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Formation of the root system of oilseed radish under long-term green manuring practices

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Abstract. The optimal selection of plant species for green manuring technologies is impossible without assessing the bioproductivity and morphometry of their root systems, which is an additional and significant factor in the effectiveness of both the growth processes of the green manure crop and its projected impact on the soil profile as a whole. Taking this into account for 11-year period, the bioproductivity of the root system of oilseed radish was assessed by morphological and weight parameters in the soil profile for two sowing dates of green manure: spring and summer. A wide range of methods based on Profile Wall, Monolith Method and Root maps of a profile wall were used to obtain the main functional indicators of the formation and spatial development of the root system.

It was determined that oilseed radish from the point of view of formation of morphological characteristics of the root system provided the yield of root biomass in dry matter of 1.19–1.77 t ha^{-1} in active interaction with the soil profile 40–80 cm deep with the formation of the following components of the root system morphotype in the range of long-term average values for sowing dates: average diameter of the root taproot 5.13–5.67 mm at its taper 0.55–0.66, volume 26.92–39.09 cm^3, volume of root spreading zone 36.75–66.39×10^3 cm^3, fractal dimension (D) 0.63–0.73, maximum root depth 47.36–64.41 cm, fraction of total root mass to the soil depth (0–30 cm) 0.77–0.79.

The dependence of the formation of indicators of bioproductivity of the root system with a direct nature on the amount of precipitation (determination 47.19–50.20%), water reserves in the soil (27.04–65.61%) and an inverse nature on the average daily temperature (21.44–25.70%), Vysotsky-Ivanov humidification coefficient (57.30–65.45), De Martonne Aridity Index (47.75–51.12) and soil hardness (37.21–59.29%) was determined.

Key words: plants' green manuring potential, root morphometrics, root maps, root biomass yield, root length density; root mass density, specific root length.

INTRODUCTION

The global trend of rising prices for both energy resources and agrochemicals (fertilizers, plant protection products, etc.) has led to changes in the planning approaches of relevant segments of agricultural crop production technologies (Li et al., 2024). A steady trend has been observed toward the transition to bio-organic fertilization systems

(Kaletnik & Lutkovska, 2020; Berezyuk et al., 2021). It has been proven that only 40–44% of applied mineral fertilizers ensure economic efficiency, while the rest pose a real threat to the agroecological sustainability of agricultural areas, are an additional factor in the chemical and agrophysical degradation of soils, and create prerequisites for increased carbon dioxide emissions (Lutkovska & Kaletnik, 2020; Tokarchuk et al., 2024).

Due to the shortage of traditional organic fertilizers caused by the development of organic matter bioprocessing from livestock (Honcharuk & Yemchyk, 2024), the described approach involves the use of green manure crops with high bioproductive potential and soil restoration capacity (Adetunji et al., 2020; Lei et al., 2022; Fonseca et al., 2023; Kucerik et al., 2024).

Green manure crops include plant species cultivated specifically to produce biomass (above-ground mass together with root residues), which is incorporated into the soil as green fertilizer. This may be done with variations, such as the addition of bio-organic fertilizers, decomposition agents, strains of various microorganisms, or conventional mineral fertilizers (Stradic et al., 2021; Lei et al., 2022; Kucerik et al., 2024).

In recent years, a comprehensive range of green manure crops has been established, comprising more than 60 plant species adapted to various soil and climate zones (Green Manure Global Market Report 2024, 2023). From the standpoint of efficiency and feasibility of using specific plant species for green manuring, the indicator of 'green manure potential' is crucial. This refers to the total biomass produced by a plant from germination to flowering, in conjunction with its biochemical composition, to evaluate its potential for enriching the soil profile with organic compounds as well as essential macro- and micronutrients (Fonseca et al., 2023). This indicator also includes the nature of the green manure crop's impact on the key dynamic processes in the soil profile, particularly in terms of humification, mineralization, and its influence on soil regimes and properties (Li et al., 2024).

Unfortunately, research on green manure mostly focuses on the quantity of above-ground biomass produced as the main source of organic matter. The role of root biomass is not always adequately assessed in terms of its dynamic impact on soil regimes and properties (Pisarčik et al., 2024; Zhang et al., 2024). It has been noted (Patra et al., 2023; Pandey & Kumar, 2024) that the effective role of a particular type of green manure should be considered by analyzing the morphological and spatial development of root systems in the context of adaptive and environmental factors.

It has also been observed (Saleem et al., 2020; dos Santos Nascimento et al., 2021; Tunguz & Pržulj, 2023) that different types of green manure plants demonstrate a wide range of root system responses to soil and climate conditions. In fact, the intensity of root development given the short growing period of green manure crops and under less favorable hydrothermal conditions, especially in the case of intermediate (summer-autumn) green manuring ensures an adequate level of green manure bioproductivity. For instance, according to estimates (Bublitz et al., 2022; Liang et al., 2023), an effective level of green manuring for areas with unstable moisture on soils of medium fertility potential is achieved when dry matter of above-ground biomass reaches about 2.5 t ha^{-1}, and root biomass at least 1.0 t ha^{-1}. It has also been noted that the root biomass of green manure crops serves as an additional source of organic carbon (Mahey et al., 2024). Moreover, due to the higher C/N ratio in root biomass compared to above-ground biomass, its decomposition in the soil occurs more slowly, which creates additional advantages in terms of slow mineralization of plant biomass in the soil profile (Ansari et al., 2022; Prajapati et al., 2023). These processes make root biomass a component in forming the organic complex of the soil profile. Due to its biochemical composition differing from that of the above-ground mass, it ensures heterogeneity in the immobilization processes of decomposition biochemical components and qualitatively changes the structure of the soil microbiological complex (Ciaccia et al., 2017; Wang et al., 2024). It has been established that the degree of root system development in green manure crops - assessed by branching levels and the intensity of vertical and horizontal spread - affects soil agrophysical parameters such as density, porosity, aggregate dispersion, content of agronomically valuable soil aggregates, and their water resistance (Ma et al., 2021; Gentsch et al., 2024). This noted positive impact confirms the participation of root systems of green manure crops, when used regularly in crop rotations, in the gradual improvement of soil air and water properties and the reduction of humus depletion and decalcification (Bodner et al., 2019, 2021; Pisarčik et al., 2024).

At the same time, these features require detailed analysis of the growth patterns of green manure root systems from the standpoint of overall vegetative and spatial morphometry, accumulation and distribution of root biomass, and the role of soil properties and hydrothermal conditions during the growing season. Ultimately, this guarantees a sufficient assessment of the effectiveness and ecological feasibility of using green manure crops of specific plant types (Pimentel et al., 2023; Mueller et al., 2024; Ridgeway et al., 2024). In this context, recent years have seen increased scientific research on the formation of root systems of different green manure plant species (Bodner et al., 2019; Bublitz et al., 2022; Hudek et al., 2022; Kemper, 2024).

Among the plants used as green manure crops, cruciferous species are among the most widely applied (Ugrenović et al., 2019). Oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers. (= *Raphanus sativus* var. *oleifer* Stokes)), as a typical representative of this group, is gaining increasing popularity as a green manure crop, particularly in areas with a temperate continental climate and soils with low fertility potential, due to its well-defined adaptive traits (Tsytsiura, 2024a; 2025). From this perspective, evaluating the patterns of spatial and weight morphometry of its root system within the soil profile under various green manuring schedules - taking into account the hydrothermal conditions of the area and several soil properties - is a relevant issue that requires further scientific investigation, especially in terms of morphology and bioproductivity level.

MATERIALS AND METHODS

The research was carried out during 2014–2024 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 (IUSS, 2015)) Haplic Greyzems according to FAO (IUSS, 2015)) of silty clay loamy texture. Weighted average soil fertility indicators: humus content: 2.68%, easily hydrolysable nitrogen 81.5 mg kg^{-1} soil, mobile phosphorus 176.1 mg kg^{-1} soil and exchangeable potassium 110.8 mg kg^{-1} soil, pHcl 5.8, hydrolytic acidity 3.29 mg-equivalent 100 g^{-1} soil. Additional average soil parameters are presented in Table 1.

The oilseed radish variety 'Zhuravka' was used in the research. The green manure type of crop design was used (seeding rate of 2.5 million seeds ha^{-1} with row spacing of 15 cm). Two terms of green manure were studied: spring and summer. The spring term involved sowing in the first or second decade of April with the flowering phase (BBCH 64–67) reaching the optimum for green manure (according to Kemper, 2024) in the second or third decade of June. The summer term corresponded to sowing in the second to third decade of July with the flowering phase (BBCH 64–67) reaching the second to third decade of October. The green manure crop was grown on unfertilized soil with moisture provided by atmospheric precipitation.

Table 1. Detailed characteristics of the soil cover of the experimental plot in the year of the experiment (average across four transects)

The horizon of the soil, cm**	Soil density, G cm^{-3}		General porosity, %	The smallestmoisture capacity, %	Maximal hygroscopicity, %	Humus,%	pH$_{KCl}$	Content, mg kg^{-1} soil		
	folding	solid phase						lightly hydrolysed nitrogen	mobile phosphorus	exchange potassium
0.0–0.1 (Oi, Oe)	1.28 ± 0.05	2.52 ± 0.04	48.24 ± 1.48	26.78 ± 1.05	8.22 ± 0.55	2.75 ± 0.21	5.8 ± 0.2	85.3 ± 1.9	177.5 ± 3.9	118.8 ± 2.9
0.1–0.2 (Ap)	1.31 ± 0.05	2.57 ± 0.04	48.25 ± 1.55	26.41 ± 1.23	8.35 ± 0.62	2.60 ± 0.18	5.8 ± 0.2	83.7 ± 1.6	179.1 ± 2.5	110.8 ± 3.9
0.2–0.3 (A_1)	1.37 ± 0.05	2.62 ± 0.05	47.71 ± 1.61	25.51 ± 1.42	8.17 ± 0.68	2.15 ± 0.16	5.7 ± 0.2	75.5 ± 1.9	171.6 ± 3.1	105.7 ± 4.2
0.3–0.4(A_2)	1.41 ± 0.03	2.66 ± 0.07	46.99 ± 1.39	23.18 ± 1.33	8.14 ± 0.55	1.75 ± 0.12	5.6 ± 0.2	65.7 ± 1.5	158.5 ± 2.2	102.5 ± 5.6
0.4–0.5 (A_2)	1.46 ± 0.04	2.69 ± 0.04	45.72 ± 1.42	23.49 ± 1.52	8.75 ± 0.57	1.10 ± 0.19	5.5 ± 0.3	61.4 ± 2.1	114.4 ± 4.2	98.8 ± 3.9
0.5–0.6 (B_a)	1.46 ± 0.04	2.69 ± 0.05	45.72 ± 1.89	24.15 ± 1.38	8.83 ± 0.67	0.85 ± 0.12	5.5 ± 0.1	49.7 ± 2.8	92.5 ± 2.7	96.7 ± 4.2
0.6–0.7 (B)	1.49 ± 0.06	2.71 ± 0.06	45.02 ± 2.17	23.85 ± 1.29	9.17 ± 0.67	0.71 ± 0.15	5.6 ± 0.3	47.4 ± 3.2	71.5 ± 3.9	102.8 ± 5.3
0.7–0.8 (B)	1.50 ± 0.06	2.70 ± 0.05	44.44 ± 2.12	24.28 ± 1.61	8.92 ± 0.54	0.57 ± 0.15	5.8 ± 0.4	41.5 ± 3.3	77.5 ± 4.2	111.3 ± 2.5
0.8–0.9 (B)	1.55 ± 0.07	2.73 ± 0.04	43.22 ± 2.25	23.00 ± 1.58	9.78 ± 0.58	0.52 ± 0.17	5.8 ± 0.3	40.2 ± 2.8	74.8 ± 2.3	110.7 ± 2.1
0.9–1.0 (B_c)	1.60 ± 0.07	2.74 ± 0.04	41.61 ± 2.47	21.48 ± 1.71	10.02 ± 0.63	0.50 ± 0.15	5.8 ± 0.3	39.3 ± 3.7	67.3 ± 3.1	114.7 ± 3.0

* SD – standard deviation; ** – according to Gupta et al. (2008).

The experimental plots were formed in quadruplicate by the method of randomisation with a plot area of 25 m^2. The growth stage of plants was identified using standard BBCH scales (Test Guidelines, 2017). The above-ground mass of plants was recorded during the flowering phase by the method of trial plots (1 m^2) (4 in each replication, weighed on a laboratory balance (WALCOM LB3002 / ± 0.01 g)). The dry matter (DM) content of the aboveground and root mass of plants was determined by drying to constant weight at 105 °C and ashing at 550 °C (according to Undersander et al., 1993).

The field analysis of bioproductivity and morphogenesis of the root system of plants was carried out at the flowering stage using a combination of Profile Wall and Monolith Method (according to the recommendations of van Noordwijk et al., 2000; Cutforth et al., 2013; Talgre, 2013; Wahlström et al., 2015; Upendra et al., 2017).

Profile Wall Method: a trench was made approximately l m wide, across 6 rows of oilseed radish at the flowering stage of the plants (BBCH 64–67). The vertical wall across the rows was smoothed with a metal dust pan and a brush. Roots were exposed by removing a soil layer of about 1 cm thick by spraying water. For the vertical spatial delineation of the soil profile, a wooden marking frame (1 m × 1 m with a 10×10 cm grid) was used. Four such frames were included in the assessment for each replication.

The length of the exposed roots was estimated by counting the number of root-length units of 0.5 cm inside each grid. Based on this, data were obtained for the construction of root maps of a profile wall in a two-dimensional coordination system (according to Atkinson & Dawson, 2000; Pagès, 2012; Atkinson & Dawson, 2014; Pagès, 2014).

Monolith Method. Monoliths were formed from a vertical soil profile in 10 cm increments. Two rows of plants were included in the analysis with a depth of coverage of up to 10 plants in quadruplicate for each replication. Open-topped metal boxes with pointed edges (scoop type, wall thickness 3 mm) measuring 30 cm × 33.3 cm × 10 cm (accounting volume ~0.01 m^3) were used. To trim the monolithic layer along the outer front wall, a vertical pointed metal plate measuring 10 cm × 34 cm × 0.3 cm was used. This made it possible to compact the walls of the monolith. Micromonoliths were labelled and packed in airtight sampling bags and then stored at 5 °C until washed out for soil removal. A sieve column (laboratory wire mesh sieves of 4.0 mm, 2.0 mm, 1.0 mm, 0.5 mm and 0.25 mm) was used for the washing separation of roots. Non-root materials were removed manually. The selected roots were stored in plastic containers at 5 ºC and subsequently air-dried for 24 h.

The dynamics of root system growth in depth was carried out at intervals of 10 days from the beginning of germination on a preliminary profile soil section along a 50 cm long row (covering at least 15 plants) in 4 locations selected in the middle part of the experimental plots in two non-contiguous replications (according to the recommendations of Atkinson & Dawson, 2000). At the same time, a micromonolith (in quadruplicate for each replication) was taken according to the above-mentioned method to the depth of root penetration to determine the dynamics of root mass growth g m^{-2}. This analysis was accompanied by soil hardness (SH, kg cm^{-2}, Walcom FM-204TR penetrometer), soil moisture (W, %, Walcom MS-7828SOI soil moisture tester) and bulk density (BD, g cm^{-3}, cylinder (core) method procedure (Blake & Hartge, 1986)).

Water reserves in the soil (WRS, mm) were determined on the basis of Eq. 1 (respectively до Dobriyal et al., 2012)

$$WRS = 0.1 \cdot h \cdot BD \cdot W \tag{1}$$

where h is the thickness of the soil layer, cm; W is the moisture content, %; BD is the bulk density, g cm^{-3}; 0.1 is for conversion to mm.

The diameter of the root system was determined by direct measurement using an electronic caliper (Digital Caliper, Germany (± 0.01 mm)).

The taperiness of the core part of the root systems, ignoring the curvature of the root shape, and the average diameter of the core part of the root (r_{aver}) were determined by Eqs. 2–3 (according to Yang et al., 2017).

$$Taperiness = \frac{(D - d)}{l} \quad (2)$$

$$r_{aver} = \frac{\sqrt{D^2 + Dd + d^2}}{3} \quad (3)$$

where D is the root diameter at the root neck, cm; d is the root diameter at the lower fixation point, mm; l is the root length between the two points of diameter fixation, mm.

To determine the volume of the root system (V_{root}), a volumetric meter was used, consisting of a cylinder with a rubber tube connected to a 0.01 mL graduated pipette. The pipette was placed at such an angle that the meniscus of water was at the beginning of the pipette. When the roots were immersed in water, the water level in the cylinder increased, which in turn led to the movement of the meniscus in the graduated tube. The volume of the root system was determined by the amount of distilled water that needed to restore the same position of the meniscus in the graduated tube. To estimate the volumetric intensity of the development of the root system of oil radish, its fractal dimension (D) was calculated (according to the approaches of Tatsumi et al. 1989; Berntson et al., 1998; Edger, 2008) based on the measurement of root length (L_i) and the number of roots (N_i) of the i-th order. The order of root branching was identified: the last lateral branching was assigned to the first order, and the main root to the last order. The coefficient of the average length of branching of roots of the corresponding order (k_L) and the coefficient of the number of roots of the corresponding order (k_N) were calculated (Eqs. 4–5).

$$k_L = \frac{L_{i+1}}{L_i} \quad (4)$$

$$k_N = \frac{N_i}{N_{i+1}} \quad (5)$$

where L_i is the length of the roots of the i-th order, L_{i+1} is the length of the roots of the next branching order, cm; where N_i is the number of roots of the i-th order, N_{i+1} is the number of roots of the next branching order, pcs.

The average root length coefficient (K_L) and the average root number coefficient (K_N) were calculated as the arithmetic mean of the k_L and k_N coefficients.

The fractal dimension of the root system of oilseed radish (D) was determined by Eq. 6.

$$D = \frac{\ln K_N}{\ln K_L} \quad (6)$$

To calculate the root spreading zone of the root system, we used the methodological approaches of Rouse (2019) and Jung et al. (2019) for the approximation of the configuration of the cut and full elliptical cones due to the longer branching length of the root system in the inter-row compared to the row (Fig. 1). In accordance with the parameters of Fig. 1 (based on Leonard et al. (2014)), the volume of root spreading zone (R_{vsz}) was determined (Eq. 7).

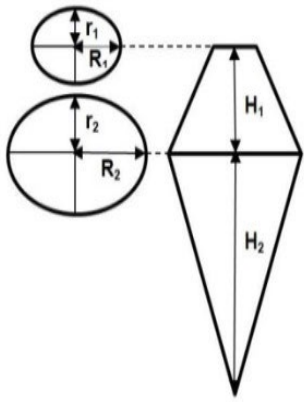

Figure 1. Shape of the root spreading zone of oilseed radish based on data from the Monolith and Profile Wall methods.

$$R_{vsz} = \frac{1}{3}\pi[(R_1r_1 + R_1r_1R_2r_2 + R_2r_2)H_1 + R_2r_2H_2] \quad (7)$$

where the relevant components of the equation correspond to those presented in Fig. 1.

The coefficient of root system productivity in dry matter (CRP_{DM}) was calculated as the ratio of formed aboveground dry biomass to formed root dry biomass of the plants. The share of root residues in total dry plant biomass (SRR_{DM}) was calculated using the inverse ratio compared to CRP_{DM} and was expressed as a percentage.

To estimate the spatial distribution of root mass, we used the Michaelis-Menten function of root distribution with depth (z; cm) (Eq. 8 according to Kätterer et al., 2011).

$$R_{m(z)} = \frac{z(z_{50} + z_r)}{z_r(z_{50} + z)} \quad (8)$$

where $R_{m(z)}$ is the fraction of total root mass to the soil depth of z (cm), z_r is maximum root depth (z_r was set at 100 cm), z_{50} is the depth of 50% of the root mass.

Based on the root length and root mass obtained from the monolith samples (according to Pagès et al. (2012) and Bardgett et al. (2014)), the following indicators were determined root length density (*RLD*, cm cm^{-3}, Eq. 9), root mass density (*RMD*, mg cm^{-3}, Eq. 10) and specifc root length (SRL, m g^{-1}, Eq. 11), percentage of root weight distribution (*PRWD* (in raw weight after 3 h normal air drying), %, Eq. 12).

$$RLD = \frac{root\ length}{soil\ volume} \quad (9)$$

$$RMD = \frac{root\ dry\ mass}{soil\ volume} \quad (10)$$

$$SRL = \frac{root\ length}{root\ dry\ mass} \quad (11)$$

$$PRWD = \frac{root\ mass\ for\ a\ specific\ soil\ horizon}{root\ mass\ in\ the\ general\ soil\ profile} \cdot 100 \quad (12)$$

To analyze the patterns of distribution of oilseed radish roots along the soil profile, nonlinear regression models were estimated using CurveExpert Professional v. 2.7.3 software package (Hyams Development). Additionally, RhizoVision Explorer 2.0.2 (Noble Research Institute, LLC, USA) and electronic scanning and USB microscopy method (CanoScan LIDE 700F scanner, Sigeta MCMOS 5100 5.1 MP USB 2.0) were used.

To analyze the hydrothermal conditions, we used the following indicators: average daily temperature (°C), precipitation (mm), relative humidity (%), hydrothermal coefficient (HTC) (Eq. 13), De Martonne Aridity Index (I_{DM}) (Eq. 14), Vysotsky-Ivanov humidification coefficient (K_h) (Eq. 15).

$$HTC = \frac{\sum R}{0.1 \cdot \sum t_{>10}} \quad (13)$$

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

$$I_{DM} = \frac{12P_m}{T_m + 10}, \quad (14)$$

where P_m and T_m are the precipitation volume and mean air temperature in the corresponding month, respectively (according to the I_{DM} the climate can be classified:

Arid $I_{DM} < 10$; Semi-Arid $10 \leq I_{DM} < 20$; Mediterranean $20 \leq I_{DM} < 24$; Semi-humid $24 \leq I_{DM} < 28$; Humid $28 \leq I_{DM} < 35$; Very Humid $35 \leq I_{DM} \leq 55$; Extremely humid $I_{DM} > 55$).

$$K_h = \frac{P}{E} \tag{15}$$

where K_h is the moisture coefficient; P is the amount of precipitation for the analyzed period, mm; E is the evapotranspiration for the analyzed period, mm, which was calculated according to Eq. 16 (the different moisture degrees of K_h: $K_h > 1.0$ – excessive, K_h close to 1 – optimal, $K_h = 1.0–0.6$ – unstable, $K_h = 0.6–0.3$ – insufficient).

$$E = 0.0018 \cdot (25 + t)^2 \cdot (100 - a), \tag{16}$$

where t is average air temperature, °C; a is average air humidity, %.

A summary assessment of hydrothermal conditions is presented in Table 2.

Table 2. Assessment of hydrothermal regimes during the active vegetation period of oilseed radish under summer and autumn green manure use (Dfa/Dfb zone according to the Köppen-Geiger climate classification), 2014–2024

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
A variant of summer green manure											
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	1.90	0.04	1.640	38.9	0.87
2024	262.1	16.27	3.259	47.5	3.18	0.577	13.19	0.24	1.660	40.4	0.98

Year	Precipitation, mm (IV–VI)	*t_{aver}, °C (IV–VI)	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
An variant for autumn green manure														
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
2024	219.8	19.6	1.190	31.1	0.66	0.771	19.8	0.41	0.445	10.6	0.22	1.173	30.5	1.06

To assess the stability of oilseed radish bioproductivity formation, we used (according to Sych, 2006) the absolute elasticity coefficient (EA), the relative elasticity coefficient of type I (E_I), and the relative elasticity coefficient of type II (E_{II}) according to Eqs. 17–19.

$$E_A = \frac{\Delta y}{\Delta x} \quad (17)$$

$$E_I = \frac{\Delta y x_{av}}{100\Delta x} \quad (18)$$

$$E_{II} = \frac{\Delta y x_{av}}{\Delta x y_{av}} \quad (19)$$

where Δy is the range of variability of the resultant indicator y; Δx is the range of variability of the environmental factor x; xav, yav is the average value of the indicators between the maximum and minimum values in the respective years.

Statistical analysis. To statistically evaluate all multi-year average values of root system morphometric indicators, the standard deviation (SD) was used based on a consolidated data set covering the entire evaluation period. Statistical significance of interannual comparisons was assessed using Tukey's test (Tukey HSD Test) with the Bonferroni correction at a significance level of $p < 0.05$, with letter-based indication of statistically different data. Additionally, interannual variation was assessed using the coefficient of variation (Cv) for the time series of average annual data.

For the main indicators of root system bioproductivity based on fresh and dry biomass yields and related parameters, as well as for indicators of root system development intensity in the soil profile (RLD, RMD, SRL, PRWD), standard ANOVA analysis was applied to determine the statistical significance of interannual differences at a significance level of $p < 0.05$. The statistical analyses were performed using Statistica 10 software (StatSoft – Dell Software Company, USA) and R (version R statistic i386 3.5.3). Correlation and regression analysis was conducted according to the standard procedure for levels of statistical significance $p < 0.05$ and $p < 0.01$ (Wong, 2018) using the coefficient of determination (R^2, with an estimate according to the Chaddock (1925)), adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), relative root mean square error (RRMSE) and prediction efficiency index (PE), the coefficient of determination of the closeness of the correlation (d_{xy}, Eq. 20).

$$d_{xy} = r_{ij}^2 \cdot 100 \quad (20)$$

where r_{ij} is the correlation coefficient.

RESULTS AND DISCUSSION

Sidereal Bioproductive Potential of the Root System. The multi-year research period, characterized by interannual variability in precipitation levels of 33.78% and in average daily temperatures of 17.55%, defines the hydrothermal regime of the study period (according to Gardner et al., 2020) as unstable - ranging from extremely arid conditions amid rapidly rising average daily temperatures (IDM 2.5; Kh 0.05; HTC 0.014 (Table 2)) to excessively humid conditions under moderate temperature levels (I_{DM} 111.0; K_h 3.29; HTC 4.902).

This allowed for the evaluation of the ecological adaptive strategy of root system formation in oilseed radish over a multi-year scale and, based on the obtained indicators of its bioproductive potential (Figs 2–3), to classify it as a highly productive and adaptive cover crop suitable for a wide range of sowing periods – under conditions of either increasing (spring sowing) or decreasing (summer sowing) average daily temperatures.

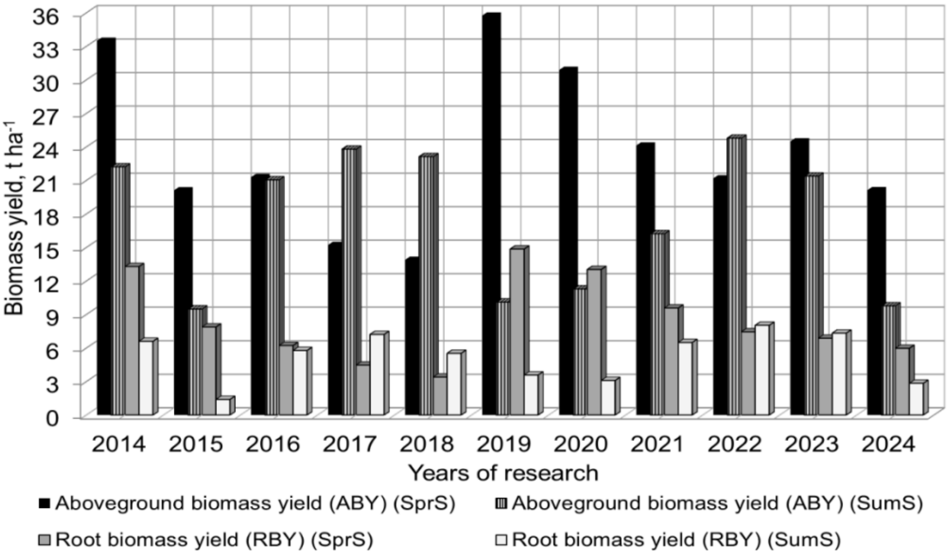

Figure 2. Formed raw aboveground and raw root biomass of oilseed radish plants for spring (SprS) and summer (SumS) sowing, t ha^{-1} (*LSD*$_{05}$ springABY 1.42; *LSD*$_{05}$ summerABY 1.24; *LSD*$_{05}$ spring RBY 1.09, *LSD*$_{05}$ summer RBY 0.65), 2014–2024.

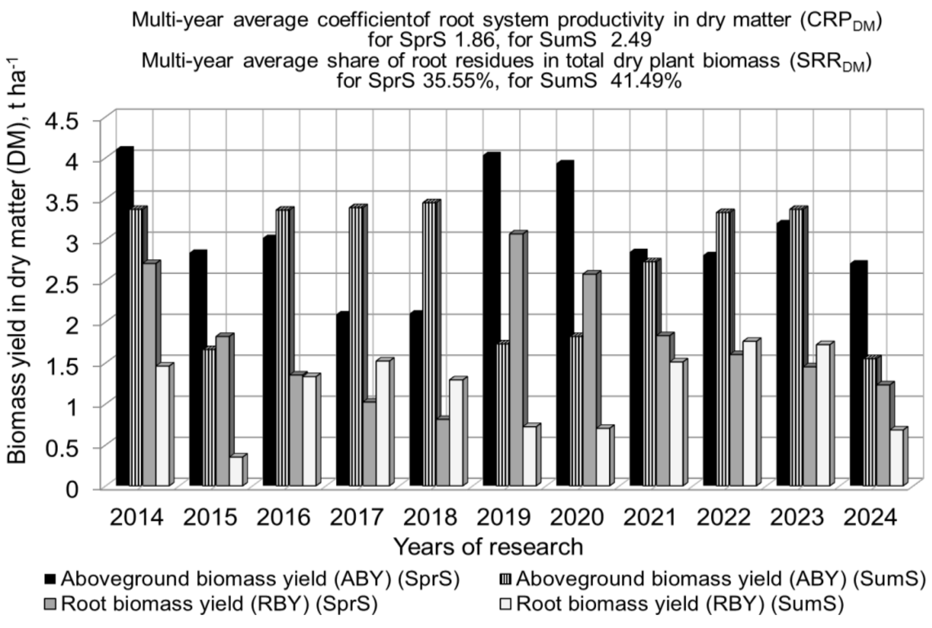

Figure 3. Formed aboveground and root biomass (in dry matter (DM)) of oilseed radish plants for spring (SprS) and summer (SumS) sowing, t ha^{-1} (*LSD*$_{05}$ springABYDM 0.23; *LSD*$_{05}$ summerABYDM 0.37; *LSD*$_{05}$ spring RBYDM 0.25, *LSD*$_{05}$ summer RBYDM 0.14), 2014–2024.

According to the results of long-term studies conducted across different soil-climatic zones, the feasibility of using specific plant species as cover crops for green manure and phytoremediation purposes has been confirmed, provided that aboveground phytomass in dry matter reaches 1.5–2.0 t ha^{-1} and root mass 0.8–1.0 t ha^{-1}, with a corresponding root system productivity coefficient of 1.8–2.0 and a total root biomass share not exceeding 50% of the overall plant biomass (Wagg et al., 2021; Zhang et al., 2023). These parameters provided a sufficient level of green manure potential in terms of replenishing soil with organic biomass, optimizing its agrophysical and agrochemical properties, and ensuring plant adaptability to limiting hydrothermal factors in specific regions - taking into account the potential of the developed root systems (Dzvene et al., 2023; Wong et al., 2024).

The presented results, along with our previous assessments (Tsytsiura, 2024a, 2024b) on grey forest soils - whose fertility potential is classified as medium (Kolbe, 2022) - determined the long-term average level of aboveground biomass formation at 23.68 t ha^{-1} for spring sowing and 17.56 t ha^{-1} for summer sowing, with interannual variation of 29.84% and 35.68%, respectively. When converted to dry matter equivalent, these values amounted to 3.06 and 2.71 t ha^{-1} (with interannual variation of 22.96% and 30.68%, respectively). At the same time, the root biomass formed was 8.45 and 5.26 t ha^{-1} in raw weight and 1.77 and 1.19 t ha^{-1} in dry matter, with interannual variation ranging between 40.86% and 44.72%. The average long-term interannual variation of the root productivity coefficient (RPC) was 21.99% (with a long-term average RPC of 1.86) for spring sowing and 32.20% (RPC = 2.49) for summer sowing, against background interannual RPC variation levels of 13.94% and 24.11%, respectively.

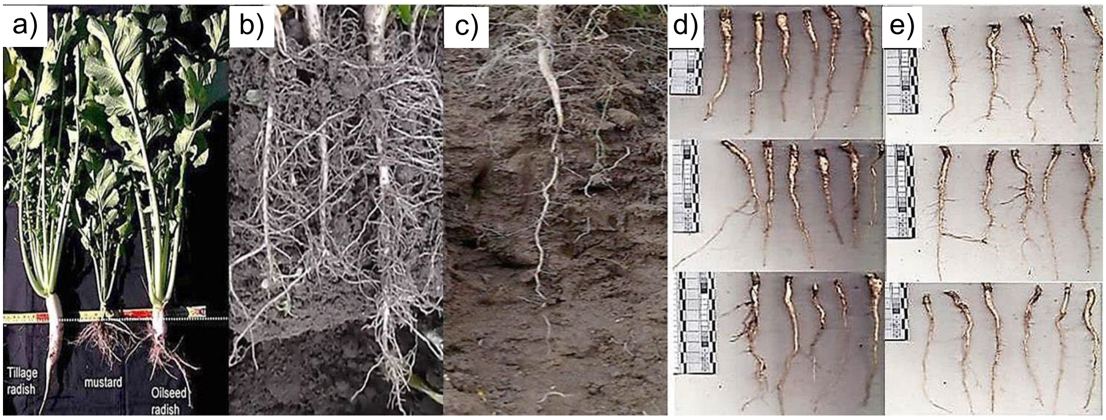

Figure 4. General morphology of root systems in cruciferous species. (a) General comparative characteristics (Radish cover crop, 2024); (b–c) Structure of the root system of oilseed radish (Raphanus sativus L. var. oleiformis Pers. [syn. Raphanus sativus var. oleifer (Stokes) Metzg]); (d) Taproot of oilseed radish with elements of primary branching under spring sowing; (e) Taproot under summer sowing conditions.

These results highlight the significant influence of the hydrothermal regime on the realization of the root productivity potential in oilseed radish. Compared to other cruciferous species (Fig. 4), the development of the oilseed radish root system under green manure usage throughout the study period exhibited certain bioproductive and morphological distinctions. Identifying these differences allowed for a more detailed characterization of its root productivity potential as a green manure crop.

Root System Morphotype and Development Intensity in the Soil Profile. The integrated system for evaluating the morphological characteristics of the root system (Table 3) has proven its value in terms of active morphogenesis and potential impact on the soil profile. In particular, oilseed radish was characterized by the formation of a taproot (Fig. 4, g, d) and an intensive network of lateral branches of corresponding orders (Fig. 4, b). The parametric morphological development of the taproot section exhibited significant differences depending on the sowing dates of oilseed radish as a green manure crop and, in our case, was defined by the average diameter and conicity (Table 3).

Table 3. General indicators of oilseed radish root system development based on the combined use of the Profile Wall and Monolith Method at the flowering stage (BBCH 64-67), 2014–2024

Year	Average diameter of the root taproot (r_{aver}), mm	Taperiness	Volume (V_r), cm^3	Volume of root spreading zone (R_{vsz}), $x10^3$ cm^3	Fractal dimension of the root system (D)	Maximum root depth (z_r), cm	Fraction of total root mass to the soil depth 0–30 cm ($R_{m(z)}$)
Spring sowing							
2014	7.94 ± 2.59^e	0.48 ± 0.13^a	57.39 ± 9.32^g	84.89 ± 8.41^d	0.85 ± 0.12^e	58.8 ± 7.19^c	0.83 ± 0.07^d
2015	4.68 ± 1.09^b	0.47 ± 0.15^a	21.93 ± 7.18^d	28.49 ± 6.69^a	0.72 ± 0.18^c	75.7 ± 8.53	0.78 ± 0.05^b
2016	5.03 ± 1.55^c	0.62 ± 0.17^c	45.39 ± 8.35^e	34.54 ± 4.58^a	0.70 ± 0.13^b	57.9 ± 8.07^c	0.81 ± 0.09^d
2017	4.20 ± 1.17^a	0.58 ± 0.12^b	25.58 ± 6.59^a	51.90 ± 5.52^b	0.61 ± 0.19^a	78.9 ± 10.19^e	0.74 ± 0.08^a
2018	4.02 ± 1.08^a	0.66 ± 0.19^d	21.96 ± 5.87^d	33.88 ± 7.18^a	0.55 ± 0.15^a	79.1 ± 9.39^e	0.73 ± 0.05^a
2019	8.48 ± 2.05^f	0.48 ± 0.11^a	55.33 ± 7.14^h	65.76 ± 8.29^c	0.89 ± 0.09^f	49.5 ± 7.21^a	0.83 ± 0.10^d
2020	7.41 ± 1.87	0.48 ± 0.08^a	50.28 ± 8.41^f	105.69 ± 12.79^g	0.81 ± 0.12^d	58.4 ± 7.09^c	0.80 ± 0.09^c
2021	5.77 ± 2.06^d	0.56 ± 0.11^b	41.27 ± 5.28^b	95.29 ± 10.88^e	0.78 ± 0.08^d	55.4 ± 7.07^b	0.76 ± 0.11^b
2022	5.08 ± 1.54^c	0.52 ± 0.14^b	38.29 ± 5.59^a	87.04 ± 9.52^f	0.75 ± 0.10^c	68.4 ± 7.22^d	0.74 ± 0.05^a
2023	4.73 ± 1.14^b	0.58 ± 0.11^b	37.37 ± 4.11^c	69.47 ± 6.87^c	0.71 ± 0.14^b	69.2 ± 8.19^d	0.76 ± 0.07^b
2024	5.06 ± 1.25^c	0.61 ± 0.14^c	35.19 ± 4.69^a	73.36 ± 9.08^d	0.67 ± 0.17^b	57.2 ± 6.74^c	0.73 ± 0.10^a
Summer sowing							
2014	4.96 ± 1.19^b	0.54 ± 0.08^a	23.39 ± 4.77^c	34.89 ± 2.56^f	0.69 ± 0.11^d	42.8 ± 6.52^b	0.85 ± 0.07^d
2015	4.23 ± 0.97^a	0.62 ± 0.12^b	15.15 ± 3.59^a	19.82 ± 1.47^b	0.43 ± 0.18^a	57.6 ± 5.89^g	0.86 ± 0.05^d
2016	5.34 ± 1.12^c	0.64 ± 0.16^b	25.36 ± 7.18^d	26.50 ± 2.09^d	0.64 ± 0.09^c	46.9 ± 5.07^d	0.80 ± 0.11^c
2017	5.44 ± 1.29^d	0.56 ± 0.11^a	46.15 ± 6.59^f	30.26 ± 3.89^e	0.72 ± 0.14^e	41.3 ± 8.42^a	0.84 ± 0.04^d
2018	5.12 ± 1.58^c	0.65 ± 0.14^b	26.77 ± 5.08^c	31.85 ± 3.52^e	0.67 ± 0.11^c	40.9 ± 7.09^a	0.81 ± 0.05^c
2019	4.81 ± 0.73^b	0.76 ± 0.11^e	23.18 ± 4.25^c	22.75 ± 2.41^c	0.58 ± 0.15^b	58.9 ± 6.14^h	0.78 ± 0.08^b
2020	4.59 ± 1.05^a	0.72 ± 0.15^d	21.39 ± 4.09^b	42.58 ± 4.07^g	0.52 ± 0.12^a	42.5 ± 5.18^b	0.76 ± 0.12^a
2021	5.47 ± 1.55^d	0.76 ± 0.09	25.56 ± 3.56^d	24.20 ± 2.59^c	0.64 ± 0.18^c	48.7 ± 3.96^e	0.74 ± 0.08^a
2022	5.86 ± 1.07^e	0.67 ± 0.11^c	34.38 ± 3.77^f	70.03 ± 9.07^h	0.78 ± 0.10^f	40.9 ± 5.12^a	0.75 ± 0.05^a
2023	6.20 ± 1.74^f	0.68 ± 0.12^c	30.28 ± 5.02^e	15.42 ± 1.49^a	0.73 ± 0.11^e	44.7 ± 4.35^c	0.77 ± 0.08^b
2024	4.41 ± 0.72^a	0.67 ± 0.14^c	24.47 ± 3.91^c	85.96 ± 10.22^i	0.52 ± 0.07^a	55.8 ± 5.71^f	0.76 ± 0.06^a

Note: Different letters indicate values that differ significantly from one another within each column, based on Tukey's test with Bonferroni correction.

The first indicator, in the long-term average for spring sowing, was 5.67 mm, and the second – 0.55. For summer sowing, their values were lower by 10.6% and 16.7%, respectively. Compared to other cruciferous green manure crops (spring and winter rapeseed, various mustard species), the diameter of the central (core) part of the oilseed radish taproot was smaller than that of winter rapeseed (Gan et al., 2009; Gao et al., 2017; Louvieaux et al., 2020; Kemper, 2024), equal to or greater than that of white mustard (Chaudhary et al., 2016; Hajzler et al., 2018; Amgain & Sharma, 2021; Kemper, 2024), and greater than that of spring rapeseed (Čepulienė et al., 2013; Marcinkevičienė et al., 2013; Liyanage et al., 2022; Kemper, 2024).

At the same time, the taproot of oilseed radish is characterized by a flexible formation of a conical profile, with an active adjustment of the main axial line of the root in response to changes in soil density and the presence of mechanical obstacles (Fig. 4, g, d). This trait creates preconditions for deep root penetration and enables growth in compacted soils. This is further confirmed by a conicity index value below 0.75, which, according to Goodman et al. (2001), Jeudy et al. (2016), and Duan et al. (2023), indicates both the intensive narrowing of the lower taproot section at maximum rooting depth (zr) and the high penetration potential of narrow-diameter root crops into the deeper horizons of the soil profile, as supported by the findings of Duan et al. (2023) and Wu et al. (2020).

This specific morphology of the core section of the root has demonstrated the value of oilseed radish as a green manure crop for improving the agrophysical properties of the soil profile up to a depth of 50 cm (based on the long-term average rooting depth (z_r) of 64.41 cm (interannual C_v = 20.97%) for spring sowing and 47.36 cm (C_v = 18.57%) for summer sowing). This effect is analogous to the so-called ‘root drainage effect’ observed in white mustard (Dharmasri et al., 1993) and winter rapeseed (Fan et al., 2016), and has been identified as a key factor in the effectiveness of these plant species when used as green manure crops (Kemper, 2024).

The green manure and phytoremediation potential of oilseed radish for both green manuring periods was also confirmed by the root system volume indicator (V_r).

On average over the study period, the root system volume (Vr) of oilseed radish was 39.09 cm³ (with interannual Cv = 31.93%) for spring sowing and 26.92 cm³ (Cv = 29.78%) for summer sowing, which is 45.22% lower. This supports the findings of Schenk & Jackson (2002), Wu et al. (2018), Kashyap et al. (2023), Maan et al. (2023), Boter et al. (2023), and Ullah et al. (2024) regarding the response of root systems - including cruciferous species - to aridization during their vegetation period, manifested in a reduction of total morphological development by 30–75%. This was also confirmed by the hydrothermal evaluation of oilseed radish’s vegetation period in both spring and summer sowing conditions (Table 2). At the same time, the obtained V_r values, according to the assessments of Talgre (2013), Duff et al. (2020), Bublitz et al. (2022), and Kemper (2024), are comparable to those of such crops as white mustard, brown mustard, and both spring and winter rapeseed, for which the range of Vr was reported to be between 20 and 117 cm³.

It is worth noting that under similar climatic conditions of the study area (climate zone Dfa/Dfb according to the Köppen-Geiger classification), the average V_r values of oilseed radish were 31.7% lower than those of winter rapeseed in long-term measurements (Talgre, 2013; Ullah et al., 2024; Chen et al., 2024), but 21.5% and 12.9% higher than those of spring rapeseed and white mustard, respectively, when used as green manure crops (Dharmasri et al., 1993; Wahlström et al., 2015; Jeudy et al., 2016; Hajzler et al., 2018).

At the same time, based on the root spread zone volume (R_{vsz}) - an important factor in the spatial distribution of root systems within the soil profile (Liu, 2009) - oilseed radish was classified as a crop with wide adaptability in the formation of spatial root morphometry. On average over the study period, this indicator was 66.39×10^3 cm³ (interannual $C_v = 39.63\%$) for spring sowing and 36.75×10^3 cm³ ($C_v = 59.82\%$) for summer sowing. The R_{vsz}:V_r ratio for oilseed radish as a green manure crop was 1.70 in spring sowing and 1.37 in summer sowing, indicating a high intensity of root system expansion through lateral branching. This ratio reflects the relationship between root system compactness and its areal spread - i.e., the extent of horizontal and vertical penetration of lateral roots under a given plant density.

Taking into account the estimates of Deus et al. (2022) and Kemper (2024), in full-fledged green manure crops, especially in the intermediate group of cultivation, a ratio above 1.25 is important to achieve the appropriate green manure and soil rehabilitation effect. From this point of view, oilseed radish, when used as green manure, meets the criteria of efficiency in terms of full root mass formation in terms of soil rehabilitation and bioorganic fertilization.

This conclusion is consistent with the results of the fractal dimension (D) of the root system. This parameter displayed specific characteristics in oilseed radish that further detail its adaptive root system architecture. The D value for spring sowing was 0.73 (with interannual $Cv = 13.76\%$) and 0.63 ($Cv = 16.87\%$) for summer sowing. According to Berntson (1996; 1998), the fractal dimension of root systems is a highly variable parameter, ranging from 0.35 to 1.95 across assessed crop species. Higher D values indicate a greater number of branches relative to their length. It has been reported (Gao et al., 2024) that for winter rapeseed under primary cultivation, depending on fertilization, the D index ranged from 1.56 to 1.76. As plant density increases in the absence of additional fertilization and under unfavorable agrophysical conditions of the soil profile, the fractal dimension of the root system tends to decrease, which may serve as an indicator of the species' response to the effectiveness of stand structure design (Berntson et al., 1998; Yang et al., 2022).

For cruciferous crops, which are sensitive to sowing dates and spatial parameters of nutrient zones, the D index can vary broadly from 0.50 to 2.10, and for cruciferous species with a spring development cycle – from 0.5 to 1.2 (Berntson, 1996). The obtained value for oilseed radish, under high-density green manure cropping (up to 2.5 million plants per hectare), and based on its demonstrated response to stand density and fertilization (Tsytsiura, 2020), confirms the presence of adaptive potential for intensive radial development and root system penetration under increasing ecological-coenotic stress, as noted by Fitter & Stickland (1992). This characteristic is also supported by the low interannual variation in both sowing terms, with only a 3.11% difference in Cv between them, and D variability being nearly half that of the hydrothermal conditions observed during the study period (Table 2). These conclusions are consistent with the findings of Wang et al. (2009), Upendra et al. (2017), and Ullah et al. (2024).

It is also important to note the characteristics of maximum rooting depth (z_r) formation, which plays a key role in the vertical distribution of the root system (Schlüter et al., 2018; Kafarski et al., 2019) and significantly determines the adaptive potential of this plant species in terms of water supply and its ability to maintain growth rates under declining optimal environmental factors during the vegetation period (Fan et al., 2017). This was a major factor in ensuring the bioproductivity of summer and early autumn green manure crops (Bublitz et al., 2022). During the research period, the long-term average z_r was 64.41 cm for spring sowing and 47.36 cm for summer sowing. Thus, the ratio between maximum rooting depth for these sowing terms was 1.36:1. The level of interannual variation in this parameter did not exceed 15.0% on average, indicating the presence of adaptive mechanisms in oilseed radish, associated with so-called hydrological deepening (Schenk & Jackson, 2002; Cutforth et al., 2013; Jabbari et al., 2016; Fan et al., 2017; Ullah et al., 2024). This effect is caused by an increase in the z_r index in response to reduced total soil moisture availability under precipitation deficit conditions and rising average daily temperatures. This is confirmed by comparisons between years with minimal precipitation and the z_r values of oilseed radish for both green manuring sowing terms (Table 2). In spring sowing, during the driest years (2015, 2017, 2018), the average z_r was 77.9 cm, which exceeded the long-term average by 21.0%. For summer sowing, in years with moisture deficit (2015, 2019, 2024), the corresponding value was 57.4 cm, exceeding the average by 24.3%.

It should also be noted that in terms of rooting depth, among other cruciferous green manure crops grown under comparable conditions (according to Cutforth et al., 2013; Amgain & Sharma, 2021; Deus et al., 2022; Boter et al., 2023; Chen et al., 2024; Kemper, 2024), oilseed radish was second only to winter rapeseed used in the autumn-winter cycle, where rooting depth reached 90–115 cm. At the same time, despite the recorded deep root penetration of oilseed radish in both sowing terms, it was found that the majority of roots were concentrated within the 0–30 cm soil layer. This is supported by the root mass distribution ratio to the 0–30 cm soil layer ($R_{m(z)}$), with an average value of 0.77 (interannual C_v = 7.91%) for spring sowing and 0.79 (C_v = 9.54%) for summer sowing. Overall, this pattern of vertical root accumulation is typical for cruciferous crops of both winter and spring types. In particular, Dharmasri et al. (1993), Bublitz et al. (2022), and Kemper (2024) noted this characteristic, indicating the depth intervals of maximum root system concentration as follows: 25–60 cm for winter rapeseed, 22–35 cm for spring rapeseed, 18–40 cm for oilseed radish, and 20–45 cm for white mustard. It has also been demonstrated (Kemper, 2024) that the vertical tropism share of roots in oilseed radish is sensitive to fertilizer application and increases in individual plant nutrient area. In densely planted cruciferous green manure agrocenoses, the majority of the root mass tends to concentrate within the upper 1-meter soil profile, accounting for 25–50% of total root biomass (Talgre, 2013; Wahlström et al., 2015).

These findings, along with the spatial distribution patterns of the oilseed radish root system in the long-term average, are supported by the results of root map construction along the profile wall in a two-dimensional coordinate system for the row spacing arrangement in both sowing terms (Fig. 5). The root map analysis was conducted according to the approaches described by Bucksch et al. (2017), Landl et al. (2018), Bublitz et al. (2022), and Faye et al. (2022). Based on the obtained data, the average geometric structure of the root spread zone of oilseed radish over the study period was confirmed and is presented in Fig. 1. It was determined that in the vertical projection of the soil profile, the root system of oilseed radish exhibited a complex, layered structure under both sowing conditions. In spring sowing, the share of roots with an identification probability of 85–100% was concentrated horizontally at a distance of 5–8 cm from the taproot and vertically at 24–28 cm from the soil surface (Fig. 5, a). The maximum horizontal spread of the root system in the long-term average occurred at a depth of 10–12 cm and at a horizontal distance of 8–12 cm from the taproot. The gradation step in horizontal spread variation ranged from 3 to 7 cm.

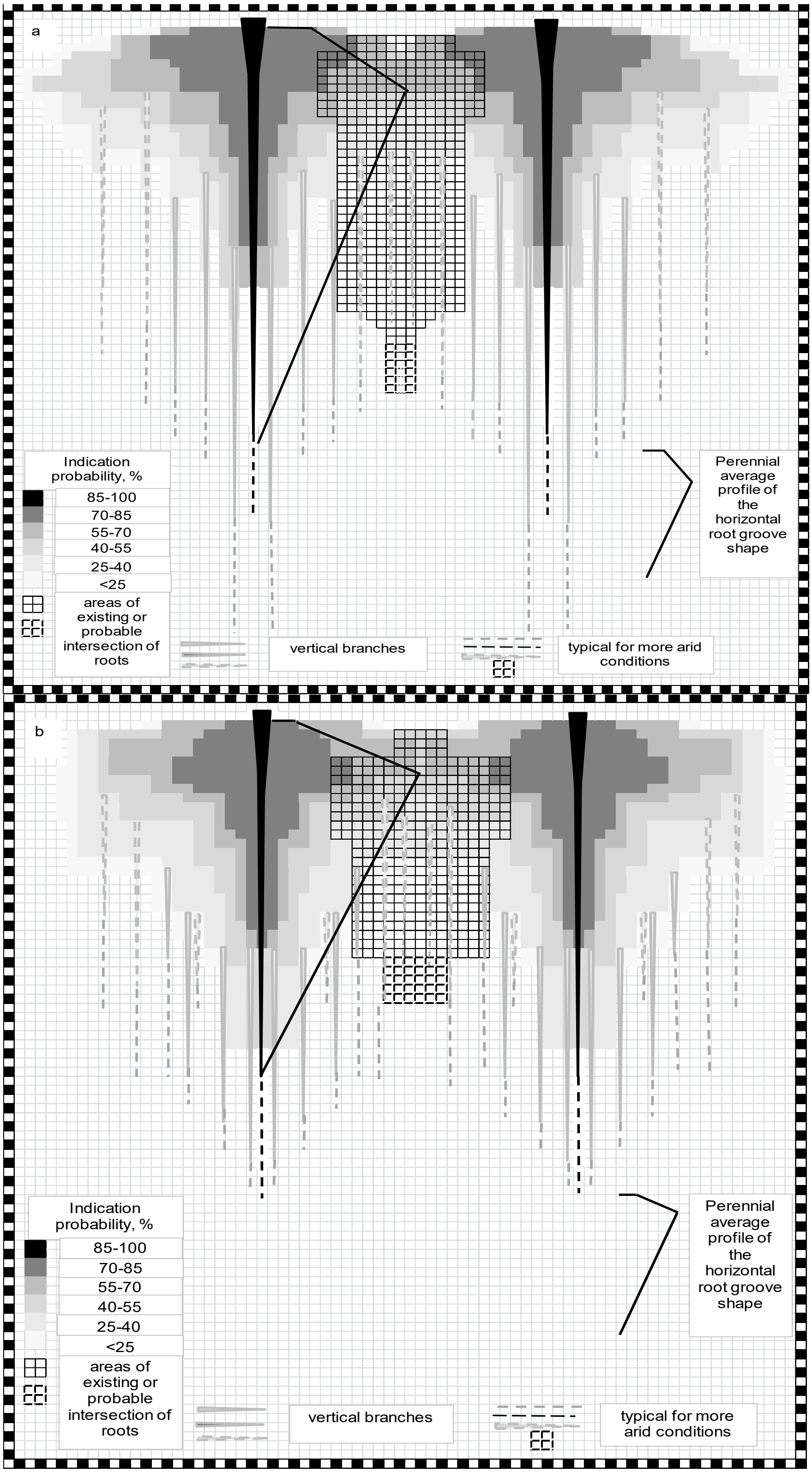

Figure 5. Root maps of the profile wall in oilseed radish, covering two rows of plants under spring (a) and summer (b) sowing conditions. Grid square size: 0.5×1.0 cm (width × depth). Maps are based on long-term analysis of the full dataset from 2014 to 2024.

Vertically oriented lateral root branches were recorded in profile zones with an identification probability of 40–85%. The length of these branches ranged from 8 to 24 cm. The intensity of such branching - in both depth and frequency - increased from the periphery toward the axial center of the taproot. The root system branch overlap zone under the studied sowing method was located within 7–9 cm from the axial centers of the plant roots in the row and peaked at depths of 6–12 cm, with a pronounced tendency to decrease beyond 14–16 cm depth, where vertical tropic lateral root interactions dominated.

Thus, the maximum compactness of root branch tropism in oilseed radish under spring sowing was observed within the 2–24 cm depth interval, while the maximum diffuseness was found in the 44–70 cm depth range.

According to the studies by Diggle (1988) and Shukla et al. (2023), based on a total average number of 3,150 root map grid squares per plant within a defined feeding area (as per the dimensional grid in Fig. 4, a), 1,854 squares remained unoccupied.

This indicates that the root system occupied 41.14% of the total grid area. Within the 0–30 cm soil layer, this occupancy increased to 61.07%, which showed a positive correlation with the $R_{m(z)}$ value (Table 3). In the summer sowing variant, roots with an identification probability of 85–100% were predominantly located horizontally at a distance of 4–7 cm from the taproot, and vertically at a depth of 18–24 cm from the soil surface (Fig. 5, b). The maximum horizontal spread of the root system, in the long-term average, was observed at a depth of 8–10 cm and at a distance of 6–8 cm from the taproot. The gradational interval for changes in horizontal spread ranged from 3 to 5 cm. The intensity of vertical branching, measured by the frequency of occurrence in the profile grid, was 22.77% higher than in the spring sowing period. These branches were predominantly located along horizontally spreading roots with an identification probability of 40–70%. However, the average depth-wise length of these vertical branches was 15.92% shorter compared to that in the spring sowing period.

The maximum compactness of root branch tropism in oilseed radish at the specified sowing time was observed in the depth range of 2–14 cm, while maximum diffusivity occurred between 22–40 cm. The zone of overlapping root branches consisted primarily of higher-order roots and, as a result, was 18.45% smaller in terms of occupied area within the root profile grid squares. The degree of root system development across the entire vertical profile was 34.85%, and 72.25% within the 0–30 cm soil layer. This indicates that during summer sowing, the root system of oilseed radish tends to develop a larger proportion of higher-order branches, accompanied by a reduction in the morphological and biomass parameters of these branches, as well as a decrease in overall rooting depth.

In general, based on assessments of the intensity of root development within the soil profile - a significant factor influencing soil parameters in addition to total organic carbon input - oilseed radish exerts a potentially strong effect on properties such as porosity, bulk density, structure, water-holding capacity, and air permeability (Han et al., 2016; dos Santos Nascimento et al., 2021; Hudek et al., 2022; Gentsch et al., 2024). Previous studies on various green manure crops (Gan et al., 2009; Cutforth et al., 2013; Duff et al., 2020; Bublitz et al., 2022; Deus et al., 2022; Kemper, 2024) confirm that oilseed radish can be classified as a valuable green manure species with potentially high impact on the physicochemical and agrophysical dynamics of the soil profile to depths of up to 70 cm. These conclusions are clearly supported by the data in Figs 5 (d, e) & 6 and are further detailed in the main morphological indicators of root system development (Table 4). According to the presented results, root system development in oilseed radish showed a consistent downward trend in both the absolute values of measured parameters and their relative proportions as depth increased. As noted by Bublitz et al. (2022) and Kemper (2024), this development pattern is common among most cruciferous species used as green manure.

Table 4. Morphological characteristics of the oilseed radish root system within the soil profile at the flowering stage (BBCH 64-67), average for the period 2014–2024

Depth, m	PRWD, %			RLD, cm cm^{-3}			RMD, mg cm^{-3}			SRL, m g^{-1}		
	$\bar{x}$	± SD	C_v	$\bar{x}$	± SD	C_v	$\bar{x}$	± SD	C_v	$\bar{x}$	± SD	C_v
For spring sowing												
0.0–0.1	38.36*	9.11	23.75	3.57*	1.605	44.97	0.2400*	0.0916	38.17	163.88*	56.30	34.35
0.1–0.2	29.85*	8.86	29.68	2.73*	1.248	45.68	0.1151*	0.0415	36.02	246.27*	100.89	40.96
0.2–0.3	14.59*	3.28	22.51	1.95*	0.864	44.32	0.0689*	0.0254	36.86	286.97*	108.17	37.69
0.3–0.4	10.42*	2.47	23.70	1.33*	0.449	33.75	0.0382*	0.0149	38.93	368.55*	118.98	32.28
0.4–0.5	3.92**	2.04	52.04	0.62**	0.269	43.39	0.0142**	0.0083	58.45	453.82**	195.27	43.03
0.5–0.6	2.12**	0.99	46.90	0.36**	0.200	56.12	0.0075**	0.0034	45.33	494.58**	246.38	49.82
0.6–0.7	1.56*	0.45	29.88	0.20*	0.059	29.50	0.0031*	0.0009	29.03	607.37*	180.45	29.71
0.7–0.8	0.83*	0.42	28.55	0.14*	0.037	26.43	0.0019*	0.0005	26.32	701.89*	181.23	25.82
For summer sowing												
0.0–0.1	44.28*	8.34	18.83	2.66*	0.612	23.01	0.170*	0.0364	21.40	190.85*	45.27	23.72
0.1–0.2	32.78*	7.55	23.03	1.96*	0.488	24.90	0.097*	0.0276	28.44	258.44*	70.53	27.29
0.2–0.3	12.98**	4.33	33.34	0.93**	0.261	28.09	0.029*	0.0094	31.79	365.46**	121.26	33.18
0.3–0.4	8.60**	4.02	46.77	0.56**	0.165	29.17	0.015**	0.0069	46.00	414.54**	148.53	35.83
0.4–0.5	1.18*	0.45	38.08	0.19*	0.041	21.58	0.004**	0.0018	49.61	606.93**	216.49	35.67
0.5–0.6	0.63*	0.22	34.92	0.18*	0.041	22.78	0.003*	0.0012	43.30	825.98*	271.42	32.86

Note. PRWD – percentage of root weight distribution; RLD – Root length density; RMD – root mass density; SRL – specific root length, m g^{-1}; Duncan's for interannual matching in the data set for 2014–2024: * – $p < 0.05$; ** – $p < 0.01$.

For spring and winter rapeseed, as well as different types of mustard and radish root crops, the percentage of root system metric and biomass characteristics found at 50–80 cm depth, compared to the upper 0–20 cm layer, ranged from 1.8% to 10.3% depending on the year (Dharmasri et al., 1993; Gan et al., 2009; Čepulienė et al., 2013; Gao et al., 2017; Duff et al., 2020; Bublitz et al., 2022; Deus et al., 2022; Boter et al., 2023). In winter cruciferous crops, these values were toward the upper end of this range, while spring–summer types typically exhibited values at the lower end.

In oilseed radish, the average values for spring sowing ranged from 1.40–2.58% for biomass and 3.51–5.39% for metric traits. For summer sowing, corresponding values were slightly higher: 2.35–3.28% for biomass and 6.77–8.14% for metric traits. This suggests that oilseed radish maintains a relatively high proportion of root presence at deeper soil layers under both sowing dates when used as green manure. In view of findings by Han et al. (2016) and Hudek et al. (2022), this root distribution has a positive impact on improving agrophysical properties in the deeper active root zone of the soil.

It should also be emphasized that several observed features of the oilseed radish root system are highly beneficial in the context of green manure practices, particularly on soils requiring fertility improvement. It was found that the bulk of the root system (as indicated by the PRWD index) was concentrated within the top 30 cm of the soil profile for spring sowing, and within 20–30 cm for summer sowing. This distribution corresponded with the primary formation zone of the taproot (Figs 5, d–e, Figs 6, a–b).

According to the RLD index values and based on several studies using the Monolith Method (Talgre, 2013; Wahlström et al., 2015; Bublitz et al., 2022; Kemper, 2024), oilseed radish demonstrates a high level of spatial development in both horizontal and vertical directions within the soil profile. This is further supported by the R_{vsz} index (Table 4) and the data presented in Figs 3 & 4 (I, e–f). On average, oilseed radish ranks just below winter rapeseed in terms of dynamic values recorded across the 0–60 cm profile depth, with 18–25% lower values for spring sowing and 27–37% lower for summer sowing.

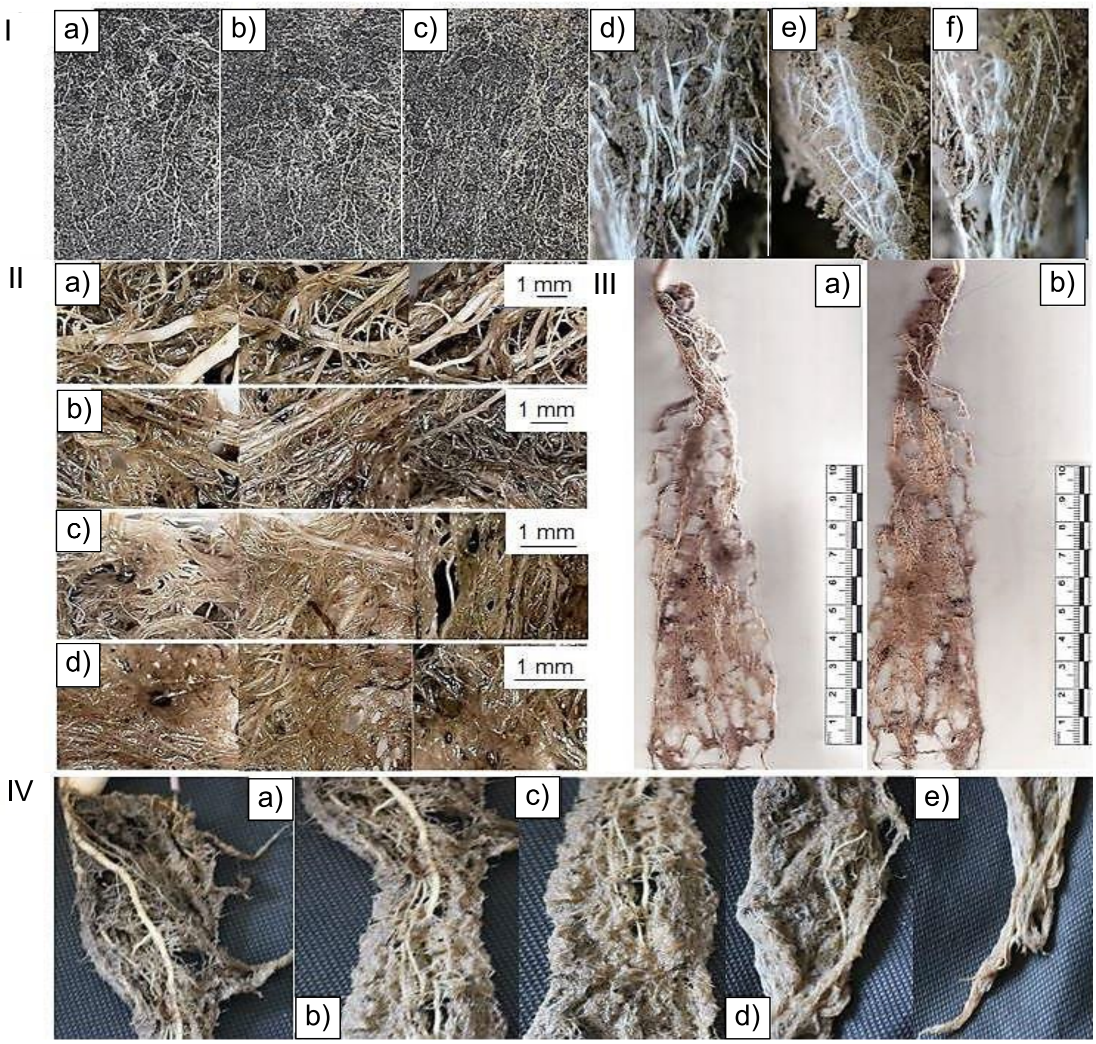

Figure 6. Spatial branching features of the oilseed radish root system at different sowing dates. I: Vertical branching of the root system at the spring sowing date (a – 2014, b – 2019, c – 2022), and magnified views using a USB microscope (x200): d – 2014, e – 2019, f – 2022. II: Root system branches of 1st (a), 2nd (b), 3rd (c), and 4th (d) order after sequential washing (first and second columns – spring sowing; third column – summer sowing), 2024. III: Root systems of two plants washed from the 0–20 cm soil layer from two adjacent rows at the summer sowing date, 2023. IV: Sequential segmental parts of the oilseed radish root system washed from the soil profile at 10 cm intervals, from top (a) to bottom (f), under spring sowing, 2024.

The crop also exhibited intensive differentiation in the weight saturation of the soil profile, as indicated by the RMD index, which showed vertical variability with a coefficient of variation (C_v) of 62.87%. This vertical stratification by root biomass created a distinct zonation across the corresponding root branches, especially in terms of length and transverse diameter. This is clearly illustrated in Fig. 6 (position II), particularly in the summer sowing variant (Fig. 4, II, third column of images), and is further confirmed by SRL values. These values dropped to 600–900 m g^{-1} at limiting profile depths in spring and to 700–1,100 m g^{-1} in summer sowing - differences that were not statistically significant when oilseed radish was used as a sole-component cover crop (Kemper, 2024). Simultaneously, the formation of vertical root branches was observed, originating from the horizontal tier of lateral roots at a depth of 15–25 cm, with intensive penetration reaching 35–60 cm, particularly in the summer green manure variant (Fig. 5, a–b). As a result, when grown as a green manure on Grey Forest Soils, oilseed radish develops a vertical interaction gradient with the soil profile in the form of a 'channel' located along the taproot axis.

According to Yang et al. (2017), the diameter of this root channel can be equated to the average diameter of the taproot (r_{aver}), which was 5.67 mm for spring and 5.13 mm for summer sowing (Table 4), with an average vertical channel length of 17–25 cm and 14–18 cm, respectively. Following the recommendations of Kolb et al. (2012) and Han et al. (2016), an active zone should be considered around this channel, with a radius of at least 25% of the maximum horizontal length of lateral branches. This equates to 2–3 cm in spring sowing and 1.0–1.7 cm in summer sowing, based on the lateral branch spread observed in root profile wall maps (Fig. 5, a–b). The full vertical extent of this channel zone can reach 40–60 cm in spring sowing and 30–40 cm in summer sowing under green manure conditions.

An intensive diffuse zone, consisting of root branches with a pronounced reduction in diameter (morphometric tapering), forms around the central 'channel' zone (as shown in Fig. 6, sections II and IV). According to the conclusions of Hatano et al. (1988), Han et al. (2015), and Hudek et al. (2022), in the case of oilseed radish, this configuration is expected to actively contribute to the restoration of microporous soil structure - particularly under spring sowing conditions for green manure application. These findings support the presence of the so-called 'root drainage' effect in oilseed radish, previously observed in other green manure crops, as reported by Rosenfeld & Rayns (2010) and dos Santos Nascimento et al. (2021).

The spatial morphological and biomass distribution patterns of the oilseed radish root system described above were further confirmed through the analysis of root fresh mass accumulation during the dynamic growth phase of the plants. The growth models describing the formation of root fresh biomass followed a power function pattern in both spring (Fig. 7) and summer sowing variants (Fig. 8), demonstrating several clear trends.

First, the exponential and stepwise nature of development indicates a gradual increase in the growth rate of the root system's fresh mass, with uneven accumulation during the course of phenological development. Under spring sowing conditions, the average root biomass accumulation rate increased from 10.22 g m^{-2} day^{-1} (interannual C_v = 40.16%) during the 10–20 days after full germination, to 22.78 g m^{-2} day^{-1} (C_v = 45.75%) during the 40–50 day period, with the peak occurring in some years between 35–45 days.

For summer sowing, root biomass accumulation increased from 5.47 g m⁻² day⁻¹ (C_v = 41.90%) during the 10–20 day period to 12.85 g m⁻² day⁻¹ (C_v = 42.10%) in the 40–50 day window, with the peak shifted in some years to 25–40 days after full germination. As a result, the total root biomass accumulation under spring versus summer green manure sowing averaged a 1.5:1 ratio (Figs 5–6, a). Under moisture-deficient years, this ratio increased to 3:1, while in years with excessive moisture, it was 1.8:1 (Figs 7–8, b–c).

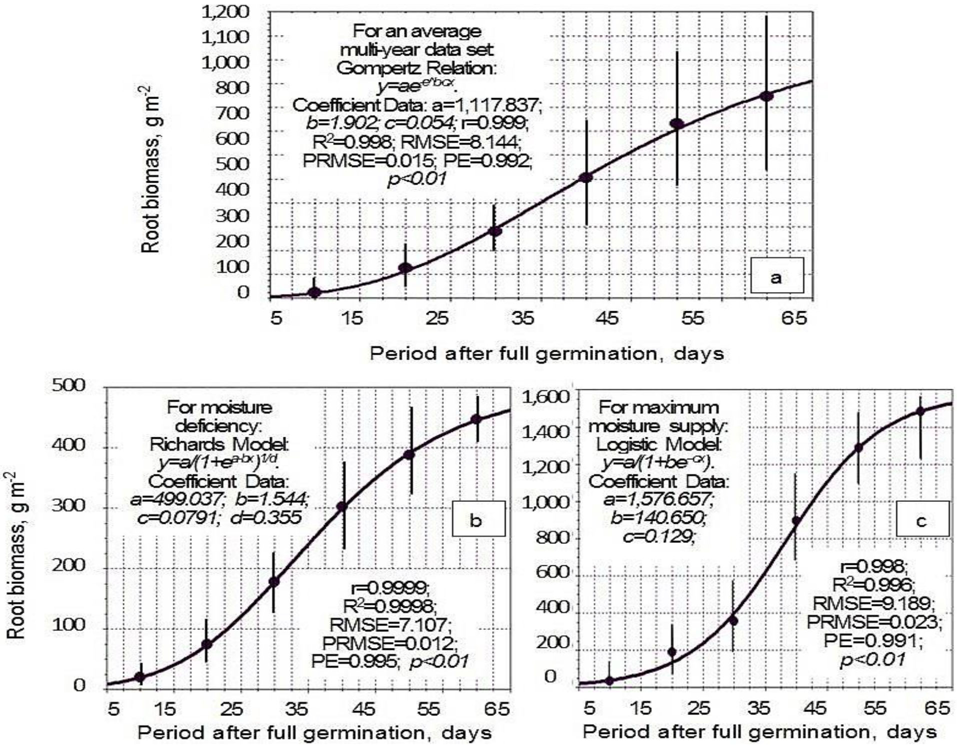

Figure 7. Functional patterns of oilseed radish root fresh weight formation under spring sowing: (a) long-term average data; (b) years with moisture deficit; (c) years with excessive moisture. Vertical lines represent standard deviation (SD). Data averaged for the period 2014–2024.

It was also found that the variability of root biomass measurements across the sampling dates (based on standard deviation) was, on average, 43.5% higher in the summer sowing period compared to spring sowing. Additionally, notable differences were observed in the mathematical models describing root biomass accumulation. In the case of spring sowing, the growth was best described by exponential models such as Gompertz, Richards, and Logistic functions, which, as noted by Tjørve & Tjørve (2017), are characterized by a gradual decline in growth rate around 55–60 days after full germination. In contrast, during summer sowing, root biomass accumulation followed classical power functions, with sustained dynamic growth beyond the 55–60 day threshold. Taking into account the previously determined peak aboveground biomass accumulation in oilseed radish under green manure conditions - 42.38 g m⁻² day⁻¹ for spring sowing and 32.00 g m⁻² day⁻¹ for summer sowing during the critical 40–50 day period after germination (Tsytsiura, 2024b) - the average value of the CRP_{DM} (Coefficient of Root Productivity in DM) over the full study period was 1.86 for spring and 2.49 for summer sowing. According to this indicator, oilseed radish belongs to the same productive niche as other cruciferous green manure crops such as mustard and rapeseed (Dupuy et al., 2010; Feller et al., 2015; Kupcsik et al., 2021; Kemper, 2024; Tsytsiura, 2024a). This confirms the existence of an ecologically adaptive mechanism characterized by the dominance of aboveground biomass growth rates over root biomass accumulation.

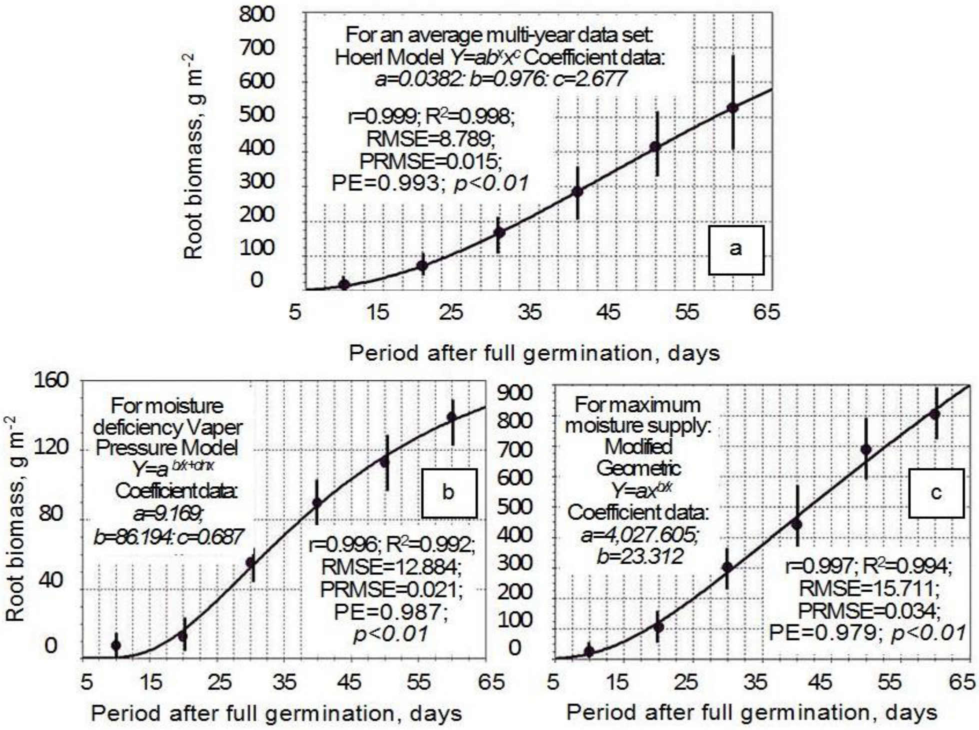

Figure 8. Functional patterns of oilseed radish root fresh weight formation under summer sowing: (a) long-term average data; (b) years with moisture deficit; (c) years with excessive moisture. Vertical lines indicate standard deviation (SD). Data averaged for the period 2014–2024.

Determinant Factors of Root Sidereal Bioproductivity. This finding is supported by the results of correlation analysis (Table 5) and is particularly valuable in the context of using oilseed radish as a cover crop for intermediate sowing periods (summer, autumn) followed by green manuring. The importance of this mechanism in selecting appropriate green manure species has been emphasized in several studies (Duff et al., 2020; Dzvene et al., 2023; Kemper, 2024; Zhang et al., 2024a).

At the same time, the high interannual variability of the morphological and biomass characteristics of the oilseed radish root system - ranging from 18% to 60% (Table 5), with maximum variation observed in the 40–60 cm soil horizon for spring sowing and in the 20–40 cm horizon for summer sowing - confirms the significant influence of environmental and edaphic factors on the morphological and biomass development of the root system. This conclusion is further supported by correlation analysis of the main parametric indicators of oilseed radish root bioproductivity, which takes into account soil properties and conditions, as well as hydrothermal parameters of the growing season, using an integrated dataset for the 2014–2024 period (Table 2). According to the coefficient of determination of correlation strength (d_{xy}), it was established that the total plant bioproductivity, represented by the share of root biomass yield (RBY), under spring sowing conditions for green manure, was directly determined by several key factors. Specifically, RBY was explained by: 77.44% by the total precipitation during the growing season prior to green manuring, 65.61% by soil moisture reserves (WRS), 81.00% by root length density (RLD), 96.04% by root mass density (RMD), 86.49% by specific root length (SRL), 94.01% by the average diameter of the core part of the root (d_{aver}), 68.89% by root system volume (V_{root}), 59.29% by the volume of the root spreading zone (R_{vsz}), 73.96% by the fractal dimension of the root system.

Table 5. Pearson's correlation coefficients for the relationship between oilseed radish root morphological and bioproductivity parameters and the hydrothermal conditions of the growing season and soil properties (combined dataset by sowing dates-replicates-years, 2014–2024; N = 88)

	2	3	4	5	6	7	8	9	10	11	12	13	14
Spring sowing													
1	-0.14	-0.94	0.97	0.88	-0.84	0.89	0.82	0.21	0.92	-0.51	0.73	0.51	0.85
2		-0.01	-0.12	-0.39	0.37	-0.27	-0.34	0.37	-0.25	0.55	-0.34	-0.43	-0.46
3			-0.87	-0.76	0.86	-0.77	-0.73	0.27	-0.80	0.40	-0.60	-0.51	-0.77
4				0.81	-0.83	0.81	0.77	-0.36	0.83	-0.46	0.59	0.57	0.81
5					-0.71	0.90	0.98	0.93	0.97	-0.41	0.83	0.77	0.86
6						-0.78	-0.55	-0.70	-0.76	0.30	-0.59	-0.34	-0.76
7							0.82	0.55	0.97	-0.72	0.86	0.71	0.93
8								0.02	0.90	-0.78	0.74	0.63	0.84
9									0.43	0.02	0.41	0.65	0.40
10										-0.69	0.90	0.43	0.91
11											-0.55	-0.39	-0.81
12												0.18	0.73
13													0.63
Summer sowing													
1	-0.07	-0.72	0.68	0.64	-0.73	0.58	0.67	0.12	0.53	-0.31	0.77	0.42	0.71
2		0.68	-0.54	-0.44	0.44	-0.51	-0.45	0.49	-0.21	0.17	-0.41	-0.48	-0.34
3			-0.75	-0.61	0.74	-0.61	-0.52	0.41	-0.34	0.40	-0.53	-0.59	-0.61
4				0.96	-0.69	0.60	0.52	-0.24	0.79	-0.29	0.83	0.45	0.96
5					-0.73	0.88	0.92	0.90	0.91	-0.22	0.87	0.63	0.82
6						-0.49	-0.22	0.04	-0.58	0.36	-0.65	-0.02	-0.72
7							0.52	0.04	0.18	-0.44	0.39	0.58	0.62
8								-0.48	0.34	0.23	0.34	0.52	0.56
9									-0.09	-0.31	0.22	0.51	0.52
10										0.03	0.83	-0.22	0.89
11											-0.12	0.01	-0.52
12												0.19	0.90
13													0.51

Level of significance for r = |0.209|–|0.264| $p < 0.05$; r = |0.265|–|0.328| $p < 0.01$; r = >|0.328| $p < 0.001$. 1 = Precipitation (Pr, mm); 2 = Average daily temperature (t_{av}, °C); 3 = Soil hardness (SH, kg cm^{-2}); 4 = Water reserves in the soil (WRS, mm); 5 = Root biomass yield (RBY, t ha^{-1}); 6 = Maximum root depth (z_r, cm); 7 = Root length density (RLD, cm cm^{-3}); 8 = Root mass density (RMD, mg cm^{-3}); 9 = Specifc root length (SRL, m g^{-1}); 10 = Average diameter of the core part of the root (d_{aver}, mm); 11 = Taperiness; 12 = Volume of the root system (V_{root}, cm^3); 13 = Volume of root spreading zone (R_{vsz}, x10^3 cm^3); 14 = Fractal dimension of the root system (FD).

Conversely, the reverse (negative) influence on the RBY index was associated with: 15.21% by average daily temperature (t_{av}), 75.69% by soil hardness (SH), 50.41% by maximum root depth (z_r), and 16.81% by the Taperiness Index.

Under summer sowing conditions, although the nature of the relationships between RBY and the explanatory variables remained consistent, the overall strength of these relationships - reflected in the determination coefficients - was on average 11.7% lower than in the spring sowing scenario. This indicates that the general decline in hydrothermal optimality due to increasing aridity during the summer-autumn growing season has a mitigating (depressive) effect on oilseed radish bioproductivity. These results are in positive agreement with the findings reported by Fletcher et al. (2015), Jabbari et al. (2016), Dayoub et al. (2022), and Shoaib et al. (2022).

For the main indicators of oilseed radish root system development - namely, root length density (RLD) and root mass density (RMD) - the determination coefficients for direct dependence on precipitation ranged from 67.24% to 79.21% for spring sowing and from 33.64% to 44.89% for summer sowing. In contrast, the relationship with average daily temperature was inverse, with determination values of 7.29–11.56% for spring and 20.25–26.01% for summer sowing. At the same time, the strength of the correlation ($d_{x\gamma}$) with precipitation was weak for both sowing dates (1.44–4.41%), while the relationship with average daily temperature was of medium strength (13.69–24.01%). Based on this, and considering the nature of the SRL (specific root length) calculation, the root mass density (RMD) indicator exhibits a stronger hydrothermal response than the root length density (RLD) indicator. This suggests that oilseed radish maintains stable rates of linear and fractal root system development under varying hydrothermal conditions, with more substantial reductions or increases occurring in the mass of lateral root branches depending on the behavior of individual SRL components.

Such a trend highlights the adaptive capacity of oilseed radish to intensify root branching despite a reduction in total root mass, particularly under increased precipitation or elevated average daily temperatures. This is further confirmed by the degree of determination of RLD, RMD, and SRL in relation to the fractal dimension (FD) of the root system, which ranged from 16.0% to 86.49% in spring and 27.04% to 38.44% in summer sowing. These findings are consistent with the conclusions of Kashyap et al. (2022), who described the adaptive potential of wild cruciferous species, and Jabbari et al. (2016), who studied root development response to drought in rapeseed. Thus, the existence of an adaptive mechanism in oilseed radish has been confirmed - allowing for the maintenance of root system development rates even under increasing environmental repressiveness during the growing season.

It was also found that the intensity of root system development in oilseed radish (as indicated by RLD and RMD) is significantly influenced by soil hardness (SH) and soil water reserves (WRS). An inverse relationship with soil hardness was observed, with determination coefficients ($d_{x\gamma}$) ranging from 53.29% to 59.29% for spring sowing and from 27.04% to 37.21% for summer sowing. For soil water reserves, the relationship was direct, with $d_{x\gamma}$ values of 52.29% to 65.61% in spring and 27.04% to 36.00% in summer.

In the case of specific root length (SRL), increased soil density was associated with an increase in SRL, while higher soil moisture reserves led to a decrease. The relatively moderate levels of these dependencies indicate a heterogeneous influence of soil moisture and density on the formation of RLD and RMD parameters when considered independently. This further confirms the adaptive nature of root system development dynamics in oilseed radish in response to combined changes in hydrothermal vegetation conditions and the physical and hydrological characteristics of the soil regime.

This is further supported by the strong relationships between these soil parameters and such indicators as root system volume (V_{root}) and root spreading zone volume (R_{vsz}), with $d_{x\gamma}$ values ranging from 26.01% to 36.00% in spring and 28.09% to 68.89% in summer sowing, all showing the same directional trend. Taking into account the findings of Fan et al. (2016), Bucksch et al. (2017), Boter et al. (2023), and Colombi et al. (2024), the observed discrepancy between the factor-based determination of RLD and RMD highlights a functional elasticity and plasticity in root system formation. This plasticity occurs in response to both hydrothermal variability and changes in soil water and mechanical properties, including those driven by weather conditions.

According to the ratio of the sum of the absolute values of correlation coefficients (as per Snecdecor & Cochran, 1991), which was 1.23 for spring and 1.11 for summer sowing, it can be inferred that the morphometric traits of the root system are less adaptive than its biomass-related traits in response to environmental and edaphic factors. As a result, under increasingly stressful environmental conditions - primarily related to moisture availability and soil compaction - a more pronounced reduction in the linear dimensions and spatial distribution of the root system in the soil profile can be expected compared to reductions in root biomass. This conclusion is supported by comparative data on the distribution of roots in the soil profile under spring (Fig. 6, a) and summer (Fig. 6, b) sowing conditions.

Regarding temperature influence, it is important to consider that air temperature and soil temperature often differ significantly, with soil functioning as a buffering medium that mitigates extreme temperature fluctuations, thereby reducing the negative impact of thermal stress on plant root system development (Kaspar & Bland, 1992; Calleja-Cabrera et al., 2020; Gavelienė et al., 2022; Yamori et al., 2022; González-García et al., 2023). Under this premise, the relationship between average daily temperature (t_{av}) and root biomass yield (RBY) in oilseed radish showed a consistent inverse correlation, with a moderate strength of association as indicated by determination coefficients ($d_{x\gamma}$) ranging from 15.21% to 27.36% – similar to trends observed in other root system parameters. This suggests a higher temperature tolerance in oilseed radish compared to white mustard (Amgain & Sharma, 2021), spring rapeseed (Čepulienė et al., 2013), and even winter rapeseed (Jabbari et al., 2016).

At the same time, the effect of hydrothermal conditions on the maximum root depth (zr) demonstrated that the oilseed radish root system exhibits adaptive deepening under conditions of soil moisture deficit - itself driven by reduced precipitation and increased air temperatures. This is reflected in the direct relationship between z_r and average daily temperature ($d_{x\gamma}$ = 13.69% for spring and 19.36% for summer sowing), and the inverse relationship with total precipitation ($d_{x\gamma}$ = 53.29% for spring and 70.56% for summer sowing). Based on these results, the root system of oilseed radish shows clear signs of moisture tropism, a phenomenon previously reported by Koch et al. (2018) and Fonseca de Lima (2021). Specifically, the plant forms a more compact root system under sufficient soil moisture and moderate air temperatures, and a more diffuse, deeper-penetrating system under conditions of moisture stress and rising temperatures. This functional plasticity allows oilseed radish to perform effectively as a green manure crop under unstable moisture conditions, particularly in intermediate (summer-autumn) sowing systems - in line with the hydrothermal adaptability criteria described by Calleja-Cabrera et al. (2020).

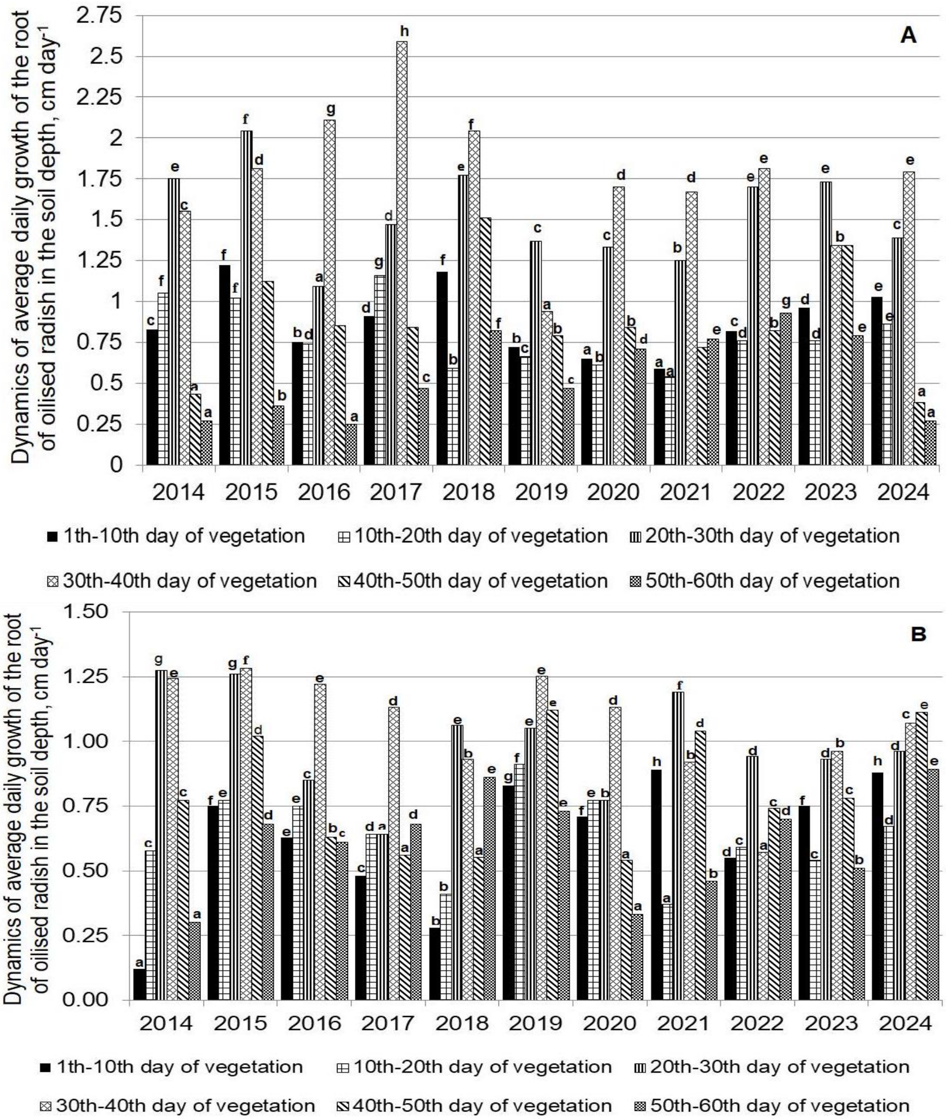

Figure 9. Dynamics of average daily root system growth in depth for oilseed radish over ten 10-day intervals during a 60-day vegetation period (A – spring sowing period; B – summer sowing period), 2014–2024.

Note: Different letters indicate values that differ significantly from one another ($p < 0.05$).

The established pattern of maximum root depth (z_r) formation in oilseed radish was further confirmed and clarified through an assessment of the dynamics of average daily root system elongation over ten 10-day accounting intervals during a 60-day vegetation period (Fig. 9). The maximum average daily root growth in depth was recorded during the 30–40 day interval prior to green manure incorporation for both the spring sowing variant (Fig. 9, A) and the summer sowing variant. For spring sowing, the peak growth rate was 1.80 cm day^{-1}, while the overall average across all periods of observation was

1.07 cm day^{-1}. For summer sowing, these figures were 1.06 cm day^{-1} and 0.79 cm day^{-1}, respectively. The lowest growth rates for both sowing periods were recorded during the 1–20 day and 50–60 day intervals, ranging from 0.46 to 0.61 cm day^{-1}.

Based on these indicators, oilseed radish demonstrates a high-intensity rooting process, which, when compared with long-term research and species-level generalizations (Dharmasri et al., 1993; Morrison, 1993; Laghari et al., 2014; White, 2015; The Biology of *Brassica napus* L. (2017); Wu et al., 2020; The Biology of *Sinapis alba* L. (2022); Kemper et al., 2024; Zhang et al., 2024a), corresponds to the upper limit of root growth rates typical for cruciferous crops with a spring development cycle. It is also important to note that the difference in average root system growth in depth between the two sowing periods was significantly influenced by hydrothermal conditions across the study years. In particular, for spring sowing, the most moisture-deficient years were 2017, 2015, and 2018 (Table 2). In those years, the average daily root elongation rates were 1.32 cm day^{-1}, 1.26 cm day^{-1}, and 1.19 cm day^{-1}, respectively, all exceeding the general average of 1.07 cm day^{-1} for the spring sowing period (Fig. 9, A). By contrast, in years with optimal or excessive moisture (e.g., 2014 and 2019), the root growth rate was 15.8% to 43.7% lower. A similar trend was observed under summer sowing conditions, confirming the inverse relationship between moisture availability and depth-wise root elongation in oilseed radish.

During the studied period, the years 2015, 2019, and 2021 were identified as moisture-deficient based on the average daily root growth rates for summer sowing, which reached 0.96 cm day^{-1}, 0.98 cm day^{-1}, and 0.81 cm day^{-1}, respectively (Fig. 9, B), compared to the overall average of 0.79 cm day^{-1}. In contrast, during years with optimal or excessive moisture supply (e.g., 2017 and 2022), the same indicator was 10.6% to 31.0% lower. This pattern can be attributed to the adaptive response of the plant root system to soil moisture stress, for which the root architecture functions as the primary compensatory mechanism.

Numerous studies (Schenk & Jackson, 2002; Guswa et al., 2012; Fan et al., 2017; Wu et al., 2018; Maan et al., 2023; Tomobe et al., 2023; Wankmüller et al., 2024) have shown that the spatial development of root systems is closely tied to the level of soil water reserves and to the dynamics of moisture retention and release in accordance with the agrophysical and hydrological properties of specific soil types (De Baets et al., 2008; Thomas et al., 2020). Furthermore, it has been well documented (Fan et al., 2017; Ni et al., 2019; Guo et al., 2023; Maan et al., 2023) that root elongation ceases when soil moisture declines below a critical osmotic threshold. Under conditions of increasing average daily temperatures combined with prolonged precipitation deficits, soil moisture is depleted more rapidly. According to several studies (Allen et al., 1998; Feddes & Raats, 2004; Gerke & Kuchenbuch, 2007; Leenaars et al., 2015; Kou et al., 2022; Guo et al., 2024), this leads to the formation of a gradient boundary between moist and critically dehydrated soil layers, which gradually deepens as drought stress persists - especially under elevated air temperatures. In perennial species and in annuals with drought-adaptive mechanisms, this stress response often results in the development of thinner, more finely branched root structures (Berntson, 1997; Dong et al., 2018), thereby increasing the absorptive surface area of the root system. This morphological shift acts as a compensatory mechanism for diminished moisture availability and has been widely observed in perennials (Faye et al., 2019; Zhang et al., 2019), cereals (Wasson et al., 2012; Zhang et al., 2020; Li et al., 2022), and various herbaceous species (Liu et al., 2020; Parkash et al., 2021; Guo et al., 2024). It is also considered a key trait in breeding programs for drought tolerance (Wasson et al., 2012; Dayoub et al., 2022; Guo et al., 2024), including in cruciferous crops such as rapeseed (Jabbari et al., 2016).

Given the higher values of maximum root depth (z_r) (Table 3) and the increased rate of root system elongation in moisture-deficient years (Fig. 9, A, 9, B), oilseed radish can be classified as a crop with this adaptive trait. This supports its high potential for use as a green manure crop, especially under intermediate summer sowing conditions with variable moisture availability. One important remark should be made regarding specific root length (SRL): under summer sowing, SRL values in the range of 700–1,100 m g^{-1} (Table 4) indicate a pronounced stress response in the deepest soil horizons, where the fine root branches may have reduced water transport capacity - a pattern consistent with findings by Schenk & Jackson (2002), Feddes & Raats (2004), and Ni et al. (2019). This limitation is indirectly supported by the observed distribution patterns of the root system in the soil profile (Fig. 5, a, b) and further confirmed by the observations of Kemper (2024). Taking into account the findings of Mcmichael & Quisenberry (1993), Bengough (2003), Cutforth et al. (2013), Jabbari et al. (2016), Cavalieri-Polizeli et al. (2022), Deus et al. (2022), Lynch et al. (2022), Duan et al. (2023), Carvalho et al. (2024), and Colombi et al. (2024), the established patterns and correlations clearly support the effectiveness of the adaptive strategies employed by oilseed radish in root system formation to ensure its long-term viability as a green manure crop. The summarized results above are logically integrated into a system of regression equations that incorporate both hydrothermal conditions during the vegetation period and key soil properties, as presented in Table 6.

In particular, it was statistically confirmed (based on the Chaddock scale, 1925) that precipitation during the growing season prior to green manure incorporation plays a direct formative role, while average daily air temperature has an inverse formative role in shaping key root system parameters (RBY, RLD, RMD, and FD). This relationship was reflected in a mean multiple regression coefficient (R) of 0.783, with an adjusted R^2 of 0.667 ($p < 0.001$), indicating a moderate but statistically significant relationship. Likewise, the direct effect of soil water reserves (WRS) and the inverse effect of soil hardness (SH) were statistically validated for the same indicators, with a mean regression coefficient of 0.790 and an adjusted R^2 of 0.670 ($p < 0.001$). The most stable model was identified in the three-factor combination of precipitation (P), soil hardness (SH), and water reserves in the soil (WRS), which collectively influenced the main morpho- and bioproductivity parameters of the root system. This model exhibited a multiple regression coefficient of 0.890, with an adjusted R^2 of 0.746 ($p < 0.001$) – indicating a strong relationship.

It is worth emphasizing that the polynomial (degree-based) character of the second- and fourth-order models supports the conclusion that these factors function in a complementary manner, governing the bioproductivity potential of oilseed radish root system development under green manure use. This also points to the existence of adaptive regulatory mechanisms that enable plants to buffer or compensate for adverse environmental conditions, thereby facilitating the realization of their genotypic potential.

Table 6. Regression relationships describing the intensity of oilseed radish root system development as a function of hydrothermal vegetation conditions and selected soil characteristics (average data for 2014–2024)

Qualitative indicator	Equation of dependence	Parameters of the equation: x	y	z	Statistical evaluation of components: Multiple *R*	Multiple $R^2_{(adj.)}$	*F*	*df1, df2*	*p*
SH	7.37-0.04*x*+1.67*y*	Precipitation (Pr, mm)	Average daily temperature (T_{av}, °C)		0.892	0.774	37.039	2.190	< 0.0001
WRS	156.60+0.32x-8.35y				0.891	0.773	36.785	2.190	< 0.0001
RBY	17.09+0.027x-1.09y				0.854	0.751	25.891	2.190	< 0.001
RSPD	132.71-0.087x-3.55y				0.700	0.436	9.119	2.190	< 0.05
RLD	2.82+0.005x-0.164y				0.735	0.622	11.163	2.190	< 0.01
RMD	0.132+0.00018x-0.0069y				0.682	0.519	8.269	2.190	< 0.05
SRL	143,23+0.286x+8.492y				0.603	0.545	4.892	2.190	< 0.05
V_{root}	35.14+0.067x-1.037y				0.730	0.483	10.803	2.190	< 0.01
R_{vsz}	249.96+0.33x-16.96y				0.540	0.320	3.926	2.190	< 0.05
FD	1.06+0.00091x-0.039y				0.861	0.763	27.114	2.190	< 0.001
RBY	-1.99-0.0084x+0.086y	Soil hardness (SH, kg cm^{-2})	Water reserves in the soil (WRS, mm)		0.859	0.682	26.950	2.190	< 0.01
RSPD	108.21-1.153x-0.236y				0.556	0.309	3.687	2.190	< 0.05
RLD	0.577-0.017x+0.012y				0.727	0.618	11.623	2.190	< 0.01
RMD	0.005-0.00011x+0.00058y				0.690	0.589	8.612	2.190	< 0.05
SRL	260.54+1.516x+0.474y				0.597	0.318	3.125	2.190	< 0.05
V_{root}	16.34+0.043x+0.17y				0.706	0.550	10.436	2.190	< 0.01
R_{vsz}	83.64-3.173x+0.566y				0.582	0.347	6.477	2.190	< 0.05
FD	0.381-0.00069x+0.003y				0.885	0.790	34.107	2.190	< 0.0001
Qualitative indicator	Equation of dependence	x	y	z	Multiple *R*	Multiple $R^2_{(adj.)}$	*F*	*df1, df2*	*p*
RBY	$-12.41-0.022x+1.504y-0.103z+0.00001x^2-0.027y^2+0.0011z^2$	Precipitation (Pr, mm)	Soil hardness (SH, kg cm^{-2})	Water reserves in the soil (WRS, mm	0.905	0.767	12.461	6.150	< 0.0001
RSPD	$293.71-0.40x-11.91y+0.009z+0.0004x^2+0.20y^2+0.0001z^2$				0.807	0.609	8.196	6.150	< 0.05
RLD	$-3.47+0.005x+0.228y-0.014z-0.0001x^4-0.0001y^4+0.0001z^4$				0.930	0.811	15.989	6.150	< 0.0001
RMD	$-0.101+0.00012x+0.0065y-0.0001z-0.0001x^4-0.0001y^4-0.0001z^4$				0.828	0.684	8.971	6.150	< 0.01
V_{root}	$-5.01+0.00043+1.528y+0.02z+0.0001x^4-0.0002y^4+0.0001z^4$				0.845	0.648	9.128	6.150	< 0.01
FD	$0.289-0.00049x+0.0074y+0.0031z+0.000001x^4-0.000001y^4+0.000001z^4$				0.895	0.723	10.099	6.150	< 0.001
d_{aver}	$-5.07+0.005x+0.378y+0.0021z-0.000001x^4-0.000001y^4+0.000001z^4$				0.921	0.796	14.621	6.150	< 0.0001

These findings align with the conclusions of Gupta & Shrestha (2023) and Zhang et al. (2023a, 2025) concerning the adaptive potential of plant organisms in response to environmental variability.

The generalizations presented here are further supported by the environmental elasticity assessment of key parameters, as shown in Table 7. According to the coefficient of absolute elasticity (EA), the environmental factor of precipitation had a direct influence on the formation of root system productivity indicators in oilseed radish. When comparing spring and summer green manure sowing dates, the gradient of change in precipitation responsiveness was twice as high under summer sowing - 0.03 t ha^{-1} mm^{-1} versus 0.015 t ha^{-1} mm^{-1} for spring sowing. In contrast, average daily air temperature showed a pronounced inverse effect on the adaptive response of oilseed radish, with only minor differences between spring and summer sowing variants.

The average gradient of absolute elasticity under temperature influence indicated a decrease in fresh root biomass by 11.32 t ha^{-1} °C^{-1} and by 2.32 t ha^{-1} °C^{-1} in dry matter equivalent. Based on the ratio of these values, the dry matter content in root biomass was estimated at 20.46%, with a direct tendency to increase as average daily temperature rose. Taking into account the findings of several studies (Mohammadi et al., 2010; Ali et al., 2017), precipitation can be considered the decisive factor in the formation of oilseed radish root biomass, as indicated by the elasticity gradient expressed in biomass units over the evaluation period.

Table 7. Coefficients of phenotypic stability and elasticity in the formation of oilseed radish bioproductivity at the flowering stage (BBCH 64–67) across different sowing dates, 2014–2024

Indicators of bioproductivity		E_A	E_I	E_{II}
By the factor of precipitation (P, mm)				
Root biomass yield (RBY), t ha^{-1}	SprS	0.050	0.125	1.484
	SumS	0.024	0.059	1.125
Root biomass yield in dry matter (RBY_{DM}), t ha^{-1}	SprS	0.010	0.025	1.397
	SumS	0.005	0.013	1.060
By the factor of average daily temperature (t_{aver}, °C)				
Root biomass yield (RBY), t ha^{-1}	SprS	-11.576	-1.692	-20.021
	SumS	-11.067	-1.840	-34.995
Root biomass yield in dry matter (RBY_{DM}), t ha^{-1}	SprS	-2.283	-0.334	-18.851
	SumS	-2.350	-0.391	-32.961

*SprS – Spring sowing; SumS – Summer sowing.

Therefore, oilseed radish demonstrated a higher level of adaptability to insufficient moisture supply than to rapid increases in air temperature. This trait is positively correlated with the general characteristics of the root systems of cruciferous crops - particularly the compensatory response involving deeper rooting and increased branching under conditions of atmospheric and soil moisture deficit, as previously noted in the studies of Dharmasri et al. (1993), Gan et al. (2009), Jung et al. (2019), and Kupcsik et al. (2021).

These conclusions are further supported by the values of the relative elasticity coefficients of type I (EI) and type II (EII), which showed a significant increase compared to the absolute elasticity coefficient (EA), especially in response to precipitation. For type I elasticity, a reduction in environmental suppression of root development and biomass formation was observed under scenarios of increased precipitation accompanied by either rising or stable average daily temperatures. In contrast, when these environmental factors operated in opposition, they caused a marked decline in root system growth. Moreover, the significantly higher values of EII compared to EI point to the existence of flexible ecological mechanisms in the formation of the oilseed radish root system. This flexibility is evident in the fact that intensive environmental variation was met with a relatively low degree of variation in the resultant bioproductivity traits.

According to the findings of Jabbari et al. (2016), Konuntakiet (2020), and Colombi et al. (2024), the identified elasticity profile of oilseed radish root productivity indicators enables its classification among cruciferous cover crops with broad adaptive potential, particularly under suppressive and environmentally stressful hydrothermal conditions. The pivotal role of hydrothermal factors was further substantiated by the results of multiple regression and correlation analyses, which incorporated the De Martonne Aridity Index (I_{DM}) and the Vysotsky-Ivanov Humidification Coefficient (K_h), along with correlation analysis applied to both basic and derived indicators of oilseed radish root system bioproductivity (Table 8). The analysis confirmed the high sensitivity of root bioproductivity formation to climatic parameters, with: a positive formative effect of precipitation, with determination coefficients ($d_{x\gamma}$) ranging from 47.19% to 50.20%, an inverse effect of average daily temperature, with $d_{x\gamma}$ = 21.44–25.70%, a strong positive relationship with K_h, at $d_{x\gamma}$ = 57.30–65.45%, and a similarly high correlation with IDM, at $d_{x\gamma}$ = 47.75–51.12%.

All these relationships were integrated into a single multiple regression model, with high values of R and adjusted R^2, demonstrating strong statistical associations as defined by the Chaddock scale (1925). Furthermore, the observed dry matter content in root biomass is consistent with findings by Liu (2009), Hudek et al. (2022), and Kemper (2024), which indicate that the aridization of the growing season leads to increased dry matter content in both aboveground and root biomass of green manure crops. This is attributed to increased salinity in physiologically active tissues and the intensification of biochemical transformations under drought-related stress.

The dry matter content in the root biomass of oilseed radish is consistent with the findings of Liu (2009), Hudek et al. (2022), and Kemper (2024), who reported that seasonal aridization increases dry matter accumulation in both aboveground and root components of green manure crops. This is attributed to changes in the salinity of physiologically active tissues and the intensification of biochemical transformation processes under drought stress. Regarding the root system productivity coefficient in both fresh (CRPRM) and dry matter (CRPDM), the observed results are in line with the studies by Thornley (1972), Bláha (2019), and Lopez et al. (2023). These authors emphasized that the ecological adaptation of plants, reflected in the ratio between the development of aboveground and root biomass, is closely linked to the climatic conditions of a given environment.

Table 8. Correlation and regression relationships between oilseed radish root system bioproductivity indicators and hydrothermal vegetation regimes (average data for 2014–2024; N = 88)

Qualitative indicator	Equation of dependence	Parameters of the equation			Statistical evaluation of components				
		x	*y*	*z*	Multiple *R*	Multiple $R^2_{(adj.)}$	*F*	*df1*, *df2*	*p*
RBY	$17.335+0.097x-0.994y-20.916z-0.0001x^2-0.0056y^2+10.073z^2$	Precipitation (mm)	Average daily temperature, (°C)	K_h	0.907	0.751	11.54	2.19	< 0.001
RBY_{DM}	$1.931+0.019x-0.015y-4.290z-0.00002x^2-0.0074y^2+2.029z^2$				0.874	0.670	8.10	2.19	< 0.001
RBY	$19.728+0.062x-1.006y-0.492z-0.00008x^2+0.00085y^2+0.0072z^2$	Precipitation (mm)	Average daily temperature, (°C)	I_{DM}	0.914	0.769	12.62	2.19	< 0.001
RBY_{DM}	$3.318+0.011x-0.099y-0.094z-0.000014x^2-0.0027y^2+0.0013z^2$				0.872	0.665	7.94	2.19	< 0.001

Correlation pairs	1	2	3	4	5	6
Total formed plant biomass in raw matter (RM), t ha^{-1}	0.78	-0.47	0.29	0.65	0.83	0.78
Total formed plant biomass in dry matter (DM), t ha^{-1}	0.75	-0.41	0.31	0.56	0.75	0.66
RBY, t ha^{-1}	0.71	-0.51	0.15	0.61	0.81	0.72
Dry matter content in biomass of root, %	-0.52	0.60	-0.32	-0.42	-0.68	-0.65
RBY_{DM}, t ha^{-1}	0.69	-0.46	0.22	0.58	0.76	0.69
The coefficient of root system productivity in raw matter (CRP_{RM})	-0.40	0.41	-0.36	-0.28	-0.42	-0.41
The coefficient of root system productivity in dry matter (CRP_{DM})	-0.45	0.49	-0.31	-0.36	-0.53	-0.47
Share of root residues in total dry plant biomass (SRR_{RM}), %	0.31	0.17	0.38	0.20	0.25	0.31
Share of root residues in total dry plant biomass (SRR_{DM}), %	0.48	0.21	0.44	0.26	0.32	0.42

Significance for r = |0.209|–|0.264| $p < 0.05$; r = |0.265|–|0.328| $p < 0.01$; r =>|0.328| $p < 0.001$. Indicators: 1 = Precipitation (P, mm); 2 = Average daily temperature (T_{av}, °C); 3 = Average relative humidity (RH_{av}, %); 4 = HTC; 5 = I_{DM}; 6 = K_h.

As a result, under unfavorable environmental conditions, the formation rate of aboveground biomass tends to outpace root development, leading to an increase in the productivity coefficient of the root system (CRPRM and CRPDM) with increasing environmental repressiveness. This pattern was also confirmed for oilseed radish. As shown in Table 5, the average $d_{x\gamma}$ values for most parameters included in the analysis were 19.72% higher compared to the same dependencies for root biomass formation alone. However, it should also be emphasized that oilseed radish demonstrates specific adaptive features compared to other cruciferous crops traditionally used as green manure. According to Jabbari et al. (2016), Singh et al. (2021), and Kashyap et al. (2023), the determining influence of precipitation and average daily temperatures in cultivated cruciferous species exceeds 50–60% and 30–43%, respectively, whereas wild cruciferous species exhibit nearly half these values. Based on this, oilseed radish displays valuable ecological adaptations characteristic of highly adaptive wild cruciferous forms, as reflected in the determined dependency levels. This supports its recommendation for use in green manure systems under high-risk or environmentally unstable conditions, in agreement with Tsytsiura (2024c).

CONCLUSIONS

It has been proven that under conditions of unstable moisture supply (during the research period, the coefficient of variation (Cv) for the hydrothermal coefficient (HTC) was 42.84%, Cv for the De Martonne Aridity Index (IDM) was 38.32%, and Cv for the Vysotsky-Ivanov Humidification Coefficient (Kh) was 38.92%), on soils with medium fertility (Greyi-Luvic Phaeozems with humus content of 2.68%) and without the application of mineral fertilizers, oilseed radish exhibits high root mass bioproductivity. This was observed under both spring and summer sowing conditions, amounting to 8.45 and 5.26 t ha^{-1} in fresh weight and 1.77 and 1.19 t ha^{-1} in dry matter, respectively. The average long-term root system productivity coefficient was 1.86 for spring sowing and 2.49 for summer sowing.

It was established that oilseed radish, during its short sidereal growth period, formed a root system with branching up to the fourth order. The maximum vertical penetration in the multi-year average was observed in the 40–60 cm interval, while radial spread was in the 15–25 cm range, with the highest diffuse branching of the third and fourth orders occurring at depths of 10–30 cm. The developed root morphometry, in comparison to other cruciferous green manure crops, corresponded to an adaptive drainage morphotype, valued for its positive impact on soil agrophysical properties. The long-term average parameters were as follows: average diameter of the taproot – 5.67 mm (spring sowing) / 5.13 mm (summer sowing), taperiness – 0.55 / 0.66, root volume (Vr) – 39.09 / 26.92 cm^3, root spread zone volume (Rvsz) – 66.39 / 36.75×10^3 cm^3, fractal dimension of the root system (D) – 0.73 / 0.63, maximum rooting depth (zr) – 64.41 / 47.36 cm, and the ratio of total root mass to the mass formed in the 0–30 cm soil layer (Rm(z)) – 0.77 / 0.79.

It was found that the bioproductivity of oilseed radish's root system, based on both primary and derivative parameters, was influenced by the following factors in order of increasing effect for spring sowing: average daily temperature (tav) – soil hardness (SH) – soil water reserves (WRS) – precipitation during the vegetation period (P). For summer sowing, the sequence was: average daily temperature (tav) – soil hardness

(SH) – total precipitation during the vegetation period (P) - soil water reserves (WRS). A direct relationship was identified between key parameters of spatial morphological development of the root system (RMD, RLD, FD) and precipitation sum, while an inverse relationship was observed with average daily air temperature (multiple regression coefficient: 0.667). A direct relationship was also found with water reserves in the soil (WRS) and an inverse one with soil hardness (SH) (multiple regression coefficient: 0.670). It was demonstrated that the root system of oilseed radish exhibits an adaptive mechanism of additional vertical and horizontal branching under conditions of moisture deficiency combined with rising average daily temperatures.

In the overall conclusion, the effectiveness and feasibility of using oilseed radish as a green manure crop for spring and summer (intermediate) sowing in monoculture in areas with unstable moisture supply and low soil fertility potential have been substantiated. The maximum realization of the root sidereal potential of oilseed radish is predicted to occur under conditions of adequate moisture, moderate thermal regime (climate zone Dfa/Dfb according to the Köppen–Geiger classification), and medium-textured soils with average fertility potential.

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