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Evaluation of Ecological Adaptability of Oilseed Radish (*Raphanus sativus* L. var. *oleiformis* Pers.) Biopotential Realization in the System of Criteria for Multi-Service Cover Crop

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ABSTRACT

The article presents the results of a ten-year cycle of studying oilseed radish in the variant of two sowing dates. The technological regulations of the applied sowing options correspond to the classical scheme of spring sowing period and intermediate (post-harvest, post-mowing varieties) in the summer sowing period. The research evaluated the first block of indicators of the multi-service cover crop (MSCC) criteria system. The assessment of the first component of the MSCC system included indicators of the formed aboveground and underground plant biomass with details on such components as the dynamics of mass growth and soil coverage, the structure of the aboveground mass by the proportion of leaves, stems and generative part, complex morphometry by the vitality index, plant survival and root system productivity for both sowing dates. Significant levels of ecological adaptability of oilseed radish with the possibility of forming levels of total bioproductivity in the range of 4–7 t·ha^{-1} of dry matter at a wide range of average daily temperatures (14–22 °C) and precipitation of 29–290 mm were established. It was determined that at high rates of growth processes with the level of achievement of the 'ground cover' indicator at 70% on 45–50 days after sowing, high plant survival at the level of 70–80% during intermediate summer use, the formation of an optimized structure with a leafiness at the level of 30–49% at the milestone date of use, with an achievable root system productivity coefficient of 4.7 (in dry matter) and the formation of total plant biomass at the level of 2.0–4.0 t·ha^{-1} of dry matter even under conditions of $I_{DM} < 10$ and $K_h < 0.5$, oilseed radish should be classified as a crop that fully corresponds the criteria of the first general productive block of the MSCC system.

Keywords: bioproductivity, aboveground biomass, root biomass, intermediate (green manure) crop use, hydrothermal regime.

INTRODUCTION

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; Honcharuk et al., 2023). 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 and Richard, 2017; Mazur et al., 2023). 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 (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; Singh et al., 2023). 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 (Boselli et al., 2020; Kenjaev and 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 (Yadav et al., 2021; Lohosha et al., 2023) and the proportion of moisture-resistant aggregates (Abdulraheem and Tobe, 2022), and increased greenhouse gas emissions (Ansari et al., 2022; Israt and Parimal, 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 (Pryshliak et al., 2022; 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, 2020, 2023) 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.

MATERIALS AND METHODS

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 forest soils (Greyi-Luvic Phaeozems (Phaeozems Albic, Dark Gray Podzolic Soils) according to WRB) 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%, clay 29.35–30.21%). Agrochemical potential of the experimental plot for the soil layer 0–30 cm (accordance with the Ukrainian National Standards for analytical laboratory methods of determination): humus content: 2.71%, mobile forms of nitrogen 79 $mg \cdot kg^{-1}$, phosphorus 184 $mg \cdot kg^{-1}$, potassium 115 $mg \cdot kg^{-1}$ soil, pH 5.8 of soil solution.

In the research, the oilseed radish variety ‘Zhuravka’ (a variety of combined use: green mass–green manure–seeds) was used for its sowing on an unfertilized background at a quantitative seeding rate of 2.5 million seeds ha^{-1} (30–35 seeds per meter of row) using the conventional row method (row spacing 15 cm). The applied seeding rate and row spacing corresponded to the variant of fodder–green manure use of oilseed radish based on the results of the vitalized structure of the agrocenosis (Tsytsiura, 2020). Two systems of oilseed radish use adopted in the research area were studied in the variant of spring intercrop (early spring sowing) and post-harvest intercrop (summer sowing):

1. 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 in the second-third decade of June (flowering stage (BBCH 64–67) according to Alonso-Ayuso et al. (2014).
2. 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 14–16 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 in the second or third decade of October. The sowing date for the first variant was determined at the early stage of physical ripeness of the soil. For the second variant, a 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 experimental plots were formed in quadruplicate using the method of small-plot randomization (total plot area 35 m^2, accounting plot area 25 m^2). The repetition in the experiment is quadruple. To control the number of weeds, a mixture of herbicides in the rosette phase (BBCH 20–22) 'Galera 334', aqueous solution (clopyralid, 267 g·l^{-1} + picloram, 67 g·l^{-1}), 0.3 l·ha^{-1} was used against dicotyledonous weeds; 3) 'Select', emulsion concentrate (kletodim, 120 g·l^{-1}), 0.7 lt·ha^{-1} – graminicide, according to the determined features of weed formation in the agrocenosis of oilseed radish. To control the number of cruciferous fleas (*Phyllotreta atra* F., *Phyllotreta nemorum* L., Phyllotreta *undulata* Kutsch, *Phyllotreta nigripes* F., *Phyllotreta* F.) widespread in the agrocenosis of oilseed radish in the research area (Tsytsiura, 2024), the insecticide 'Bliskavka' (emulsion concentrate, alphacypermethrin 100 g·l^{-1}) was applied at 0.2 lt·ha^{-1} in the phase of cotyledons–first true leaves (BBCH 10–12). Survival rate of plants is calculated by counting the number of plants of each species that have survived, divide it by the number of plants originally planted of that species and multiply by 100 to express as a percentage of survival (McDowell et al., 2008). Stage growth was recorded using the Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie (BBCH) scale (Test Guidelines, 2017). Accounting of aboveground plant biomass was carried out at the full flowering stage (BBCH 64–67) in four randomized plots using the method of 1 m^2 trial plots in each replication (16 plots in total) with subsequent weighing. Before weighing and subsequent field and laboratory manipulations, any non-native plant impurities were removed from the sample sheaves. The flowering phase was chosen for both green manure options as the one that is achievable for both options and corresponds to the recommended option for biofumigant and green manure use of oilseed radish under conditions of unstable moisture in different soil zones (Duff et al., 2020). Some of the accounting plots were selected on the condition that the perimeter of the aboveground biomass accounting coincided with the system of monolithic analysis of the formed root systems. The characteristics of the plant mass were determined using a laboratory scale YP50002 (5 kg) with a discretion of 0.01 g. For the dynamic display and graphical analysis of aboveground biomass formation, the accounting periods were converted to 'degree days after sowing (°C/day) by multiplying the average daily temperature (°C) by the length of the period (days) between the accounting dates (previous and next) according to Ramírez-García et al. (2014).

The leaf and stem mass of oilseed radish plants was divided by the structural fraction (in %) of leaves, stem and inflorescence in the corresponding ratio to the total plant mass in the sheaf biomass sampling per unit area (Tsytsiura, 2020). This allowed us to formulate typological features of vegetative development of oilseed radish plants according to Poorter et al. (2012). The root system productivity coefficient was calculated according to Poorter et al. (2012) as the ratio of the crude (dry) aboveground biomass of plants to the mass of formed roots, and the proportion of root residues in the total plant biomass was determined as the ratio of root mass to aboveground plant mass expressed in %.

To evaluate the vegetative development of plants in different variants of cultivation periods against the background of a multi-year accounting cycle, the index vitality coefficient (IVC) (Equation 1) was used to comprehensively assess plant morphogenesis in view of its successful application in assessing the optimal design of oilseed radish agrophytocenoses under different combinations of cultivation and fertilization technologies (Tsytsiura, 2020).

$$IVC = \frac{1}{\quad} \times \sum_{=1} \frac{\quad}{\quad} \tag{1}$$

where: *IVC* – index vitality coefficient; *N* – total number of features that are determined in agrophytocenosis; x_i – the value of the i-th feature in agrophytocenosis with certain cultivation technology parameters; X_i – the average of the i-th feature for all agrophytocenosises for the entire period of research (2014–2023). The methodology for accounting for indicators and the list of the formed morphometric base of indicators (modular blocks for morphological and productive analysis of oilseed rape plants) are presented in detail in our previous published studies (Tsytsiura, 2020).

The ground cover and biomass were monitored during the entire crop cycle for both variants of the timing of oilseed radish green manure use. Ground cover (GC) was always measured in a marked surface inside each plot (the same 16 plots each with an area of 1 m^2 were taken to account for the formed aboveground biomass of green manure). The indicator was recorded starting from the phenophase of true leaf formation (BBCH 12–13) with an interval of 5 days up to the date of final green manure use in the flowering phase (BBCH 64–67). To account for GC, the following methodology was applied (Ramirez-Garcia et al. (2012, 2014)) wich was based on digital pictures of the marked surface taken from a perspective at a 1.5 m height. The images were taken with a Canon EOS 750D Kit + Canon EF 50 mm f/1.8 STM processed using SigmaScan Pro 5® software. An overlay was used corresponding to green colour in the light conditions of an overcast day. The ground cover was calculated as the number of pixels of the layer divided by the total number of pixels that constitute the image of the marked plot.

To assess the dynamics of the GC, we used the selection of a graphical model of the indicator formation in accordance with the recommendations of Bodner et al. (2010) in the environment of the software package Curve Expert Professional v. 2.7.3 software package (Hyams Development).

The assessment of the formation of biomass of the root system of oilseed radish plants was carried out at a similar phenophase as for the assessment of the formation of aboveground biomass of plants by the method of monoliths, taking into account the methodological approaches of Talgre (2013) and Wahlström et al. (2015). Roots were washed from monoliths in the laboratory. For the washing separation, a column of sieves arranged in descending order of mesh size was used (laboratory wire mesh sieves woven (according to the technical conditions of Ukraine 14-4-507-99): 4.0 mm, 2.0 mm, 1.0 mm, 0.5 mm and 0.25 mm. Sieve separation was accompanied by the use of an additional water supply for more thorough washing. Non-root materials were removed manually with tweezers. The selected roots were stored in closed plastic containers at 5 °C. The washed and selected root residues for the subsequent analysis were air-dried for 24 h and then weighed on a laboratory balance (3100 g) WALCOM LB3002 with a discretion of 0.01 g. The locations of both soil profile analyses were previously marked and maintained from the initial stages of oilseed radish vegetation in a completely weed-free state to avoid biological contamination by plant roots of other plant species.

The dry matter (DM) and organic dry matter (ODM) contents were measured by drying in an oven at 105 °C.

The analysis of weather conditions and the level of its variability for the period 2014–2023 was based on the hydrothermal coefficient (HTC) in accordance with Equation 2:

$$IVC = \frac{1}{N} \times \sum_{i=1}^{N} \frac{x_i}{X_i} \tag{2}$$

where: ΣR – the sum of precipitation (mm) over a period with temperatures above 10 °C, $\Sigma t_{>10}$ – the sum of effective temperatures over the same period. Ranking of HTC values (Tsytsiura, 2020): $HTC > 1.6$ – excessive humidity, HTC 1.3–1.6 – humid conditions, HTC 1.0–1.3 – moderately dry conditions, HTC 0.7–1.0 – dry conditions, HTC 0.4–0.7 – very dry conditions.

De Martonne aridity index (I_{DM}) (in accordance with Moral et al., 2016) was used to characterize the arid/humid conditions of a territory for a month according to Equation 3:

$$I_{DM} = \frac{12P_m}{T_m+10} \tag{3}$$

where: P_m and T_m are the precipitation volume and mean air temperature in the corresponding month, respectively. According to the I_{DM} values calculated using the equation above, the climate of a region can be classified (type of climate according to the De Martonne aridity index (I_{DM}, adapted after Baltas, 2007) Arid $I_{DM} < 10$; Semi-Arid $10 \le I_{DM} < 20$; Mediterranean $20 \le I_{DM} < 24$; Semi-humid $24 \le I_{DM} < 28$; Humid $28 \le I_{DM} < 35$; Very Humid $35 \le I_{DM} \le 55$; Extremely humid $I_{DM} > 55$.

The evapotranspiration was calculated using Equation 4 (according Latief et al. (2017)):

$$E = 0{,}0018 \times (25 + t)^2 \times (100 - a) \tag{4}$$

where: E – the evapotranspiration of plants for a certain period, mm; t – the average air temperature for the analyzed period, °C; a – the average air humidity for the analyzed period, %.

The Vysotsky-Ivanov humidification coefficient (K_h) was determined by Equation 5 according to Latief et al. (2017):

$$K_h = \frac{P}{E} \tag{5}$$

where: K_h – the moisture coefficient; P – the amount of precipitation for the analyzed period, mm; E – the evaporation for the analyzed period, mm. The different degrees of moisture is carried out according to gradation: $K_h > 1.0$ – territory (time period) with excessive moisture, K_h close to 1 – optimal moisture, K_h = 1.0–0.6 – unstable moisture, K_h = 0.6–0.3 –insufficient hydration.

Evaluation of weather and hydrothermal conditions during the period of oilseed radish cultivation under intermediate (summer) green manure use is presented in Table 1. According to the results of the presented data, the weather conditions during the study period had both significant differences within the interannual comparison and in the system of average long-term deviations. Taking into account the optimal parameters for the formation of oilseed radish leaf and stem mass in the HTC interval at the level of 0.900–1.400 with precipitation at the level of 220–240 mm (Tsytsiura, 2020) and taking into account the grouping classification according to the De Martonne aridity index (I_{DM}) and Vysotsky-Ivanov humidification coefficient (K_h), the years of research can be placed in the following order of increasing favorability of growth processes (based on the data in Table 1) 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

Table 1. Estimation of the values of hydrothermal regimes of the period of active vegetation of oilseed radish for the variant of summer and autumn sowing, 2014–2023

Year	Precipitation, mm (IV–VI)	$t_{aver.}$, °C (IV–VI)	Months of the growing season								
			IV			V			VI		
			HTC	I_{DM}	K_h	HTC	I_{DM}	K_h	HTC	I_{DM}	K_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											
			VII			VIII			IX			X		
			HTC	I_{DM}	K_h	HTC	I_{DM}	K_h	HTC	I_{DM}	K_h	HTC	I_{DM}	K_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
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
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
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
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
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
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
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
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

(StatSoft – Dell Software Company, USA) and Past 4.13 software (Øyvind Hammer, Norway). Analysis of variance was used to compare the differences between means among treatments by the Duncan test at a statistical level of $p < 0.05^*$ and $p < 0.01^{**}$. The data obtained were analyzed using the analysis of ANOVA with determination of the share of influence of factors in the dispersion scheme (Wong, 2018).

In order to compare the regression models and determine the statistical significance of the selection of individual models for the formation of indicators, according to Snecdecor and Cochran (1991), the coefficient of determination (R^2), adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), relative root mean square error (RRMSE) and prediction efficiency (PE) index were used. To assess the closeness of the relationship between the studied indicators, we used the Chaddock scale (1925), which at R^2 of 0.1–0.3 = weak; 0.3–0.5 = moderate; 0.5–0.7 = significant; 0.7–0.9 = high; 0.9–0.99 = very high.

The degree of integrated connection of the biochemical composition of oilseed radish leaf-stem with the main indicators of the basic factors of the experiment system was estimated by the value of the coefficient of determination of the connection (Equation 6) and the use of the method of correlation graph in two interpretations (Equations 7 and 8):

$$d_{yx} = r_{ij}^2 \times 100 \quad (6);$$

$$G = \sum_{|r_{ij}| \geq \alpha} |r_{ij}| \quad (7);$$

$$G' = \Big(\sum_{|r_{ij}| \geq \alpha} |r_{ij}| \Big) / n \quad (8)$$

where: r_{ij} is the correlation coefficient between the i-th and j-th indicator. Only reliable correlation coefficients were used in the calculation; n is the number of statistically significant correlation coefficients.

RESULTS AND DISCUSSION

Both in spring (Table 2) and summer sowing (Table 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%. Root biomass yield for the same period was 8.70 t·ha^{-1} and 44.70%. At the summer sowing date, the indicators were noted at the following consistent level: 18.34 t·ha^{-1} (32.80%) and 5.50 t·ha^{-1} (38.95%). As a result, the total bioproductivity of oilseed radish (the sum of aboveground and root biomass) during the spring sowing period amounted to 32.74 t·ha^{-1} in crude weight (34.06% of interannual variability) and 4.92 t·ha^{-1} in dry matter (29.47%). These figures are 8.90 and 0.86 t·ha^{-1} lower than the average for the summer sowing date. The disparity between the value of the risk in terms of raw and dry weight is due to the higher level of dry matter content in the summer sowing period of oilseed radish in the range of 3–5% for the aboveground mass and 1.8–3.7% for the roots. At the same time, the average dry matter content in the aboveground mass during the study period for the spring sowing period was 13.16% (with an interannual variation of 8.99%) and for the summer sowing period 15.71% (8.22%). For root biomass, this indicator was 21.43% (interannual variation of 7.13%) for spring sowing and 22.64% (6.20%) for summer sowing. The achieved level of bioproductivity can be assessed as high for conditions of unstable moisture, taking into account a number of studies on oilseed radish and other cruciferous crops of multiple uses. Thus, Bhogal et al. (2019) indicate, depending on soil and climatic conditions, fluctuations in oilseed radish biomass yield in the range from 15 to 45 t·ha^{-1}. In the study of Quintarelli et al. (2022), oilseed radish was classified as a high-yielding cover crop for conditions of sufficient moisture. The possibility of its use in the system of bioorganic fertilization as a green manure and intermediate crop in crop rotation with a productivity level above 15 t·ha^{-1} was also noted (White et al., 2016; Wollford and Jarvis 2017; Lövgren, 2022).

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}.

Table 2. Indicators of bioproductivity of oilseed radish in spring sowing for flowering stage (BBCH 64–67), 2014–2023

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

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

The formed underground (root) biomass for the same group of crops was 5–15 t·ha^{-1} and 12–25 t ha^{-1}. 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 1, Table 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 and Tjørve, 2017), according to the results of statistical evaluation for adequacy, were ineffective for oilseed radish with a moderate closeness of dependence ($R^2 < 0.5$) and were not included in Table 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 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

Table 3. Indicators of bioproductivity oilseed radish in summer sowing for flowering stage (BBCH 64–67), 2014–2023

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

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

°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).

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 1), 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

Table 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

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 ($y = a + b\ln x$)	-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 ($y = a + b\ln x$)	-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

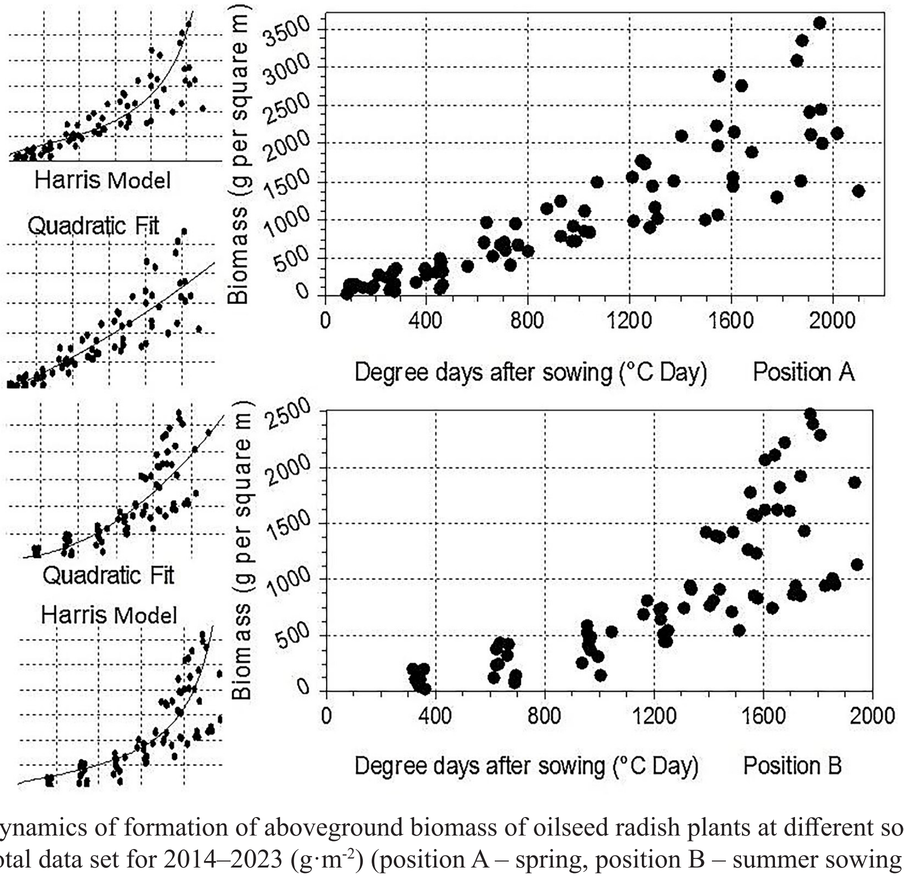

Figure 1. Dynamics of formation of aboveground biomass of oilseed radish plants at different sowing dates in the total data set for 2014–2023 ($g \cdot m^{-2}$) (position A – spring, position B – summer sowing dates)

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 and 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 and 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 Feller et al. (2015), Agathokleous et al. (2019). 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 2). 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 2–3). 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

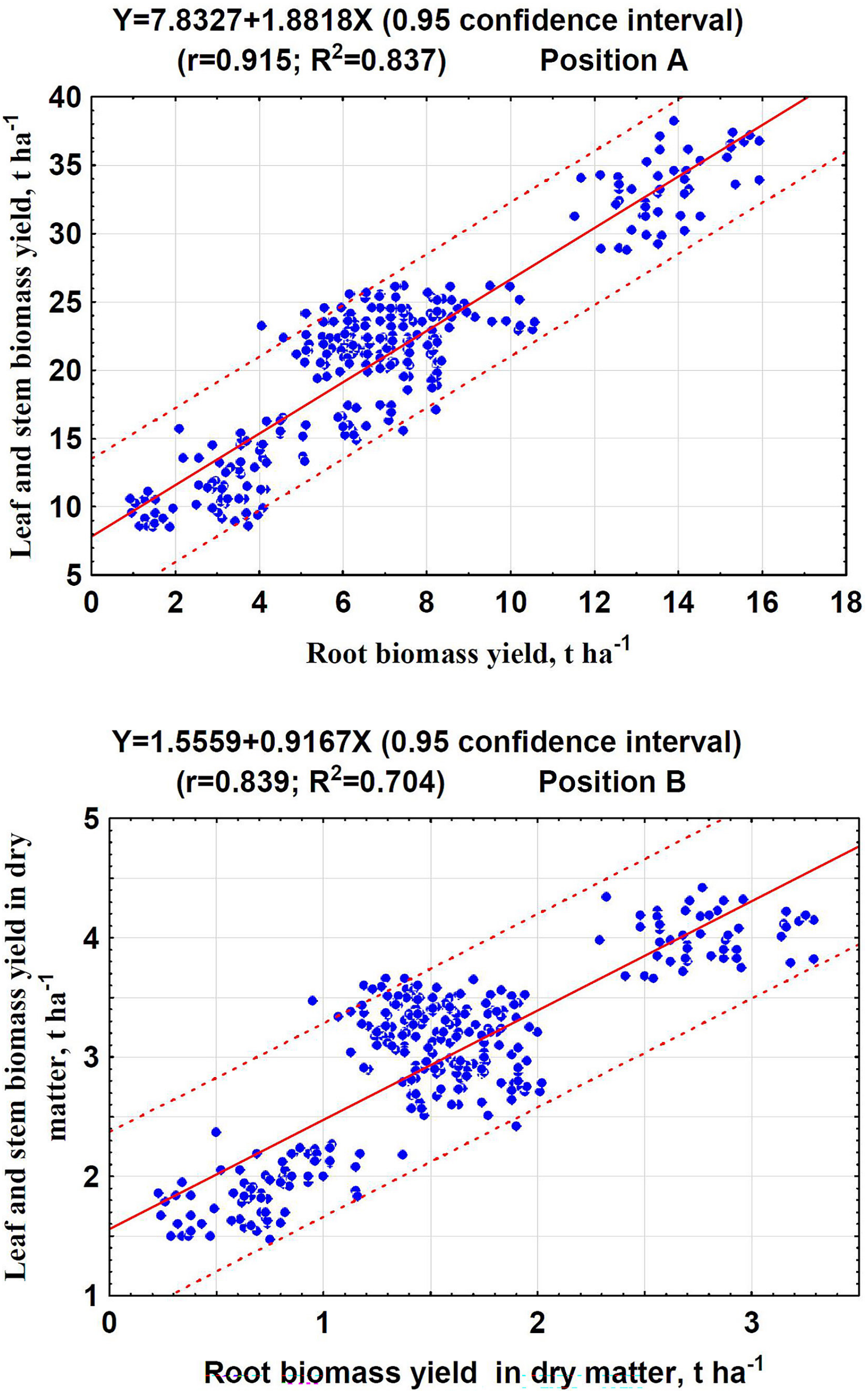

Figure 2. Relationship between aboveground biomass yield and formed root biomass in oilseed radish, 2014–2023 (in a single data system of replication–year–sowing date for N = 320; position A – in raw mass, B – in dry matter)

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. 2023).

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 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, 2020) 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 and 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 2, 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 3. 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, 2020) 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).

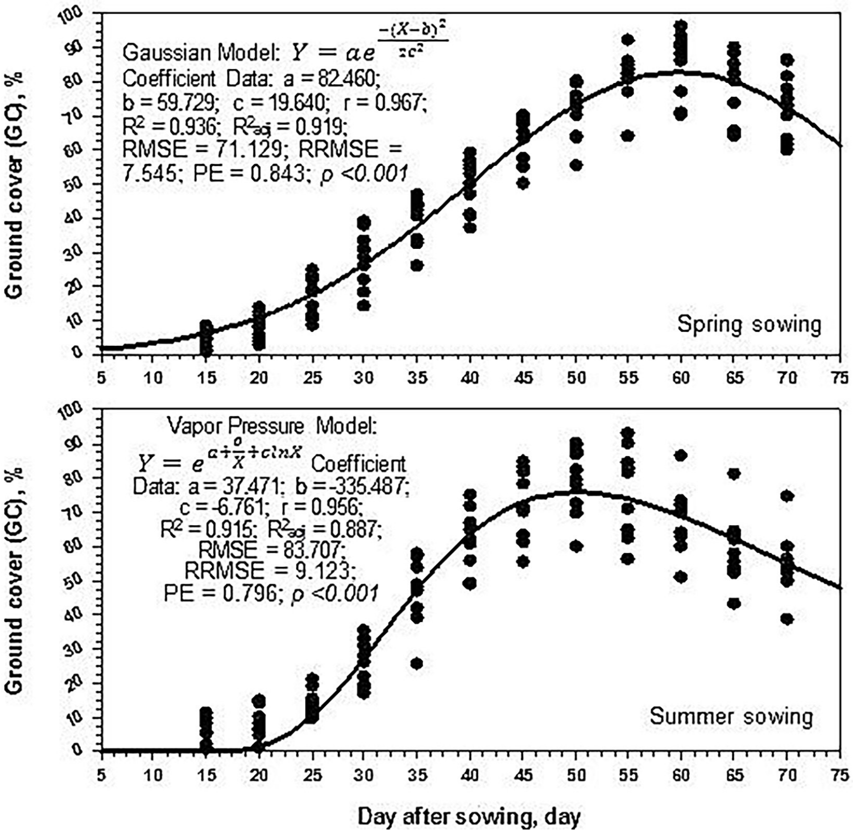

Figure 3. Graphical model with statistical evaluation parameters for the indicator 'ground cover' (GC) in oilseed radish (vertical marks on the dates of accounting – indicator values in the experimental interval 2014–2023)

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 and 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. 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 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.

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 5). 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

Table 5. 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))

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

Note: 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.

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 (Saseendran et al., 2010; Deligios et al., 2013), white mustard (Dorsainvil et al., 2005) in variants of its multiple use (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 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 6). According to the results of this regression assessment, a complex

Table 6. 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))

Resulting indicator	Compo-nents of the equation		Regression equation of dependence	Multiple regression coefficient R/R^2_{adj}	Statistical significance criteria R
	x	y			
Leaf and stem biomass yield, $t \cdot ha^{-1}$ (LSBY)	Precipitation, mm	Average daily temperature, °C	$LSBY = 13{,}4158 - 0.0037x + 0.2923y + 9.7657E - 5x^2 + 0{,}0048xy - 0.0334y^{2\;****}$ *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, $t \cdot ha^{-1}$ (RBY)			$RBY = 14.8153 - 0{,}0076x - 1.2633y + 9.7858E - 5x^2 + 0.0014xy + 0.0294y^2$ *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, $t \cdot ha^{-1}$ in dry matter ($LSBY_{DM}$)			$LSBY_{DM} = 0.7987 + 0.0041x + 0.1289y - 5.9224E - 6x^2 + 0.0006xy - 0.0057y^2$ 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, $t \cdot ha^{-1}$ in dry matter (RBY_{DM})			$RBY_{DM} = 4.7469 - 0.0107x - 0.3982y + 2.9518E - 5x^2 + 0.0007xy + 0.0089y^2$ 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, $t \cdot ha^{-1}$ (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, $t \cdot ha^{-1}$ (RBY)			$RBY = 2{,}5733 + 0{,}6683x - 2.6161y + 0.6215x^2 - 7.9348xy + 25.5887y^2$ 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, $t \cdot ha^{-1}$ in dry matter ($LSBY_{DM}$)			$LSBY_{DM} = 1.0683 + 0.676x - 3.3215y - 0.0293x^2 + 0.2705xy - 0.6023y^2$ 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, $t \cdot ha^{-1}$ in dry matter (RBY_{DM})			$RBY_{DM} = 0.2148 + 0.3391x - 1.5257y - 0.0411x^2 + 0.5154xy - 1.6147y^2$ 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)

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

power law (second order) nature of the formation of bioproductivity of oil 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 Han et al. (2020), Rajković et al. (2022) and by modeling the dynamic series of components 'x' and 'y', its values were determined to obtain adequate maximum levels of the resulting indicators of plant bioproductivity (Rameeh, 2014) 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 oilseed 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 IDM 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 K_h, 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 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).

CONCLUSIONS

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.

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