronomically valuable processes in the soil, including the transformation of humus substances and the accumulation of mineral nutrients, primarily ammonia. In the studied variants, the number of ammonifying bacteria (NAB) was 1.5–4 times higher than in the control variant. An increase in the number of microorganisms that assimilate mineral forms of nitrogen (MN) was observed in the soil under a mixture of white mustard with winter vetch and annual lupine (plowing depth 15–18 cm). The activation of ammonifying and nitrifying microflora after plowing green manure crops ensured the supply of mineral nitrogen to the soil.

Due to the difference in the chemical composition of plant organic matter, the number of microorganisms in some cases increased due to different groups.

When plowing white mustard with winter vetch and annual lupine, the activity of ammonifying microorganisms, actinomycetes, and pedotrophs increased to a greater extent. An increase in the number of microorganisms of these groups provides a greater supply of mineral nitrogen to the soil. The joint application of slowly decomposing mustard components with a lightly hydrolyzed legume component – winter vetch – contributed to a faster assimilation of these organic substances by soil microorganisms and increased the rate of their mineralization.

After plowing a mixture of oats with rapeseed and barley, the number of fungi, ammonifiers, and oligonitrophiles increased. The high number of pedotrophic microflora (28.6 million per hectare of soil) and pedotrophicity coefficients (1.3–1.6) indicated enrichment of the soil with mobile organic matter and increased humus formation.

Due to the lack of nitrogen in the chemical composition of the green manure mixture, the decomposition of plant mass was restrained. This situation is unfavorable because microorganisms will replace the lack of nitrogen by mineralizing humus compounds. Therefore, after plowing green mass with a huge predominance of cereals, it is necessary to apply additional amounts of nitrogen fertilizers.

The fresh organic mass of green fertilizers stimulated the activity of cellulose-degrading bacteria (cellulose destruction reached 80–90%). Due to the activation of cellulose degraders, the supply of new carbohydrates to the soil increased. High cellulosic activity was observed for three years after the green manure was planted and contributed to maintaining a positive humus balance in the soil.

Table 3.65

The influence of green manure crops on the number and ratio of major and trophic groups of microorganisms in meadow-sod soil (thousand/ha of soil) (Slavkina, 2019)

Variant	Depth of earnings, cm	Bacteria	Actinomycetes	Mushrooms	Oligotrophs	Pedophiles	Total number of micro-organisms	The ratio of trophic groups		
								KAA MPA	Olig MPA	PA MPA
I experience										
Control 0–20 см		12733	4839	83.0	10869	13486	49547	1.1	0.9	1.0
20–40		9720	4720	97.0	9120	13280	45137	1.2	0.8	1.2
White mustard + winter mustard										
0–20 cm	15–18	55063	8063	83.0	25292	44666	164167	0.7	0.5	0.8
20–40 cm	25–28	12607	2397	77.0	14094	19592	57571	0.7	1.0	1.3
Oats + rape + barley 0–20 cm	15–18	17812	2155	78.0	14843	28625	76445	0.8	0.8	1.6
20–40 cm	25–28	16250	2125	250.0	19250	19500	68167	0.8	1.2	1.3
II experience										
Control 0–20 cm		21043	3068	121.0	12233	10069	51057	0.4	0.6	0.8
20–40 cm		8320	2000	74.0	7560	9720	47914	1.1	0.9	0.8
Oilseed radish 0–20 cm	15–18	11968	3136	58.9	32938	33110	90043	1.5	2.7	2.8
20–40 cm	25–28	6435	2117	37.3	12785	15240	40212	0.9	1.9	2.4
Annual lupine 0–20 cm	15–18	17466	6507	100.0	40784	44540	137390.0	2.0	2.3	2.6
20–40 cm	25–28	19234	5113	113.0	244544	38822	104464	1.1	1.3	2.0
Oilseed radish + lupine										
0–20 cm	15–18	18102	5796	147.0	39648	51828	130263	1.1	2.2	2.9
20–40 cm	25–28	12886	3328	134.0	25770	45568	99015	1.1	2.0	3.5

When oil radish, annual lupine and their mixture were used as green manure, the most effective effect on soil fertility was provided by annual lupine and joint application of oil radish with annual lupine.

Despite the high yield of green mass of oil radish, plowing this crop did not contribute to a noticeable increase in microbiological activity, the number of all trophic groups studied was low. The maximum humus content was observed after the annual lupine was embedded in the soil. The highest cellulosolytic activity was observed here, which is the main link in microbiological activity. The leading position of lupine in increasing the content of labile humus substances, despite the low yield of green manure, is associated with an increase in the soil of easily mobilized nitrogen compounds. The microbiological activity of the soil has increased significantly. A sufficient amount of nitrogen substances determined the most optimal mode of life of microorganisms in terms of humus formation.

A microbiological indicator of the intensity of humus formation processes is the indicator of microflora pedotrophicity. The highest coefficients of pedotrophicity were after plowing annual lupine and lupine together with oilseed radish (2.6–3.5). An increase in pedotrophicity by 1.5 times was observed after all green manure.

The increase in the total number of spore-forming bacteria, especially p. Bacsubtilis, the appearance of Bac. megaterium bacilli, the enrichment of the species composition of actinomycetes, oligonitrophils indicated an increase in mineralization processes and a more intense nature of the transformation of organic nitrogen and carbon in the soil after plowing green manure.

An increase in the total number of fungal microflora and its diversity indicated an improvement in carbohydrate balance. As a result of decomposition of plant organic matter in the soil, favorable nutritional conditions were created for the saprophytic fungus Trichoderma.

The decrease in the number of fungi p. Penicilium and p. Fusarium indicated an improvement in the phytosanitary situation in the soil.

The authors of the study (Slavkina, 2019) concluded that the impact of green manure biomass was manifested in an increase in the total number and species diversity of microorganisms, and enrichment of the soil with mobile organic matter. The most favorable microbiological regime was observed in the variant of white mustard + winter vetch, where the processes of nitrogen and carbon transformation were more balanced as the plant mass decomposed. The activation of the vital activity of all trophic groups of microorganisms after plowing green fertilizers created favorable conditions for the synthesis of organic matter.

The positive impact of green manure on a number of soil regimes was also noted in soil studies at Agroecology, where the green manure fertilization system is widely used.

The degree of supply of soil with mobile forms of phosphorus and potassium is very high against the background of low humus and mineral (ammonium) nitrogen content (Table 3.66).

The average content of humus and phosphorus in the soil after plowing mustard is somewhat lower than in the soil of the background variant, which is due to the data obtained from the analysis of the sample of the third elemental plot. At the same time, the availability of mobile potassium and ammonium nitrogen, on the contrary, is much lower in the background plot.

Table 3.66

Accounting of green mass yield of experimental crops, kg m^{-2} (Kharitonov and Shakhov, 2016)

Crop	Repeatability				On average
	1	2	3	4	
First sowing period					
Oilseed radish	2.06	2.15	2.04	2.06	2.08
White mustard	0.84	1.14	0.97	0.90	0.96
The second sowing season					
Oilseed radish	2.10	2.04	2.10	1.34	1.90
White mustard	2.23	2.55	2.29	2.61	2.42

The content of mobile potassium is the most stable, with only 4% variability. The most pronounced spatial heterogeneity of the site is in the content of mobile phosphorus compounds, with a strong variability of 46%. Moderate variability was observed in the content of organic matter (humus) and ammonium nitrogen in the soil – 22%. Thus, when mustard was plowed, there was a slight increase in the absorption capacity due to an increase in the amount of absorbed bases, as well as ammonium nitrogen and mobile potassium compounds.

The yield of green mass of oil radish averaged 2.08 kg m^{-2} (with a plot area of 3.14 m^2), which is 2.2 times higher than the yield of white mustard, or 11.2 t ha^{-1} (Table 3.67). It should be noted that the crop yields were very low even compared to the data obtained under production conditions. Accounting for the yield of green manure crops of the second sowing period showed that at late sowing dates, white mustard developed more actively, which provided a green mass yield of 2.42 kg/m^2 (plot area 1.57 m^2), which is 1.3 times higher than the yield of oil radish, and 5.2 t ha^{-1}. When assessing the total green mass of green manure incorporated into the soil, it should be borne in mind that re-sowing of crops was not carried out over the entire plot area, only on half of it. Accordingly, for variant 2, the average yield of green mass of white mustard and oil radish of the first mowing should be calculated based on the results of the fourth and third replication, and for variant 1 – the first and second replication (Table 3.68).

Thus, the amount of white mustard applied in variant 2 (two terms of sowing and embedding the crop in the soil) was 3.5 times higher than in variant 1 (one-time sowing of the crop); for oil radish, the difference between the variants was 1.9 times. The advantage of radish over mustard in variant 2 is less pronounced than in variant 1, the differences were 1.2 and 2.2 times, respectively.

The conditions for the growth and development of crops are not least determined by the physical and chemical characteristics of soils, and green fertilizers have a positive effect on them.

Evaluating the change in soil acidity, was note the following: according to the value of pH_{KCl} (exchangeable acidity), the soil can be characterized as slightly acidic. The double dose of green manure contributed to a slight decrease in acidity (by 0.1 pH units in the soil under mustard and by 0.05 – under radish), the soil under radish was slightly more acidic than under mustard. Similar changes were observed in hydrolytic acidity, which varied from 1.4 to 1.74 mg-eq 100 g^{-1} of soil.

At the same time, oil radish had a slightly greater positive effect than mustard on the amount of absorbed bases: after “smelling” one dose of fertilizer (green mass of the first sowing period), the difference was 0.7 mg-eq 100 g^{-1}, and a double dose (embedding the green mass of two mowing) – 1.2 mg-eq 100 g^{-1}. Thus, mustard influenced the change in soil acidity, and radish influenced the amount of absorbed bases, as a result of which the soil saturation with bases under both crops was equivalent and very high, increasing as the plant mass was added to the soil.

Table 3.67

The influence of siderates on the physical and chemical parameters of the soil (Kharitonov and Shakhov, 2016)

Variant	White mustard		Oilseed radish	
	"plowing" of the 1st term sowing	"ploughing" of two terms sowing	"plowing" of the 1st term sowing	"ploughing" of two terms sowing
C/humus, %*	1.04/1.79	1.07/1.84	1.09/1.84	1.30/2.24
pHкcl	5.10	5.20	5.05	5.10
$H_г$, mg–ekv/100 г	1.54	1.40	1.74	1.68
S, мг–екв/100 г	9.20	12.50	9.90	13.70
ЕКО, мг–екв/100 г	10.74	13.90	11.64	15.38
V, %	85.7	89.9	85.0	89.1

* in the numerator – carbon, in the denominator – humus (coefficient of conversion 1.724).

Table 3.68

The effect of siderates on the retention of available forms of nutrients (Kharitonov and Shakhov, 2016)

Indicator	White mustard		Oilseed radish	
	"plowing" of the 1st term sowing	"ploughing" of two terms sowing	"plowing" of the 1st term sowing	"ploughing" of two terms sowing
P_2O_5, mg kg^{-1}	158	150	138	151
K_2O, mg kg^{-1}	164	185	163	159
NH_4, mg kg^{-1}	4.5	4.5	9.0	5.5
NO_3, mg kg^{-1}	29.0	45.0	36.5	47.5
$N–NO_3$ + N–NH, mg kg^{-1}	10.0	13.7	15.2	15.0

The content of organic matter in the soil increased with the introduction of green mass, and its growth corresponded to the amount of plant mass that entered the soil: The minimum content of organic carbon was noted at the "flavoring" of mustard in the first term of sowing (1.79%), which is 0.05% less than when planting oil radish, and the maximum – at two-time cultivation and introduction of radish green mass into the soil (2,24%) when using mustard (by 20 mg kg^{-1}), and at a double dose (total application of green fertilizer of two sowing dates) was equivalent, and in the soil under mustard there was a slight decrease (by 8 mg kg^{-1}), and under radish – an increase (by 13 mg kg^{-1}). Other data were obtained taking into account changes in the content of mobile potassium compounds. Accounting for the amount of K_2O in the soil after a single application of green fertilizer showed the equivalence of crops, while with two applications under mustard, a significant increase in soil potassium availability was observed (by 21 mg kg^{-1}), while under radish the changes were insignificant with a downward trend.

The content of ammonium nitrogen in the soil under mustard did not change depending on the amount of green mass incorporated into the soil and was lower than in the soil after radish cultivation. The change in the amount of NH4 in the soil under radish was inversely related to the amount of planted green mass: with one-time planting, the amount of this form of nitrogen in the soil was 1.6 times higher than with two-time planting. The nitrate content varied from 29.0 to 47.5 mg kg^{-1}. As with ammonium nitrogen, a slightly higher amount of NO_3, especially when taking into account the content after plowing one dose of green fertilizer, was observed in the soil when planting oil radish, the difference with mustard was 7.5 mg kg^{-1}. With the introduction of a "double" dose of green manure, the differences decreased to 2.5 mg kg^{-1}, and the total nitrate content in the soil increased by 55 and 30%, respectively, when mustard and radish were "plowed" together.

The use of oil radish as a green manure ensured a greater accumulation of mineral nitrogen in the soil than mustard (by 5.2 and 1.3 mg kg^{-1}, respectively, for variants 1 and 2). At the same time, the stock of mineral nitrogen in the soil under this crop was practically independent of the dose, and when mustard was planted, it increased as the mass of plants introduced into the soil increased.

In the transitional zone of the southern Forest-Steppe – northern Steppe, previous studies have shown (Kolomiets et al., 2013) that after harvesting spring barley, using the optimal use of periods when favorable weather conditions prevail, green manure crops with a short growing season can be grown. Improving soil fertility is one of the main ways to increase agricultural production, save energy and preserve environmental sustainability. It is achieved mainly through mineral fertilizers and ameliorants in combination with agrotechnical measures. When applying chemicals, it is necessary to take into account their negative impact on the environment and toxicological and hygienic characteristics of plant products. In the current environment, the role of local organic fertilizers, which stabilize the humus content in the soil when applied systematically, is significantly increasing. To adapt green manure crops to the farming system, we studied the growth processes of green manure and their impact on sugar beet yields. Mineral fertilizer application rates for the crop were determined depending on the soil nutrient supply and the planned yield (Table 3.69).

The yield of green mass of sideral crops was in the range of 243–332 c/ha (Table 3.70). In terms of value, this can be equated to the application of 30 tons of manure/ha. A comparison of the yield of sugar beets grown on black steam, siderate and the variant with the introduction of a calculated dose of mineral fertilizer shows the feasibility of sideration, since the collection of root crops with mineral and organic fertilization amounted to 361 and 365 t ha^{-1}, respectively, the control (black steam) without fertilizer provided a lower yield level – 282 t ha^{-1} (Table 3.71)

Table 3.70

Fertilizer rates (kg/ha per year) for sugar beet depending on the height of the planned harvest and the availability of nutrients in the soil (Kolomiets et al., 2013)

Planned harvest, t ha^{-1}	The content of nutrients in the soil layer, mg per 100 g											
	nitrogen				phosphorus				potassium			
	0–10	10–15	15–20	20–25	2–5	5–10	10–15	15–20	2–4	4–8	8–12	12–18
250	75	50	40	25	70	55	30	10	65	55	40	25
350	105	75	55	30	100	75	45	15	95	75	55	30
450	135	95	70	40	125	95	55	20	120	95	70	40

Table 3.71

Yield of green mass of sideral crops, 2011–2012. (Kolomiets et al., 2013)

Sidereal culture	Productivity, c ha^{-1}		
	2010	2011	Average for 2010–2011
White lupine annual	284	298	290
Buckwheat	277	293	285
White mustard	237	249	243
Oilseed radish	329	335	332

Sugar beet is a moisture-loving crop, but at the same time, thanks to a powerful root system capable of extracting moisture from deep horizons, it is relatively resistant to drought. The presence of about 30–40 mm of moisture in the arable layer of the soil ensures friendly seedlings of beets (Table 3.72).

They consume the largest amount of water in July-August. 300–320 mm of moisture is needed during this period to obtain the maximum yield, and approximately 450–500 mm during the entire growing season. In general, sugar beets in the regions of the northern steppe and southern forest-steppe are provided with a sufficient amount of moisture during the entire growing season. The occupied steam has a higher supply of moisture, since the above-ground mass of plants prevents its evaporation, which explains the increase in the yield of root crops after fertilizing with siderates.

On the basis of the translated researches, its authors concluded that with a well-established organization of production in the zone of unstable and sufficient moisture in Ukraine, green fertilizers can become a reliable planned measure for returning nutrients to the soil, improving the phytosanitary condition of fields, reducing environmental pollution and reducing production costs in crop production. The introduction of siderable crops as an integral component in the system of organic or ecological agriculture will ensure the sustainable restoration of soil fertility and the desired quality of the obtained products.

One of the important agrophysical indicators of soil fertility and structure is porosity and the ratio of volumes of different pore sizes. Porosity determines water permeability, water-holding and mobility capacity, and evaporation of water from the soil. It has a direct impact on the formation of reserves of productive moisture in the soil, which determines the level of yield of cultivated crops. Porosity affects the moisture content and its infiltration into the lower layers of the soil. Pores provide soil drainage, contribute to the inflow of oxygen and the release of carbon dioxide, the growth and spread of roots. Indirectly, the pores affect the change in the mechanical properties of the soil, facilitate its cultivation.

Table 3.72

Sugar beet yield, 2011–2012, depending on the type of fertilizer (Kolomiets et al., 2013)

Variants	Yield. c ha^{-1}			Increase, c ha^{-1}	
	201	2012	Average for 2010–2011	to control	to mineral fertilizer
Control – without fertilizer (black field)	279	285	282	–	–
Application of mineral fertilizer ($N_{76}P_{88}K_{48}$)	352	370	361	79	–
White lupine annual	369	380	375	93	14
Buckwheat	364	378	371	89	10
White mustard	356	375	366	84	5
Oilseed radish	358	370	364	82	3

The most favorable soil water-air regime and conditions for the growth and development of plants are created under the conditions of its total porosity at the level of 50–60% of the total volume of the soil, non-capillary – 12.5–30 and capillary – 30–37.5% and the ratio between non-capillary and capillary porosity in the range from 1:1 to 1:3 (Krut, 1986). For normal growth and development of plants, prevention of oxygen starvation of the root system of plants in the soil, high capillary porosity should be ensured, and aeration porosity should be at least 15% from the total soil volume (Berezhnyak, 1998; Tikhonenko, 2009).

Experimental studies (Mishchenko, 2004) were conducted on the basis of the educational scientific and industrial complex of the Sumy National University, which is part of the Myrhorod-Sum agro-soil district of the Left Bank forest-steppe part of Ukraine.

The following options were included in the scheme of the field experiment:

– Control (return of harvest and stubble residues to the soil).
– Post-harvest cultivation for siderate of oil radish.
– Cultivation after harvest on siderate of phacelia pysmolystia.
– Post-harvest cultivation of seeded buckwheat siderate.
– Application of 25 t ha^{-1} of manure.
– Application of mineral fertilizers $N_{125}P_{63}K_{150}$.

Cultivation of post-harvest crops was carried out after harvesting grain ears from the beginning of August to the end of October. For sideration, oil radish of the Raiduga variety was used at the rate of 30 kg/ha and Phacelia Balo – 25 kg/ha, Ivanna buckwheat – 90 kg/ha.

Experiments were carried out on typical low-humus, medium-loam chernozem. The average annual amount of precipitation at the research site ranges from 550 to 480 mm. The duration of the growing season is 170–180 days on average. The average date of autumn frosts is October 4–6. The duration of the postharvest vegetation period is 80–90 days, with an amount of precipitation of 130–134 mm.

Long-term loosening of the soil is facilitated by the activation of its biological activity, which is ensured by the use of post-harvest crops on green manure. The root system of sidereal plants also carries out microdrainage of the arable layer of the soil, which improves its porosity (Table 3.73). Compared to the control without siderates, a significant increase in the total, capillary, non-capillary and porosity of aeration in the soil layer 0–30 cm was observed for the variants of the studied sideral crops: after oil radish, respectively, by 2.5–3.3%, 2.1–2.6 , 0.3–0.7 and 3.5–4.1%; in the variant of post-harvest phacelium per siderate by 1.3–3.7%, 1.3–2.5, 0.7–1.1 and 1.9–4.7%, respectively.

Among the soil horizons, according to all experimental options, the highest indicators of general, non-capillary, and porosity aeration were in the 0–10 cm soil layer, which is associated with higher looseness, a better pronounced structure, a greater presence of root remains, burrowing animal movements, etc. With the deepening of the soil horizons to 30 cm, there is a tendency to a certain decrease of these types of porosity: total by 0.4–5.1%, non-capillary – by 0.6–3.1%, and aeration – by 2.7–9.8% .

Capillary porosity was the highest in the 10–20 cm soil layer – 32.2–34.3%, which is associated with the destruction of capillaries in the 0–10 cm layer as a result of mechanical loosening. The smallest capillary porosity was in the soil layer of 20–30 cm, 30.9–33.2%.

In the soil layer of 0–30 cm, among the studied sideral crops, the highest porosity indicators were after oil radish and phacelia; compared to the control and buckwheat on siderate, the difference in these options was significant – in terms of total porosity by 2.9–2.4%, capillary porosity – by 2.4–1.4%, and aeration – by 3.7–3.1%. The porosity of the soil in the variants of the application of post-harvest sideral crops directly depended on the root mass formed by them.

In oilseed radish, a direct and close correlation was established between root mass and capillary and aeration porosity (r = 0.82 and 0.71) and an average correlation with total aeration porosity (r = 0.4). On the variant with buckwheat per siderate, there was a high correlation dependence only for aeration porosity (r = 0.74), and an average one for total (r = 0.65) and capillary (r = 0.69) porosity. In phacelium per siderate, the correlation dependence was medium for capillary porosity (r = 0.64) and aeration (r = 0.59), and weak for total porosity (r = 0.29).

Thus, oil radish turned out to be the best post-harvest crop for the optimization of porosity parameters.

It is known that the use of traditional organic fertilizer – manure, improves the porosity of the soil. The influence of sider crops on soil porosity remains an insufficiently studied issue. Therefore, the influence of siderates and traditional fertilizers on the formation of optimal soil porosity during the cultivation of sugar beets and potatoes was further investigated (Table 3.74).

Both under sugar beets and potatoes, the highest indicators of total (51.4–54.7%), capillary (26.6–31.7%), non-capillary (20.8–27.2%) and porosity aeration (20.9–28.0%) in all soil layers were on the option of applying oil radish for siderate.

The indicators of total (by 0.6–0.7%), capillary (by 0.3–0.4%) and aeration porosity (by 0.6–0.8%) were significantly lower than the best option for the option of using phacelia on siderate; general (by 0.5–1.0%), capillary (by 0.3–0.4% – when growing sugar beets), non-capillary (by 0.5–0.8% – when growing potatoes) (Table.) and aeration porosity (by 0.5–0.8%) for the application option of 25 t/ha of manure; all types of porosity – on the option of using buckwheat for siderate.

Table 3.73

Effect of post-harvest siderates on soil porosity, % (average for 2000–2004) (Mishchenko, 2004)

Soil porosity	Soil layer, cm	Variant				LSD_{05}
		Control (without green manure)	Post-harvest green manure from oilseed radish	Post-harvest green manure from phacelia	Post-harvest green manure from buckwheat	
general	0–10	54.0	57.3	57.7	54.7	1.37
	10–20	53.6	56.1	56.4	53.7	1.25
	20–30	51.3	53.9	52.6	51.3	0.91
	0–30	52.9	55.8	55.6	53.2	1.10
capillary	0–10	31.2	33.8	33.7	32.1	0.83
	10–20	32.2	34.3	34.1	32.5	0.68
	20–30	30.9	33.2	32.2	31.4	0.40
	0–30	31.4	33.8	33.4	32.0	0.52
non-capillary	0–10	22.8	23.5	23.9	22.6	0.87
	10–20	21.4	21.9	22.3	21.2	0.65
	20–30	20.4	20.7	20.4	19.9	0.64
	0–30	21.5	22.0	22.2	21.2	0.68
aeration	0–10	33.5	37.6	38.2	34.1	1.57
	10–20	30.8	34.3	34.7	31.1	1.55
	20–30	26.5	30.1	28.4	26.6	1.18
	0–30	30.3	34.0	33.7	30.6	1.36

In general, the organic fertilizer variants resulted in an increase in all types of porosity compared to the control. The application of mineral fertilizers instead of organic fertilizers compared to the control led to a decrease in all types of porosity.

In the variants of sugar beet and potato cultivation with depth, there was a tendency to reduce the total soil porosity by 0.4–2.0%, non–capillary porosity by 0.1–1.2% and aeration porosity by 2.4–3.9%, which is associated with the illuvial process, in which products from the higher layers move to the lower ones, clog some pores and reduce the porosity of the lower horizons. In addition, the lower horizons of the soil are less structured.

Table 3.74

Influence of fertilizers and green manure on the porosity of soil horizons under sugar beet and potato, % (average for 2001–2005) (Mishchenko, 2004)

Option of fertilizer	Porosity, %											
	total			capillary			non-capillary			aeration		
	Шар ґрунту, см											
	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30
Sugar beet												
Control (without green manure)	51.7	51.3	50.1	30.4	30.9	30.0	21.3	20.4	20.1	25.7	22.9	20.1
Post-harvest green manure from oilseed radish	53.4	53.0	51.4	31.4	31.7	30.6	22.0	21.3	20.8	26.7	24.3	20.9
Post-harvest green manure from phacelia	52.8	52.3	50.7	31.0	31.3	30.2	21.7	21.0	20.5	26.1	23.6	20.1
Post-harvest green manure from buckwheat	52.0	51.6	50.3	30.7	30.9	30.0	21.4	20.7	20.3	25.6	23.1	20.0
Manure 25 t ha^{-1}	52.7	52.3	50.9	31.1	31.3	30.3	21.6	21.0	20.6	26.2	23.7	20.5
$N_{125}P_{63}K_{150}$	51.2	50.6	49.6	29.9	30.5	29.7	21.2	20.0	19.9	25.1	22.2	19.7
LSD_{05}	0.34	0.40	0.46	0.23	0.19	0.20	0.28	0.32	0.43	0.39	0.39	0.47
Potatoes												
Control (without green manure)	52.5	51.9	50.4	26.3	26.9	26.0	26.2	25.0	24.4	27.0	23.5	20.4
Post-harvest green manure from radish	54.7	54.0	52.0	27.4	27.7	26.6	27.2	26.3	25.4	28.0	24.9	21.0
Post-harvest green manure from phacelia	54.1	53.3	51.3	27.1	27.3	26.3	27.0	25.9	25.0	27.3	24.2	20.3
Post-harvest green manure from buckwheat	52.8	52.4	50.8	26.7	26.9	26.1	26.1	25.5	24.7	26.8	23.7	20.2
Manure 25 t ha^{-1}	53.8	53.0	51.4	27.3	27.5	26.4	26.5	25.5	24.9	27.3	24.1	20.5
$N_{125}P_{63}K_{150}$	51.9	51.3	49.8	25.9	26.5	25.7	26.0	24.8	24.0	26.3	22.8	19.9
LSD_{05}	0.61	0.62	0.37	0.33	0.27	0.27	0.62	0.50	0.35	0.34	0.46	0.43

The capillary porosity was also the lowest in the lower 20–30 cm soil layer. In the 10–20 cm soil layer, it was higher than in the upper 0–10 cm layer by 0.2–0.6%, which is due to the destruction of the vertical pores of the horizon during mechanical loosening when caring for sugar beet and potato crops. The dynamics of soil layer porosity of 0–30 cm under sugar beet and potato shows that the total porosity during the growing season decreased from 52.3–55.2 to 48.6–51.9 % and remained within optimal limits (> 50 %) only in the variants of plowing for green manure of post–harvest oil radish and application of 25 t/ha of manure.

The non–capillary porosity also decreased from 23.7–29.0 to 17.1–23.4 %, but did not exceed the optimal limits (12.5–30 %) for these crops.

The reason for its decline is the gradual compaction of the soil over time, which simultaneously contributed to an increase in capillary porosity from 24.7–30.2 to 26.1–32.5 %, which was within the optimal range (30–37.5 %) only when growing sugar beets using oil radish for green manure.

The porosity of aeration is related to the degree of soil loosening and moistening. At the beginning of sugar beet and potato cultivation in the soil layer of 0–30 cm, it was the highest – 22.6–25.8%, and in the middle of the growing season it decreased as much as possible (to 21.3–23.4%), and at the time of harvesting it increased to 23.1–24.7%, which is associated with a decrease in soil moisture reserves.

In all variants of nutrition backgrounds, the aeration porosity exceeded the limit of 15%.

When growing sugar beet and potatoes in the variant of using oil radish for green manure in the soil layer of 0–30 cm, the indicators of all types of porosity were the highest and closest to optimal (Table 3.75).

The total, capillary porosity (except for the variant of potato cultivation on the background of manure) and aeration porosity in the variants of using phacelia and 25 t/ha of manure for green manure were significantly lower than the best variant – by 0.6–0.9, 0.3–0.4 and 0.5–0.7%, respectively.

The use of oil radish and phacelia for green manure and the application of 25 t/ha of manure significantly exceeded the use of buckwheat for green manure and the control variant for all types of porosity of 0–30 cm of the soil layer. The variant of mineral fertilizers application in 0–30 cm soil layer significantly reduced the total, capillary and porosity of aeration compared to both the control and organic fertilizer backgrounds.

In our opinion, the increase in soil porosity under the influence of green manure and green manure is associated with an improvement in both soil structure and density.

This is due to an improvement in the intensity of micro– and mesofauna activity on the background of plowing radish and phacelia green manure and manure application, as evidenced by a close positive correlation between the structural coefficient and total soil porosity – r = 0.71–0.78; on the control and mineral fertilizer background, the correlation was of medium strength – r = 0.37 and 0.49.

The closest inverse relationship in sugar beet and potato crops was established in the variants of plowing post-harvest oil radish and phacelia for green manure between the density and total porosity of 0-30 cm of the soil layer – r = -0.98 and -0.99; it was slightly lower in the variants of buckwheat for green manure and the introduction of 25 t/ha of manure – -0.96 and -0.95, respectively.

The connection between the value of phytomass of post-harvest green manure crops and the total porosity and porosity of soil aeration is indicated by close and medium-density positive correlations.

The highest correlation between the amount of phytomass and total and porosity of aeration was found in the variant of growing oil radish on green manure – r = 0.66 and 0.73.

It was somewhat lower when using phacelia for green manure – r = 0.62 and 0.71 and the lowest in the variant of post-harvest buckwheat for green manure.

A positive and medium-density correlation was established between green manure phytomass and soil capillary porosity both in the cultivation of sugar beet and potatoes.

In the variant of using oil radish for green manure, the correlation coefficient was the highest when growing sugar beets (r = 0.52), and in the variant of using phacelia for green fertilizer – under potato crops (r = 0.55). In the variant of post-harvest buckwheat for green manure, the correlation coefficients were the lowest – r = 0.35 and 0.32. Thus, due to the improvement of soil structure and its density, the use of post-harvest green manure – oil radish – provided the most optimal indicators of total, capillary, non-capillary and porosity aeration for growing sugar beet and potatoes. Accordingly, the use of post-harvest green manure from oil radish, having the best indicators of soil porosity according to the results of the research, ultimately led to the highest yields of potato tubers of 30.9 t/ha and root crops of 36.6 t ha^{-1} (Table 3.76).

Table 3.75

Influence of fertilizers on soil layer porosity 0–30 cm under sugar beet and potato cultivation, % (average for 2001–2005) (Mishchenko, 2004)

Porosity, %	Mineral nutrition background						LSD_{05}
	control, without fertilizers	post-harvest green manure			Manure 25 t ha^{-1}	$N_{125}P_{63}K_{150}$	
		oilseed radish	phacelia	buck-wheat			
Sugar beet							
Total	51.0	52.5	51.9	51.3	52.0	50.5	0.34
Capillary	30.4	31.2	30.8	30.5	30.9	30.1	0.17
Non-capillary	20.6	21.3	21.1	20.8	21.1	20.4	0.28
Aeration	22.9	24.0	23.3	22.9	23.5	22.3	0.27
Potatoes							
Total	51.6	53.5	52.9	51.9	52.6	51.1	0.45
Capillary	26.4	27.2	26.9	26.5	27.0	26.1	0.27
Non-capillary	25.2	26.3	26.0	25.4	25.6	25.0	0.37
Aeration	23.6	24.6	23.9	23.6	24.0	23.0	0.23

Table 3.76

Effect of fertilizers on the yield of test crops, t ha^{-1} (Mishchenko, 2004)

Variants	Sugar beet		Potatoes	
	yield t ha^{-1}	increase, t ha^{-1}	yield t ha^{-1}	increase, t ha^{-1}
Control (without green manure)	30.0	–	24,8	–
Post-harvest green manure from radish	36.6	6.6	30,9	6,1
Post-harvest green manure from phacelia	35.2	5.2	29,3	4,5
Post-harvest green manure from buckwheat	31.3	1.3	25,7	0,9
Manure 25 t ha^{-1}	36.1	6.1	29,2	4,4
$N_{125}P_{63}K_{150}$	35.6	5.6	29,7	4,9
LSD_{05}	1.02		0.76	

During the analysis of soil porosity, it was found that the studied variants of post-harvest green manure had a significant increase in porosity compared to the control variant – plowing straw and post-harvest residues of winter wheat. Among the post-harvest green manure, oil radish had the advantage in porosity due to the highest yield of green manure, the root system of which contributed to the deepest soil drainage, and the wrapped phytomass – to the most intensive activity of soil biota, which resulted in improved soil structure and better soil loosening. Compared to an equivalent amount of manure, oil radish green manure also had a higher soil porosity during the period of sugar beet and potato cultivation. The background of mineral nutrition could not significantly compete with the variants of post-harvest green manure in terms of soil porosity, since this variant was inferior to the control one for the entire period of cultivation of row crops. Based on the above, we recommend to use post-harvest green manure of oil radish to improve soil porosity in the cultivation of sugar beet and potatoes.

It should also be noted that the importance of fertilizer biologization for the agricultural sector of Ukraine is an urgent issue of its successful implementation in the European space and allows to ensure the implementation of sustainable development goals in terms of ensuring food security of the state. Vinnytsia National University and the Uladovo–Lyulynetska breeding and research station as part of the All–Ukrainian Scientific and Educational Consortium are actively researching the issues of alternative fertilization systems, ensuring their environmental and soil protection component, transition to organic fertilization systems, development of regulations for the use of biofertilizers and biological products of growth–stimulating and growth–regulating nature within the framework of task 27. 00.02.01.F “To develop the scientific basis for biologization and improvement of fertilizer systems that increase crop productivity and stabilize soil fertility in the right–bank Forest–Steppe of Ukraine”.

Our research was conducted in 2019–2020 simultaneously at the experimental field of VNAU and at the Uladovo–Lyulynets breeding and research station. The research site, the VNAU experimental field, is represented by dark gray forest soils. Agrochemical potential of the field: humus content: 2.02–3.2%, easily hydrolyzed nitrogen 67–92, mobile phosphorus 149–220, exchangeable potassium 92–126 mg/kg of soil at pHxl 5.5–6.0. The research format is small plot, replicated 3 times. The research site of the Uladovo–Lyulynetska breeding research station (laboratory for agricultural problems and stationary agrochemical research in the Western Forest–Steppe zone of Ukraine) is represented by deep low–humus leached chernozems of medium loamy mechanical composition. The humus content is 3.9–4.4%. The reaction of the soil solution is pH 5.9–6.3, the degree of saturation with bases is 86–91%. The content of easily hydrolyzed nitrogen is 99–115, mobile phosphorus is 119–159, and exchangeable potassium is 116–142 mg/kg of soil. The research format was small plot, replicated 3 times. The research program included the study of the impact of green manure crops application options, taking into account the peculiarities of their morphogenesis and phytomass formation, on certain soil properties, the level of weediness of the field after their application with an assessment of the yield of corn (winter wheat precursor).

The object of the study was used to compare the effectiveness of different green manure options using white mustard (Carolina variety), oil radish (Zhuravka variety) and spring rape (Diamant variety).

The sowing time for all green manure variants was in the middle of the second decade of July in 2018 and in the beginning of the third decade of July in 2019. The sowing of green manure was preceded by disking to a depth of 8–10 cm in two traces. The parameters of green manure agrocenoses design were formed on the basis of general methodological recommendations for intermediate green manure, taking into account the species characteristics of the green manure crop: sowing was carried out by the usual row (15 cm) and wide–row (30 cm) method with a planting density of 2.2–2.5 and 1.5–1.7 million. units/ha of germinating seeds for white mustard, 2.7–3.0 and 1.5–1.7 million units/ha of germinating seeds for oil radish and 2.0–2.2 and 1.2–1.4 million units/ha of germinating seeds for spring rape. After sowing, the seeds were rolled. The process of soil green manure production corresponded to the same period for all types of green manure plants – budding and flowering by preliminary disking. The final incorporation of the green manure into the soil was carried out by plowing to a depth of 25–27 cm to ensure optimization of the agricultural requirements for growing corn for grain.

The determination of agrophysical parameters of the soil, such as total porosity, capillary porosity, aeration porosity, and density of compaction, was carried out in accordance with standardized methods. These parameters were determined in the field where the green manure was produced with the onset of physical maturity of the soil in spring. The herbological situation on the field was assessed by quantitative weight and structural and species methods in accordance with generally accepted methods. In the process of setting up experiments and their general methodological support, the peculiarities of conducting research with cruciferous crops were taken into account. Statistical processing of the research results was carried out in accordance with standard statistical methods using a package of appropriate computer programs.

Assessment of hydrothermal conditions of the growing season of the studied green manure crops (August-October) showed some differences during the relevant period of research, which affected the intensity of growth processes of different green manure crops and determined the direction of their influence on the formation of corn yield. It should be noted that in accordance with the biological characteristics of green manure crops, the conditions of the research period (July 2018-October 2018 and similarly July 2019-October 2019) can be attributed to moderately favorable from the point of view of ensuring the appropriate growth processes and the formation of an appropriate level of leaf mass. At the same time, the conditions of the fall of 2018 were more favorable for the growth and development of green manure plants in all respects than the conditions of 2019. Thus, for the conditions of the experimental field of VNAU, the vegetation period of green manure (Figures 3.19–3.20) in 2018 was characterized by the amount of precipitation of 273.4 mm at an average daily temperature of 16.6 ◦C and a value of GTC of 1.34. The same parameters for the green manure growing season in 2019 were 161.7 mm, 16.2 ◦C and 0.81, respectively.

The climatic parameters of the green manure growing season for the conditions of the Uladovo-Lyulynetska breeding and research station were similar in terms of both the average daily temperature and the amount of precipitation and amounted to 265.5 mm, 16.5 ◦C, 1.31 for the period of 2018, and 116 mm, 16.4 ◦C and 0.65 for the period of 2019, respectively. This nature of the differences affected the peculiarities of growth processes and the amount of green manure mass of green manure plants in comparison of the two research sites and allowed to further evaluate the role of the factor of climatic parameters in the efficiency of their use among the species group of cruciferous crops.

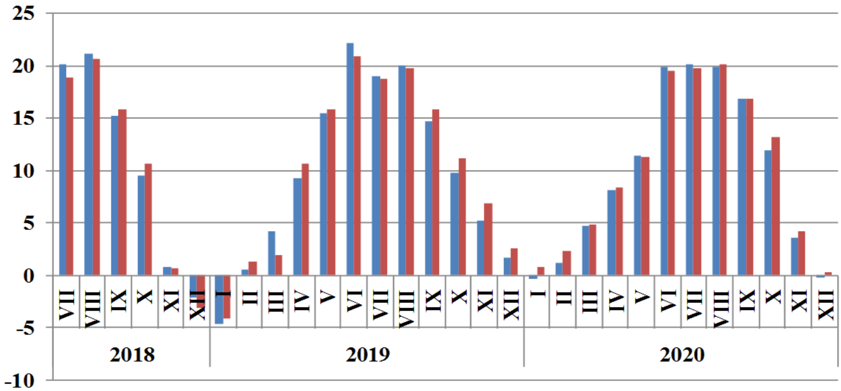

Figure. 3.19 – Average daily temperature over the study period, ◦C. (Blue color – Uladovo-Lyulynets DS, red color – VNAU Experimental Field) (based on the results of the author's own research)

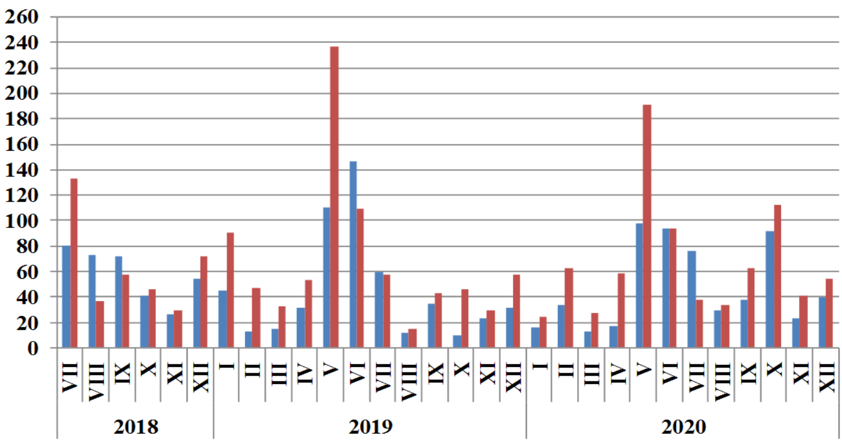

Figure 3.20 – Amount of precipitation over the study period, mm (blue – Uladovo-Lyulynets SSS, red – VNAU Experimental Field) (based on the results of the author's own research)

The obtained results of the research showed a significant difference in the effect of different types of green manure plants on the basic indicators of soil physical properties – porosity and density in the context of the studied layers of the arable horizon (0–30 cm) (Table 3.77) before the start of the main technological operations for growing corn for grain.

The use of all types of green manure plants contributed to the overall increase in both the total void space, including its subcategories, and the aeration void space. At the same time, this feature of the formation of porosity was noted both for chernozem soils in the conditions of the Uladovo–Lyulynets breeding and research station and for gray forest soils in the conditions of the experimental field of VNAU. This ultimately contributed to a decrease in soil density compared to the control variants. The most positive impact on this nature of changes was noted on average over the period of research in the variant of post–harvest green manure using oil radish, the use of which provided in the variant of conventional row sowing of green manure on chernozem soils an increase in total porosity in the soil layer of 0–30 cm by 8.4%, capillary – by 9.8%, non–capillary – by 6.5%, aeration porosity – by 13.1%. For the variant of wide–row sowing, these indicators were significantly lower and amounted to 3.5%, 3.9%, 2.8% and 6.0%, respectively.

On gray forest soils, the effectiveness of the formative effect in the trend of growth of indicators of agrophysical properties of the soil with the use of green manure was significantly higher. At the same time, as in the previous variant, the use of oil radish as a green manure had.

Thus, with row sowing, an increase in total porosity in the soil layer of 0–30 cm was observed by 12.5%, capillary porosity – by 11.9%, non–capillary porosity – by 13.3%, and aeration porosity – by 13.3%. With wide–row sowing, the corresponding range of indicators is almost two times lower. Compared to the variant of green manure with oil radish, the variant of green manure with white mustard on chernozem soils provided an increase in the total porosity by 5, 4 % (row sowing) and 1.7 % (wide–row sowing), capillary porosity – 7.2 % and 2.3 %, respectively, non–capillary porosity – 2.8 % and 0.9 %, respectively, aeration porosity – 11.3 % and 4.3 %, respectively.

Table 3.77

Soil porosity and density averaged at the stage of physical maturity of the soil before the start of mechanized operations for corn depending on the green manure variant (average for 2019-2020) (based on the results of the author's own research)

Porosity	Depth, cm	Control	White mustard		Oilseed radish		Rocket-cress		**LSD 05
			R*	W*	R*	W*	R*	W*	
1	2	3	4	5	6	7	8	9	10
In the conditions of the Uladovo-Lyulynets breeding and research station (deep low-humus black soil)									
Total	0-10	53.0	56.3	53.8	58.1	55.3	53.6	53.3	1.33
	10-20	52.8	55.3	53.9	57.1	54.5	53.8	53.2	1.18
	20-30	50.5	53.2	51.4	54.3	51.8	51.5	50.9	0.84
	0-30	52.1	54.9	53.0	56.5	53.9	53.0	52.5	1.08
Capillary	0-10	30.3	32.9	30.9	33.9	31.8	30.6	30.4	0.79
	10-20	31.5	33.1	32.3	34.2	32.7	32.1	31.7	0.64
	20-30	30.1	32.4	30.7	32.8	30.9	30.6	30.3	0.41
	0-30	30.6	32.8	31.3	33.6	31.8	31.1	30.8	0.67
Non-capillary	0-10	22.7	23.4	22.9	24.2	23.5	23.0	22.9	0.82
	10-20	21.3	22.2	21.6	22.9	21.8	21.7	21.5	0.61
	20-30	20.4	20.8	20.7	21.5	20.9	20.9	20.6	0.59
	0-30	21.5	22.1	21.7	22.9	22.1	21.9	21.7	0.74
Aeration	0-10	33.3	35.8	34.2	38.6	36.1	34.1	33.8	1.45
	10-20	30.6	33.9	32.1	34.9	32.1	31.5	30.9	1.47
	20-30	26.3	30.7	27.8	28.8	27.5	27.2	26.8	1.09
	0-30	30.1	33.5	31.4	34.1	31.9	30.9	30.5	1.39
Density, g cm^{-3}	0-10	1.30	1.23	1.28	1.20	1.25	1.28	1.29	0.05
	10-20	1.37	1.29	1.33	1.26	1.30	1.33	1.35	0.06
	20-30	1.40	1.34	1.36	1.31	1.36	1.36	1.38	0.05
	0-30	1.36	1.29	1.32	1.26	1.30	1.32	1.34	0.05
In the conditions of the VNAU experimental field (gray forest soils)									
Total	0-10	42.7	47.7	45	49.3	46.1	44.6	43.7	1.41
	10-20	40.4	43.7	41.8	45.2	42.8	42.0	41.4	1.22
	20-30	38.9	41.6	39.8	42.8	40.6	40.5	39.5	0.92
	0-30	40.7	44.3	42.2	45.8	43.2	42.4	41.5	1.20
Capillary	0-10	23.3	26.5	25.1	27.2	25.5	24.5	23.9	0.83
	10-20	22.6	24.1	23.5	25.1	23.9	23.6	23.2	0.71
	20-30	22.2	23.2	22.7	23.9	23.1	22.9	22.5	0.49
	0-30	22.7	24.6	23.8	25.4	24.2	23.7	23.2	0.69

(End of Table 3.77)

1	2	3	4	5	6	7	8	9	10
Non-capillary	0-10	19.4	21.2	19.9	22.1	20.6	20.1	19.8	0.91
	10-20	17.8	19.6	18.3	20.1	18.9	18.4	18.2	0.75
	20-30	16.7	18.4	17.1	18.9	17.5	17.6	17	0.68
	0-30	18.0	19.7	18.4	20.4	19.0	18.7	18.3	0.80
Aeration	0-10	20.5	22.4	21.9	23.6	21.8	20.9	20.7	0.56
	10-20	17.6	18.5	17.9	19.4	18.7	18.3	17.8	0.47
	20-30	13.9	14.9	14.2	15.8	14.3	14.3	14	0.41
	0-30	17.3	18.6	18.0	19.6	18.3	17.8	17.5	0.45
Density, g cm^{-3}	0-10	1.40	1.34	1.35	1.30	1.36	1.39	1.37	0.03
	10-20	1.50	1.38	1.43	1.35	1.41	1.49	1.49	0.04
	20-30	1.57	1.50	1.54	1.46	1.50	1.53	1.55	0.05
	0-30	1.49	1.41	1.44	1.37	1.42	1.47	1.47	0.04

Notes. * R – row seeding option, W – wide-row seeding option; ** – for values in % after conversion to arctg.

On gray forest soils, these growth values were generally 28.2% (row sowing) and 59.8% (wide-row sowing) higher than on black soil. The lowest level of growth of indicators was noted in the variant of using spring rape as a green manure – the average increase in the types of porosity by 2.0% for row and 0.92% for wide-row sowing on chernozem soils, and by 3.84% and 1.75%, respectively, on gray forest soils. As a result, the dynamics of porosity formation had a positive effect on the value of soil density with the maximum value of soil density optimization in the variant of row sowing with oil radish on chernozem soils at 1.26 g/cm^3, and on gray forest soils with the same sowing variant at 1.37 g/cm^3, which is 7.4% and 8.1% lower, respectively, compared to the control. We explain the results obtained by the specifics of the development and formation of the root systems of the studied green manure plants. In the case of oil radish (Fig.), a thickened taproot system with deep penetration into the soil is formed during the summer sowing period.

At the appropriate planting density, this ensures intensive drainage of the root layer of the soil, and the presence of morphologies with intensive thickening and intensive skeletal branching ensures intensive skeletonization of the corresponding soil layer, which ultimately provides a change in the corresponding values of porosity and density. In addition, the intensive radial growth of the root system of oil radish provides intensive differentiation of the soil layer into capillary and non-capillary structures with an increase in the overall aeration porosity.

In contrast to oil radish, in white mustard, the formation of the root system is aimed at the development of a pronounced taproot, but it is characterized by the formation of pronounced horizontal branching, less thickness and lower penetration depth in the part of maximum thickening. As a result, we noted less pronounced drainage of the topsoil and its differentiation into structural aggregates. These differences are more clearly noted in other studies, the results of which on the study of the dynamics and features of the formation of root systems of white mustard and oil radish are presented in Figures 3.21–3.22.

For spring rape during summer sowing, the formation of the root system in comparison with oil radish and white mustard was noted as the least intensive: the least development and radial thickening at a lower depth of penetration. As a result, these features are reflected in the influence of the respective types of green manure on the formation of soil porosity and its density. At the same time, based on our research, it should be noted that the use of green manure on soils with less favorable agrophysical properties provides a more significant positive effect in their optimization.

Regarding the influence of the sowing method on these indicators, it should be noted that for all types of green manure under wide-row sowing, a general increase in the habitus of the root system with its thickening and branching was observed, while reducing the overall depth of its penetration. However, this general increase does not compensate for the differentiation of the soil layer into strips with green manure plants and interstrip space without them.As a result, the average value of radial and vertical drainage is lower than in the variant of the row seeding method.

This is confirmed by the values of indicators for all types of green manure in comparison of row and wide–row sowing methods.

Our studies also showed a positive effect of the use of all types of green manure on the formation of quantitative and weight and species forms of weeds in the field before plowing green manure. The significance of this effect in comparison to the control was determined by the type of green manure plant. Thus, in the conditions of the Uladovo–Lyulynetska experimental breeding station, the maximum reduction of total weediness was noted in the variant of post–harvest green manure with oil radish for row sowing for different locations of the research by 59.8–66.3%, for wide–row sowing – by 50.5%–55.4%, which in the values of weed mass was 62.9–67.0% and 31.2–50.6%, respectively. The herbicide–regulating role of white mustard at its close value was on average 10.2–15.3% lower compared to oil radish. A similar indicator for spring rape was almost twice lower compared to the same variant of oil radish.

Figure 3.21 – Root system of oil radish (upper left position), white mustard (upper right position), spring rape (lower left position) and possible morphotypes of the root system of oil radish (lower left position) (black square size 2x2 cm) (based on the results of the author's own research)

It should also be noted that the maximum effect of the use of all types of green manure on both chernozem and gray forest soils was observed for biological groups of wintering weeds (total reduction within the types of green manure 32.3–70.3% for row and 26.0–47.5% for wide–row sowing) and late spring weeds (54.7–74.2% and 50.3–65.4%, respectively).

This species specificity of green manure effect is due to the development cycle of specific biological groups of weeds and aspects of their abundance when cultivating green manure in the summer and autumn growing season.

Figure 3.22 – Dynamics of root system formation of white mustard (left position) and oil radish (right position) (1 – 72 days, 2 – 64 days; 3 – 59 days; 4 – 52 days after full germination) (Source: https://kursi–floristiki.ru/ovoshchi/redka–maslichnaya–kak–siderat.html). Source: based on our own research.

It is also worth noting the effect of green manure not only on the number of weeds, but also on their weight.In particular, in the variant with a larger number of weeds, their weight is lower than the same number in other variants.

In particular, such a disparity in weed weight reduction while maintaining their number should be noted in the variant of white mustard and oil radish, which is evidence of the general suppressive effect of these types of green manure not only at the stage of weed germination, but, importantly, at the stage of its active growth.

Again, the explanation for such peculiarities of the impact of different green manure on the level of weed infestation should be noted that for all green manure variants, weed control efficiency depended on the growth rate of the aboveground vegetative mass, the intensity of closing the total field coverage with the assimilation surface of green manure plants. In turn, the growth rate of vegetative green manure aboveground mass depended primarily on the moisture conditions that develop in the first two to three weeks after sowing green manure. For both years of research and their locations, hydrothermal conditions were moderately favorable for the formation of the corresponding leaf–stem mass. However, the variants of conventional row sowing were more productive in terms of both the intensity of mass formation and herbological control of oil radish plants in relation to weeds of the post–harvest or post–mowing cycle of development (Fig. 3.23).

Thus, in the comparison of the row and wide-row variants of siderate formation, the intensity of exposure coverage of the surface of the accounting plots with siderate before the beginning of the stemming phase was on average 18.4–33.7% (depending on the year of observation) higher in the variant of conventional row sowing. The structure of the leaf-stem mass also varied. Thus, in the phase of the beginning of stemming in the version of the usual row sowing of oil radish, the share of the stem accounted for 25.6–30.9% and the share of leaves – 69.1–74.4%. For white mustard and spring mustard, these indicators were 32.6–40.2 and 59.8–67.4% and 35.1–46.3 and 53.7–64.9%, respectively. For the variant of wide-row sowing, this ratio in oil radish had a different character: 39.5–44.9 and 55.1–60.5%, respectively. For white mustard under wide-row sowing, the stem share was 2.8–5.2% less than for oil radish. In the version of the spring suripitia, the share of the stem increased by 2.8–4.5%. At the same time, we noted significant differences in the intensity of the rate of development of siderates. Thus, among the initial stages before the rosette phase, white mustard showed more intensive growth rates than oil radish and spring horseradish. However, starting from the stemming phase, oil radish plants show more intense growth rates, which, taking into account the greater biological adaptability of oil radish itself to low temperatures, are maintained until the period of siderate plowing. For the variant of spring sorghum with a lower level of autumn adaptation, the intensity of the growth of leaf-stem mass had the lowest rates and, accordingly, the format of its use by the factor of reducing field weediness had the lowest overall effect. These conclusions are clearly confirmed by the preliminary data analysis (Table 3.78).

Table 3.78

Number and mass of weeds before plowing post-harvest siderates, average for 2018–2020 (based on the results of the author's own research)

Варіант сидерації		Number of weeds, pcs. m^{-2}					Mass of weeds, g m^{-2}				
		Biological group of weeds				In total	Biological group of weeds				In total
		vigorous early	vigorous late	overwintering	perennial		vigorous early	vigorous late	overwintering	perennial	
In the conditions of the Uladovo-Lyulynetsk breeding and research station											
Without siderate (control)		9.6	10.2	2.3	1.5	23.6	72.3	65.3	18.9	9.8	166.3
Post-harvest siderate of oilseed radish	R*	3.2	2.1	0.6	0.7	6.6	20.6	24.5	7.7	2.1	54,9
	W*	4.2	3.3	1.2	1.0	9.7	56.2	41.8	12.3	4.2	114,5
Post-harvest siderate of white mustard	R	4.4	3.5	0.9	0.9	9.7	28.9	35.0	12.4	3.6	79,9
	W	5.2	4.1	1.3	1.2	11.8	32.9	41.6	17.8	5.3	97,6
Post-harvest siderate of rocket-cress	R	7.2	5.1	1.9	1.3	15.5	61.8	50.9	16.0	8.1	136,8
	W	7.9	5.6	2.0	1.3	16.8	65.3	54.8	16.9	8.7	145,7
LSD_{05}		1.4	0.9	1.1	0.3	0.9	10.8	11.3	8.1	1.5	24.1
In the conditions of the experimental field of VNAU											
Without siderate (control))		14.8	15.5	3.6	2.6	36.5	95.2	93.0	35.6	12.2	236.0
Post-harvest siderate of oilseed radish	R*	5.6	4.8	1.2	1.1	12.7	30.9	40.5	12.8	3.4	87,6
	W*	6.9	5.7	1.9	1.6	14.1	46.4	50.5	14.9	4.9	116,7
Post-harvest siderate of white mustard	R	6.6	6.2	1.5	1.4	15.7	41.8	45.0	18.4	8.6	113,8
	W	8.4	7.7	1.8	1.9	19.8	47.9	49.3	20.1	9.8	127,1
Post-harvest siderate of rocket-cress	R	8.2	6.3	1.9	1.3	17.7	49.8	49.6	20.0	10.5	129,9
	W	8.8	6.9	2.2	1.6	19.5	51.2	52.6	20.9	11.3	136,0
LSD_{05}		1.1	0.8	1.0	0.5	1.2	11.4	11.5	8.5	1.9	25.3

Note: * R – row sowing option, W – wide row sowing variant

Source: based on own research.

It should also be noted that the hydrothermal conditions during the period from sowing to plowing of the siderate had a significant effect on the productivity of the siderate culture. As already noted, the conditions of 2018, both in terms of the amount of precipitation and the value of the hydrothermal coefficient, met certain requirements of weather models to ensure sideration, which positively affected the size of the leaf-stem mass of all without excluding siderate plants. However, it should be noted that the level of adaptability of siderats (according to the difference in the yield of leaf stem mass in the optimal and less favorable year) was maximum in the option of applying oil radish, especially in the option of row sowing, ensuring the level of productivity on average for the years and places of research by 11 .6% higher than in white mustard and by 49.6% higher than in the case of spring mustard. A positive influence of the potential of soil fertility on the formation of leaf-stem mass of siderates was also established. So, on black soil soils, the yield of oil radish was 3.9 t ha^{-1} higher than on gray forest soils. And for white mustard and spring mustard, this difference was 3.2 and 2.7 t ha^{-1}, respectively. This emphasizes the edaphic features of oil radish noted in a number of publications.

The results of the study of the aftereffect of sider crops on the amount of weediness of corn on the grain under which the actual version of siderization is carried out (Table 3.79) showed a decrease in general and specific weediness at the 8–10 leaf phase. At the same time, it was established that the level of reduction of the total number of weeds averaged for the research sites was 50.1% for the row sowing variant and 40.0% for the wide-row sowing during the period of the research using oil radish as a post-harvest siderate. For the sideration option using white mustard and spring mustard – 48.6 and 39.5% and 30.6 and 23.7%, respectively. Under these conditions of overall efficiency, the maximum reduction in the number of weeds was noted for spring early group, perennial and winter weeds. In our opinion, this nature of the formation of indicators is consistent with the previously made conclusions regarding the level of weediness during the plowing period of siderate and the specifics of the influence of siderate in the process of mineralization of the leaf-stem mass of cruciferous siderates from the point of view of their influence on the germination and viability of the seeds of perennial and spring cycle weeds development The obtained positive effect on the agrophysical properties of the soil, the improvement of the phytosanitary condition of the field, and the applied leaf-stem mass as an alternative to organic fertilization contributed to an increase in the yield of corn per grain in our experiment (Table 3.79). It should be noted that the period of 2019–2020 for the formation of the yield of corn hybrids in Vinnytsia was difficult, especially the conditions of 2020 with a long abnormally cold period in the first period of its vegetation up to the 810 leaf phase.Due to these reasons, the level of corn yield per grain for both study sites had significant differences in accounting for the harvest of 2019 and 2020. The average yield of corn grain did not exceed 7.4 t ha^{-1} in the conditions of the Uladovo-Lyulynetsk selection and research station and 6.2 t ha^{-1} in the conditions of the VNAU experimental field on gray forest soils. The averaged results of the yield value for different sideration options show its positive influence on the formation of corn grain yield.

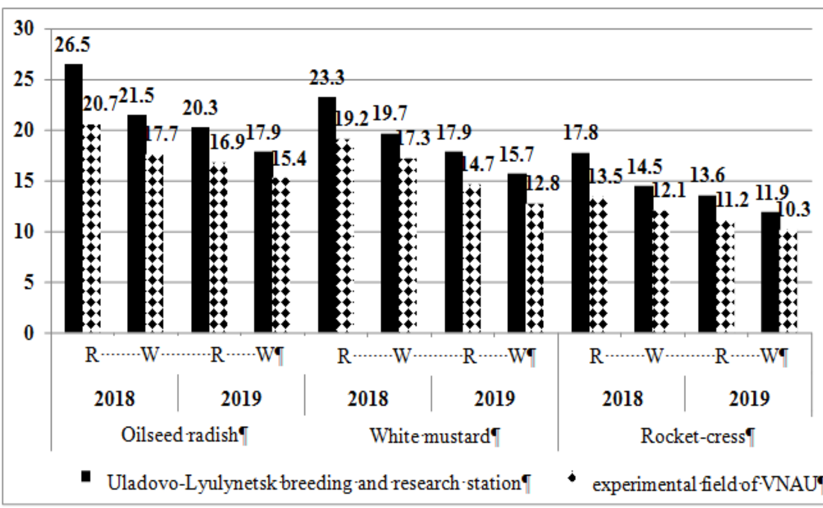

Figure 3.23 – Leaf-stem mass of siderates before plowing, t/ha, 2018–2019 (Р – row sowing variant, Ш – wide-row sowing variant; LSD$_{05}$ (t ha^{-1}) for the comparison group 1.14)

Source: formed on the basis of own research (based on the results of the author's own research)

Table 3.79

Distribution of biological groups of weeds in corn crops for grain under different sideration options for the 8-10 leaf phase (hybrid SI Respect (FAO 240)), average for 2018-2020 (based on the results of the author's own research)

Option of sideration		Biological group of weeds												In total	
		vigorous early			vigorous late			over-wintering			perennial				
		pcs. m^{-2}	% to all	g m^{-2}	pcs. m^{-2}	% to all	g m^{-2}	pcs. m^{-2}	% to all	g m^{-2}	pcs. m^{-2}	% to all	g m^{-2}	pcs.m^{-2}	g m^{-2}
In the conditions of the Uladovo-Lyulynetsk breeding and research station															
Without siderate (control)		20.6	43.9	216	18.5	39.4	211	3.9	8.3	49.9	3.9	8.3	50.0	46.9	526.9
Oiseed radish	R*	11.4	52.8	154	8.6	39.8	159	0.9	4.2	19.8	0.7	3.2	19.6	21.6	352,4
	W*	13.5	51.3	171	10.2	38.8	178	1.4	5.3	28.4	1.2	4.6	25.6	26.3	403,0
White mustard	R	13.9	52.1	183	10.8	40.4	168	1.1	4.1	26.3	0.9	3.4	23.8	26.7	401,1
	W	15.2	49.8	196	12.4	40.7	175	1.6	5.2	31.5	1.3	4.3	30.9	30.5	433,4
Rocket-cress	R	16.5	48.4	209	13.3	39.0	180	2.2	6.5	37.3	2.1	6.2	33.4	34.1	459,7
	W	17.2	46.2	212	14.8	39.8	189	2.7	7.3	41.8	2.5	6.7	41.5	37.2	484,3
LSD$_{05}$		1.5	–	21.7	1.9	–	33.6	0.6	–	15.8	0.5	–	12.5	1.4	21.0
In the conditions of the experimental field of VNAU															
Without siderate (control)		27.8	43.8	254	25.8	40.6	292	4.3	6.8	67.8	5.6	8.8	62.8	63.5	676.6
Oiseed radish	R	16.3	47.8	169	13.5	39.6	185	2.2	6.5	29.7	2.1	6.2	25.7	34.1	409,4
	W	18.2	44.8	179	16.9	41.6	192	2.8	6.9	32.5	2.7	6.7	37.4	40.6	440,9
White mustard	R	14.5	49.8	168	9.4	32.3	183	2.8	9.6	36.3	2.4	8.2	37.8	29.1	425,1
	W	18.1	50.8	184	11.2	31.5	225	3.1	8.7	45.6	3.2	9.0	42.3	35.6	496,9
Rocket-cress	R	18.5	44.0	216	17.3	41.2	223	3.5	8.3	54.1	2.7	6.4	46.3	42.0	539,4
	W	20.2	43.4	224	18.6	40.0	242	3.9	8.4	60.3	3.8	8.2	50.4	46.5	576,7
LSD$_{05}$		1.9	–	25.3	1.9	–	36.9	0.7	–	19.8	0.5	–	14.2	1.6	24.2

Note. * R – row sowing variant, W – wide row sowing variant

Source: formed on the basis of own research

The maximum yield increases for both the row and wide row seeding options were noted for the use of oil radish with an increase compared to the control without sideration for row sowing of 0.77 t $ha^{-1}$for growing corn on chernozem soils and 0.80 t $ha^{-1}$for growing on gray forest soils. In the variant of wide-row seeding, the yield indicators of corn were 19–27% lower compared to the row variant of sowing siderate. The yield of corn under other variants of siderates was on average 4.5% less than using white mustard and 7.7% less than using spring mustard. Smaller values of increments compared to the values of optimization of agrophysical parameters of the soil and the level of weediness indicate that there are aspects of the mechanistic action of sideral crops on the formation of yield and the actual chemistry of the transformation of leaf-stem mass in soils and its agronomic value from the standpoint of chemical composition, the content of macro- and microelements and other derivatives, which affect both chemical reactions in the soil-absorption complex, as well as the availability of plants and their physiological growth processes.Thus, we established that the use of sideration with cruciferous plant species is an effective means of regulating the agrophysical properties of the soil, controlling segetal vegetation and biologizing soil nutrition. Such an accumulative technological effect ensures the growth of agricultural productivity. crops and corn in particular, at least in the range from 0.3 to 0.8 t ha^{-1}.

Among the cruciferous siderates, it is worth noting the oilseed radish, which, possessing the already noted high adaptive potential and a guaranteed high level of leaf-stem mass formation, relatively undemanding to soil fertility conditions, provides significant advantages in the format of post-harvest sideration providing all existing advantages of cruciferous sideral cultures. Taking into account the data obtained by us, oil radish should be recommended as a component of biologized systems of alternative fertilization of agricultural crops for the conditions of the Pravoberezhny Forest Steppe in the option of row sowing with a sowing rate of 2.7–3.0 million pieces/ha of similar seeds immediately after the collection of the predecessor, provided the appropriate minimum level of soil moisture reserves.

The perspective of further research is to study the features of the processes of mineralization of the leaf-stem mass of oil radish and aspects of the influence of this process on the agrochemical properties of the soil, humus accumulation, soil microbiota and other related processes. Clarification also requires the study of cruciferous siderates for combined use with straw and its own species combination.

Table 3.80

Corn grain yield depending on sideration options, average for 2019-2020, t ha^{-1} (hybrid SY Respect (FAO 240), A is a factor of year conditions) (based on the results of the author's own research)

Option of sowing post-harvest siderate (B)	Variant of the siderata plant (C)			
	Control	White mustard	Oilseed radish	Rocket-cress
In the conditions of the Uladovo-Lyulynetsk breeding and research station				
Normal string (R)	7.41	7.87	8.18	7.66
Wide-row (W)		7.69	8.03	7.44
LSD05, t/ha (for the interaction of ABC factors before control)		0.15		
In the conditions of the experimental field of VNAU				
Normal string (R)	6.18	6.64	6.98	6.42
Wide-row (W)		6.47	6.78	6.29
LSD05, t/ha (for the interaction of ABC factors before control)		0.18		

Source: formed on the basis of own research

The effectiveness of oil radish in the option of post-harvest sideration has been proven (Gudz et al., 2011). Experimental studies were carried out in 2006–2009 in a stationary field experiment based on the scientific and practical center of the Sumy National University, which is part of the Myrhorod-Sum agro-soil district of the left-bank part of the Forest Steppe of Ukraine. The scheme of the field experiment included the following variants of the main tillage:

1. Shelf plowing to a depth of 28–30 cm (control).
2. Shelf-less processing to a depth of 28-30 cm (with a combined KLD-3.0 unit).
3. Shallow tillage to a depth of 13-15 cm (BDT-3 disk harrow).
4. Shelfless processing to a depth of 6-8 cm (combined unit AG-2,4).

The effectiveness of the main tillage methods was studied on two backgrounds: – siderable (follow-up sowing of oil radish) and siderless (returning post-harvest and root residues of winter wheat to the soil).

The use of post-harvest siderate, as well as the main tillage, directly affected the density of the soil under potato crops. Thus, against the background of siderate, the volumetric mass of the arable layer of the soil decreased significantly – on average by 0.04 g/cm^3 during both tillage and plowing (Table 3.81).

Table 3.81

The influence of the methods of main cultivation and sideral background on the volume mass in the 0-30 centimeter soil layer during potato cultivation, g cm^{-3} (average for 2006–2009) (Gudz et al., 2011)

Organic fertilizers (factor A)	Methods of basic soil cultivation (factor B)				Average for factor A	+, -
	Organic fertilizers (factor A)	Police-less to a depth of 28-30 cm	Shelfless to a depth of 13–15 cm	Shelfless to a depth of 6-8 cm		
Without green manure	1.20	1.18	1.21	1.21	1.20	-
Post-harvest siderate	1.15	1.13	1.17	1.18	1.16	-0.04
Average factor B	1.17	1.16	1.19	1.20		
Difference	-	-0.018	0.014	0.024		

$LSDR_{05}$ total = 0.017. factor A = 0.009. factor B = 0.012

A greater reserve of productive moisture in the arable soil layer in potato crops was facilitated by the incorporation of siderate into the soil, compared to the wrapping of only root and stubble residues of winter wheat (Table 3.82).

During the period of growing potatoes, the reserves of productive moisture of a meter-long soil layer decreased by 28–29 mm, depending on the studied factors (Table 3.83).

Among the studied factors, the use of post-harvest siderate had the greatest influence on the tuber yield, the share of which was 15.3%.

In order to ensure better conditions of soil density, water consumption of potato crops and the formation of high yields, it is advisable to carry out deep tillage without the main tillage with the earning of post-harvest siderates of oil radish.

The comprehensive integrated indicator of the research was the determination of the yield of potato tubers (Table 3.84).

Table 3.82

The influence of the methods of main cultivation and siderate on the reserves of productive moisture in the 0-30-centimeter soil layer during potato cultivation, mm (average for 2006–2009) (Gudz et al., 2011)

Organic fertilizers (factor A)	Methods of basic soil cultivation (factor B)				Average for factor A	+, -
	Organic fertilizers (factor A)	Police-less to a depth of 28-30 cm	Shelfless to a depth of 13–15 cm	Shelfless to a depth of 6-8 cm		
Without green manure	30.4	32.2	31.7	32.5	31.7	-
Post-harvest siderate	32.7	34.7	33.4	34.8	33.9	2.2
Average factor B	31.6	33.4	32.5	33.6		
Difference	-	1.9	1.0	2.1		
LSD_{05} total = 1.02, factor A = 0.51					Factor B = 0.72	

Application of post-harvest green manure, compared to non-sideral background, significantly increased potato yield on all variants of soil tillage methods – by 3.96.2 t ha^{-1}. On a non-sidereal background, inhibitory zone of falling line showing response of the yield to average daily temperature during potato vegetation period is clearly evident after 19^0C. On the background of covering oil radish siderate, negative impact of increase in average daily temperatures appears out of optimum zone of 20–21^0C. This regularity proves that application of green fertilizer increases stress resistance of the crops to negative impact of average daily air temperatures during vegetation period, which explains higher yield of the crop.

On the background with green manure application, the highest yield of potato was received with smaller amount of precipitation during its flowering, as optimal zone of yield response curve was within 110–130 mm of precipitation.

Table 3.83

Moisture consumption and water consumption coefficient of potato crops (average for 2006-2009) (Hudz et al., 2011)

<table>
<tr><th rowspan="2" colspan="2">Variant</th><th colspan="2">Productive moisture reserves in the 0-100 centimeter soil layer, mm</th><th rowspan="2">Precipitation during the growing period, mm</th><th rowspan="2">Total water consum-ption, mm ha-1</th><th rowspan="2">Coefficient of water consumption</th></tr>
<tr><th>at the time of planting</th><th>at the time of harvesting</th></tr>
<tr><td rowspan="2">Deep plowing 28–30 cm</td><td>Without green manure</td><td>87.2</td><td>58.0</td><td rowspan="8">255.5</td><td>284.8</td><td>10.4</td></tr>
<tr><td>Post-harvest siderate</td><td>91.1</td><td>61.6</td><td>285.1</td><td>8.9</td></tr>
<tr><td rowspan="2">Shelfless depth processing 28–30 cm</td><td>Without green manure</td><td>90.4</td><td>61.5</td><td>284.4</td><td>10.4</td></tr>
<tr><td>Post-harvest siderate</td><td>94.0</td><td>65.4</td><td>284.0</td><td>8.3</td></tr>
<tr><td rowspan="3">Shelfless depth processing 13–15 cm</td><td>Without green manure</td><td>88.7</td><td>59.3</td><td>284.9</td><td>11.4</td></tr>
<tr><td>Post-harvest siderate</td><td>92.0</td><td>62.5</td><td>285.0</td><td>9.5</td></tr>
<tr><td>Without green manure</td><td>91.3</td><td>61.5</td><td>285.3</td><td>11.9</td></tr>
<tr><td>Shelfless depth processing 6–8 cm</td><td>Post-harvest siderate</td><td>94.8</td><td>64.9</td><td>285.4</td><td>10.1</td></tr>
</table>

According to results of another research (Mischenko et al., 2024), the variant with application of oilseed radish siderate and its covering by the method of tillage without ploughing to the depth of 28–30 cm provided the highest yield of potato – 30.3 t ha^{-1} (Figure 3.24).

Table 3.84

The effect of siderate and main cultivation methods on potato yield, t ha^{-1} (average for 2006–2009) (Hudz et al., 2011)

Organic fertilizers (factor A)	Methods of basic soil cultivation (factor B)				Average for factor A	+, -
	Organic fertilizers (factor A)	Police-less to a depth of 28-30 cm	Shelfless to a depth of 13–15 cm	Shelfless to a depth of 6-8 cm		
Without green manure	27.3	27.3	25.0	24.0	25.9	-
Post-harvest siderate	32.1	34.3	30.0	28.3	31.2	5.3
Average factor B	29.7	30.8	27.5	26.2		
Difference	-	1.1	-2.2	-3.5		
LSD_{05} total = 1.04		Factor A = 0.52			Factor B =	0.73

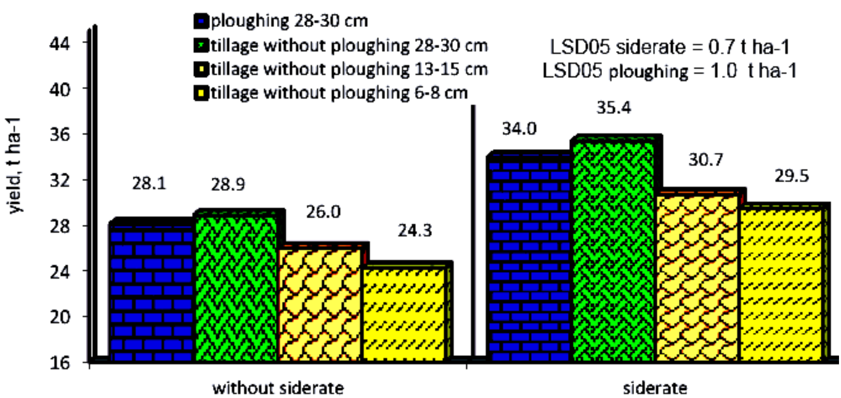

Figure 3.24 – Influence of siderate and main soil tillage on potato yield, t ha^{-1} (Mischenko et al., 2024)

The largest collection of starch was obtained with application of green manure – oil radish under tillage without ploughing in a depth of 28–30 cm – 4.03 t ha^{-1}, which was 0.3 t ha^{-1} more than under ploughing (Table 3.85).

Starch content in potato tubers ranged from 12.7 to 13.2%, it was significantly lower (by 0.4%) comparing with the control, with application of mineral fertilizer $N_{125}P_{63}K_{150}$. With organic fertilization, increase in starch content in tubers was greater than the control without siderate by 0.1%, largely due to green fertilizer of buckwheat.

Starch collection in all fertilization backgrounds was significantly higher than in the control without siderate, except for buckwheat siderate. The share of fertilizer influence on starch collection was 52%, year weather conditions – 42%, and other factors – 6%.

So, application of sideral background and deep tillage without ploughing contributed to formation of potato tuber yield with the best quality.

Table 3.85

Influence of basic tillage method and sideral background on technological indices of potato (Mischenko et al., 2024)

Background	Basic soil tillage			
	Ploughing 28–30 cm	Without ploughing 28–30 cm	Without ploughing 13–15 cm	Without ploughing 6–8 cm
starch content, %				
Without siderate	12.9	13.1	13.2	13.2
Siderate	13.1	13.3	13.4	13.5
starch collection, t ha^{-1}				
Without siderate	3.11	3.16	2.94	2.81
Siderate	3.73	4.03	3.56	3.40

Application of post-harvest siderate of oil radish and its covering by tillage without ploughing to a depth of 28–30 cm on typical black soil contributes to obtaining higher and better potato yields under conditions of unstable moisture in the North-Eastern Forest-Steppe of Ukraine.

When growing potato on the background of post-harvest oil radish siderate and with soil tillage without ploughing, lack of precipitation and high average daily temperatures had smaller effect on limiting yield level of the crop.

Based on yield data of our research, were calculated indices of economic attractiveness of potato growing. In general, green fertilizer of oil radish significantly increased potato value – by 18-25% for all methods of soil tillage comparing with background without siderate, Among the methods of covering oil radish, the highest value of potato – 3475.6 € ha^{-1} was obtained for non-ploughing tillage to a depth of 28–30 cm (Table 3.86).

Table 3.86

Technological indices of potato quality for different fertilization backgrounds (Mischenko et al., 2024)

Technological indices	Variant						LSD$_{05}$
	Without siderate (control	postharvest siderate				$N_{125}P_{63}K_{150}$	
		oilseed radish	phacelia	buckwheat	manure 25 t ha^{-1}		
Starch content, %	13.1	13.2	13.2	13.1	13.2	12.7	0.14
Starch collection, t ha^{-1}	3.25	4.08	3.87	3.37	3.92	3.71	0.25

Growing of post-harvest siderate of oil radish is a low-cost agricultural measure, and its covering by the method of tillage without ploughing provides saving of financial resources, comparing with ploughing. Covering of post-harvest oil radish siderate by tillage without ploughing to a depth of 28–30 cm, when growing potato, provided the lowest prime cost of potato tubers.

The effectiveness of oil radish as a siderate in the cultivation of pea crops has also been established. Thus, in the research of Muzika and Onychko (2016), it was noted that the highest yield of green mass of sideral plants in harvest crops (under the next year's vegetables) was obtained when sowing white mustard + oil radish (30.8 t/ha) against the background of the harvest residues of the predecessor + N_{10} for each ton of residues (Table 3.87). A slightly lower yield (29.6, 23.9 and 22.6 t ha^{-1}) was obtained when sowing oil radish, white mustard and spring rape against this background.

The highest content of nitrogen in terms of dry matter was noted in the seed mass of vetch (3.69%), peas (3.42%) and winter rape (2.99%). The content of other nutrients in the section of sideral plants was more stable. The supply of nutrients to the soil with the green mass of siderates depended on both their yield and the relative content of certain nutrients based on their dry matter. The highest nitrogen values were obtained on the plots of white mustard + oil radish, oil radish, peas and white mustard (respectively 105.6; 102.0; 92.1; 84.4 1 kg ha^{-1}). In terms of the total phosphorus content (P_2O_5), the best were – oil radish, white mustard +

oilseed radish, white mustard and wild rapeseed (35.5, 30.9 and 26.2 and 26.2 kg ha^{-}1, respectively).

The content of potassium in the crop of green mass of sideral plants exceeded the content of phosphorus by 1.5–3.7 times and was in the range of 65.5–156.7 kg ha^{-1}. According to this indicator, sideral plants are the best: oleaginous radish, white mustard + oleaginous radish and white mustard (the content of green mass in the harvest is 156.7¬124.5 1 kg ha^{-1}). Thus, the highest total content of nutrients in the harvest of the green mass of siderates in the autumn of 2010–2012 was obtained when growing against the background of harvest residues (+N10 per 1 t of residues) oil radish, joint sowing of white mustard and oil radish and white mustard, the plowing of green mass of which provided 294.2–235.1 kg ha^{-1} of NPK.

Table 3.87

Agrochemical characteristics and yield of siderates in harvest crops (sowing at the beginning of August, plowing at the end of the second to the beginning of the third decade of October) (Muzyka and Onychko, 2016)

№	Green manure	Yield, t ha^{-1}		Nutrient content, % on dry matter				The content of nutrients in the yield of siderat from 1 ha, kg CaO			
		raw mass	Dry mass	N	P_2O_5	K_2O	CaO	N	P_2O_5	K_2O	
Harvest residues of winter wheat + Nio for each ton of residues											
1.	White mustard	23.9	3.797	2.22	0.69	3.28	2.36	84.4	26.2	124.5	89.7
2.	White mustard + oilseed radish	30.8	4.150	2.54	0.74	3.26	2.45	105.6	30.9	135.2	101.7
3.	Sowing vetch	13.8	1.893	3.69	0.92	3.46	2.03	69.8	17.4	65.5	38.5
4.	Buckwheat	14.8	2.500	2.36	0.87	2.74	2.32	59.1	21.7	68.6	58.1
5.	Pea	17.8	2.693	3.42	0.73	2.86	1.96	92.1	19.8	77.1	52.7
6.	Winter rape	20.5	2.540	2.99	0.87	3.02	2.20	75.9	22.2	76.8	55.8
7.	Rape	22.6	3.057	2.63	0.86	3.40	2.28	80.4	26.2	104.0	69.8
8.	Oilseed radish	29.6	3.873	2.63	0.92	4.05	2.26	102.0	35.5	156.7	87.7

Calcium content in sidereal fertilizer is important for improving soil structure and reducing acidity. The content of CaO in the harvest of various sideral plants in the harvest crops of 2010-2012 was in the range of 101.7–38.5 kg ha^{-1}. In terms of the total amount of nutrients in the harvest of the green mass of sideral plants from one hectare in the autumn of 2010-2012, the best were the harvest crops of sideral plants: oil radish (381.9 kg ha^{-1}); white mustard + oilseed radish (373.4 kg ha^{-1}); white mustard (324.8 kg ha^{-1}); spring rapeseed (280.4 kg ha^{-1}).

Sowing sidereal plants on the harvest residues of the predecessor + N10 for each ton of residues with subsequent placement of them on the background of onion from seeds had a positive effect on the growth and development of plants (Table 3.88).

Table 3.88

Influence of green manure plants in stubble crops on biometric parameters of onion plants in the phase of 4–5 leaves, average 2011-2013. (Muzyka and Onychko, 2016)

№ п/п	Green manure	Фаза 4–5 листків					
		number of leaves, pcs..	total length of leaves, cm	average length of one leaf, cm	weight, g		
					plant	leaves	bulbs
1.	Control (no fertilizer)	4.6	109.7	23.8	9.6	6.1	3.5
2.	$N_{60}P_{60}K_{60}$	5.6	145.0	25.9	13.0	8.3	4.8
3.	White mustard	5.1	119.4	23.3	10.3	6.4	3.9
4.	White mustard + oilseed radish	5.3	125.9	23.8	11.0	7.0	4.0
5.	Sowing vetch	5.0	118.1	23.5	9.9	6.2	3.7
6.	Buckwheat	4.7	106.1	22.7	8.9	5.5	3.4
7.	Pea diaper	4.8	113.0	23.7	9.7	5.6	3.7
8.	Winter rape	4.9	118.0	23.9	9.7	6.0	3.7
9.	Spring rape	5.0	120.1	24.2	10.0	6.2	3.8
10.	Oilseed radish	5.0	126.3	25.1	10.8	5.6	4.2

Thus, the formation of the fifth leaf and bulbs against the background of sideral fertilization occurred 2–6 days earlier than plants from plots without fertilization. During the period of bulb formation, the best growth and development of onion plants was noted when placing its crops against the background of the harvest sowing of sideral plants: oil radish, white mustard + oilseed radish, spring rape, diaper pea – the total length of leaves of one plant is 279; 274; 266 and 264 cm, respectively, against 204 cm in plants of the control variant (without fertilizer). The weight of the plants of these variants was 114–107 g and the bulbs 31.9–30 g against 73 and 23 g in the control variant (increase of 56.246.6 and 38.7–30.5 %) (Table 3.89).

Table 3.89

Influence of green manure plants in stubble crops as the main fertilizer on biometric parameters of onion plants in the phase of bulb formation, average 2011-2013 (Muzyka and Onychko, 2016)

№	Green manure plants	Bulb formation phase					
		number of leaves, pcs.	total length of leaves, cm	average length of one leaf, cm	mass, g		
					plant	leaves	bulbs
1.	Control (no fertilizer)	6.05	203.5	33.6	73.0	50.0	23.0
2.	$N_{60}P_{60}K_{60}$	7.1	282.0	39.7	103.0	74.0	29.0
3.	White mustard	7.1	262.1	36.9	101.3	72.4	28.9
4.	White mustard + oilseed radish	7.3	273.9	37.5	112.0	80.5	31.5
5.	Sowing vetch	7.0	263.5	37.6	107.0	77.0	30.0
6.	Buckwheat	6.6	238.6	36.2	96.3	69.1	27.2
7.	Pea diaper	7.0	264.1	37.7	107.3	77.3	30.0
8.	Winter rape	6.9	260.2	37.7	104.0	74.4	29.6
9.	Spring rape	7.2	265.5	36.9	107.7	76.2	31.5
10.	Oilseed radish	7.3	279.0	38.2	114.3	82.4	31.9

Thus, when growing onions from seeds against the background of crop residues of the predecessor (root + straw) + N_{60} + green manure, oil radish should be used as a green manure plant, and oil radish + white mustard, spring rape should be grown together. In this case, the yield of onions is 20.4–19.6 t ha^{-1}.

The effectiveness of oil radish use in the system of typical models of organic crop rotation was also investigated. Thus, Khalep and Moskalenko (2020) developed basic (typical) models of organic crop rotations for crop farms in Polissya of Ukraine:

– Model 1: 1. Clover for seeds. 2. Winter rye + lupine (post-harvest for green manure). 3. Millet + oil radish (post-harvest for green manure). 4. Potatoes + winter rye (after harvesting potatoes for green manure). 5. Spring wheat with clover.

– Model 2: 1. Clover for seed. 2. Winter wheat + radish (after harvesting for green manure). 3. Soybeans + winter rye (post-harvest for green manure). 4. Buckwheat + oil radish (post-harvest for green manure). 5. Spring barley with clover.

– Model 3: 1. Clover for seeds. 2. Winter rye + radish (post-harvest for green manure). 3. Corn for grain + winter rye (after harvesting corn for green manure). 4. Peas. 5. Winter wheat + radish (after harvesting for green manure). 6. Oats with clover sowing.

– Model 4: 1. Clover for seeds. 2. Winter rye + lupine (post-harvest for green manure). 3. Millet + oil radish (post-harvest for green manure). 4. Peas. 5. Winter wheat + radish (post-harvest for green manure). 6. Potatoes + winter rye (after harvesting potatoes for green manure). 7. Spring wheat with clover.

In the above crop rotation schemes, along with their saturation with legumes and the cultivation of perennial grasses (clover), it is proposed to widely use green manure crops in the intermediate (after harvesting the main crops) periods – after all the main crops of the rotation (except for clover and winter crops predecessors), and not only after early cereals, as is now generally accepted. It should be emphasized that the natural and climatic conditions of Polissya (first of all, increased moisture availability compared to other natural and climatic zones and, in general, sufficient for the growth, development and accumulation of the necessary biomass of green manure sown in the intermediate (after harvesting the main crops) period, the length of the growing season after harvesting the main crops) fully allow for this approach.

The fertilizer potential and the share of green manure shown in the table will be formed in the process of crop rotation development and (after all the fertilizer system components are included in the fertilizer cycle and the projected crop yields with the corresponding by-product yields are achieved) will eventually reach stable values. This is confirmed by the graphical representation of the alignment of the series of dynamics of the actual values of the share of green manure in the total supply of nutrients from all sources according to the developed crop rotations.

The contribution of green manure to the processes of preserving and reproducing humus in the soils of organic agrocenoses is also important. According to the above-mentioned model calculations, the supply (preservation) of humus from the humification of biomass of different types of green manure is 0.11–0.25 t ha^{-1} per year (depending on the timing of sowing and the corresponding biomass yield). At the same time, their share in the total volume of humus formation is 6.4–27.2% in the fields of various main crops, where we offer them for cultivation in intermediate crops. On the basis of 1 hectare of crop rotation area, the contribution of green manure to the processes of humus formation is 0.09–0.13 tons or 4.7–6.4% of the share according to the models (Table 3.90).

At the same time, out of several tested statistical analysis functions, the polynomial function of the sixth degree was chosen, the results of which demonstrated the highest closeness of connection (R^2) – from 0.9898 for model №. 3 to 0.9942 for model № 1.

Table 3.90

Forecast of the supply of basic nutrient compounds for modeled crop rotations (in accessible form for an average year after crop rotation development) (Khalep and Moskalenko, 2020)

Indicators	Model № 1			Model № 2			Model № 3			Model № 4		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
From all sources per 1 ha of crop rotation area, kg	106	44	108	101	42	89	109	45	108	106	45	104
including green manure, kg ha^{-1}	25	9	20	19	8	24	23	9	26	26	10	23
Share of green manure, %.	23.6	20.5	18.5	18.8	19.0	27.0	21.2	20.5	24.0	24.5	22.2	22.1

Based on the comparison of the data in Table 3.91 and Table 3.92, we conclude that the contribution of green manure to the formation of potential soil fertility (share in the volume of humus formation) of the considered models is less significant than the contribution to the formation of effective fertility (share in the volume of supply of basic nutrients). At the same time, it should be emphasized that it is thanks to green manure biomass as an additional source of humus supply (preservation) that positive humus balances are achieved in a number of cases, in particular, in models 2 and 4. Along with the above-mentioned great general importance of using green manure crops in the intermediate (after harvesting the main crops) periods for green fertilization in organic farming, attention should be paid to the features and factors of their selection for inclusion in crop rotation schemes. Legumes, especially lupine, are considered to be the best green manure crops in terms of NPK (especially nitrogen) content and other biologically beneficial traits. We have calculated the supply of nutrients with green manure biomass per hectare of sown area in terms of the main green manure crops (Table 3.91).

Table 3.91

Forecast of organic matter (humus) supply to agrocenoses of the developed crop rotation models (on average for a year after crop rotation development) (Khalep and Moskalenko, 2020)

Indicators	Model № 1	Model № 2	Model № 3	Model № 4
Total amount of newly formed (preserved) humus per 1 ha of crop rotation area, t	2.10	1.85	2.13	2.02
including from humification of green manure biomass, t ha^{-1}	0.10	0.09	0.10	0.13
Share of green manure, %.	4.8	5.1	4.7	6.4

The authors of this study (Khalep and Moskalenko, 2020) concluded that green manure, including sowing green manure crops in the intermediate (after harvesting the main crops) period, is the most versatile, balanced, publicly available, relatively easy to reproduce and manageable reserve for increasing productivity, in particular of organic agrocenoses. For organic crop production farms, in the absence of the possibility of using such an important source of fertilizer as manure, sowing green manure crops in the intermediate (after harvesting the main crops) period is an important factor in increasing the fertilizing potential of crop rotations. This is especially true for the agrocenoses of Polissya with their relatively low–fertility soils.

Table 3.92

Calculation of nutrient compound yields for the main green manure cropscrops (by gross content) (Khalep and Moskalenko, 2020)

Green manure	Biomass accumu-lation, t ha^{-1}	Content in 1 ton of biomass, kg (after Berdnikov et al., 2012)			Output per 1 ha, kg			
		N	P2O5	K2O	N	P2O5	K2O	NPK
Narrow-leaved lupine	24.0	4.1	1.1	2.3	98.4	26.4	55.2	180.0
Lupine perennial	20.0	4.8	0.9	3.0	96.0	18.0	60.0	174.0
Seradella	18.0	4.5	1.3	3.5	81.0	23.4	63.0	167.4
White sweet clover	15.0	6.5	0.7	2.1	97.5	10.5	31.5	139.5
Diaper	15.0	4.7	1.3	4.2	70.5	19.5	63.0	153.0
Phacelia	12.0	3.6	1.2	4.4	43.2	14.4	52.8	110.4
Winter rye	20.0	3.2	1.1	2.7	64.0	22.0	54.0	140.0
White mustard	10.0	3.7	1.2	4.0	37.0	12.0	40.0	89.0
Winter rape	13.0	3.7	1.2	4.0	48.1	15.6	52.0	115.7
Perko	15.0	3.7	1.2	4.0	55.5	18.0	60.0	133.5
Oilseed radish	23.0	3.7	1.2	4.0	85.1	27.6	92.0	204.7
Annual ryegrass	21.0	3.8	1.2	2.8	79.8	25.2	58.8	163.4

The natural and climatic conditions of Polissya (first of all, increased moisture availability compared to other natural and climatic zones) are generally sufficient for the growth, development and accumulation of the necessary biomass of green manure crops sown in the intermediate (after harvesting the main crops).

It was found (Mishchenko, 2015) that on average in 2006–2010, when growing sugar beets, oil radish green manure, compared to the control without green manure, provided an increase in the content of hydrolyzed nitrogen in the 0–30 cm layer by 8–12% to 105–107 mg kg^{-1}, mobile phosphorus by 7–11% to 123125 mg kg^{-1} and potassium by 9–12% to 120–122 mg kg^{-1}under all soil treatments. Under potato crops, the advantage of green manure over the control is more pronounced, which resulted in a higher content of nitrogen –111–114 mg kg^{-1}, phosphorus – 127–130 mg kg^{-1}, and potassium – 121124 mg kg^{-1}against the background of green fertilizer.

The incorporation of oil radish green manure by deep moldboardless tillage at 28–30 cm provided the highest content of nutrients in the

0–30 cm soil layer. This method of incorporation of green fertilizer of oil radish provided significantly higher nutrient supply to the test crops and differed within the error range before moldboardless loosening to a depth of 13–15 cm under potatoes in terms of nitrogen content (where it was determined to be 113 mg kg^{-1}) and before plowing to 2830 cm in terms of phosphorus content (129 mg kg^{-1}). The highest localization of nutrients to the soil surface was determined when green manure was not plowed to a depth of 6–8 cm in the soil layer of 0–10 cm (Table 3.93).

Table 3.93

Content of nutrients in soil layers under test crops under different fertilization and tillage backgrounds, average for 2006-2010, mg/kg (Mishchenko, 2015)

Variant		**hydrolyzed nitrogen | mobile phosphorus | mobile potassium**								
fertilizer background	**soil cultivation**	**soil layer, cm**								
		0-10 1 10-20 1 20-30 1 0-10 1 10-20 | 20-30 | 0-10 | 10-20 | 20-30								
sugar beet										
without green manure (control)	plowing 28–30	105	98.3	88.4	125	117	103	117	110	101
	shelfless 28–30 cm	110	97.3	83.7	131	115	97.6	122	108	97,7
	shelfless 13–15 cm	113	94.1	80.5	135	111	94.1	125	105	94,5
	shelfless 6–8 cm	117	86.0	78.5	139	106	89.5	127	103	90,9
post-harvest green manure of oilseed radish	plowing 28–30	117	105	92.3	135	126	109	131	121	109
	shelfless 28–30 cm	126	105	89.7	143	124	107	139	120	107
	shelfless 13–15 cm	131	100	85.5	149	121	101	141	118	103
	shelfless 6–8 cm	136	96.5	82.2	154	116	98.1	143	116	100
LSD_{05} green manure		0,9	1.0	1.0	0.8	0.7	1.0	0.9	0.8	0.8
LSD_{05} processing		1,3	1.4	1.4	1.1	1.0	1.4	1.2	1.1	1.1
potato										
without green manure (control)	plowing 28–30	109	102	93.7	125	120	109	119	112	103
	shelfless 28–30 cm	113	100	88.4	129	118	105	121	109	101
	shelfless 13–15 cm	116	97.5	84.3	133	114	102	123	107	96.9
	shelfless 6–8 cm	119	93.3	81.5	136	110	99.0	124	104	92.7
post-harvest green manure of oilseed radish	plowing 28–30	122	111	98.8	139	131	115	131	124	111
	shelfless 28–30 cm	137	110	94.7	146	130	113	139	123	109
	shelfless 13–15 cm	142	108	88.6	150	127	107	140	120	105
	shelfless 6–8 cm	146	104	86.2	154	123	105	142	118	102
LSD_{05} green manure			1.3	1.2	1.2	0.9	0.7	1.0	0.7	1.2
LSD_{05} processing			1.8	1.7	1.7	1.3	1.1	1.5	1.0	1.7

On average, in 2006–2010, nitrogen 75.4 kg ha^{-1}, phosphorus 55.4 kg/ha and potassium 97 kg ha^{-1} were supplied to the soil on the background without green manure with by–products; on the background of oil radish green mass application, 211, 111 and 238 kg $ha^{-1}$of the same macronutrients were supplied, respectively.

According to the balance of nutrients, the agrochemical efficiency of methods of planting post–harvest residues and green manure is estimated (Table 3.94). The removal of nutrients by crops, as well as the value of their yield, was the highest for plowing and moldboardless tillage to a depth of 28–30 cm with the use of green fertilizer; the lowest removal rates were found for moldboardless loosening to a depth of 6–8 cm on a green manure–free background. When growing sugar beets, a higher nitrogen removal was obtained – by 23.931.8 kg ha^{-1}, and potatoes – phosphorus and potassium – by 4.4–11.5 and 17.159.6 kg ha^{-1}.

Under sugar beet in the control without green manure, the nitrogen balance was negative and under no–till cultivation to a depth of 6–8 cm it was minimal – 56.9 kg ha^{-1}. With deep moldboardless tillage at a depth of 28–30 cm, the nitrogen deficit increased to 74.8 kg ha^{-1}.

Against the background of green manure, a positive nitrogen balance was established, respectively, for the above treatments – 56.2 and 34.4 kg ha^{-1}. Similar patterns of nitrogen balance were determined under potatoes.

The phosphorus balance in the control without green manure under sugar beet varied within 8 kg ha^{-1}. With oil radish green manure, it increased by 7 times, and under potatoes, respectively, by 12 times, which is associated with a greater removal of phosphorus by the yield of potato tubers.

The potassium balance in the control without green manure under sugar beet was negative and amounted to 78 kg ha^{-1}under no–till tillage at 28–30 cm and plowing at the same depth, while under shallow tillage at 6–8 cm the potassium deficit decreased to 59 kg ha^{-1}. With the introduction of oil radish green manure, the potassium balance was positive and increased to 61–74 kg $ha^{-1}$with different tillage methods. Due to the intensive removal of potassium by the potato crop in the control without green manure, the deficit of this element in deep tillage was 98 kg ha^{-1}, and with the introduction of green manure it increased and did not exceed 34 kg ha^{-1}in no–till tillage to a depth of 6–8 cm.

Table 3.94

Nutrient balance under row crops with different fertilization and tillage backgrounds, average for 2006–2010 (Mishchenko, 2015)

Variant		Receipts, kg ha-1			Harvest yield, kg ha^{-1}			Balance, kg ha^{-1}			Intensity of the balance sheet, %		
fertilizer background	tillage	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
sugar beet													
without green manure (control)	plowing 28–30 cm	75.4	55.4	97	150	49.5	175	- 74.3	5.9	-77.5	50.4	112	55.6
	shelfless 28–30 cm	75.4	55.4	97	150	49.7	175	-74.8	5.7	-77.7	50.2	112	55.5
	shelfless 13–15 cm	75.4	55.4	97	140	46.5	163	-65	8.9	-65.5	53.7	119	59.7
	shelfless 6–8 cm	75.4	55.4	97	132	43.7	156	-56.9	11.7	-58.6	57.0	127	62.3
post-harvest green manure of oilseed radish	plowing 28–30 cm	212	112	238	175	54.4	175	36.4	57.1	62.8	121	205	136
	shelfless 28–30 cm	212	112	238	177	54.9	177	34.4	56.6	60.8	119	203	134
	shelfless 13–15 cm	212	112	238	161	51.3	172	50.3	60.2	65.9	131	217	138
	shelfless 6–8 cm	212	112	238	155	49.8	164	56.2	61.7	74.3	136	224	145
potato													
without green manure (control)	plowing 28–30 cm	75.4	55.4	97	122	52.9	195	-46.8	2.5	-98	61.7	101	49.8
	shelfless 28–30 cm	75.4	55.4	97	122	53.0	195	-46.9	2.4	-98.1	61.7	101	49.7
	shelfless 13–15 cm	75.4	55.4	97	113	51.0	180	-37.7	4.4	-83.3	66.7	109	53.8
	shelfless 6–8 cm	75.4	55.4	97	108	49.0	173	-33.0	6.4	-75.7	69.5	113	56.2
post-harvest green manure of oilseed radish	plowing 28–30 cm	212	112	238	143	63.1	229	68.3	48.5	9.1	148	177	104
	shelfless 28–30 cm	212	112	238	152	66.4	237	59.8	45.1	1.3	139	168	101
	shelfless 13–15 cm	212	112	238	134	59.4	214	77.4	52.2	23.7	158	188	111
	shelfless 6–8 cm	212	112	238	127	56.7	203	84.3	54.8	34.6	166	197	117

The authors of the study (Mishchenko, 2015) concluded that in the conditions of the Left–Bank Forest–Steppe of Ukraine, post–harvest oil radish green manure formed phytomass – 29.1–29.7 t ha^{-1}, and accumulated nitrogen – 136.1–144.4.1 kg/ha, phosphorus – 51.7–56.1 kg ha^{-1}, potassium – 140.9–157.1 kg $ha^{-1}$and calcium – 174.6–178.3 kg ha^{-1}.

The use of oil radish green manure under sugar beet and potatoes contributed to an increase in the content of easily hydrolyzed nitrogen in the root layer of soil 0–30 cm by 9.813.8 mg kg^{-1}, mobile phosphorus by 8.0–13.8 mg $kg^{-1}$and exchangeable potassium by 7.8–13.0 mg kg^{-1}compared to the unfertilized background.

The planting of oil radish green manure by moldboardless tillage at a depth of 28–30 cm provided the highest content of easily hydrolyzed nitrogen – 106.7 and 113.8 mg kg^{-1}, mobile phosphorus – 124.6 and 129.6 mg $kg^{-1}$and exchangeable potassium – 121.7 and 123.6 mg kg^{-1} during the period of sugar beet and potato cultivation.

The phytomass of green manure had the greatest influence on the content of nitrogen in the root layer of soil 0–30 cm – 49–52%, and the least – on phosphorus – 24–25%. The content of nutrients was more dependent on the post–harvest green manure of oil radish – by 21.9–31.9% than on the main tillage – 0.3–1.3%. Green fertilizer of oil radish had a higher share of influence on the content of nutrients in plowing – 33–66% and moldboardless tillage with a depth of 28–30 cm – 19–61%.

The post–harvest green manure of oil radish provided a positive balance of nutrients for sugar beet and potatoes. The most positive balance of nutrients –34.6–84.3 kg ha^{-1} was on the background of green manure under moldboardless tillage by 6–8 cm; increasing the depth of moldboardless tillage to 28–30 cm brought the balance closer to a balanced one. The highest yield of sugar beet (35.4 t ha^{-1}) and potatoes (30.3 t/ha) was obtained with moldboardless incorporation of oil radish green manure to a depth of 28–30 cm; the difference to plowing was significant – by 1.4 and 1.8 t ha^{-1}, respectively, as well as to shallow moldboardless soil loosening – by 4.7 and 3.7 t $ha^{-1}$and surface loosening – by 5.9 and 5.1 t ha^{-1}.

It is noted (Shevchenko, 2021) that one of the important methods of biologization is the introduction of green manure pairs. The importance of green manure in modern agriculture is due to their participation in the reproduction of soil organic matter, which globally affects the entire range of agronomic properties of the soil. Humus and nitrogen reserves in agricultural soils are restored both through the application of mineral fertilizers and organic matter that enters the soil in the form of plant residues of various origins, in particular, as a result of plowing green manure from green manure crops. Its systematic plowing in the amount of 15–20 t/ha provides an effect that is equivalent to the application of 20 t $ha^{-1}$of manure.

The choice of green manure crops is an important priority in the issue of green manure in Ukraine. It is necessary for this crop to have a short growing season, to grow a large amount of vegetative mass, and to be economically profitable in terms of seed production. It is known that in the steppe zone, such crops as peas, spring vetch, white sweet clover, sainfoin, white mustard, spring and winter rape, buckwheat and oil radish can be grown for green manure.

For eight years, the Erastiv Research Station has been conducting research to determine the effectiveness of various legumes and cruciferous crops as green manure crops for the purpose of using their biomass as organic fertilizer. According to the results of the research, it was found that the most effective and appropriate for widespread implementation were sowings of oil radish either in pure form or in a mixture with spring vetch (Table 3.95).

Table 3.95

Comparison of green manure crops efficiency (Shevchenko et al., 2021)

Crops	Green mass		Root remains		Total dry matter yield, t ha^{-1}
	harvest, t ha^{-1}	dry matter content, %	harvest, t ha^{-1}	dry matter content, %	
White mustard	19.1	13.1	4.7	30	3.91
Spring vetch	22.1	18.2	4.9	33	5.64
White mustard + spring vetch	21.5	15.6	5.5	31	5.06
Oilseed radish + spring vetch	28.2	16.8	6.7	32	6.88

The effectiveness of green fertilizer largely depends on the size of the green manure crop. The more green mass is incorporated into the soil, the more noticeable will be its effect and aftereffect on the productivity of the following crops in the rotation.

The authors of the study emphasize (Shevchenko et al., 2021) that the analysis of oil radish plants showed that its green mass in terms of absolutely dry matter contained an average of 2.10% nitrogen, 1.54% phosphorus, and 3.88% potassium, and 1.47%, 0.97%, and 3.56% in the roots. When oil radish crops were harvested, 5.48 t ha^{-1} of organic matter was applied to the soil, which is equivalent to 29 t ha^{-1} of manure. Similar results are achieved by growing spring vetch, and the best results are achieved by growing them in a mixture.

So, the maximum yield of green manure in all years of research was formed when growing oil radish in a mixture with spring vetch, but the seed production of spring vetch and the use of its seeds in mixtures significantly increase the cost of green mass. Therefore, oil radish can be considered the most optimal crop for use as green manure in the northern Steppe.

The effectiveness of green manure application is confirmed by the experiments of the Erastiv Experimental Station: in fertilized crops, the yield of winter wheat on green manure under a favorable moisture regime is only 5–9% less than its yield on black manure, which is considered the most favorable predecessor for this crop. (But in unfavorable years, this difference can reach 20–25%).

A fairly thorough study was conducted by Sendetsky (2021). His research found that the destruction of straw and post–harvest residues with the biological product Vermistim–D, combined with sowing crops on green manure, led to an improvement in the agrophysical and agrochemical parameters of the soil.

According to the analysis of the structural composition of the soil, at the time of corn sowing, the number of clumpy (>10 mm) and small (<0.25 mm) fractions decreased by 2.53–2.3 and 0.4–0.8%, respectively, and the content of agronomically valuable aggregates (0.25–10 mm) increased by 2.0–3.2%, which led to a higher structural coefficient in these variants compared to the control by 0.09–0.21 and, respectively, by 0.10–0.17% at the time of harvest.

The total porosity of the 0–10 cm soil layer increased by 6.1–9.9%, and in the 10–20 cm soil layer – by 4.6–8.1%. The water resistance of structural aggregates of the 0–30 cm soil layer was higher by 5–9 relative % compared to the control. There was a positive trend of increasing the humus content by 0.06–0.15% compared to the control.

Table 3.96

Comparative characteristics of the fertilizer value of green manure crops (Shevchenko et al., 2021)

Crops	Dry matter added to the soil, t ha^{-1}	Amount of nutrients in total biomass, kg ha^{-1}				Litter equivalent, t
		N	P_2O_5	K_2O	total	
Oilseed radish	5.48	102	73	206	381	29
White mustard	3.91	71	37	91	199	15
Spring vetch	5.64	126	46	158	330	25
White mustard + spring vetch	5.06	103	46	130	279	21
Oilseed radish + spring vetch	6.88	141	75	226	442	34

The release of carbon dioxide (CO_2) increased compared to the control by 67 mgCO2/m^2 per day in the germination phase, by 144 mg CO_2 m^{-2} per day in the panicle ejection phase, and by 111 mg CO_2 m^{-2} per day in the waxy ripeness phase.

The studied agricultural measures on the use of straw and green manure in the cultivation of maize hybrids influenced the reduction of acidity of sod–podzolic soil, which in turn contributed to an increase in crop yield. A significant decrease in acidity (on average by 0.65 pH) occurred during the years of research in the variant of straw destruction "Vermistim–D" (6 l ha^{-1}) and sowing a mixture of white mustard and oil radish on green manure.

In all variants of the experiment, there was an improvement in field germination, plant density and plant survival until the harvesting period. The best results were observed in the variant of straw destruction and sowing a mixture of green manure (white mustard + oil radish): field germination of plants of the hybrid NC Lemero was 89.5%, NC Thermo – 88.9%, the number of plants after full germination, respectively, was 71360 and 71120 pcs. ha^{-1}, the number of plants before harvesting was 71075 and 70906 pcs. ha^{-1} (survival – 99.6 and 99.4%).

According to the results of the three–factor analysis of variance, the influence of the studied factors on the field germination of maize plants was 90.1%, of which: factor A (destruction) – 17.1%, factor B (green manure) – 59.6%, and factor C (maize hybrid) – 13.4% The rate of linear growth of plants was highest in the variant of straw and green manure with a mass of white mustard and oil radish. The average daily growth was 12 cm ahead of the growth of plants of the hybrid NK Termo and 16 cm ahead of the hybrid NK Lemero compared to the control.

It was found that when using straw and green manure, the assimilation surface of maize plants in the phase of panicle ejection was 6.12–5.71 thousand m^2 ha^{-1} higher, in the flowering phase – 4.20–3.10 thousand m^2 ha^{-1}, compared to the control. From the germination phase of maize plants to waxy ripeness, the photosynthetic potential of crops was higher than in the control by 0.614 million m^2day ha^{-1}.

Analysis of the structural elements of corn yield formation of the hybrid NK Termo showed that when straw was used in combination with green manure, on average over the years of research, the number of productive cobs per 100 plants was 1.0–1.7 pieces, the weight of the stem with leaves per plant was 20.7–52.2 g, the length of the cob was 0.7–1.6 cm and the weight of grain in one cob was 10.0–12.1 g higher compared to the control.

The weight of grain in the cob in the studied maize hybrids was influenced by certain factors: factor A (destruction of straw by Vermistim D) – 23.1%, factor B (green manure) – 48.0%, factor C (corn hybrids) – 6.4%, interaction of factors AB – 10.8%, interaction of other factors had no significant effect on the result The indicators of improvement of agrophysical and agrochemical, biological activity of the soil established in the variants of the experiment provided an increase in the yield of corn grain of hybrids NK Termo and NK Lemero (Table 3.97).

In all variants, the yield of corn grain of the hybrid Termo increased by an average of 7.0–37.4%, and of the hybrid Lemero by 8.1–36.0% compared to the control. The highest yield of NC Thermo – 11.7 t ha^{-1} (+ 3.2 t ha^{-1}), NC Lemero 11.6 t/ha (+ 3.0 t ha^{-1}) more compared to the control, was obtained in the variant of straw destruction in combination with sowing white mustard on green manure mixed with oil radish.

Corn grain yield was influenced by factors: A (straw destruction with Vermistim D) – 36.3%, B (green manure) – 38.9%, C (corn hybrid) – 6.6%, and the share of the influence of the interaction of factors A and B is 6%.

Studies have shown that the highest content of crude protein 9.7%, crude fat 5.12% and crude fiber 2.76% in the hybrid NK Termo was in the variant of straw destruction by Vermistim–D and sowing a mixture of white mustard and oil radish on green manure (increase in crude protein – 0.7%, crude fat – 0.76%, crude fiber – 0.36% compared to the control).

Table 3.97

Corn grain yield of NK Termo and NK Lemero hybrids using straw and siderate (average for 2013–2017), t ha^{-1} (Sendetskyi, 2021)

Variant	Year					Average for 5 years	± to control	
	2013	2014	2015	2016	2017		t ha^{-1}	%
hybrid NK Termo								
1	7.4	9.2	8.6	8.8	8.4	8.5	-	-
2	8.9	9.3	8.7	9.2	9.4	9.1	+0.6	7.0
3	9.3	10.8	10.1	10.8	10.3	10.3	+1.8	21.2
4	9.4	10.9	10.2	10.9	10.4	10.4	+1.9	22.3
5	9.5	11.1	10.3	11.0	10.5	10.5	+2.0	23.5
6	9.7	11.4	10.5	11.2	10.7	10.7	+2.2	25.9
7	10.2	11.7	10.8	11.5	11.6	11.2	+2.7	31.8
8	10.8	12.3	11.4	12.0	11.9	11.7	+3.2	37.4
hybrid NK Lemero								
1	7.8	9.4	8.9	8.8	8.1	8.6	-	-
2	9.1	9.5	8.9	9.4	9.6	9.3	+0.7	8.1
3	9.7	10.8	10.5	10.6	10.4	10.4	+1.8	20.9
4	9.8	10.9	10.6	10.8	10.5	10.5	+1.9	22.1
5	9.9	11.0	10.7	10.9	10.6	10.6	+2.0	23.3
6	10.2	11.2	10.9	11.2	10.8	10.9	+2.3	26.7
7	10.5	11.7	11.2	11.5	11.3	11.2	+2.6	30.2
8	11.0	12.1	11.6	12.0	11.7	11.6	+3.0	36.0
LSD_{05} *A*	-	-	-	-	-	*0.98*	-	-
LSD_{05} *B*	-	-	-	-	-	*0.49*	-	-
LSD_{05} *C*	-	-	-	-	-	*0.77*	-	-
LSD_{05} *AB*	-	-	-	-	-	*0.80*	-	-
LSD_{05} *AC*	-	-	-	-	-	*0.34*	-	-
LSD_{05} *BC*	-	-	-	-	-	*0.20*	-	-
LSD_{05} *ABC*	-	-	-	-	-	*0.06*	-	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

As a result of the calculations, straight–line regression dependencies of the resultant traits of crude protein content and crude fat content in corn grain of hybrids NK Termo and NK Lemero were established on the combined use of straw destruction with Vermistim D preparation with sowing of green manure in the technology of cultivation For both hybrids, optimal variants of the experiment were determined, which are characterized by the following linear equations: crude protein content – y 0.0475x + 8.89, $R^2 = 0.8824$; crude fat content – $y = 0.0405x + 4.3248$, $R^2 = 0.8523$. In both cases, a close correlation was established between the resultant and factor attributes, as evidenced by the high values of the determination coefficients.

The results of the research (Sendetskyi, 2021) on the study of the structural composition of the soil under corn sowing and the determination of the structural coefficient showed a fairly high structuring under the influence of the use of straw and green manure. In particular, at the time of sowing, the number of clumpy (>10 mm) and small (<0.25 mm) fractions decreased by 2.53–2.3 and 0.4–0.8%, respectively, and the content of agronomically valuable aggregates (0.25–10 mm) increased by 2.0–3.2%. This, in turn, led to a higher structural coefficient in these variants at the time of sowing compared to the control by 0.09–0.21 and, respectively, by 0.10–0.17% at the time of harvest (Table 3.98).

The highest indicators of the structural and aggregate composition of the soil were in the variant where the destruction of straw “Vermistim–D” 6 l ha^{-1} and sowing of crops on green manure (white mustard + oilseed radish) were performed. In this variant, the amount of aggregates in the 0–10 cm soil layer with a size of 0.25–10 mm at the time of sowing was 66.2%, or 6.1% more compared to the control with a structural coefficient of 1.72.

Our research has shown that the combined use of straw and green manure contributed to a decrease in soil density. In all variants of straw destruction with Vermistim–D in combination with green manure sowing, the density of the tilth (0–10 cm) layer was on average 0.08–0.10 g cm^{-3} less at the time of corn sowing and 0.10–0.12 g cm^{-3} at the time of corn harvesting compared to the control (Table 3.98).

Table 3.98

Structural and aggregate composition of tilthy soil under the use of straw and green manure of maize agrocenosis (average for 2013–2017) (Sendetskyi, 2021)

Variant	Share of units (%) by size						Structural coefficient	
	>10		10-0,25		<0,25			
	at the time of sowing	at the time of harvesting	at the time of sowing	at the time of harvesting	at the time of sowing	at the time of harvesting	at the time of sowing	at the time of harvesting
1	25.3	25.8	60.1	59.0	14.6	15.2	1.51	1.44
2	24.0	24.6	61.6	60.7	14.4	14.7	1.60	1.54
3	23.9	24.5	61.8	60.9	14.3	14.6	1.62	1.56
4	23.9	24.5	61.8	60.9	14.3	14.6	1.62	1.56
5	23.8	24.4	61.9	61.0	14.3	14.6	1.63	1.57
6	23.7	24.3	62.1	61.2	14.2	14.5	1.64	1.58
7	23.4	24.3	62.8	61.4	13.8	14.3	1.69	1.60
8	23.0	24.1	66.2	61.7	13.8	14.2	1.72	1.61

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Studies (Sendetskyi, 2021) have also shown that when straw and green manure were used compared to the control during sowing, the total porosity of the 0–10 cm soil layer increased by 8.4–9.9%, and the 10–20 cm layer by 6.1–8.1%, creating more favorable conditions for the growth and development of grain corn, better soil permeability as a basis for more productive use of precipitation (Table 3.100).

Soil moisture supply. Moisture is one of the most important factors in soil fertility, and its conservation and rational use largely depends on the impact of different farming systems. When straw destruction was carried out with Vermistim D in combination with sowing green manure, more favorable conditions were created for the growth and development of corn plants, better soil permeability as a basis for more productive use of precipitation (Table 3.101).

Table 3.99

Influence of straw and green manure on the density of sod-podzolic medium loam soil (average for 2013–2017), g cm^{-3} (Sendetskyi, 2021)

Variant	At the time of sowing		At the time of harvesting	
	soil layer, cm		soil layer, cm	
	0-10	10-20	0-10	10-20
1	1.26	1.27	1.32	1.35
2	1.23	1.24	1.27	1.30
3	1.22	1.22	1.26	1.28
4	1.20	1.21	1.25	1.27
5	1.19	1.20	1.24	1.26
6	1.18	1.19	1.22	1.24
7	1.17	1.18	1.21	1.23
8	1.16	1.18	1.20	1.23
LSD_{05} A	0.003	0.024	0.004	0.004
LSD_{05} B	0.002	0.016	0.003	0.003
LSD_{05} AB	0.002	0.008	0.001	0.001

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

The accumulation of larger moisture reserves in the variants of combined use of straw and green manure compared to the control is explained by the overall improvement of the main agrophysical parameters of the soil, as well as the influence of straw and green manure as mulching material and organic matter, which reduce unproductive moisture loss from the soil.

Table 3.100

Influence of straw and green manure on the porosity of sod-podzolic soil (average for 2013–2017), % (Sendetskyi, 2021)

Variant	At the time of sowing		At the time of harvesting	
	soil layer, cm		soil layer, cm	
	0-10	10-20	0-10	10-20
1	50.3	51.2	48.2	48.0
2	56.4	55.8	53.4	52.8
3	56.8	56.2	55.1	55.1
4	56.9	56.4	55.5	55.4
5	57.6	56.8	56.3	56.7
6	58.7	57.3	57.8	57.1
7	59.1	58.6	59.0	58.1
8	60.2	59.3	59.4	59.6
LSD_{05} A	0.84	0.80	0.99	0.97
LSD_{05} B	0.48	0.37	0.57	0.54
LSD_{05} AB	0.27	0.19	0.24	0.30

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

The level of soil structure in soils with heavy particle size distribution reflects not only natural fertility but also erosion resistance. Therefore, minimizing the physical degradation of soils is one of the conditions for increasing the environmental and economic efficiency of agricultural production. An important characteristic of soil macro-aggregates is their resistance to destruction, in particular under the influence of water. The water resistance of aggregates determines the quality of the soil structure and its agronomic value. Therefore, the study of the water resistance of soil aggregates under the influence of applied measures is important, since the physical condition of the soil and the conditions for plant development depend on their stability and stability. There is a close correlation between the amount of water-resistant aggregates >0.25 mm in size, on the one hand, and crop yields, humus reserves, soil density, soil moisture, and nutrient content, on the other. Increasing the number of water-resistant aggregates to 80% increases and extends the effect of these indicators.

It was found (Sendetskyi, 2021) that the use of straw in combination with green manure improved the water resistance of soil aggregates. Thus, in the variants of straw use in conjunction with green manure, the water resistance of structural aggregates of the 0–30 cm soil layer during the years of study was 5–9% higher compared to the control (Table 3.102).

Table 3.101

Moisture content of the tilth layer of soil (0-30 cm) under the use of straw in in combination with green manure (average for 2013-2017), % (Sendetskyi, 2021)

Variant	At the time of sowing corn	On average, when growing corn
1	19.8	19.1
2	20.4	19.5
3	20.5	19.7
4	20.5	19.7
5	20.7	19.9
6	20.9	20.1
7	21.2	20.6
8	21.4	20.8
LSD_{05} A	0.23	0.23
LSD_{05} B	0.06	0.05
LSD_{05} AB	0.02	0.02

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Studies have shown that in the maize field in all variants under different tillage methods, sowing the crop on green manure after incorporating straw into the soil increased the humus content in sod-podzolic soil.

Table 3.102

Effect of green manure on water resistance of soil structural aggregates in the layer 0–30 cm (average for 2013–2017), % (Sendetskyi, 2021)

Variant	At the time of sowing of corn		On average, during the growing season of corn	
	coefficient water resistance	% to control	coefficient water resistance	% to control
1	15.1	100	14.8	100
2	15.8	105	15.4	104
3	15.9	106	15.5	105
4	15.9	106	15.5	105
5	16.0	106	15.6	105
6	16.1	107	15.7	106
7	16.4	109	16.0	108
8	16.5	109	16.1	109
LSD_{05} A	*0.18*	-	*0.18*	-
LSD_{05} B	*0.05*	-	*0.05*	-
LSD_{05} AB	*0.02*	-	*0.02*	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

The results of the research showed that the combined use of straw and green manure provided an average increase in the humus content in the tilth layer of soil by 0.09-0.15% in 2013-2018 compared to the control The largest increase in humus content (+ 0.15%) in sod-podzolic soil was in the variant with the combined use of straw and a mixture of green manure (white mustard + oil radish).

Studies (Sendetskyi, 2021) have shown that the combined use of straw and green manure in all variants of corn cultivation significantly reduced the acidity of sod-podzolic soils (Table 3.103).

Table 3.103

The impact of combined use of straw and green manure on the humus content in the tilth layer of soil (2013-2017), % (Sendetskyi, 2021)

Variant	Year					Average	± to control
	2013	2014	2015	2016	2017		
1	3.24	3.39	3.18	3.26	3.25	3.25	-
2	3.32	3.42	3.23	3.28	3.28	3.31	0.06
3	3.33	3.49	3.26	3.30	3.31	3.32	0.07
4	3.33	3.50	3.26	3.32	3.31	3.32	0.07
5	3.34	3.52	3.27	3.33	3.31	3.32	0.07
6	3.35	3.57	3.28	3.34	3.32	3.34	0.09
7	3.36	3.58	3.29	3.35	3.36	3.36	0.11
8	3.39	3.62	3.34	3.36	3.29	3.40	0.15
LSD_{05} A	-	-	-	-	-	*0.04*	-
LSD_{05} B	-	-	-	-	-	*0.01*	-
LSD_{05} AB	-	-	-	-	-	*0.003*	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Thus, on the basis of research during 2013–2017, it was found that in the variants where straw was destructed with Vermistim-D and incorporated into the soil and sown with white mustard and oil radish as green manure, the soil acidity was 0.39-0.65 pH lower than in the control (straw harvesting without destruction and sowing green manure).

A significant decrease in acidity (on average by 0.65 pH) occurred during the years of research in the variant of straw destruction with Vermistim-D (6 l ha^{-1}) and sowing a mixture of white mustard and oil radish for green manure.

The analysis of the study results showed that the combined use of straw and green manure influenced the dynamics of the respiration rate of sod-podzolic soil (Table 3.103). The biological activity of sod-podzolic soil in maize crops was different and depended on natural and climatic conditions, straw and green manure application, as well as on the time of its determination in different phases of growth and development of maize plants. Thus, in the variants where straw destruction was performed in combination with the green mass of white mustard and oilseed radish, the production of carbon dioxide by the soil increased during the growing season of the crop. When straw and a mixture of green manure (white mustard + oil radish) were applied, CO_2 emission in the maize agrocenosis increased by 66 mg CO_2 m^2 per day in the germination phase and by 144 mg CO_2 m^2 per day in the panicle ejection phase compared to the control.

Table 3.104

Effect of combined use of straw and green manure on the acidity of sod podzolic soil (average for 2013–2017), pH (Sendetskyi, 2021)

Variant	Year					Average	± to control
	2013	2014	2015	2016	2017		
1	4.8	5.2	4.9	5.0	5.1	5.03	-
2	4.9	5.5	5.2	5.1	5.3	5.22	+ 0.19
3	5.0	5.6	5.3	5.2	5.5	5.32	+0.29
4	5.0	5.6	5.3	5.2	5.5	5.32	+0.29
5	5.0	5.6	5.3	5.2	5.5	5.32	+0.29
6	5.1	5.7	5.4	5.3	5.6	5.42	+ 0.39
7	5.2	5.9	5.5	5.4	5.7	5.53	+ 0.50
8	5.3	6.1	5.7	5.6	5.8	5.68	+ 0.65
LSD_{05} A	-	-	-	-	-	*0.11*	-
LSD_{05} B	-	-	-	-	-	*0.03*	-
LSD_{05} AB	-	-	-	-	-	*0.009*	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Table 3.105

Intensity of carbon dioxide emission from sod-podzolic soil depending on the use of straw and green manure in agrocenosis corn (average for 2013-2017), mg CO_2 m^{-2} per day (Sendetskyi, 2021)

Variant	The phase of plant growth and development		
	seedlings	panicle ejection	wax ripeness
1	191	354	263
2	229	432	296
3	233	462	296
4	235	467	300
5	238	471	303
6	245	486	312
7	251	492	328
8	257	498	374
LSD_{05} A	1.28	2.06	1.37
LSD_{05} B	0.40	0.65	0.44
LSD_{05} AB	0.20	0.42	0.24

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

The process of decomposition of organic matter begins with the hydrolysis of cellulose, which is a component of the cell membranes in plant residues. The resulting sugars are rapidly utilized by cellulosic bacteria and converted into other compounds.

Determination of the total biological activity by the degree of decomposition of flaxen fabric makes it possible to assess the intensity and characteristics of biological processes in the soil in the most general integrated form.

In the variants of straw and green manure application, the decomposition of flaxen fabric was more intense than in the control (Table 3.106).

Table 3.106

The effect of combined use of straw and green manure in corn agrocenosis on the decomposition of linen fabric in sod-podzolic soil (average for 2013–2017), % (Sendetskyi, 2021)

Variant	Observation period					
	phase 6-8 leaves			harvesting		
	horizon depth, cm					
	0-10	10-20	0-30	0-10	10-20	0-30
1	20.8	23.7	20.4	23.4	26.7	23.1
2	26.7	28.6	25.7	28.7	30.2	27.4
3	27.4	30.9	26.2	28.9	28.9	28.1
4	27.6	30.9	26.5	29.2	29.2	28.4
5	27.9	31.2	26.8	29.5	29.5	28.7
6	28.8	31.5	27.6	30.4	33.1	29.6
7	29.3	32.8	28.3	31.8	33.4	30.5
8	29.6	33.5	28.8	32.1	35.5	31.9

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

In the first half of the maize growing season, the dynamics of the intensity of flaxen fabric decomposition in the phase of 6–8 leaves was higher (by 8.8 relative %) in the soil layer of 0-10 cm, and 9.8 % in the soil layer of 10–20 cm in the variant of combined straw and green manure than in the control. This difference is leveled in the future. However, the decomposition of linen fabric in the variant of straw destruction “Vermistim-D” and a mixture of oil radish and white mustard was noticeably more active during the entire corn growing season.

The effect of using green manure is also manifested in a reduction in the level of weed infestation of crops and plant damage by pests and diseases that limit the growth of crop yields.

The aim of the research was to determine the effect of green manure on weed infestation of field crops in the Western Forest-Steppe. Our research on the impact of green manure on weeds in corn crops also showed their high efficiency (Table 3.107).

Table 3.107

Influence of destruction of residues of the predecessor and green manure on weed infestation of corn crops (average for 2013–2017) (Sendetskyi, 2021)

Variant	Number of weeds in the full germination phase			
	pcs. m^{-2}	± to control	dry weight, g m^{-2}	± to control
1	321	-	41.2	-
2	276	-45	36.3	-4.9
3	252	-69	32.4	-8.8
4	231	-90	31.9	-9.3
5	226	-95	29.6	-11.6
6	193	-128	24.6	-16.6
7	185	-136	20.5	-20.7
8	164	-157	18.7	-22.5
LSD_{05} A	4.12	-	2.29	-
LSD_{05} B	2.71	-	0.85	-
LSD_{05} AB	4.76	-	0.09	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

When counting the number of weeds in corn crops in the phase of full germination, it was found that in variants 4 and 5 the number of weeds was 185 and 164 pcs. m^{-2} , respectively, which is 136 and 157 pcs. m^{-2} less than in the control.

The best rate of weed reduction (51%) was observed in the variant of destruction with Vermistim-D, 6 l ha^{-1} with sowing a mixture of white mustard and oil radish on green manure. The physiological reaction of the most common weed species in the cenosis due to soil green manure was different. The stimulating effect of organic substances due to the humification of straw and green mass of oil radish was manifested in those weeds, the number of which did not decrease under the influence of green manure – common couch grass and creeping wheatgrass. The content of green pigment in the leaves of the tenacious marigold was stable and did not change.

The use of straw and green manure provided an increase in grain yield of maize hybrid Lemero by 8.1–36.0%. The highest yield on average over the years of research of 11.6 t ha^{-1} or 3.0 t ha^{-1} (36%) more than the control was in the variant where straw destruction was carried out with the preparation “Vermistim D” (6 l ha^{-1}) with simultaneous sowing of a mixture of white mustard and oilseed radish.

The results of the research showed that in all variants where straw destruction with Vermistim D (6 l ha^{-1}) in combination with green manure significantly improved the quality of corn grain of hybrids NK Termo and NK Lemero (Table 3.108).

Studies have established the highest content of crude protein 9.7%, crude fat 5.12% and crude fiber 2.76% in the hybrid NC Thermo in the variant of straw destruction by Vermistim-D and sowing a mixture of white mustard and oil radish on green manure (increase in crude protein – 0.7%, crude fat – 0.76%, crude fiber – 0.36% compared to the control).

In the hybrid NK Lemero on this variant, the content of crude protein was 9.6%, crude fat 4.92% and crude fiber 2.75% (an increase in crude protein – 0.9%, crude fat – 0.58%, crude fiber – 0.33% compared to the control).

The use of oil radish as a green manure for potato cultivation was effective (Molotskyi, 2005). The results of many research institutions and production practice show that the most promising for use as green manure crops are:

– crops suitable for intermediate cultivation;

– crops with a short growing season and high intensity of yield and biomass formation;

– crops that are undemanding to soil fertility elements, moisture and temperature;

– crops that do not require a large amount of fertilizers, protection products with the possibility of using a minimized method of soil cultivation;

– crops that do not reduce the productivity of subsequent crops and do not worsen the phytosanitary condition of the soil and crops.

Table 3.108

Grain yield of maize hybrids NK Termo and NK Lemero with the use of straw and green manure (average for 2013–2017), t ha^{-1} (Sendetskyi, 2021)

Variant	Year					Average	± to control	
	2013	2014	2015	2016	2017		t ha^{-1}	%
hybrid NK Thermo								
1	7.4	9.2	8.6	8.8	8.4	8.5	-	-
2	8.9	9.3	8.7	9.2	9.4	9.1	+0.6	7.0
3	9.3	10.8	10.1	10.8	10.3	10.3	+1.8	21.2
4	9.4	10.9	10.2	10.9	10.4	10.4	+1.9	22.3
5	9.5	11.1	10.3	11.0	10.5	10.5	+2.0	23.5
6	9.7	11.4	10.5	11.2	10.7	10.7	+2.2	25.9
7	10.2	11.7	10.8	11.5	11.6	11.2	+2.7	31.8
8	10.8	12.3	11.4	12.0	11.9	11.7	+3.2	37.4
hybrid NK Lemero								
1	7.8	9.4	8.9	8.8	8.1	8.6	-	-
2	9.1	9.5	8.9	9.4	9.6	9.3	+0.7	8.1
3	9.7	10.8	10.5	10.6	10.4	10.4	+1.8	20.9
4	9.8	10.9	10.6	10.8	10.5	10.5	+1.9	22.1
5	9.9	11.0	10.7	10.9	10.6	10.6	+2.0	23.3
6	10.2	11.2	10.9	11.2	10.8	10.9	+2.3	26.7
7	10.5	11.7	11.2	11.5	11.3	11.2	+2.6	30.2
8	11.0	12.1	11.6	12.0	11.7	11.6	+3.0	36.0
LSD_{05} A	-	-	-	-	-	*0.98*	-	-
LSD_{05} B	-	-	-	-	-	*0.49*	-	-
LSD_{05} C	-	-	-	-	-	*0.77*	-	-
LSD_{05} AB	-	-	-	-	-	*0.80*	-	-
LSD_{05} AC	-	-	-	-	-	*0.34*	-	-
LSD_{05} BC	-	-	-	-	-	*0.20*	-	-
LSD_{05} ABC	-	-	-	-	-	*0.06*	-	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

According to the requirements and a set of economically valuable traits, we selected green manure crops that meet the soil and climatic conditions of the zone, which were grouped into two blocks: spring oil radish, white mustard and their mixture and winter rye, winter rape and their mixture (Molotskyi, 2005).

Table 3.109

Corn grain quality indicators for the use of straw and green manure (average for 2013–2017), % (Sendetskyi, 2021)

Variant	Contained in an absolutely dry substance				
	Crude protein	Crude fat	Crude fibre	Crude ash	Nitrogen-free extractives
hybrid NK Thermo					
1	9.0	4.36	2.41	1.80	82.47
2	9.2	4.54	2.56	1.68	82.02
3	9.3	4.58	2.57	1.61	81.94
4	9.3	4.63	2.59	1.59	81.86
5	9.3	4.68	2.62	1.56	81.82
6	9.4	4.82	2.67	1.42	81.69
7	9.5	4.95	2.67	1.35	81.53
8	9.7	5.12	2.76	1.36	81.06
hybrid NK Lemero					
1	8.7	4.34	2.42	1.75	82.78
2	9.1	4.53	2.45	2.45	81.69
3	9.2	4.57	2.47	2.52	81.61
4	9.2	4.59	2.50	2.55	81.55
5	9.3	4.62	2.52	2.57	81.41
6	9.4	4.65	2.60	2.60	80.32
7	9.5	4.80	2.65	2.65	80.24
8	9.6	4.92	2.75	2.75	79.98
LSD_{05} A	*0.62*	*0.28*	-	-	-
LSD_{05} B	0.17	0.09	-	-	-
LSD_{05} C	*0.13*	*0.02*	-	-	-
LSD_{05} AB	*0.07*	*0.05*	-	-	-
LSD_{05} AC	*0.13*	*0.02*	-	-	-
LSD_{05} BC	*0.02*	*0.03*	-	-	-
LSD_{05} ABC	*0.04*	*0.03*	-	-	-

Experiment variant: 1 – control (straw production without its destruction and siderate sowing); 2 – destruction of straw Vermystim-D, 6 l ha^{-1} without sowing siderate; 3 – sowing of white mustard on siderat; 4 – sowing oilseed radish on siderate; 5 – sowing of a mixture of white mustard and oilseed radish on cider; 6 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of white mustard on siderate; 7 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of oil radish on siderate; 8 – destruction of straw Vermystim–D, 6 l ha^{-1} + sowing of a mixture of white mustard and oilseed radish on siderate.

Table 3.110

Experimental design (Molotsky, 2005)

Factor A	**Bearded pink (Ai)**		**Yavir (A2)**	
Factor B	Continuous cultivation (B i)	In crop rotation (B2)	Continuous cultivation (B i)	In crop rotation (B2)
Factor C.	- No fertilizer (C) - Manure 40 t ha^{-1} (C2) 3. Manure 40 t/ha + $N_{45}P_{45}K_{45}$ (C3) 4. $N_{45}P_{45}K_{45}$ (C4) 5. Oilseed radish (C5) 6. Oiseedl radish + $N_{45}P_{45}K_{45}$ 7. White mustard (C7) 8. White mustard + $N_{45}P_{45}K_{45}$) 9. White mustard + oil radish (C9) 10. White mustard + oilseed radish + $N_{45}P_{45}K_{45}$ 11. Winter rye 12. Winter rye + $N_{45}P_{45}K_{45}$ 13. Winter rape 14. Winter rape + $N_{45}P_{45}K_{45}$ 15. Winter rapeseed + winter rye 16. Winter rapeseed + winter rye + $N_{45}P_{45}K_{45}$			

It should be noted that in addition to the yield (roots + green mass) of green manure biomass, the content of basic nutrients in them is important, which depends on the growing conditions. It was found (Molotskyi, 2005) that on average over three years, green manure crops developed better and accumulated more nutrients when grown in a crop rotation compared to placement after potatoes, which were grown permanently (Table 3.111).

The biomass yield in permanent plantations and in crop rotation was dominated by spring green manure, where it averaged 213 and 262 c ha^{-1}, respectively, which is 35 and 44 c/ha more than in winter crops. However, winter crops prevailed in the accumulation of nutrients in the biomass of green manure.

If in a short-rotation crop rotation, when plowing biomass of spring crops, 77 kg/ha of nitrogen enters the soil, including 62 kg of green mass, 15 kg of roots; 21 kg of phosphorus, including 13 and 8 kg; 78 kg of potassium, including 60 and 18 kg; 1450 kg of carbon, including 868 and 590 kg, while using winter crops – 95 kg of nitrogen (69 and 26 kg); 26 kg of phosphorus (14 and 12 kg); 99 kg of potassium (76 and 23 kg); 1495 kg of carbon (792 and 709 kg), respectively.

With the constant cultivation of potatoes, the accumulation of nutrients in the biomass of green manure decreased, especially nitrogen, potassium and carbon. The phosphorus content remained almost unchanged.

The best green manure in terms of nutrient accumulation over an average of three years was a mixture of winter rye and winter rape, which was used to add 91–101 kg ha^{-1} of nitrogen, 26–28 kg of phosphorus, 88108 kg of potassium, and 1313–1544 kg ha^{-1} of carbon to the soil. However, it should be noted that pure winter rye was not inferior to the above variant in terms of nitrogen and phosphorus accumulation.

Table 3.111

Biomass yields of green manure crops and nutrient content, average for 2002–2004 (Molotskyi, 2005)

Variant	Continuous cultivation					In crop rotation				
	Harvest, c ha^{-1}	Content of the main elements nutrition, kg ha^{-1}				Harvest, c ha^{-1}	Content of the main elements nutrition, kg ha^{-1}			
		N	P_2O_5	K_2O	C		N	P_2O_5	K_2O	C
Oilseed radish	199	63	15	69	1141	250	66	15	77	1318
Oilseed radish*	215	66	18	80	1199	250	66	15	77	1318
White mustard	209	78	23	70	1284	273	89	26	76	1581
White mustard*	228	84	28	81	1367	273	89	26	76	1581
Oilseed radish + white mustard	204	73	20	70	1228	262	77	21	80	1450
Oilseed radish + white mustard*	225	80	24	82	1323	262	77	21	80	1450
Winter rye	165	97	26	67	1276	210	102	31	81	1497
Winter rye*	178	107	31	79	1346	210	102	31	81	1497
Winter rape	173	73	19	88	1225	221	83	19	108	1445
Winter rape*	187	79	22	100	1296	221	83	19	108	1445
Winter rye + winter rape	176	91	26	88	1313	224	101	28	108	1544
Winter rye + winter rapeseed*	189	98	30	101	1387	224	101	28	108	1544
Average for spring crops	213	74	21	76	1257	262	77	21	78	1450
Average for winter crops	178	91	26	87	1307	218	95	26	99	1495
Average for green manure	196	82	24	81	1282	240	86	23	88	1473
LSD_{05} (yield)=10,8 ц/га										

Notes. * – variants with subsequent application of mineral fertilizers ($N_{45}P_{45}K_{45}$)

Table 3.112

Yield of potato tubers depending on growing conditions, t ha^{-1}, average for 2002-2004 (Molotskyi, 2005)

Variant	Continuous cultivation		In crop rotation		Average by factor C	± to control		± to manure	
	variety Borodyanskaya pink	Variety Yavir	variety Borodyanskaya pink	Variety Yavir		c ha^{-1}	%	c ha^{-1}	%
No fertilizer (control)	177	199	209	228	2o3	-	-	-83	-29
40 tons of manure	252	271	304	315	286	83	41	-	-
40 t of manure + $N_{45}P_{45}K_{45}$	297	315	356	361	332	129	64	46	16
$N_{45}P_{45}K_{45}$	214	234	258	273	245	42	2o	-41	-14
Oilseed radish	205	225	248	266	236	33	16	-50	-17
Oilseed radish + $N_{45}P_{45}K_{45}$	239	258	289	303	272	69	34	-14	-5
White mustard	207	229	250	271	239	36	18	-47	-16
White mustard + $N_{45}P_{45}K_{45}$	243	262	293	307	276	73	36	-10	-3
Oilseed radish + white mustard	207	227	250	268	238	35	17	-48	-17
Radish + mustard + $N_{45}P_{45}K_{45}$	241	260	291	305	274	71	35	-12	-4
Winter rye	21o	232	254	273	242	39	19	-44	-15
Winter rye + $N_{45}P_{45}K_{45}$	251	271	302	317	285	82	40	-1	0
Winter rape	208	229	252	271	24o	37	18	-46	-16
Winter rape + $N_{45}P_{45}K_{45}$	251	268	302	315	284	81	4o	-2	-1
Winter rye + winter rape	212	234	256	275	244	41	2o	-42	-15
Winter rye + winter rape + $N_{45}P_{45}K_{45}$	254	273	307	319	288	85	42	2	1
Average by factor B	239		284						
Average by factor A	253	270	Factor (AB): F(1.192)=1.31; p<0.2540; LSD_{05}=5.57 c Factor (AC): F(15.192)=0.47; p<0.9527; LSD_{05}=15.74 c Factor (BC): F(15.192)=0.13; p<1.0000; LSD_{05}=15.74 c Factor (ABC):F(15.192)=0.05; p<1.0000; LSD_{05}=22.26 c						
Factor (A): F (1.192)=78.29; p<0.0000; LSD_{05}=3.93 c									
Factor (B): F (1.192)=502.21; p<0.0000; LSD_{05}=3.93 c									
Factor (C): (15.192)=73.42; p<0.0000; LSD_{05}=4.3 c									

Plowing of winter green manure crops (winter rye, winter rape and their mixture) increased the yield by 19, 18 and 20%, and the additional use of $N_{45}P_{45}K_{45}$ against the background of the listed green manure crops – by 40, 40 and 42%, respectively, compared to the variant where no fertilizers were applied.

Dobryva increased potato yields significantly. For the application of 40 t/ha of pus it increased by 41%, mineral dorivs ($N_{45}P_{45}K_{45}$) – by 20%, yarikh siderativs – by 16–18%, winter crops – by 1820%. At sodding of siderates with mineral fertilizers, the yield increased by 40–42%, which was equal to the indicators of the variant with the introduction of pus. Thus, siderates with low doses of mineral fertilizers are an alternative to pus.

According to the results of analysis of soil samples before sowing these crops, it was found that the presence of nematodes reached the level of 5–8 pcs l^{-1} of soil. After the grown sideral crops were used for green fertilizer, the number of nematodes in this volume of soil decreased by 1.7–4 times and was at the level of 1–3 pcs l^{-1} of soil. It was noted that when growing white mustard for green fertilizer, nematodes were not found in the soil. It should be concluded that in the process of plant growth and development, white mustard secretes mustard oils by its root system, which negatively affect the presence of nematodes in the soil (Table 3.113).

Table 3.113

Effect of green fertilization of sideral crops on the number of nematodes in the soil, pcs l^{-1}

Green manure crop	Prior to sowing sideral crops	After plowing of sideral crops		
		2021	2022	average
Without sidedress (control)	6–7	5	3	4
Pea-oat mixture 24.0 t ha^{-1}	5–6	4	2	3
Oilseed radish чная, 29,0 t ha^{-1}	6–8	3	1	2
White mustard, 30.6 t ha^{-1}	5–8	0	0	0
Narrow-leaved lupine, 26.0 t ha^{-1}	5–7	1	1	1

For 2021 and 2022 years of research, the average yield of cucumber fruits in the variant without fertilizers was 7.6 kg m^{-2} (Tables 3.114–3.115). Application of green fertilizer of sideral crops at the rate of 24.030.6 t ha^{-1}

against the background of mineral fertilizer dose N60P60K90 provided an increase in fruit yield at the level of 2.5-4.2 kg m^{-2}, or 32–55 % in relation to the control. The highest yield of cucumber fruits 11.8 kg m^{-2} and marketability of 88% was obtained with the use of sideral crop white mustard with its stocking on green fertilizer 30 t ha^{-1} + $N_{60}P_{60}K_{90}$.

The use of sideral crops as a green fertilizer on soils of protected ground allows saving mineral fertilizers in physical weight: nitrogen – 109.2–110.4 kg ha^{-1}, phosphorus respectively 31.2–42.8 and 96.2–127.6 kg ha^{-1} of potassium.

Studies on the effect of basic tillage on the productivity of beet cenosis were also carried out. No differences in yield were found between plowing and no-tillage loosening – 63.1 t ha^{-1} and 63.4 t ha^{-1}, and at zero tillage the yield of root crops decreased by 4.3 t ha^{-1} (6.8%). In variants with no-tillage loosening and plowing, sugar yield was 10.4–10.5 t ha^{-1} and was 0.7–0.8 t ha^{-1} (6.7–7.7%) higher than in the variant with zero tillage.

Table 3.114

Effect of green fertilization of sideral crops in cucumber cultivation in greenhouses, 2021–2022

Green manure crop	Yield, kg m^{-2}	Increment		Marketability, %
		kg m^{-2}	%	
Without sidedress (control)	7.6	-	-	74
Pea-oat mixture 24.0 t ha^{-1}	10.1	2.5	32	82
Oilseed radish чная, 29,0 t ha^{-1}	10.3	2.7	36	84
White mustard, 30.6 t ha^{-1}	11.8	4.2	55	88
Narrow-leaved lupine, 26.0 t ha^{-1}	11.4	3.8	50	86
LSD_{05}	0.48			

The influence of oilseed radish as a green manure in the assessment of carbon dioxide emissions (Sokolova et al., 2019). Field experiments were performed during 2015–2017. Experience variants: 1 – pure fallow (control), 2 – fallow with short-term sowing of oil radish. The studies were carried out in four-field (2 rotation) and five-field (1 rotation) crop rotations.

Table 3.115

Influence of technology elements on sugar beet productivity when sown in mulch

Variants	Yield, t ha^{-1}	Sugar content, %	Sugar yield, t ha^{-1}
Plowing (benchmark)			
Pre-sowing cultivation with an AKSH (Combined Wide Seed Tiller) (standard)	62.7	18.56	10.4
Cultivation with reverse compaction + ACSH	66.7	18.70	11.1
Direct seeding	59.9	18.68	9.9
Stubble (reference)	63.1	18.74	10.5
Straw	64.9	18.60	10.7
Oiseed radish	65.2	18.65	10.8
White mustard	61.5	18.50	10.1
Phacelia	60.9	18.74	10.2
Average	63.1	18.65	10.4
Tillage-free loosening			
Pre-sowing cultivation with an AKSH (Combined Wide Seed Tiller) (standard)	65.1	18.63	10.8
Cultivation with reverse compaction + ACS	66.6	18.71	11.0
Direct seeding	58.5	18.64	9.7
Stubble (reference)	61.9	18.64	10.2
Straw	64.6	18.63	10.6
Oiseed radish	65.1	18.67	10.7
White mustard	61.9	18.68	10.3
Phacelia	63.7	18.67	10.6
Average	63.4	18.66	10.5
Zero-treatment			
Pre-sowing cultivation with an AKSH (Combined Wide Seed Tiller) (standard)	57.2	18.49	9.5
Cultivation with reverse compaction + ACS	66.5	18.56	11.0
Direct seeding	52.7	18.26	8.6
Stubble (reference)	56.8	18.47	9.3
Straw	57.8	18.34	9.5
Oiseed radish	62.8	18.44	10.3
White mustard	59.6	18.42	9.8
Phacelia	57.1	18.51	9.4
Average	58.8	18.44	9.7
Average for pre-sowing treatment			
Pre-sowing cultivation with an AKSH (Combined Wide Seed Tiller) (standard)	61.7	18.56	10.2
Cultivation with reverse compaction + ACS	66.6	18.66	11.0
Direct seeding	57.0	18.52	9.4
Stubble (reference)	60.6	18.62	10.0
Straw	62.4	18.66	10.3
Oiseed radish	64.3	18.59	10.6
White mustard	61.0	18.53	10.1
Phacelia	60.6	18.64	10.1

Table 3.116

Productivity and technological qualities of sugar beet root crops

Variants	Mulch	Yield, t ha^{-1}	Sugar content, %	Sugar yield, t ha^{-1}
Plowing				
Pre-sowing cultivation with an AKSH	Stubble (reference)	61.4	18.65	10.2
	Straw	66.4	18.34	10.8
	Oiseed radish	64.8	18.65	10.7
	White mustard	61.5	18.37	10.1
	Phacelia	59.4	18.80	10.0
Cultivation with reverse compaction + ACSH	Stubble (reference)	66.1	18.93	11.0
	Straw	67.0	18.64	11.0
	Oiseed radish	69.0	18.70	11.5
	White mustard	65.1	18.51	10.7
	Phacelia	66.5	18.72	11.1
Direct seeding	Stubble (reference)	61.9	18.65	10.2
	Straw	61.2	18.82	10.2
	Oiseed radish	61.7	18.61	10.2
	White mustard	57.8	18.62	9.6
	Phacelia	56.7	18.69	9.4
Tillage-free loosening				
Pre-sowing cultivation with an AKSH	Stubble (reference)	62.0	18.53	10.2
	Straw	66.6	18.51	10.9
	Oiseed radish	67.3	18.72	11.2
	White mustard	64.0	18.70	10.7
	Phacelia	65.6	18.68	11.0
Cultivation with reverse compaction + ACSH	Stubble (reference)	66.0	18.63	10.8
	Straw	68.4	18.62	11.2
	Oiseed radish	68.3	18.80	11.3
	White mustard	64.4	18.84	10.8
	Phacelia	66.1	18.65	11.0
Direct seeding	Stubble (reference)	57.7	18.75	9.6
	Straw	58.7	18.77	9.8
	Oiseed radish	59.6	18.49	9.7
	White mustard	57.3	18.50	9.4
	Phacelia	59.3	18.68	9.9

Oilseed radish (*Raphanus sativus* var. *oleífera* Metzg) was used as a green manure crop in both crop rotations. Sowing was carried out in the second decade of June, when the conditions for temperature, light, and moisture were the most optimal for the rapid growth and accumulation of biomass plants. A 35–40 days later sowing, the biomass of oilseed radish was introduced into the soil using dump plowing to a depth of 22 cm.

Vegetation of oilseed radish helped to increase the total flow of CO_2 from the soil surface over this period. Indicators increased about 1.5 times compared to the control variant, regardless of experience and year of research. The exception was the 2016 data for experiment II, where the relative increase in the total CO_2 flux was 10%. Since the release of CO_2 from the soil with actively growing plants is associated mainly with respiration of the roots and rhizosphere microflora, this could be the result of a significant thinning of sowing against the background of a prolonged drought (Table 3.117).

Comparison of the results obtained simultaneously in the fallow and cropland, allowed us to estimate the proportion of root respiration and rhizosphere microflora in the total flux of CO_2 from the soil surface in the short-term cultivation of oilseed radish. The value of their joint contribution to the total CO_2 emissions during the growing season was 40–63%. Close estimates of the parameter (up to 50% of the total flux), obtained including isotope methods, are shown.

After plowing up the green mass of oilseed radish into the soil, the total CO_2 flux from its surface increased 1.4–2.3 times as compared with the control, and the differences in all years were statistically significant ($p < 0.05$). Relative to pure fallow, the increase in experience I for the period amounted to 106, 108 and 38%, respectively in 2015, 2016 and 2017. In experience II, the increase in flux over the years reached 130, 48 and 50%. A smaller increase of values in the variants with the green manure of both experiences in 2017 was apparently associated with unfavorable hydrothermal conditions for mineralization, especially temperature. As is known, the dependence of the rate of decomposition of organic matter on temperature is linear or exponential in nature. The low intensity of the mineralization processes in experience II under the conditions of 2016 could be due to the lower inflow of plant biomass in the soil due to sparse sowing. During the period of high availability of organic matter of plant origin, the contribution of soil organic matter to the outflow of CO_2 is insignificant.

Accounting for oilseed radish yielded estimated the amount of plant matter formed by its aboveground and underground biomass for a short period of cultivation (~ 40 days) in the conditions of the forest-steppe. The total biomass ranged from 170 to 705 g dry matter m^{-2}. Regardless of experience, the maximum yield of green manure crops was obtained in 2017, and the minimum – in 2016, which corresponds to the severity of the aridity period during the growing season of these years.

Table 3.117

The total CO_2 emission from the surface of gray forest soil in the field experiences (Sokolova et al., 2019)

Variant	Year	On the whole for the season (May – Sept)	In the periods of observation		
			before green manure planting	during green manure vegetation	after plowing green mass
Experience I					
1	2015	210 [194;230]	83 [75; 93]	81 [72;84]	49 [38; 61]
	2016	201 [192; 219]	89 [82; 98]	70 [63; 73]	46 [35; 57]
	2017	166 [154; 204]	52 [47; 76]	81 [74; 85]	52 [50; 53]
2	2015	301 [277;328]**	70 [68; 76]	124 [117; 149]**	102 [87; 112]**
	2016	266 [251; 301]**	64 [58; 76]	108 [102; 130]**	95 [80; 104]**
	2017	272 [247; 278]**	56 [49; 57]	130 [109; 137]**	72 [70; 75]**
Experience II					
1	2015	91 [79;105]*	20 [18; 24]	42 [35; 49]	29 [25; 31]*
	2016	173 [157; 182]	43 [42; 46]	77 [69; 85]	52 [43;54]
	2017	129 [127; 142]	44 [41; 54]	46 [40; 50]	42 [40; 44]
2	2015	143 [129; 156]*/**	21 [20; 24]	59 [45; 65]	67 [56; 79]**
	2016	214 [184; 231]**	46 [42; 50]	85 [83; 101]*	77 [72; 95]**
	2017	175 [164; 190]**	32 [32; 36]	75 [75; 87]**	63 [60; 64]**

Note: 1 – pure fallow; 2 – fallow with short-term sowing of oilseed radish. * statistically valuable ($p<0.05$) differences in years; ** statistically valuable ($p<0.05$) differences between variants.

The initial fertility of the soil had no less influence on the formation of productivity. So, in experiences I, where its level was higher, the yield of oilseed radish in all years was higher. The ratio of the above-ground mass / roots (6.7-9.6) indicates that in all years the flow of organic matter into the soil was provided by the green mass.

Due to the unequal productivity of oilseed radish in experiences, the parameters of net primary production (NPP) varied widely (81–197 g C m^{-2}). In half the cases, the photosynthetic carbon sink did not compensate for its loss due to respiration of heterotrophic microflora. As a result, a negative carbon balance was formed. The largest deficit (-128 g C m^{-2}) differed in the variant of fallow with short-term sowing of oilseed radish in experiences II under the conditions of 2016, when its productivity was low, and the loss of carbon due to the active mineralization of green mass and barley plant residues was significantly higher. High yields of green manure culture in the experiences of 2017, combined with unfavourable conditions for the mineralization of newly introduced organic matter, contributed to the formation of a positive carbon balance (+64 – +166 g C m^{-2}). Also positive (+26 g C m^{-2}) turned out to be a balance in the variant with the green manure of experience II in 2015, when the crop rotation field was located after the fallow. The reason could be a smaller stock and activity of the microbial pool in the absence of plant residues of the previous culture.

The carbon balance in the pure fallow, as is characteristic of this farming technique, was characterized by a significant deficit (-91 – -210 g C m^{-2}). Its value was influenced by the soil carbon resource and the pool of plant residues of the previous culture, which is confirmed by the data in literature. Short-term green manure of the fallow reduced the deficit, and when combined conditions that are favorable for plant growth, but unfavorable for the mineralization of their green mass, contributed to the formation of a positive carbon balance. The important role of green manure in carbon sequestration and replenishment of its reserves in soils in the semi-arid climate of even tropical regions is shown in.

Thus, the short-term green manure of the fallow in the conditions of the forest-steppe zone contributes to a significant change in carbon fluxes in the agroecosystem, not only by increasing its gaseous losses, but also by intensive accumulation of phytomass. Short-term cultivation of oilseed radish due to rapid growth can be considered an effective farming technique, since it reduces and/or completely compensates for the deficit in the carbon balance in comparison with pure fallow.

It was also established (Oliveira et al., 2017) that oil radish is a reliable source of macro and microelements in the soil as a result of their release during the decomposition of green manure in the soil. In 2013, the litterbags were placed directly on the soil surface, between onion rows. Twenty-four bags of each treatment were placed (six bags in each plot), for a total of 144 litterbags. Bags were secured on the ground by iron bars to prevent shifting in the wind. Bags were collected at the time of deposition (time 0) and at 15 and 45 days after deposition (DAD) of the litterbags. The bags were opened in the laboratory; the residue removed after the bag remained in the experimental area contained soil particles and poultry litter, given that the experimental area contains soil particle waste. The litter bags were opened in the laboratory and the remaining plant residues were removed, washed in distilled water and then in 0.1 mol L^{-1} HCl solution and again in distilled water. Residues were dried in a drying oven with circulation at 65 °C, weighed, ground and reserved for chemical fractionation of P in the tissue.

The other part of fresh shoot matter was homogenized, weighed, and placed in nylon fabric litterbags (0.40 x 0.40 m, with 2 mm mesh) (Tagliavini et al., 2007). The following amounts of fresh shoot matter were placed in separate litterbags: 235.13 g of WD, 767.99 g of BO, 434.50 g of RY, 460.46 g of RD, 570.67 g of RD + BO, and 416.82 g of RD + RY. These values, in terms of kg ha-1 of DM, amounted to 4620 WD, 5263 BO, 5060 RY, 3640 RD, 4030 RD + BO, and 3730 RD + RY, and they are equivalent to DM amounts obtained in the field at the sampling carried out on July 11, 2013. The other initial chemical characteristics of the residues and amounts of nutrients added to each treatment are shown in Table 3.118.

Residue DM was subjected to P chemical fractionation. The following P fractions were obtained: total acid-soluble P (TASP), soluble inorganic P (Psi), soluble organic P (Pso) (by the difference between TASP and Psi), lipid P (Plip), P associated with RNA (P-RNA), P associated with DNA (P-DNA), and the residual P fraction (Pres).

The distribution of P forms in plant tissue at time 0 (0 DAD) occurred in the following order of importance for all treatments: Psi > Pso ≈ Plip ≈ P-RNA > P-DNA ≈ Pres. The Psi form exhibited a content of 3068 ± 566 mg kg^{-1} in the overall average, representing approximately 73 ± 14 % of the total P content (Figures 3.25–3.26). In addition to total P concentration, the release of P from cover crop tissue also depends on the form of P accumulated in the tissue and the quality of the residue.

Table 3.118

Initial chemical characterization of weed (WD), black oat (BO), rye (RY), oilseed radish (RD), oilseed radish + black oat (RD + BO), and oilseed radish + rye (RD + RY) residues and added amounts of dry matter and nutrients (Oliveira et al., 2017)

Parameter	WD	BO	RY	RD	RD + BO	RD + RY
TOC	409.4 ± 1.02[1]	375,0 ± 0.40	401.0 ± 2.06	365.2 ± 1.21	369.7 ± 0.80	366.8 ± 1.50
N	26.2 ± 0.17	19.8 ± 0.21	18.0 ± 0.19	22.3 ± 0.37	21.9 ± 0.34	24.2 ± 0.22
P	5.5 ± 0.12	6.0 ± 0.02	5.7 ± 0.02	6.5 ± 0.06	6.6 ± 0.01	6.6 ± 0.01
K	21.5 ± 0.10	42.9 ± 0.59	24.9 ± 0.30	33.4 ± 0.45	36.3 ± 0.32	33.0 ± 0.81
Ca	4.9 ± 0.10	3.5 ± 0.04	6.4 ± 0.12	6.9 ± 0.06	10.4 ± 0.11	8.0 ± 0.16
Mg	1.9 ± 0.05	1.6 ± 0.03	2.1 ± 0.11	2.1 ± 0.01	4.6 ± 0.05	2.6 ± 0.04
Cel	182.3 ± 1.02	239.6 ± 7.21	161.8 ± 7.59	211.0 ± 2.87	220.7 ± 2.34	192.9 ± 1.12
Lig	69.2 ± 0.77	86.1 ± 2.23	102.8 ± 5.33	71.7 ± 1.63	93.5 ± 2.41	80.6 ± 0.63
Bio	748.4 ± 1.28	674.3 ± 5.78	735.5 ± 9.01	717.3 ± 4.09	685.6 ± 4.19	726.5 ± 1.57
C/N	16 ± 0.99	19 ± 1.93	22 ± 2.32	17 ± 2.72	17 ± 2.50	15 ± 1.53
Lig/N	3 ± 0.17	4 ± 0.21	6 ± 0.19	3 ± 0.37	4 ± 0.34	3 ± 0.21
C/P	75 ± 14.82	62 ± 2.61	70 ± 5.36	56 ± 4.91	56 ± 6.28	56 ± 7.59
Cel/Lig	3 ± 0.17	3 ± 0.21	2 ± 0.19	3 ± 0.37	2 ± 0.34	2 ± 0.22
Added amount (kg ha^{-1})						
DM	4620.0	5263.1	5060.0	3640.0	4030.0	3730.0
TOC	1891.6	1973.7	2029.0	1329.4	1490.1	1368.0
N	120.9	104.4	91.1	81.1	88.3	90.2
P	25.2	31.7	28.8	23.9	26.6	24.5
K	99.2	225.8	126.0	121.5	146.2	123.1
Ca	22.4	18.6	32.2	25.0	42.0	29.8
Mg	8.8	8.4	10.9	7.7	18.7	9.8

[1]Mean ± standard deviation (n = 4). Cel: cellulose, Lig: lignin, Bio: no structural biomass, DM: dry matter, TOC: total organic carbon.

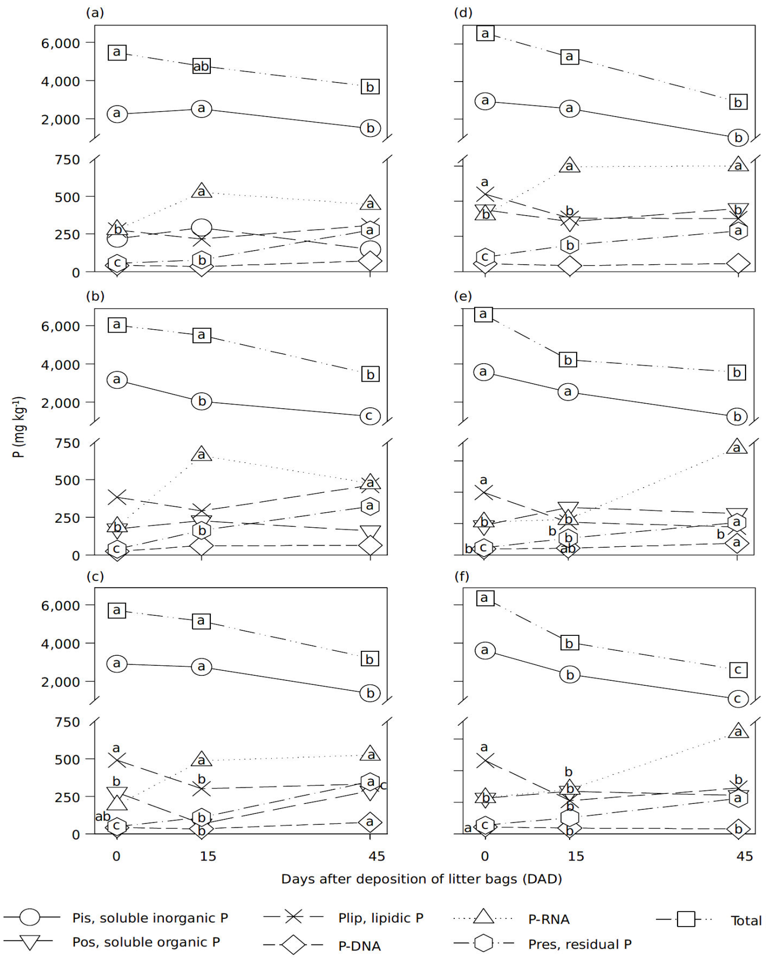

Figure 3.25 – Changes in phosphorus forms (a) in residues of weeds (WD); (b) black oat (BO); (c) rye (RY); (d) oilseed radish (RD); (e) oilseed radish + black oat (RD + BO); and (f) oilseed radish + rye (RD + RY) at 0, 15, and 45 days after deposition (DAD) of the litterbags on the soil surface in agroecological no-till onion. Means followed by the same letter in DAD do not differ by the Tukey test (*p<0.05*) (Oliveira et al., 2017)

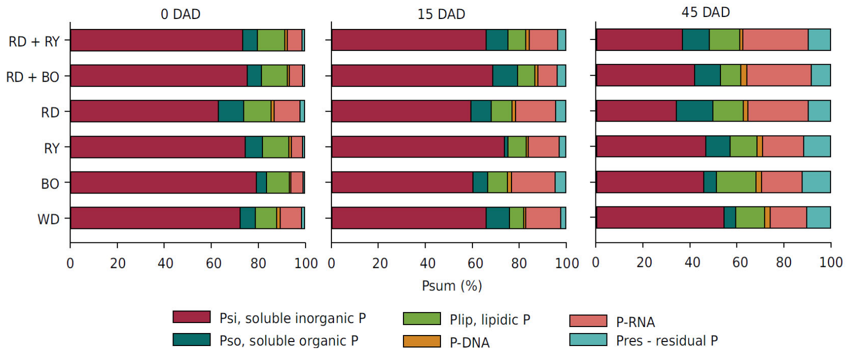

Figure 3.26 – Relative percentage of P fractions in the plant tissue of the residues of weed (WD), black oat (BO), rye (RY), oilseed radish (RD), oilseed radish + black oat (RD + BO), and oilseed radish + rye (RD + RY) extracted by chemical fractionation in cover crop residues at the time of deposition of cover crop residues on the soil (time 0) and at 15 and 45 days after the deposition (DAD) of litterbags on the soil surface in agroecological no-till onion (Oliveira et al., 2017)

The highest accumulation of P in cover crops occurred in the soluble inorganic P fraction, which is the fraction of fastest release in the tissue of all the plants.

Black oat had the highest initial release rate of soluble inorganic P, but the rate became equal to the release rate of other cover crop residues at 45 days after deposition. However, weeds released only half the amount of soluble inorganic P in the same period, despite accumulating a considerable amount of P in their biomass.

The oilseed radish + rye and oilseed radish + black oat mixtures showed a higher release of P-RNA at 45 days after deposition compared to the single treatments.

The effectiveness of the sideral mass as a reserve of macro and microelements in the soil was also confirmed in the studies of Antonets et al. (2010), who notes that the use of sideral crops is a significant replenishment of the soil with basic nutrients, which improves the mineral nutrition of plants. The agrochemical characteristics of siderate plants are given in the Table 3.119.

Table 3.119

Agrochemical characterization of green manure plants using the calculation-equivalent method (Antonets et al., 2010)

Green manure	Yield green mass, c ha^{-1}	Accumulated in the total biomass of nutrients, kg ha^{-1}			Total, kg ha^{-1}	In gross mass, kg ha^{-1*}
		N	P_2O_5	K_2O		
Sainfoin	275	145	25	75	245	510.4
Winter vetch	250	160	75	200	435	906.3
Rye-oat mixture	275	120	35	80	235	489.6
Buckwheat for two earnings	650	200	135	305	640	1333.3
White mustard	250	60	40	90	190	395.8
Suripa	340	135	55	240	430	895.8
Oilseed radish	450	85	65	245	395	822.9
Phacelia	300	80	50	200	330	687.5

1* Calculation of the amount of the active substance in fats is based on its content in the complex mineral fertilizer – nitroammophos.

The materials in the table show that the use of sider crops (as organic fertilizers) ensures the accumulation of a significant amount of nutrients. Thus, after two crops of buckwheat, the soil accumulates about 640 kg/ha of N, P_2O_5, K_2O. A significant amount of these macronutrients also remains after spring and winter vetch, suripa, oil radish, phacelia, and safflower. Undoubtedly, the largest amount of biological nitrogen remains after such leguminous crops as spring and winter vetch, asparagus, although with two earnings of buckwheat biomass, this indicator is also significant.

Buckwheat is characterized by the ability to assimilate difficult-to-dissolve macroelements, in particular, phosphorus, and convert them into readily available forms used by other plants. By converting the active substance of the main nutrients listed in the table into the physical mass of mineral fertilizers (weights), we get the volume of fertilizers that mainly provide the recommended regime of mineral nutrition of the main agricultural crops.

Thus, increasing the specific mass of biological nitrogen and other nutrients in agroecosystems due to the expansion of siderate areas (primarily leguminous sideral crops) is an important lever for stabilizing productivity, energy and economic efficiency of agriculture.

The author of the study (Antonets et al., 2010) emphasizes that green manure is one of the main factors of the organic farming system. This measure is mandatory in the transition from intensive to organic farming. Its use enriches the soil with organic matter, increases the amount of nutrients, and generally improves soil fertility and profitability. The use of green manure virtually eliminates the need for additional mineral fertilizers, which is an environmentally and economically sound measure. All of this ensures an increase in production profitability, contributes to the ecological rehabilitation of the soil, and improves its fertility based on biological principles of farming and environmental protection. The organic farming system has developed and uses methods to maximize the use of solar energy by covering the soil with plants almost throughout the entire growing season. Crops of main crops, green manure, vetch-oat mixture, and cereal crops form a permanent soil cover, which increases the utilization rate of incident solar radiation energy by maximizing the activity of the plant photosynthetic apparatus.

The technologies for growing oil radish as a green manure have been developed by the Union of Organic Agriculture (Union of Organic Agriculture, 2022). According to their data, the most difficult conditions for oil radish green manure are during its cultivation in the post-harvest period (July-August), which is characterized by the greatest moisture deficit in Ukraine. Its reserves in the 0–10 cm layer on the black soils of the Central Forest-Steppe are 3–8 mm and much less in other, less fertile, soil types. In order to prevent complete evaporation of water from the soil intended for green manure, it is necessary to apply surface tillage, consisting of disking the soil by 5–6 cm, harrowing and rolling the surface with ring rollers, together with harvesting the predecessor and, as an exception, one day after harvesting. Such tillage, especially at night, destroys the capillaries between the upper tilled and lower untilled, more moistened layers (from which water rises up through the capillaries), which stops its evaporation and contributes to the gradual moistening of the upper layer.

Another, less effective source of soil surface moisture during this period is dew that falls as a result of water vapor condensation (after the soil temperature drops at night and the surface air cools). The layer of dew formed overnight reaches 0.1 to 0.5 mm. And in a year, it falls up to 40 mm, which is the amount that corresponds to the monthly precipitation rate in the Central Forest-Steppe in April or August-November. Many factors influence the formation of dew and its amount, including wind. If it has a low speed, then new portions of water vapor rise to each object (lumps, plants) on which dew settles, which increases the amount of moisture. Dew does not form when the wind is strong. Dew forms mostly on a flat, but rough, soil surface, which is the case with the technology of directed surface tillage for green manure. But most modern agronomists are not familiar with these production and natural features. That is why they are in no hurry to create the right conditions for green manure production, believing that green manure will grow even under late tillage, and at the first failure they conclude that green manure is inappropriate.

Figure 3.27 – Seed mixtures of siderates, which include oilseed radish seeds

The generalized recommendations of the authors (Table 3.120) for oil radish green manure in the zone of sufficient moisture are reduced to the implementation of the above-mentioned soil preparation methods in a short time, the use of nitrogen fertilizers (30–60 kg ha^{-1}), high-quality seeds with their mandatory treatment before sowing and the incorporation of green manure to a depth of 15–30 cm. This technology helps to preserve the remaining water in the soil that was not used by the predecessor, promotes the accumulation of water in the surface soil layer by rising from the lower layers, which ensures the emergence of full germination of plants in 3 to 4 days after sowing, and their dense grass stand is an environment for the formation of a large amount of dew, which saves plants from death in the first days of the growing season.

Table 3.120

The main technological parameters of the use of oil radish as a siderate (generalization of the author of the monograph)

Technological components	**Parameters**
1	2
The optimal crops for this green manure	All non-cruciferous vegetables, potatoes, sugar and fodder beets, spring cereals, garden aisles (stone fruits and pome fruits)
Sowing dates for green manure	The widest range is from the end of March to the second decade of September, depending on the type and nature of green manure
Terms of green manure	No later than 30 days before sowing the next crop
Preparing the soil for sowing green manure	Option for surface cultivation to a depth of 8–10 cm. In dry season, post-sowing rolling
Seeding rate	The recommended seeding rate is 2.0–2.5 million germinating seeds/ha with a row spacing of 15–30 cm, or a spreading (continuous) seeding rate of 2.5–3.0 million germinating seeds/ha. In dry conditions, the rate is increased by 25-40% at the time of sowing. The use of dosed seed packets per 1 hectare of sowing is also possible (Fig. 3.30)
Preparation of seed material	The seeds are treated against pests (in particular cruciferous fleas, especially during summer sowing) with the recommended preparations
Possibility of compatible sowing with other crops	It is possible to use green manure mixtures with other cruciferous and leguminous components
Sowing depth of green manure	From 3 to 5 cm depending on the mechanical composition of the soil and soil moisture conditions
Fertilizing green manure	Recommended doses of N 30–60 kg/ha
The optimal phase of green manure production	Depends on the nature of the green manure: as a component of organic fertilizer from the budding to flowering phase; as a green mulch – stemming – budding. On poor soils during winter sowing from the budding phase to the fruiting phase («green pod»)

(End of Table 3.120)

1	2
Depth of green manure production	15–30 cm, depending on the type of soil and subsequent crop, or intensive mixing of the cider with the topsoil of 8–12 cm
The method of green manure	Embedding in the soil; mulching with dried leaf and stem mass with subsequent embedding; mulching with dried parts of stems in a crushed or whole state with subsequent embedding in the soil
The need for preliminary preparation of green manure	Required. We recommend 1–2 disking to a depth of 8–12 cm or mowing. In the case of combined modern machines, the need for final tillage is minimal. On private plots, mowing with the mass of the crop followed by plowing or sowing green manure before winter with the residues in the spring is used
Requirements for the humidity regime of green manure	It is advisable to plow into moist soil or during periods of sufficient atmospheric moisture. Plowing in dry soil or during prolonged soil drought is undesirable and inefficient

Even the smallest rains (3–5 mm), which are considered ineffective in agronomy, are very useful for post-harvest siderates. Further, more abundant rains (up to 10 mm or more) moisten the soil first to a depth of 15 cm, and later to the entire depth of the root layer. Such conditions, combined with warm weather in July and September, contribute to its intensive growth, prevent the reproduction of weeds and pests. In case of insufficient soil moisture, dew provides especially great help to the young siderate plants of oil radish, because only it saves the plants from death in dry, hot weather, and when it falls from the plants, it improves the moisture of the soil surface and subsoil air.

In the zone with less stable moisture, direct sowing of oil radish with stubble seeders without pre-sowing soil preparation deserves attention.

Mixtures of oil radish with other fodder crops (oats, peas, diapers, etc.) as siderate are mostly needed in farms with developed animal husbandry, where sideration is combined with strengthening the fodder base.

It is recommended to mow the green mass of oilseed radish for siderate during the period of budding before the beginning of flowering, when it contains the largest amount of nitrogen. It is also necessary to take into account the difficulties of wrapping oil radish biomass in the soil. A large land mass (200 t/ha and more) is poorly incorporated into the soil, the quality of plowing is unsatisfactory. With a high mass yield, the field is cultivated with disc tools in one or two tracks. After 3–4 days after the siderate has dried, peeling or disking is carried out again, and then plowing according to the generally accepted technology.Siderate with a small biomass is plowed directly. The following technology is also recommended: the siderate is rolled with smooth rollers, after which the plowing is carried out in the direction of the passage of the rollers.

Research conducted at the Podillia Institute of Forage and Agriculture of the National Academy of Sciences (Getman, 2007) shows that when growing oil radish in post-harvest crops, preparation of the soil after harvesting the predecessor is important (Table 3.121). It should also be remembered that the cabbage species included in the post-harvest mixtures have small seeds, and therefore, to guarantee friendly seedlings and uniform wrapping of the seeds during sowing, it is necessary to level the soil carefully. The choice of the method of cultivation depends on the condition of the soil, its weediness and humidity. In weather conditions, when the upper layer of the soil is wet, and the lower layer is dry, it is advisable to carry out surface treatment with combined aggregates (AG–2.4, AKG–6, APB–6, RVK–3.6, «Europak», etc.), which makes it possible to combine several tillage operations. At the same time, the terms of work are shortened, which prevents the upper layer from drying out, and the seeds fall into moist soil. In the absence of the above-mentioned technical means, disking is carried out to a depth of 10–12 cm with subsequent cultivation and pre- and post-sowing soil rolling. It should also be noted that the use of combined units makes it possible to reduce fuel consumption by 1.5–2 times compared to plowing.

Mineral fertilizers are applied in a dose of $N_{30-90}P_{30-45}K_{30-60}$, or nitrogen – N_{30-90}. In the steppe zone and, especially, in its southern regions, on irrigated lands, one more harvest can be obtained during this period.The irrigation regime consists of pre-sowing irrigation of 500 m^3 and 2–3 vegetation irrigations at the rate of 400–450 m^3 ha^{-1}.

Table 3.121

The influence of soil cultivation methods on the yield of post-harvest oil radish, c/ha (Shuvar, 1994)

Method of soil cultivation	Fuel consumption for basic tillage	Leaf and stem mass	Dry matter	Digestible protein
Plowing	19.6	221	22.1	4.0
Disking	5.4	195	20.1	3.9
Chiseling	6.2	198	20.0	3.9
Cultivation	5.1	196	19.3	3.8
Stubble sowing	0	165	17.1	3.5

On soils supplied with phosphorus and potassium, only nitrogen fertilizers are used in the dose of N_{45-60} in post-harvest crops. Sowing of oil radish in post-harvest crops must be completed by August 15. Later sowing times, especially in the Forest Steppe and Polissia, lead to a 20–30% decrease in productivity. Sowing rates of oil radish in single-species crops are 2.0–2.5 million seeds per hectare, in mixtures 50–70% of the full sowing rate. Mixtures are sown in the usual row method to a depth of 2–3 cm for oil radish. In addition, it is necessary to pay special attention to the cutting height of the predecessor; too high stubble can become a serious obstacle when working the soil, especially the surface, and further complicates the work of planters and reduces the quality of sowing. It is desirable to reduce to a minimum the break between harvesting the precursor and sowing of post-harvest crops, using minimal tillage (disking, chiselling) or combined tillage-sowing units instead of plowing. With sufficient humidity of the upper soil layer, direct sowing on stubble is possible with seed drills with disc coulters (Figures 3.28–3.29). In general, summarized recommendations on the technology of sowing post-harvest fodder crops where one of the components is oil radish are presented in Table 3.122.

As a result, all the positive features mentioned above allowed oil radish to occupy a prominent place in the recommended mixtures for the main soil and climatic zones of Ukraine (Table 3.123, Figure 3.30) and typical schemes of the green conveyor for the Forest-Steppe zone (Table 3.25), as well as to be recommended in all terms outlined by agrarian science for intermediate crops and even in winter sowing options.

Table 3.122

Technological scheme of growing oil radish in post-harvest and post-harvest crops in single-species and multi-component versions

Sowing option	Technological parameters
Post–harvest sowing	Sowing should be completed by August 1–5. Preference should be given to stubble predecessors, or one–year fodder mixtures for fodder where cruciferous components were absent. The rate of sowing in its pure form is 2 – 2.5 million pcs./ha of similar seeds, pre–poisoned, from seedling pests, seeds (insecticide treatment) with a row spacing of 15 – 19 cm, depending on the type of seeder and sowing. The method of sowing is mainly the usual row sowing. The rate of sowing in the composition of mixtures according to their structural formula is increased by at least 10–15%. Sowing depth for oil radish is 2 – 4 cm. Rolling after sowing, under the conditions of a dry period, is mandatory. The principle of soil preparation for sowing is to focus on the most small–seeded crop included in the mixture. Preference should be given to moisture–saving surface tillage systems based on the principle of controlled mulching with plant residues of the predecessor and the implementation of pre–sowing preparation and sowing in a single technological cycle. Application of mineral fertilizers under pre–sowing treatment for phosphorus and potassium and, if possible, fractionally for nitrogen. The dose of fertilizers is determined by the complex of conditions of soil fertility, abiotic factors of the environment and the composition of the mixture and varies within N30–90P30–60K30–60. It is possible to adjust the doses of fertilizers based on the removal of nutrients by new (previous) and intermediate (next) cultures. On soils sufficiently supplied with phosphorus and potassium, only nitrogen fertilizers are applied.Nitrogen fertilizers are used mainly in the form of top dressing in the peak period of linear growth of these crops for mixtures in which, together with oil radish, cereal components prevail. In the case of the presence of leguminous components in the mixture – N15–30P30–60K30–60. Preference should be given to factory mixtures of fertilizers. Applying fertilizers is advisable under the conditions of a minimum level of atmospheric moisture and certain parameters of the GTC of the period from the collection of the predecessor to the beginning of the harvest maturity of the crop (precipitation at least 50–60 mm, GTK at least 0.75–1.0)
Post–harvest sowing	Sowing should be completed by August 15 after stubble ultra early maturing and early maturing predecessors that vacate the field early. Mowing the predecessor on low stubble. The maximum gap between harvesting the precursor and sowing the intermediate crop under conditions of sufficient technological soil moisture is 2–3 days. Preference should be given to surface tillage systems in a combined combination of loosening operations with maximum preservation of plant residues and sowing with post–sowing rolling or in the option of direct sowing. The rate of sowing in its pure form is 2.5 – 3.0 million pcs./ha of similar seeds with a row spacing of 15 – 25 cm, depending on the type of seeder and sowing. The method of sowing is mainly the usual row sowing. The seeding rate has been increased by at least 15–25%. It is recommended to treat the seeds with systemic insecticides to protect against seedling pests. Sowing depth for oil radish is 2–4 cm. Rolling under conditions of a dry period is recommended before sowing and mandatory after. Features of fertilization and their adaptive substantiation are similar to those for the option of post–harvest sowing.

Figure 3.28 – Seedlings of oil radish obtained in direct sowing options, 2011

Figure 3.29 – The yield of green mass of oil radish for sowing on August 18 is 212 t/ha (Likhochvor, 2008)

Table 3.123

Grass mixtures of post-harvest crops of multipurpose use for zones of Ukraine (sowing rates, million/ha) (Kovbasyuk, 2011)

Zone	Variants of mixtures with oilsed radish for post-harvest sowing
Forested	*• corn (0.3 – 0.4) + sunflower (0.1 – 0.2) + yellow lupine (0.4 – 0.5) + oilseed radish (1.6 – 1.9) • corn (0 .3 – 0.4) + sunflower (0.1 – 0.2) + field peas (0.4 – 0.5) + winter vetch (0.6 – 0.8) + oilseed radish (1.6 – 1.8) • barley (2.4 – 2.6) + corn (0.1 – 0.2) + field peas (0.3 – 0.4) + winter vetch (0.6 – 0.8) + white mustard (1.0 – 1.1) + oilseed radish (0.8 – 1.0) • oats (1.6 – 1.8) + fodder sorghum (1.0 – 1.2) + field peas (0.5 – 0.6) + white mustard (0.8 – 1.0) + oilseed radish (0.9 – 1.1)*
Forest steppe	*• barley (2.5 – 2.7) + oats (1.2 – 1.3) + field peas (0.5 – 0.6) + winter vetch (0.6 – 0.7) + oilseed radish (0 .9 – 1.2) + white mustard (0.8 – 1.0) •barley (2.4 – 2.6) + fodder sorghum (0.9 – 1.0) + fodder beans (0.3 – 0.4) + white mustard (0.9 – 1.1) + oilseed radish (1.0 – 1.2) • oats (2.5 – 3.0) + barley (1.0 – 1.2) + field peas (0.5 – 0.7) + oilseed radish (1.7 – 1.9) • fodder sorghum (1.3 – 1.4) + corn (0.1 – 0.2) + sunflower (0.1 – 0.2) + field peas (0.6 – 0.7) + oilseed radish (1.7 – 1.9)*
Steppe (for irrigation)	*• corn (0.3 – 0.4) + oats (1.3 – 1.5) + winter vetch (0.9 – 1.2) + field peas (0.2 – 0.3) + oilseed radish (1 .7 – 1.9) • corn (0.3 – 0.4) + barley (1.5 – 1.7) + plantain (0.8 – 1.0) + white mustard (0.9 – 1 ,0) + oilseed radish (1.1 – 1.3) • corn (0.3 – 0.4) + oats (1.4 – 1.6) + sorghum (0.5 – 0.7) + spring vetch (0.6 – 0.8) + oilseed radish (1.0 – 1.2) + winter rape (1.2 – 1.3) • corn (0.3 – 0.4) + fodder sorghum (0.9 – 1.1) + field peas (0.5 – 0.6) + winter vetch (0.8 – 1.0) + winter turnip (1.0 – 1.2) + oilseed radish (1. 0 – 1.2) • fodder sorghum (1.6 – 1.7) + corn (0.1 – 0.2) + oats (0.6 – 0.7) + seed sorghum (0.6 – 0, 7) + winter vetch (0.8 – 1.0) + white mustard (0.9 – 1.1) + oilseed radish (0.9 – 1.1)*

Due to their high ecological stability, the cultures indicated in the Table, unlike traditional fodder plants, intensively build up biomass until late autumn and make it possible to extend the green conveyor for 3–4 weeks. They withstand a short-term drop in temperature to minus 5–7 °C and are used until the first decade of November, and in some years – during the month of December. As high-protein crops, annual mallow, amaranth, oilseed radish, spring and winter rapeseed are excellent components for cereal crops that are unbalanced in terms of digestible protein – corn, oats, sorghum, rye.

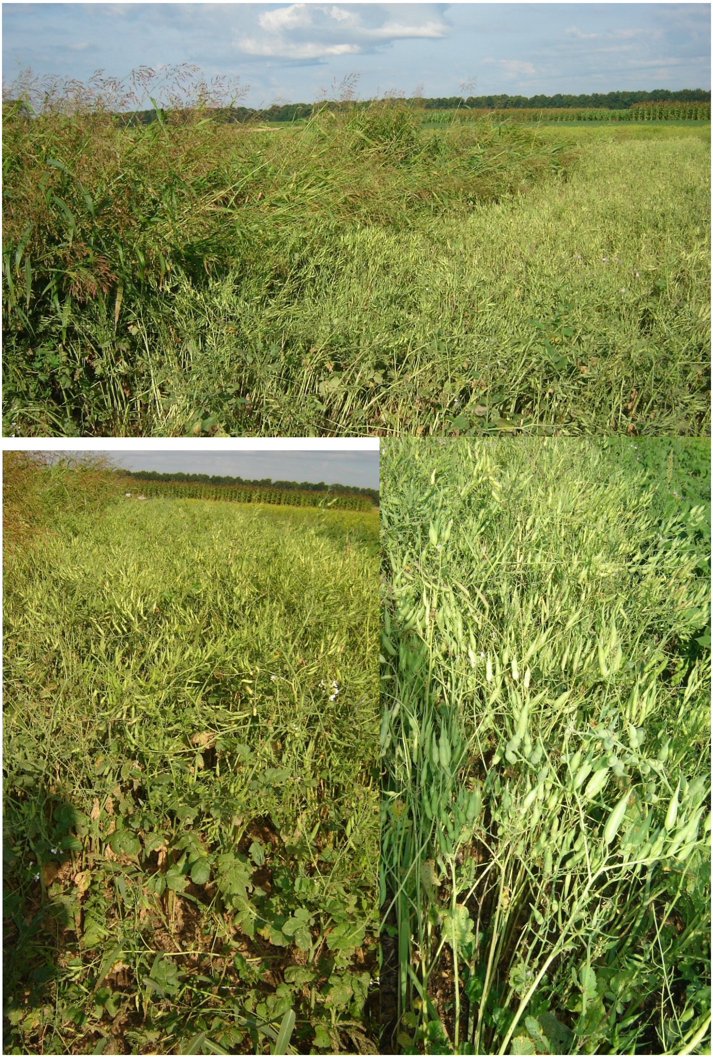

Figure 3.30 – Variants of summer post-harvest sowing of horseradish in the conditions of the experimental hospital of the Institute of Fodder and Agriculture of the Podillia National Academy of Sciences, 2014

Table 3.124

A typical scheme of a green conveyor for cattle (forest-steppe zone) (Zinchenko, 2005)

Sources of green fodder	Sowing terms	Terms of use
Natural pastures	–	10.5–20.10
Winter rapeseed + winter rye	15–31.8	25.4–15.5
Winter rye + woolly vetch	25.8–5.9	10–25.5
Winter wheat + woolly vetch	25.8–5.9	20.5–10.6
Alfalfa, asparagus, clover + perennial cereals	Past years	20.5–15.6
The first bunch of perennial grasses	Past years	10–25.7
The second row of perennial grasses	Past years	10–20.9
Perennial grasses with four to five slope irrigation	Past years	20.5–10.10
Oats + legumes + oil radish of the first sowing period	10–20.4	15–30.6
The same for the second sowing period	25–30-4	1–15.7
Oilseed radish as clean crops	10.4–10.5	1.6–1.7
Corn + Sudan grass	5–10.5	15–31.7
Ottawa Sudan grass	5–10.5	10–25.9
Corn + soy	15–25.5	10–31.8
Corn + Sudanese grass + plantain	5–10.6	20.8–5.9
Ottawa Sudan grass	5–10.6	20–30.9
Corn (after autumn) after rye + vetch + oilseed radish	1–10.6	20.8–10.9
Corn or Sudanese grass (after autumn) after wheat + woolly vetch + oilseed radish	20–25.6	15–30.9
Corn + oilseed radish (subsequently)	20–25.7	20.9–10.10
Ottawa natural haymakers	–	10.8–10.10
Late autumn sowing of oilseed radish	1–10.8	10.9–10.10
Forage pumpkins	10–15.5	1.9–20.11
A bunch of root crops	10–20.4	10.9–31.10

The possibility of using oil radish as an intermediate crop is determined by the timing of its sowing and the temperature regime of the period of residual vegetation after harvesting the main crop (Table 3.126). In addition to this, according to the generalization of Kovbasyuk (2011), an important factor that determines the possibility and expediency of growing fodder crops in intermediate crops is the moisture indicator during the growing period – the hydrothermal coefficient (HTC). The optimal value of GTK for post–harvest and post–harvest crops is 1.4–1.6 and higher, satisfactory – 1.0–1.4, unsatisfactory – 0.6. With the value of GTK – 0.6, it is economically impractical to grow post–harvest and post–harvest crops. With such moisture, types of intermediate crops are grown only under irrigation.

Table 3.125

Productivity of spring crops in intermediate crops (Rakhmetov et al., 2008)

Crop	Productivity of above-ground mass, t ha^{-1}	Yield of absolutely dry mass, t ha^{-1}	Protein yield, t ha^{-1}
Oilseed radish *(Raphanus sativus L. var. oleiformis Pers.)*	40–65	5–7	1,1–1,3
Rocket crass *(Brassica campestris var. oleifera f. annua L.)*	30–40	3–4	0,6–0,7
Spring rape *(Brassica napus var. oleifera f. annua D.C.)*	40–45	5–6	1,0–1,1
White mustard *(Sinapis alba L.)*	35–42	4–5	0,7–0,8
Sarepta mustard *(Sinapis juncea Czern.)*	36–44	4–5	0,8–0,9
Malva melyuka *(Malva meluca Graebn.)*	44–62	6–8	1,4–1,5
Amaranth *(Amaranthus caudatus L.)*	40–55	5–7	1,2–1,3

Also important is the fact that oilseed radish is characterized by a less pronounced, to a certain extent, regular dynamics of a decrease in overall productivity when the sowing period changes from early spring to late summer (Table 3.127).

Table 3.126

The possibility of growing cruciferous crops in intermediate crops depending on the time of their sowing (Shpaar, 2006)

Crops	Days from sowing to the transition of the average daily air temperature below + 5 ^{0}C				
	more 80	80 – 76	75 – 71	70 – 65	65 – 60
Oilseed radish	+ +	+ + + +	+ +	+ +	+
Spring rape	+ +	+	+ +	+	+
Winter rape	+ +	+ +	+ +	+	+
Rocket crass	+ +	+ +	+ +	+	–
White mustard	+ +	+ +	+ +	+ +	+
Turnips on green mass	+ +	+	+	+	–

"++" – for green fodder and silage; "+ "– for green fodder; – cultivation is impractical

Table 3.127

The influence of sowing dates on the yield of intermediate crops of cruciferous crops (Shpaar, 2006)

Sowing date	Unit of measurement	Oilseed radish	Spring rape	Winter rape	White mustard
15.07	c ha^{-1}	346	277	383	169
	in % to the first term	*100*	*100*	*100*	100
22.07	c ha^{-1}	374	289	341	234
	in % to the first term	*108*	*104*	*89*	138
29.07	c ha^{-1}	367	297	284	255
	in % to the first term	*106*	*107*	*74*	151
05.08	c ha^{-1}	230	180	197	167
	in % to the first term	*66*	*65*	*51*	99
12.08	c ha^{-1}	199	160	140	172
	in % to the first term	*58*	*58*	*37*	102
19.08	c ha^{-1}	107	80	58	92
	in % to the first term	*31*	*29*	*15*	54

The Ministry of Agrarian Policy and Food of Ukraine also in its recommendations (Kvitko et al., 2010) regarding the optimal composition of fodder mixtures for Polissia and the Forest-Steppe zone assigns a significant role to oil radish. The composition of the recommended mixtures is as follows: 1) corn in mixtures with cruciferous vegetables or a mixture of corn with soy; 2) barley + oats + peas; 3) oats + peas + oilseed radish; 4) oats + white mustard + peas; 5) oats + white mustard; 6) oats + oilseed radish; 7) oats + oilseed radish + peas, etc.

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