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Ecological adaptive tactics of oil radish root formation at different terms of green manure application

Yaroslav Tsytsiura[1]

[1] Vinnytsia National Agrarian University, Sonyachna St. 3, 21008 Vinnytsia, Ukraine
E-mail: yaroslavtsytsyura@ukr.net

ABSTRACT

Over an 11-year period, a comprehensive assessment of the bioproductivity of the root system of oilseed radish was carried out based on the basic indicators of morphospatial and fire distribution in the soil profile for two variants of sowing it as a 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 spatial development of the root system and ecological adaptive strategies of its formation. It has been determined that oil radish, according to the formation of morphological characteristics of the root system in a short period before use for green manure (40–50 days), belongs to highly productive cruciferous species with an achievable level of root biomass yield in dry matter of 1.19–1.77 t ha^{-1}. The active interaction of its root system with the soil profile 40–80 cm deep was established due to active branching to the fourth level and active diffuse spread of these branches in the radial and vertical directions. An adaptive mechanism for deepening the roots into the soil with a decrease in the moisture supply of the soil profile with an average increase in the depth of penetration in the range of 13–14 cm in comparison with conditions of sufficient or excessive moisture was proved. Based on the generalisation of the dynamics of oilseed radish root system formation in the soil profile, root maps with a comprehensive indication of the interaction of plant root systems for inter-row directions were formed. The direct dependence of the formation of indicators of bioproductivity of the root on the precipitation (determination 47.19–50.20%), moisture reserves in the soil (27.04–65.61%) and the inverse dependence on the average daily temperature (21.44–25.70%) and soil hardness (37.21–59.29%) was established.

Keywords: root maps, root biomass yield, root length density; root mass density; specific root length.

INTRODUCTION

The paradigm of crop fertilisation systems is changing both in terms of the gradual mainstreaming of circular green economy approaches and as a result of a pronounced shortage of organic fertilisers caused by the processing of livestock waste into biogas (Kaletnik et al., 2020; Lohosha et al., 2023). Such approaches have led to the search for an alternative to classical manure and mineral fertilisers through the use of green manure (Lutkovska and Kaletnik, 2020; Kucerik et al., 2024). Unfortunately, in the study of green manure efficiency, the main focus is on the study of factors that determine the quality and volume of the formed aboveground biomass (Razanov et al., 2021; Lohosha et al., 2025). Such approaches leave unexplained a number of important issues and processes of spatial morphometry of roots in the soil profile, which ensure the dynamism of aboveground mass formation, ecological adaptation of the respective species of green manure plants to changes in hydrothermal regimes of vegetation (Gentsch et al., 2024). The effective role of green manure should be considered both from the point of view of the direct influence of the formed aboveground biomass as a result of its transformation in the soil profile, and from the point of view of the influence of root biomass on the same processes. This influence is determined by assessing the peculiarities of the dynamism of root formation under different branching options, spatial distribution and others (Kemper, 2024). It has been determined that different types of green manure plants forming significantly different variants of the root system productivity coefficient, spatial morphometry and tropation within the thickness of the soil profile, vertical/radial growth and implementation of soil drainage effects, structuring, an increase in total porosity and total aeration of the soil profile (dos Santos Nascimento et al., 2021; Hudek et al., 2022; Gentsch et al., 2024). According to Pimentel et al. (2023), only a combined analysis guarantees the effectiveness and feasibility of green manure for various bioorganic crop cultivation technologies.

In this context, by different researchers emphasised that a green manure plant as the main component of the bioorganic cycle in the soil-plant-environment system should be considered in a single complex of dynamism of multidirectional processes of aboveground biomass formation in a mirror image of similar processes inherent in the root system (Bublitz et al., 2022; Hudek et al., 2022; Kemper, 2024).

Considering the above arguments, the aim of a long cycle of evaluations was to study the formation of the root system of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) from the point of view of the features of ecological adaptability, its spatial morphometry for terms of green manure use on grey forest soils.

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) with silty clay loamy texture. Weighted average soil fertility indicators: humus content: 2.68%, easily hydrolysable nitrogen 81.5 mg kg^{-1} of soil, mobile phosphorus 176.1 mg kg^{-1} of soil and exchangeable potassium 110.8 mg kg^{-1} of soil, pHcl 5.8. 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 decade of July with the flowering phase (BBCH 64–67) reaching the second decade of October.

The experimental plots were formed in quadruplicate by randomisation with a plot size of 25 m^2. The growth stage of plants was identified using standard BBCH scales. Accounting of the aboveground mass of plants was carried out at the flowering stage by the method of trial plots (1m^2) (4 in each replication, weighing on a laboratory balance (WALCOM LB3002 (± 0.01 g)). The dry matter (DM) content in the aboveground and root mass of plants was determined by drying to constant weight at 105 °C and ashing at 550 °C. The field analysis of bioproductivity and root morphogenesis was carried out at the flowering stage using a combination of Profile Wall and Monolith Method. Profile Wall Method: a trench was made approximately 1 m wide, across 6 rows of oilseed rape at the flowering stage (BBCH 64–67). The vertical wall across the rows was smoothed with a metal dust pan and a brush. The roots were exposed by removing a soil layer of about 1 cm thick by spraying water. A wooden marking frame (1 × 1 m with a 10 × 10 cm grid) was used to delineate the soil profile vertically. The length of the exposed roots was estimated by counting the number of root-length units of 0.5cm inside each grid. Based on this, was built root maps in a two-dimensional coordination system.

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 up to 10 plants in quadruplicate. Open-topped metal boxes with pointed edges (scoop type, 3 mm wall thickness) measuring 30 × 33.3 × 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 × 34 × 0.3 cm was used. This made it possible to compact the walls of the monolith. Each sampled micromonolith was labelled and packed in airtight 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. This analysis was accompanied by soil hardness (SH, kg cm^{-2}, Walcom FM-204TR penetrometer), soil moisture (W, %, Walcom MS-7828SOIL soil moisture tester) and bulk density (BD, g cm^{-3}, cylinder (core) method procedure. Water reserves in the soil (WRS, mm) were determined based on Equation 1.

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

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

Linear morphological parameters of the root were determined by direct measurement using an electronic caliper (Digital Caliper, Germany (± 0.01 mm)). The methodological approaches of Rouse (2019) were used to determine and approximate the root spreading zone of the root system according to the generated root maps.

Root biomass yield (RBY) and root system productivity (RSP) were calculated according to Atkinson and Dawson, 2000. Based on the root length and root mass obtained from the monolith samples, the following parameters were determined: root length density (RLD, cm cm^{-3}, Equation 2), root mass density (RMD, mg cm^{-3}, Equation 3) and specifc root length (SRL, m g^{-1}, Equation 4), percentage of root weight distribution (PRWD (in raw weight after 3 h normal air drying), %, Equation 5).

$$RLD = \frac{root\ length}{soil\ volume} \tag{2}$$

$$RMD = \frac{root\ dry\ mass}{soil\ volume} \tag{3}$$

$$SRL = \frac{root\ length}{root\ dry\ mass} \tag{4}$$

$$PRWD = \frac{RM\ SH}{RM\ SP} \times 100 \tag{5}$$

where: $RM\ SH$ – root mass for a specific soli horizon, $RM\ SP$ – root mass in the general soil profile

To analyse the patterns of distribution of oilseed radish roots in the soil profile were estimated using CurveExpert Professional v. 2.7.3 software (Hyams Development), RhizoVision Explorer 2.0.2 (Noble Research Institute, LLC, USA), electronic scanning and USB microscopy method (CanoScan LIDE 700F, Sigeta MCMOS 5100 5.1 MP).

The following indicators were used to analyse hydrothermal conditions (Table 1): average daily temperature (°C), precipitation (mm), relative humidity (%), hydrothermal coefficient (HTC) (Equation 6), De Martonne Aridity Index (IDM) (Equation 7), Vysotsky-Ivanov humidification coefficient (K_h) (Equation 8).

$$HTC = \frac{\sum R}{0.1 \times \sum t_{>10}} \tag{6}$$

where: ΣR – the sum of precipitation (mm) over a period with temperatures above 10 °C, $\Sigma t_{>10}$ – the sum of effective temperatures over the same period.

$$I_{DM} = \frac{12P_m}{T_m + 10} \tag{7}$$

where: P_m and T_m are the precipitation volume and mean air temperature in the corresponding month, respectively.

$$K_h = \frac{P}{E} \tag{8}$$

where: K_h – the moisture coefficient; P – the amount of precipitation for the analysed period, mm; E – the evapotranspiration for the analysed period, mm, calculated according to Equation 9.

$$E = 0{,}0018 \times (25 + t)^2 \times (100 - a) \tag{9}$$

where: for the analysed period: t – average air temperature, °C; a – average air humidity, %.

The basic indicators of variation statistics (standard deviation (SD), coefficient of variation (C_v) at $p < 0.05$ and $p < 0.01$) were used using Statistica 10 (StatSoft – Dell Software Company, USA). The data were analysed using the analysis of ANOVA. Correlation and regression analysis was performed according to the standard procedure using coefficient of determination (R^2), adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), relative root mean square error (RRMSE) and prediction efficiency index (PE), the coefficient of determination of the closeness of the correlation (d_{xy}, Equation 10):

$$d_{yx} = r_{ij}{}^2 \times 100 \tag{10}$$

where: r_{ij} is the correlation coefficient between the i-th and j-th indicator.

RESULTS AND DISCUSSION

The long-term study period with an interannual variation of precipitation at 33.78% and mean daily temperature at 17.55%, details the hydrothermal regime of the study period (according to Gardner et al, 2020) as

Table 1. Evaluation of hydrothermal regimes of the period of active vegetation of oilseed radish for the variant of summer and autumn sedimentation (zone Dfa/Dfb (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			
Spring sowing														
2014	339.6	13.84	0.725	45.7	1.18	3.928	88.9	2.11	1.545	34.8	0.83			
2015	142.3	14.36	0.645	37.3	0.78	0.917	20.6	0.41	0.715	16.9	0.27			
2016	193.4	15.06	0.296	21.6	0.44	0.489	40.4	0.99	1.265	29.9	0.75			
2017	125.1	14.07	3.919	39.2	0.75	0.777	16.8	0.34	0.504	11.9	0.22			
2018	170.8	16.38	0.290	10.8	0.19	0.308	7.2	0.12	4.404	103.7	2.31			
2019	398.5	15.39	0.565	33.5	0.72	4.902	111.0	3.29	1.682	41.4	0.96			
2020	343.8	13.67	0.091	36.4	0.50	5.327	106.4	3.18	1.548	37.3	0.89			
2021	282.8	13.26	0.233	38.8	0.96	3.125	66.7	1.64	1.679	39.8	1.00			
2022	242.1	14.30	0.563	57.4	2.33	1.430	31.3	0.79	1.496	36.1	0.85			
2023	239.8	14.18	1.543	91.5	3.33	0.085	1.90	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 (VII-X)	$^{*}t_{aver}$, °C (VII-X)	Months of the growing season											
			VII			VIII			IX			X		
			HTC	I_{DM}	K_h	HTC	I_{DM}	K_h	HTC	I_{DM}	K_h	HTC	I_{DM}	K_h
Summer sowing														
2014	250.8	15.4	1.312	32.7	0.77	1.049	26.0	0.51	1.252	25.7	0.56	1.770	35.8	0.93
2015	160.8	16.6	0.321	8.1	0.14	0.124	3.1	0.05	1.184	26.8	0.63	3.039	49.4	1.25
2016	212.7	15.6	1.056	26.5	0.55	0.898	22.0	0.43	0.014	2.5	0.05	0.548	63.4	2.45
2017	318.0	16.0	1.524	37.5	0.72	0.819	20.7	0.38	3.100	61.2	1.57	1.065	30.0	1.26
2018	273.4	16.4	2.158	53.4	1.63	0.585	14.6	0.30	1.378	27.2	0.71	0.873	27.6	0.95
2019	161.7	16.0	1.013	24.4	0.56	0.237	5.9	0.11	0.994	20.7	0.42	0.383	27.4	0.93
2020	245.4	17.6	0.589	14.7	0.31	0.527	13.2	0.22	0.859	27.5	0.54	2.544	60.6	3.05
2021	176.9	15.4	0.782	20.1	0.45	1.459	35.7	0.91	0.705	17.6	0.51	0.000	1.7	0.04
2022	436.6	16.0	0.900	22.4	0.58	1.712	43.1	1.06	4.960	98.1	2.60	3.167	51.4	1.50
2023	247.1	18.3	1.414	35.8	0.82	0.652	16.9	0.36	1.015	23.4	0.63	1.025	29.9	0.93
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

unstable (from extra-arid conditions against the background of an intensive increase in the average daily temperature (I_{DM} 2.5; K_h 0.05; HTC 0.014 (Table 2) to conditions of excessive moisture against the background of moderate temperatures (I_{DM} 111.0; K_h 3.29; HTC 4.902)). This made it possible to evaluate the ecological adaptation strategy of oilseed radish root system formation and indicators of its bioproductive potential (Table 2). According to the results of long-term assessments in different soil and climatic zones (Wong et al., 2024), the expediency of using a certain plant species as a cover crop for green manure and phytoremediation was determined, provided that the formation of aboveground phytomass in dry matter at the level of up to 1.5–2.0 t ha^{-1} and root mass at the level of 0.8–1.0 t ha^{-1} with a root system productivity coefficient of 1.8–2.0. Such values formed a sufficient level of plant sideration potential in terms of replenishing the soil with organic biomass, optimising its agrophysical and agrochemical properties, and provide the possibility of plant adaptation to the limiting hydrothermal factors of the territories, given the potential of the formed root systems (Wong et al., 2024). The presented results and previous estimates (Tsytsiura, 2024 a-c) on grey forest soils, whose fertility potential is assessed as medium, revealed an average long-term level of aboveground biomass of 23.68 t ha^{-1} in spring and 17.56 t ha^{-1} in summer sowing with interannual variation of 29.84% and 35.68%, respectively.

Table 2. Indicators of bioproductivity of oilseed radish in flowering stage (BBCH 64–67), 2014–2024

Indicators of bioproductivity		Year of the study											*$LSD_{0.5}$
		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	
Aboveground biomass yield (ABY), t ha^{-1}	SprS**	33.49	20.11	21.29	15.22	13.89	35.75	30.88	24.12	21.18	24.48	20.12	1.42
	SumS	22.21	9.49	21.05	23.79	23.12	10.11	11.29	16.22	24.77	21.39	9.77	1.24
Aboveground biomass yield in dry matter (ABY_{DM}), t ha^{-1}	SprS	4.10	2.84	3.02	2.09	2.10	4.03	3.93	2.85	2.81	3.20	2.71	0.23
	SumS	3.37	1.66	3.36	3.39	3.45	1.73	1.82	2.73	3.33	3.37	1.55	0.37
Root biomass yield (RBY), t ha^{-1}	SprS	13.28	7.88	6.22	4.47	3.39	14.85	13.02	9.57	7.44	6.87	5.97	1.09
	SumS	6.59	1.39	5.77	7.21	5.52	3.58	3.09	6.49	8.03	7.33	2.84	0.65
Root biomass yield in dry matter (RBY_{DM}), t ha^{-1}	SprS	2.71	1.82	1.35	1.02	0.81	3.07	2.58	1.83	1.60	1.45	1.23	0.25
	SumS	1.46	0.35	1.33	1.52	1.29	0.72	0.70	1.51	1.76	1.72	0.68	0.14
The coefficient of root system productivity in dry matter (CRP_{DM})	SprS	1.51	1.56	2.24	2.05	2.59	1.31	1.52	1.56	1.76	2.21	2.20	0.33
	SumS	2.31	4.75	2.52	2.23	2.68	2.40	2.59	1.80	1.89	1.95	2.28	0.37

Note: *LSD_{05} for values in % after *arctg*-transformation; **SprS – spring sowing; SumS – summer sowing.

In terms of equivalent dry matter, these figures were 3.06 and 2.71 t ha^{-1} (with interannual variation of 22.96% and 30.68%, respectively). At the same time, the formed root biomass was 8.45 and 5.26 t ha^{-1} in raw and 1.77/1.19 t ha^{-1} in dry matter at the level of interannual variation in the range of 40.86–44.72%. The average long-term value of interannual variation of CRP_{DM} at the level of 21.99% (with the average long-term CRP_{DM}=1.86) in spring and 32.20% (CRP_{DM}=2.49) in summer sowing proved the significant role of hydrothermal regime of oilseed radish vegetation in the realisation of its root productive potential.

To compare the determined levels of bioproductivity, it should be noted that under conditions of unstable moisture, the yield of aboveground biomass of such crops as white mustard, spring rape, fodder radish (daikon radish) was determined at the level of 12–27 t ha^{-1}. For winter rape in the variant of spring green manure use, it was noted in the range of 25–60 t ha^{-1}. Under these conditions, the yield of root mass was significantly lower and for these crops was noted at the levels of 3–15 t ha^{-1} and 9–25 t ha^{-1}, respectively. Also, a high sensitivity of cruciferous green manure species to the moisture regime was found, with a decrease in the yield of aboveground mass by 42–60% and root mass by 45.8–67.7% in climatically stressful years (Kemper, 2024; Tsytsiura, 2024b).

From the point of view of the percentage of root weight distribution (PRWD) (Table 3), a number of features were established. It was determined that the bulk of the roots in the average perennial measurement is concentrated both in spring and summer sowing at a depth of 30 cm – 82.80% and 90.05%, respectively. The structural ratio of root mass concentration for the depths of 10-20-30 cm was 1.00:0.78:0.38 in the variant of spring sowing and 1.00:0.74:0.29. The boundary at the depth of 30–40 cm was dominant in all years as a transition zone between a densely concentrated variant of spatial distribution of roots of different branching options to a diffuse one with dominance of thin morphological elements of root branches of different orders.

At the same time, the potential probability of identifying the root system beyond 40 cm depth in the soil profile is significantly reduced. As a result, the average long-term proportion of root mass for a depth of up to 50 cm was 2.12–3.92% for spring and 0.63–1.18% for summer sowing. The probability of finding roots at a depth of more than 50 cm is reduced to 1.5% for spring and 0.5% for summer sowing. At the same time, the average depth of the root system during the evaluation period was 64.41 cm for spring and 47.36 cm for summer sowing. These parameters at the date of 50 days after germination allowed to classify the development of the root system of oil radish as medium intensive with high rates of vertical and medium rates of radial growth. This is consistent with the data of the maximum achievable level of the formed root biomass of 8.45 t ha^{-1} in the spring and 5.26 t ha^{-1} in the summer sowing period. This nature of formation, taking into account the studies of dos Santos Nascimento et al (2021), Deus et al. (2022), Kucerik et al. (2024), allowed to attribute oilseed radish to green manure crops of intensive soil

Table 3. Percentage of root weight distribution (PRWD) of oilseed radish at flowering stage (BBCH 64–67) at different sowing dates, %, 2014–2024

Horizon of the soil profile, m	Year of observation											*LSD$_{0.5}$
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	
Spring sowing												
0.0–0.1	45.8	36.0	43.6	31.1	29.9	47.8	44.3	35.2	34.3	35.3	38.7	1.9
0.1–0.2	33.4	34.5	30.6	25.6	26.8	31.5	28.9	28.5	30.7	31.3	26.5	1.1
0.2–0.3	10.3	11.2	11.5	15.4	15.9	12.1	12.8	20.9	16.9	15.7	17.8	0.8
0.3–0.4	7.1	11.8	10.1	13.2	12.5	6.8	9.7	9.7	10.5	10.9	12.3	0.7
0.4–0.5	2.5	2.9	3.5	8.5	8.9	1.8	2.4	3.4	3.9	2.5	2.8	1.2
0.5–0.6	0.9	1.8	0.7	4.3	2.6		1.9	2.3	2.5	2.3	1.9	0.5
0.6–0.7		1.3		1.2	2.1				1.2	2.0		0.5
0.7–0.8		0.5		0.7	1.3							0.6
0.0–0.3	89.5	81.7	85.7	72.1	72.6	91.4	86	84.6	81.9	82.3	83	1.2
0.0–0.5	99.1	96.4	99.3	93.8	94	100	98.1	97.7	96.3	95.7	98.1	0.7
0.5–1.0	0.9	3.6	0.7	6.2	6.0	0.0	1.9	2.3	3.7	4.3	1.9	1.4
ARPD**, cm	58.8	75.7	57.9	78.9	79.1	47.5	58.4	55.4	68.4	69.2	57.2	2.3
Summer sowing												
0.0–0.1	47.5	49.1	44.1	51.8	49.8	40.4	43.2	35.8	48	39.2	38.2	2.1
0.1–0.2	32.4	43.5	30.8	36.8	32.6	33.5	33.9	29.1	25.7	30.7	31.6	1.7
0.2–0.3	11.5	4.2	13.2	8.4	10.9	14.1	12.8	20.3	16.9	16.3	14.2	1.5
0.3–0.4	8.1	1.4	11.2	2.2	6.3	8.8	9.7	14.1	8.9	13.1	10.8	1.9
0.4–0.5	0.5	1.1	0.7	0.8	0.4	2.7	0.4	0.7	0.5	0.7	4.5	0.5
0.5–0.6		0.7				0.5					0.7	0.3
0.0–0.3	91.4	96.8	88.1	97	93.3	88	89.9	85.2	90.6	86.2	84	2.1
0.0–0.5	100	99.3	100	100	100	99.5	100	100	100	100	99.3	1.1
0.5–1.0	0.0	0.7	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.7	0.5
ARPD**, cm	42.8	57.6	46.9	41.3	40.9	58.9	42.5	48.7	40.9	44.7	55.8	3.5

Note: *LSD$_{05}$ according to the principle of arctangent transformation for values in percentage terms according to Snecdecor and Cochran (1991); ARPD – average root penetration depth.

drainage in the upper and middle part of the soil profile. The average growth rate of root biomass, taking into account the rate of soil deepening, was at the spring sowing date at the level of 0.85% day^{-1} for a depth of 0–10 cm, 0.81% day^{-1} for a depth of 10–20 cm, 0.49% day^{-1} for a depth of 20–30 cm and 0.39% day^{-1} for a depth of 30–40 cm. Similar indicators in the variant of summer sowing were 0.84, 0.73, 0.32 and 0.25% day^{-1}, respectively. According to these growth rates, oilseed radish is second only to winter rape in the variant of its traditional autumn sowing period followed by spring sowing (according to Kemper, 2024). In comparison to other cruciferous oilseed rape (Bublitz et al., 2022), oilseed radish showed higher growth rates in terms of coverage of the corresponding soil profile thickness. The presented nature of deep penetration of the root system of oilseed radish also confirmed in the studies of Deus et al. (2022), Maan et al. (2023) regarding the increase in the depth of penetration of the root system under deteriorating moisture conditions due to both a deficit of atmospheric moisture and intense evaporation. Such conditions in the spring sowing period variants were observed in 2017, 2015 and 2018, and for the summer sowing period variant in 2015, 2019 and 2021 (Table 2). In these years that the maximum depth of branches of the root system of oilseed radish was noted for depth of 60–80 cm at the level of 0.86–1.53% in the spring and for depth of 40–60 cm at the level of 0.63–1.18% in the summer sowing variant.

The nature and value of the rate of formation of oilseed radish root biomass was confirmed by analysing the main constants of spatial development of roots. In the variant of spring sowing (Table 4), a sharp differentiation of the soil profile was determined by the linear distribution of the root system. According to the RLD indicator, its average long-term value for depths up to 10 and up to 40 cm was 2.68:1.00. Given the similar ratio for the RMD index of 6.28:1.00, oilseed radish showed significantly higher rates of linear development in the soil profile than the same rate of weight development with a decrease in their mass in the direction from the axis of the taproot to the periphery of potential branching. In all years of spring sowing, this formed gradient zones with a decrease in root mass while maintaining high rates of linear root spread. These conclusions are consistent with the value of the SRL indicator in comparing the upper and lower zones of the soil profile with the fixation of an increasing rate of its growth with a ratio of 0.23:1.00 for the upper and lower ten-centimetre layer. The determined nature of the formation of the basic parameters of the root system of oilseed radish had common features in different species of cruciferous plants (Gan et al., 2009; Bublitz et al., 2022; Kemper, 2024). At the same time, high rates of branching with the formation of thin morphological elements, which dominates at depths more than 40 cm, was maintained.

The morphological development of branching at a depth of 0–30 cm was positive in the case of oilseed radish as a green manure in comparison with such traditional cruciferous green manures as different types of mustard, spring rape for comparable hydrothermal conditions, based on the generalisation of Bublitz et al. (2022), was on average 11.7% higher. It should be noted that a certain character of vertical accumulation of the root system in oil radish is generally typical for cruciferous crops of both winter and spring forms. In particular, Dharmasri et al. (1993), Bublitz et al. (2022) and Kemper (2024) noted this feature, indicating the intervals of maximum overlap of the root system with the depth of the soil profile for winter rape in the range of 25–60 cm, for spring rape 22–35 cm, for oil radish 18–40 cm, for white mustard 20–45 cm. It has also been proven (Kemper, 2024) that a change in the proportion of vertical root distribution in oil radish is characteristic of additional fertilization and an increase in the area of individual plant nutrition. In the case of dense green manure construction of cruciferous agrocenoses, the main part of roots is concentrated with a share of 25–50% in the soil profile with a thickness of 1 m (Talgre, 2013; Wahlström et al., 2015). According to the presented results, the formation of the root system of oil radish in relation to changes in the depth of the soil profile for all the main parameters tended to decrease intensively both in terms of the value of indicators and their ratio. It should be noted that, according to the generalizations of Bublitz et al. (2022) and Kemper (2024), this was also characteristic of most species of cruciferous plants for green manure use. Thus, for spring and winter rape, different types of mustard and root forms of radish, the percentage of the main metric and weight characteristics of the root system at a depth of 50–80 cm compared to the upper layer of 0–20 cm ranged from 1.8 to 10.3% in different studies (Dharmasri et al, 1993; Bublitz et al, 2022; Deus et al, 2022; Boter et al, 2023). At the same time, for the winter group of cruciferous plants, these values corresponded to the interval zone within the maximum achieved value. For cruciferous plants of the spring-summer development cycle, they were within the minimum level. For oil radish, on average, during the spring sowing period, the value of this ratio was 1.40–2.58% for weight and 3.51–5.39% for morphometric traits.

The similarity of the formation of the above indicators for the conditions of summer sowing of oilseed radish green manure was also positive (Table 5), which proved its value for variants of intermediate green manure.

Against the background of a long-term average decrease in RLD by 28.50–48.49% in the depth of the soil profile when comparing summer and spring sowing and with a similar decrease in RMD by 33.50–70.50%, the advantages of oil radish over other traditional cruciferous green manure for spring and summer use for conditions of unstable moisture were noted. For example, for white mustard in summer use, high rates of morphological branching with an increase in root biomass weight were observed for depths up to 30 cm, followed by a sharp decrease in the depth of the soil profile (Cutforth et al., 2013). For spring oilseed rape, this index was 17.9% lower on average for the same green manure period compared to the values obtained for oilseed radish (Gan et al., 2009; Marcinkevičienė et al., 2013; Jabbari et al., 2016). At the same time, despite the increase in the overall level of aridisation of the terms of green manure use during the summer sowing period, oilseed radish retained high rates of linear morphological spread, but formed a network of small-diameter branches with low mass but intensive profile coverage. This character is confirmed by the value of SRL, which was

Table 4. Morphological characteristics of the root system of oilseed radish at the spring sowing date for the flowering phase (BBCH 64–67), 2014–2024

Horizon of the soil profile, m	Year of observation											$LSD_{0.5}$
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	
Root length density (RLD), cm cm^{-3}												
0.0–0.1	5.53	3.58	3.08	1.89	1.71	6.56	5.27	3.85	3.23	2.31	2.24	0.32
0.1–0.2	4.15	3.09	2.71	1.12	1.02	4.89	4.05	2.91	2.19	2.05	1.88	0.68
0.2–0.3	2.92	1.89	0.97	0.91	0.85	3.17	2.84	2.81	1.87	1.59	1.62	0.97
0.3–0.4	1.72	1.55	1.03	0.84	0.72	1.89	2.07	1.58	1.12	1.03	1.09	0.71
0.4–0.5	0.77	0.64	0.52	0.78	0.7	0.68	0.82	0.72	0.44	0.34	0.38	0.29
0.5–0.6	0.32	0.25	0.11	0.71	0.25		0.69	0.44	0.32	0.25	0.22	0.14
0.6–0.7		0.19		0.17	0.18				0.21	0.23		0.05
0.7–0.8		0.12		0.15	0.16							0.03
Root mass density (RMD), mg cm^{-3}												
0.0–0.1	0.5050	0.2370	0.0821	0.1280	0.1230	0.3150	0.3520	0.2150	0.2960	0.1830	0.2040	0.27
0.1–0.2	0.1960	0.1008	0.0576	0.0960	0.0920	0.1250	0.1880	0.0984	0.1020	0.0960	0.1140	0.74
0.2–0.3	0.1050	0.0790	0.0217	0.0520	0.0350	0.0880	0.0960	0.0750	0.0800	0.0580	0.0680	0.26
0.3–0.4	0.0690	0.0550	0.0190	0.0320	0.0210	0.0320	0.0510	0.0335	0.0350	0.0410	0.0320	0.17
0.4–0.5	0.0190	0.0210	0.0110	0.0180	0.0180	0.0090	0.0180	0.0140	0.0120	0.0080	0.0080	0.08
0.5–0.6	0.0070	0.0070	0.0020	0.0170	0.0060		0.0110	0.0079	0.0080	0.0057	0.0030	0.04
0.6–0.7		0.0033		0.0025	0.0026				0.0035	0.0037		0.01
0.7–0.8		0.0017		0.0019	0.0020							0.01
Specifc root length (SRL), m g^{-1}												
0.0–0.1	109.40	150.90	374.68	147.51	138.89	208.05	149.57	178.89	109.01	126.10	109.69	7.11
0.1–0.2	211.52	306.36	469.73	116.55	110.76	390.81	215.21	295.51	214.49	213.33	164.75	5.29
0.2–0.3	277.82	239.00	447.38	174.83	242.61	359.87	295.54	374.29	233.52	273.86	238.00	6.14
0.3–0.4	249.03	281.54	540.90	262.24	342.51	590.03	405.48	471.42	319.68	250.97	340.28	8.42
0.4–0.5	404.86	304.46	472.25	432.90	388.50	754.80	455.10	513.77	366.30	424.58	474.53	10.21
0.5–0.6	456.69	356.79	549.45	417.23	416.25		626.65	553.66	399.60	436.92	732.60	5.08
0.6–0.7		575.18		679.32	561.94				599.40	621.00		9.03
0.7–0.8		630.95		713.57	761.14							11.23

16.35–27.41% higher for the soil layer 0–30 cm and 33.74–67.01% higher for the soil layer 40–60 cm in comparison of summer and spring sowing of oilseed radish. As a result, the SRL value for the lower horizons decreased to 825.98 m g^{-1} in the summer sowing period compared to 701.89 m g^{-1} in the spring sowing period. It should be noted that for cruciferous green manure species, in a number of studies for profile depths of 50–70 cm, the SRL value was in the range of 680–950 m g^{-1} (Rouse, 2019; Kemper, 2024). The presented features of the spatial formation of the root system of oilseed radish in the soil profile were confirmed by the results of mathematical model analysis (Table 6).

The obtained dependencies with the highest levels of approximation belonged to power functional on the soil depth factor. In the variant of spring sowing the formation of the root length density (RLD) with the highest probability of realization was described by the expression Logistic Model ($a(1+be^{-cx})^{-1}$) (level of multiple regression determination 97.81%), which indicated the hyperbolic nature of the formation with an intense decline in its value with an increasing dynamic coefficient with a change in profile depth. The significance of the use of model variations in the functional single or binary ratio to one (Harris Model, level of determination 91.77%) or the starting free term of the equation (MMF Model, level of determination 87.75%) had a significantly lower level of predicted realization. For Root mass density (RMD), the predicted model of formation was the Gaussian Model (97.42% determination level). The probability of formation described by the Exponential Fit

Table 5. Morphological characteristics of the root system of oilseed radish at the summer sowing date for the flowering phase (BBCH 64–67), 2014–2024

Horizon of the soil profile, m	Year of observation											$LSD_{0.5}$
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	
Root length density (RLD), cm cm^{-3}												
0.0–0.1	3.22	2.58	2.88	3.47	3.05	3.16	2.27	2.14	2.06	2.14	2.28	0.29
0.1–0.2	2.12	1.93	1.74	3.05	2.29	2.19	1.77	1.81	1.52	1.56	1.55	0.55
0.2–0.3	1.04	0.35	1.05	1.38	1.15	1.04	0.91	0.89	0.81	0.77	0.82	0.41
0.3–0.4	0.48	0.21	0.79	0.39	0.62	0.69	0.72	0.64	0.53	0.51	0.63	0.27
0.4–0.5	0.11	0.16	0.33	0.21	0.25	0.32	0.11	0.12	0.15	0.19	0.17	0.03
0.5–0.6		0.16				0.25					0.14	0.03
Root mass density (RMD), mg cm^{-3}												
0.0–0.1	0.1480	0.1520	0.1790	0.0965	0.0739	0.2480	0.1960	0.1740	0.1850	0.1770	0.1250	0.21
0.1–0.2	0.0536	0.0820	0.0910	0.0686	0.0484	0.1600	0.1140	0.0980	0.0690	0.0810	0.0720	0.53
0.2–0.3	0.0410	0.0120	0.0360	0.0217	0.0162	0.0450	0.0350	0.0270	0.0250	0.0210	0.0250	0.37
0.3–0.4	0.0140	0.0060	0.0260	0.0055	0.0140	0.0220	0.0180	0.0170	0.0120	0.0110	0.0150	0.09
0.4–0.5	0.0025	0.0026	0.0061	0.0030	0.0040	0.0060	0.0018	0.0022	0.0020	0.0030	0.0024	0.01
0.5–0.6		0.0020				0.0030					0.0016	0.02
Specifc root length (SRL), m g^{-1}												
0.0–0.1	217.35	169.57	160.73	359.14	412.43	127.29	115.70	122.87	111.24	120.78	182.22	7.55
0.1–0.2	395.39	235.13	191.02	444.34	473.04	136.74	155.11	184.51	220.07	192.40	215.06	5.92
0.2–0.3	253.40	291.38	291.38	635.31	710.48	230.88	260.31	329.30	323.68	366.30	327.67	10.31
0.3–0.4	342.51	349.65	303.54	708.38	442.41	313.32	401.82	376.09	441.23	461.36	419.58	14.25
0.4–0.5	439.56	614.77	532.25	699.30	629.37	524.48	610.50	563.07	739.26	616.05	707.63	15.72
0.5–0.6		789.21				845.82					842.91	16.37

Model was 7.3% lower. The dominance of the Gaussian model in the model range for the formation of weight parameters of root system branches confirmed the pronounced dynamics of intensive reduction of the weight of oilseed radish root system branches for its morphological radial development starting from the taproot. Due to this, oilseed radish has the ability to form intensive diffuse branches of the root system of a small deametric nature, which provided appropriate mechanisms for its adaptation to a decrease in the moisture supply of the soil profile. From the point of view of the impact on the agrophysical properties of the soil, ensured the formation of intensive root horizontal drainage. As a result, the correlation in the peculiarities of the formation of linear morphometry of the root system and its accompanying weight parameters by the SRL index described by Richards Model (determination level 97.61%). This confirmed the pattern for the root system of oilseed radish with greater stability of linear development and prevalence of roots of different branching order with intensive concomitant decrease in its mass in the direction from the axial center to the periphery. The maximum reliability established in the model of PRWD formation in accordance with the MMF Model expression (determination level 97.42%) confirmed the intensive downward nature of the formation of root system with increasing soil profile depth. Due to the presence of a hyperbolic ratio in this model, this decline is gradually increasing.

For the variant of summer sowing, based on similar modeling, the same trends in the formation of indicators of spatial and weight development of the root system were determined. In particular, the dependencies in the formation of RLD and RMD indicators belong to the Exponential Association group (determination level 93.70–96.43%). For RMD, these dependencies were statistically described mainly by power-law dependencies (determination level more than 90.0%) in relation to the effective factor of soil profile depth. This nature of the dependencies indicated a decrease in the overall rates of both the formation of linear and weight development of the root system under more stressful conditions, due to the indicated

Table 6. Regression models for estimating the distribution of morphometric and weight characteristics of the root system of oilseed radish (in the total aggregate of records for 2014–2024)*

Model no.	Form of model tested	Fitted coefficients and costant				R^2	Test of the models			
		a	b	c	d		RMSE	RRMSE	PE	*p*
Spring sowing										
Root length density (RLD, cm cm^{-3})										
1	$a+b\ln x$	6.540	-1.561			0.962	0.119	0.016	0.994	<0.001
2	$a/(1+be^{-cx})$	2.5E+006	4.8E+005	-0.0534		0.989	0.108	0.012	0.996	<0.001
3	$1/(a+bx^c)$	0.284	0.000148	2.475		0.958	0.127	0.018	0.992	<0.001
4	$(ab+cx^d)/(b+x^d)$	-0.986	0.0198	4.634	-1.299	0.972	0.121	0.014	0.995	<0.001
Root mass density (RMD, mg cm^{-3})										
1	$ae^{-(x-b)^2/c^2}$	16.270	-51.845	36.059		0.987	0.159	0.024	0.987	<0.001
2	ax^{bx}	5.200	-0.0142			0.974	0.164	0.027	0.976	<0.001
3	$(a+bx)/(1+cx+dx^2)$	4.560	-0.058	-0.0124	0.00189	0.912	0.197	0.030	0.984	<0.001
Specifc root length (SRL, mg^{-1})										
1	$a(1+e^{b-cx})^{1/d}$	0.0481	32.181	0.621	24.396	0.988	11.893	0.017	0.992	<0.001
2	$a/(1+be^{-cx})$	509.380	4.868	0.0647		0.956	13.280	0.020	0.975	<0.001
4	ab^xx^c	71.228	1.018	0.075		0.968	12.944	0.019	0.983	<0.001
Percentage of root weight distribution (PRWD, %)										
1	$(a+bx)/(1+cx+dx^2)$	64.818	-0.841	0.0228	0.00116	0.967	2.308	0.044	0.884	<0.001
2	$(ab+cx^d)/(b+x^d)$	-13.871	0.0201	58.490	-1.253	0.987	2.105	0.041	0.904	<0.001
3	$a+b\ln x$	84.281	-19.888			0.932	2.515	0.048	0.815	<0.001
Summer sowing										
Root length density (RLD, cm cm^{-3})										
1	$a(b-e^{-cx})$	-5.169	0.0219	0.0874		0.968	0.236	0.042	0.959	<0.001
2	$(ab+cx^d)/(b+x^d)$	-0.212	0.00135	2.867	-2.420	0.946	0.287	0.051	0.908	<0.001
3	$a+bx+c/x^2$	0..397	-0.00947	174.810		0.921	0.289	0.048	0.874	<0.001
Root mass density (RMD, mg cm^{-3})										
1	$a-be^{-cx^d}$	2.408	2.535	5371.023	-2.836	0.982	0.167	0.022	0.972	<0.001
2	$ae^{-(x-b)^2/c^2}$	2.607	3.710	15.914		0.977	0.181	0.027	0.964	<0.001
3	ax^{bx}	3.616	-0.0163			0.948	0.205	0.031	0.927	<0.001
Specifc root length (SRL, mg^{-1})										
1	$a+bx+cx^2$	122.600	2.429	0.120		0.977	13.985	0.019	0.985	<0.001
2	$a(1+e^{b-cx})^{1/d}$	1274.700	4.578	0.0638	1.901	0.975	14.090	0.019	0.983	<0.001
3	$a-be^{-cx^d}$	3025.770	2885.189	0.00009	1.902	0.972	14.147	0.020	0.981	<0.001
Percentage of root weight distribution (PRWD, %)										
1	$a+b\ln x$	106.430	-26.555			0.964	3.144	0.052	0.939	<0.001
2	$(ab+cx^d)/(b+x^d)$	-30.902	0.0315	74.168	-1.080	0.972	3.017	0.045	0.956	<0.001
3	$a+bx+c/x^2$	34.072	-0.634	1718.882		0.936	3.744	0.064	0.850	<0.001

Note: * x – depth (cm) within the soil profile.

hydrothermal regimes (Table 2) for the summer sowing period. However, the proximity of index values in the dependence equations confirmed the adaptive potential of oilseed radish in view of the growth of limiting environmental factors. These findings consistented for other cruciferous green manure (Jabbari et al., 2016; Bublitz et al., 2022; Kemper, 2024). This research has determined that the size of the taproot of oilseed radish under green manure use depended on the area of plant nutrition (Figure 1, a–b). The formed root maps models using the analytical approaches of Diggle (1988), Bublitz et al. (2022) and Faye et al. (2022) allowed to detail the development of the root system within the soil profile with intra-ecotype competition of plants (Figure 2).

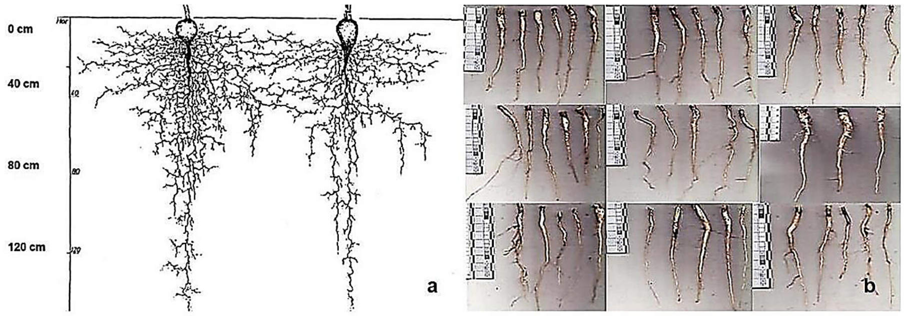

Figure 1. General development of the root system of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.): (a) (under sparse agrocenosis, wide-row sowing scheme (according to Kutschera et al. (2009)) and morphometry of the taproot part of the root system of oilseed radish under dense green manure use (b, 2024)

The maximum radial spread of lateral roots in the range of 10 to 17 cm was found, depending on the year of research, with a minimum indication for depth in the range of 50–75 cm. A detailed segmental analysis of root maps in vertical projection proved the complex tiered nature of the formation of the root system of oilseed radish for both sowing dates in the application of six gradations of the percentage spread of branches within the soil profile. In the assessment of the inter-row segment of the assessment during the spring sowing period, the proportion of roots with a probability of identification in the range of 85–100% was concentrated in the horizontal direction at a distance of 5–8 cm from the taproot, and in the vertical direction at a distance of 24–28 cm from the surface (Figure 2a). The maximum horizontal spread of the root system in the average perennial measurement was noted at a depth of 10–12 cm at a distance of 8–12 cm from the taproot. The gradational step of change in the horizontal spread of the root system was in the range from 3 to 7 cm. Branches of the root system with vertical placement in the profile were noted in areas with a probability of identification in the profile in the range of 40–85%. The length of these branches is from 8 to 24 cm. The intensity of such branching in terms of depth and frequency of occurrence increased from the periphery to the axial center of the taproot. The zone of overlap of branches of the root system of oilseed radish in the variant of sowing was within 7–9 cm from the axial centers of plant roots in the row and was maximum at a depth of 6 to 12 cm and tended to decrease significantly from a depth of 14–16 cm where the interaction of roots of lateral branching of vertical tropation prevailed. The maximum compactness of the system of tropization of branches of the root system of oilseed radish in the spring sowing period was noted in the depth range of 2–24 cm, and the maximum diffusivity in the depth range of 44–70 cm. Based on the research of Diggle (1988) and Shukla et al. (2023) was determined 1854 unfilled grid squares (of its total number 3150). The degree of development of the root system in terms of presence in each square was 41.14%. For a depth of 0–30 cm, this value was 61.07%. In the variant of summer sowing, the proportion of roots with a probability of identification in the range of 85–100% on the profile was concentrated in the horizontal direction at a distance of 4–7 cm from the taproot, and in the vertical direction at a distance of 18–24 cm from the surface (Figure 2b). The maximum horizontal spread of the root system was noted at a depth of 8–10 cm at a distance of 6–8 cm from the taproot. The gradational step of change in the horizontal spread of the root system was in the range from 3 to 5 cm.

The intensity of vertical branching in accordance with the frequency of occurrence in the profile grid was 22.77% higher than in the spring sowing period with a predominance of its placement on the roots of horizontal spread with a probability of identification of 40–70%. The length by depth of vertical branches was on average 15.92% less than the same indicator for the spring sowing period. The maximum compactness of the system of tropation of branches of the root system of oilseed radish at a given sowing period was determined in the depth range of 2–14 cm, and the maximum diffusivity in the depth range of 22–40 cm. The zone of overlapping branches of the root system was represented mainly by branches of higher orders and, as a result, was 18.45% smaller in terms of the area of presence in the grid of profile squares. The degree of development of the root system in the overall vertical profile

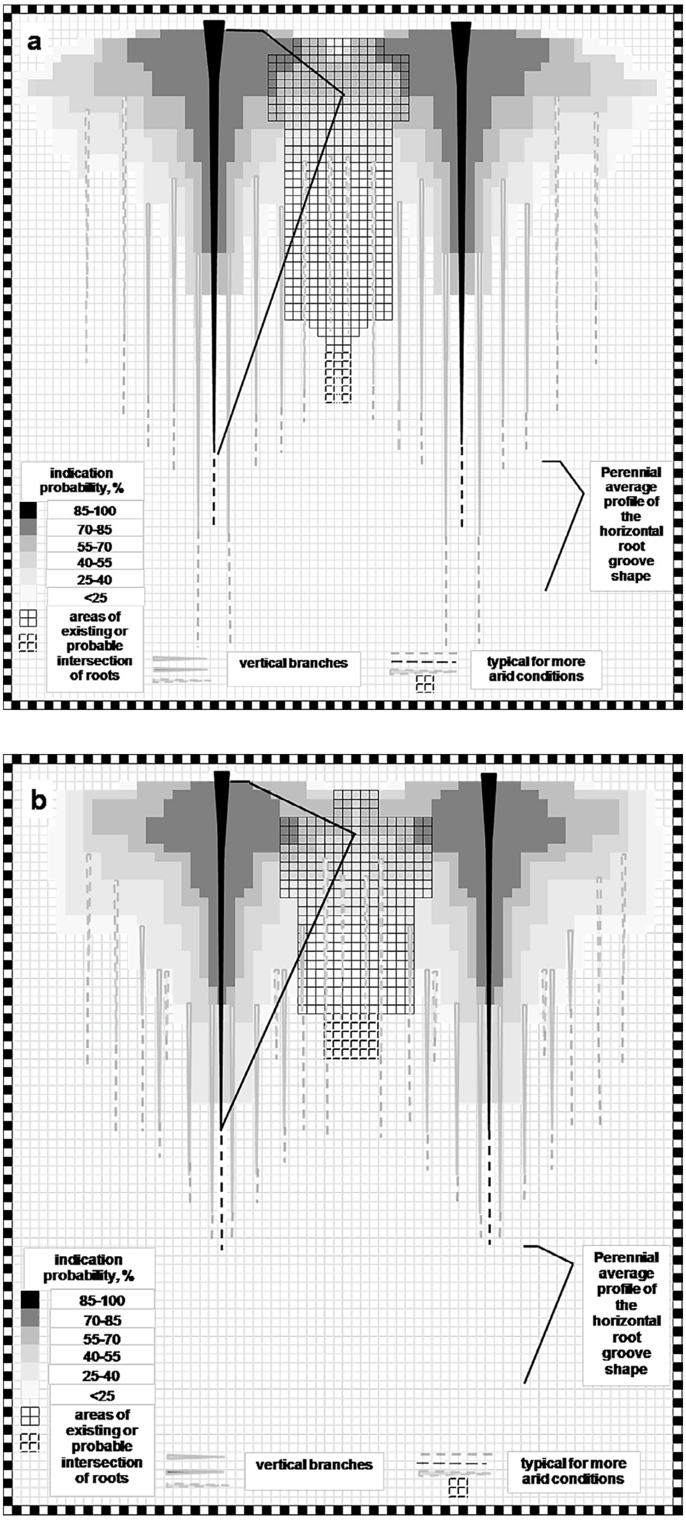

Figure 2. Root maps in oilseed radish covering two rows space of plants at spring (a) and summer (b) sowing dates (grid (square) dimension of the map (width x depth): 0.5 × 1.0 cm) based on the total data for the period 2014–2024

was 34.85% and 72.25% for the depth of 0–30 cm. During the summer period, oilseed radish formed a root system with a larger proportion of higher-order branches against the background of minimization of morphological and weight parameters of these branches (Figure 3). A simultaneous increase in the intensity of branching in the overlapping zones by 41.8% in the spring and 27.5% in the summer sowing period of green manure were determined. This nature of interaction,

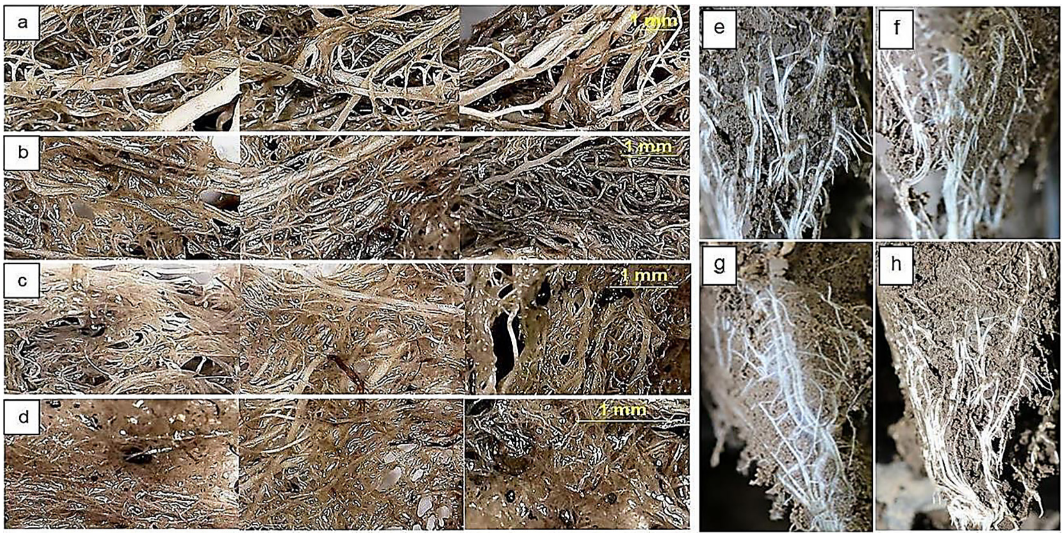

Figure 3. Branches of the 1st (a), 2nd (b), 3rd (c) and 4th (d) order of the root system of oilseed radish was arranged sequentially (3 positions each) after washing, 2024 (first and second columns for spring, third for summer sowing. Branches of the 2nd order for spring (e, f) and summer (g, h) sowing

in contrast to the assessment of the row spacing, covered mainly the gradation interval of the probability of root system prevalence of 55–85% both in spring and summer sowing. This formed a gradient difference in the spatial morphology of the root system of oilseed radish, which determined the elliptical structure of the basis of the applied model for the root spreading zone in relation of the design of its green manure agrophytocenosis for both sowing dates. This was confirmed by the idiogram structure of the profile of the root system distribution, which was a twice smaller in comparison with the inter-row and intra-row interval for the spring sowing and average 1.68 times smaller in the summer sowing period.

Based on the conclusions of Schnepf et al. (2018) and Dowd et al. (2022), the identified features gave grounds to assess the root system of oilseed radish as highly sensitive to changes in plant nutrition area with a predicted increase in the main morphological parameters with an increase in its value.

The analysis of the shape of the root spreading zone in the context of the years of research confirmed the previously noted geometric shape (Figures 4–5) allowed us to identify a number of adaptive and ecological features of oilseed radish from the point of view of the spatial formation of the root system.

In the variants of spring sowing of green manure, a change in the nature of its high-altitude and radial tropation was determined as a reaction to a decrease in the level of moisture supply, especially against the background of an intensive increase in average daily temperatures. In the years with a high level of aridization 2015 (Figure 4, positions 2 a–b), 2017 (Figure 4, positions 4 a–b) and 2018 (Figure 4, positions 5 a–b) in comparison with the years with optimized hydrothermal parameters (2019 (Figure 4, positions 6 a–b), 2014 (Figure 4, positions 1 a–b) and 2020 (Figure 4, positions 7 a–b)), a decrease in the overall variability of the indicators of the spatial morphological development of the root system by 15.7–19.3% was determined. It was especially in the vertical profile for a depth of 10–20 cm, while the area of the root profile decreased by an average of 14.9%. For the variant of summer sowing time with a similar comparison (years with a high level of aridization 2015 (Figure 5, positions 2 a–b), 2019 (Figure 5, positions 6 a–b), 2021 (Figure 5, positions 8 a–b) to years with sufficient and excessive moisture supply 2014 (Figure 5, positions 1 a–b), 2017 (Figure 5, positions 4 a–b), 2022 (Figure 5, positions 9 a–b)), a decrease in the area of the identification profile was determined. At the same time, the following reductions were established by a decrease in the total variability of the indicators of the spatial morphological development of the root system by 17.82–28.37% with a simultaneous decrease in the area of the root profile by an average of 19.55%. For both sowing dates, a significant difference was found in the configuration of spatial zoning of the root

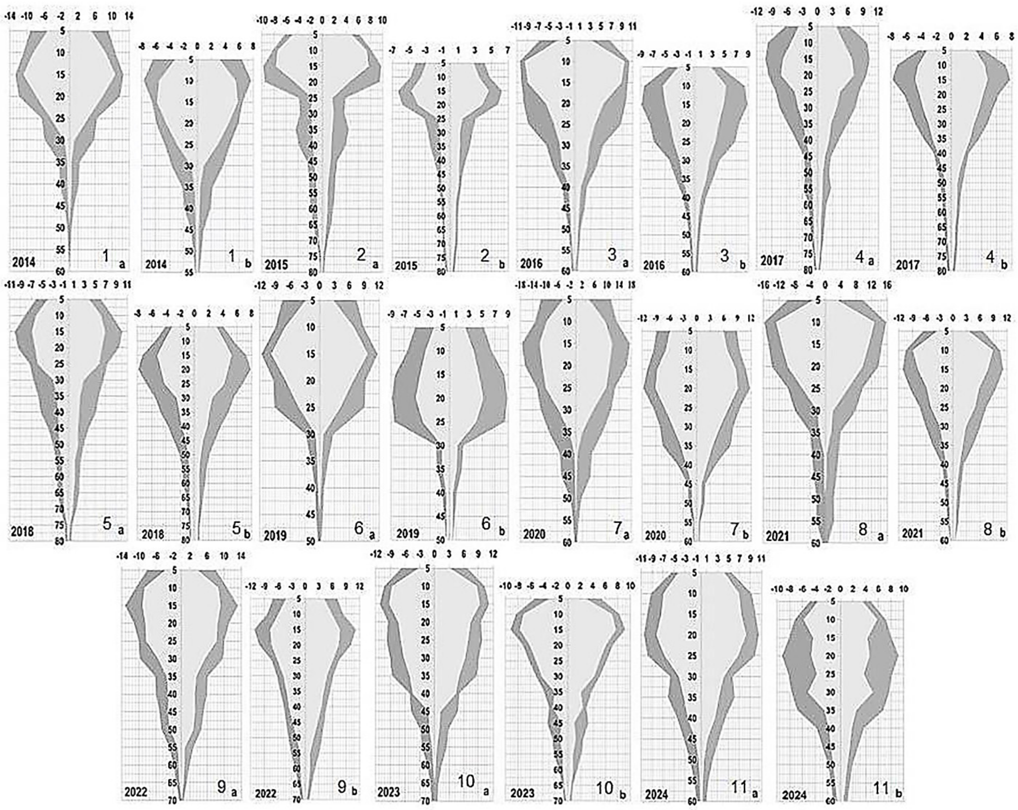

Figure 4. Projections of the simulated spatial zoning of the root system onto two orthogonal vertical planes for spring sowing (cm), 2014–2024 (light gray area – average value of lateral branching paths of the root system, dark gray area – limits of the variable spread of lateral branches; position a – for the inter-row spacing zone, position b – for the row spacing zone)

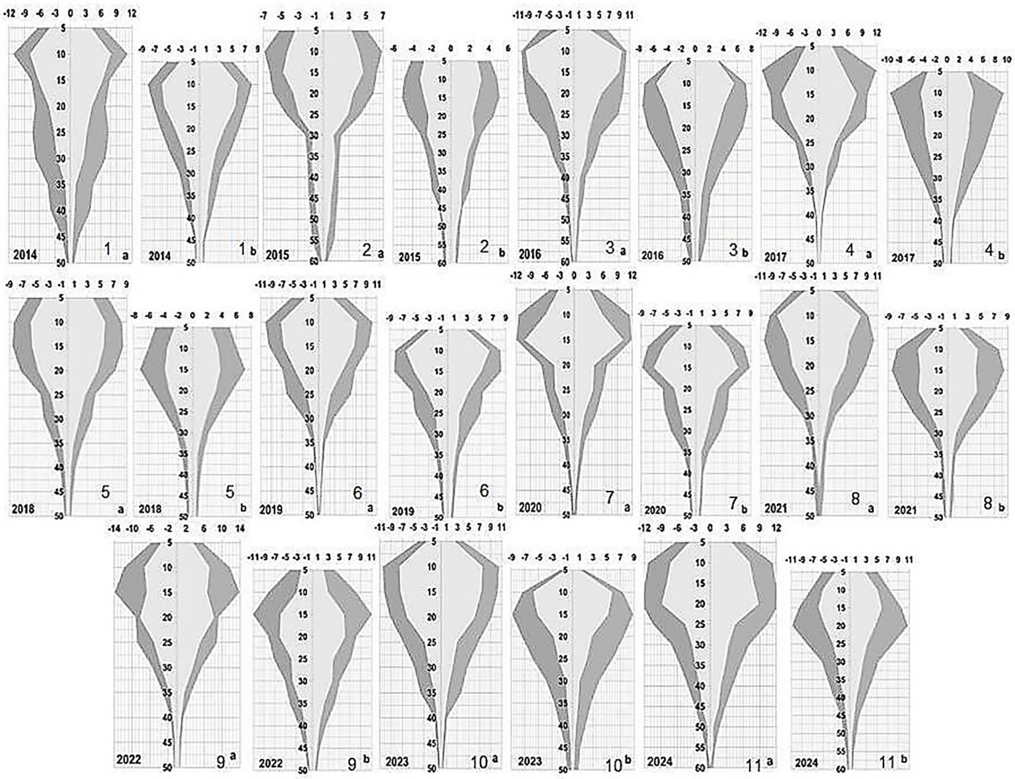

Figure 5. Determinants as in Figure 5 for summer sowing conditions, 2014–2024

system with a tendency to a planar decrease. The degree of development of the root system in terms of presence in each quadrat was on average 12.14% lower than in spring and 17.75% lower than in summer sowing. As a result, the deterioration of atmospheric moisture for both sowing dates formed a narrowing of the profile of identification of the root system prevalence from the axial center of the taproot with the formation of a simpler profile relief.

A more complex profile configurations on the contrary, for the conditions of sufficient (2014, 2021, 2022, 2024) and excessive (2019) were determined with an increase in the radial spread of lateral branches from the root axis by 15.5–20.7%, while increasing the range of variation in the number of the maximum achievable length and the ordinal position of the intensive branching zone for the profile depth of 25–40 cm. Therefore, under such conditions, the formation of a wide zone of potential branching at the level of 20–30 cm with a sharp transition to an intensive narrowing of the radial distribution of roots was noted. In general, based on estimates of the intensity of root system development within the soil profile oilseed radish should be considered as a valuable green manure crop with a potentially high impact on the dynamism of physicochemical soil processes in a soil profile up to 70 cm.

Under the conditions of dry growing season for both terms of sawing, the zone of intensive lateral branching acquires a pronounced diffuse character with a slow decrease in the indication of root distribution in the horizontal direction of the profile. At the same time, an adaptive pattern of increasing the depth of penetration of the root system of oilseed radish was determined due to a decrease in moisture supply which formes a gradient boundary between moistened and critically dehydrated soil. This limit, according to Maan et al. (2023), gradually decreased with the duration of the drought against the background of high air temperatures. As a result, the roots stop growing when soil moisture in its osmotic value decreases to a certain limit. However, in plants with adaptive mechanisms of drought tolerance, the growth processes of the root system were enhanced due to its fine morphological elements with the formation of more intense diffuse coverage of the corresponding layer of the soil profile. This formed a compensating mechanism for the deterioration of soil moisture supply by increasing the suction area (Jabbari et al., 2016; Kou et al., 2022). Presented ordinal values of vertical permeability of the root system of oilseed radish in years with an unfavorable weather conditions (Table 2, 2015, 2016, 2017 and 2018 for spring and 2015, 2016, 2019, 2021 for summer sowing) coincided with an average depth of root system penetration indication of 72.9 cm and 55.07 cm, respectively. It was on average 13.3 cm and 14.03 cm higher than for conditions of sufficient moisture (2014, 2019, 2020, 2021 for spring and 2014, 2017, 2018, 2022 for summer sowing). It was proved the high potential use of oilseed radish as a green manure in the system of intermediate multi-term use.

The above generalizations about the significant role of hydrothermal conditions of the growing season were confirmed by the results of correlation and regression analysis (Table 7). It was found that the total bioproductivity of plants in terms of root biomass yield (RBY) for conditions of spring sowing had a direct dependence: with the amount of precipitation (Pr) (d_{xy}=77.44%), moisture reserves in the soil profile (WRS) (d_{xy}=65.61%), root length density (RLD) (d_{xy}=81.00%), root mass density (RMD) (d_{xy}=96.04%) and specifc root length (SRL) (d_{xy}=86.49%). The reverse nature of the dependence of RBY was determined by the average daily temperature (t_{av}) (d_{xy}=15.21%), by soil hardness (SH) (d_{xy}=75.69%). In the summer sowing period, while maintaining the same nature of the relationship between the resultant trait RBY and the variable parameters, the closeness of the relationship in the determination expression was on average 11.7% lower than for the spring sowing variant. The overall decrease in the optimality of hydrothermal conditions against the background of increased aridization of the growing season noted for the conditions of summer-autumn vegetation of oilseed radish levels the overall impacted as an additional depressing factor. These results was positive agreement with the findings of Jabbari et al. (2016), Shoaib et al. (2022). For the main indicators of oilseed radish root system development (RLD, RMD) direct dependence on the amount of precipitation was determined for spring (d_{xy}= 67.24–79.21%) and for summer sowing (d_{xy}= 33.64–44.89%). For the average daily temperature, the relationship was inverse with a determination of 7.29–11.56% for spring and 20.25–26.01% for summer sowing. At the same time, the nature of dependence on both parameters was weak for both sowing dates for

Table 7. Pearson's correlation coefficients of dependence of oilseed radish root morpho- and bioproductivity parameters on hydrothermal parameters and soil propertiess, 2014–2024 (*N=88*))

No.	2	3	4	5	6	7	8	9	2	3	4	5	6	7	8	9
	Spring sowing								Summer sowing							
1	-0.14	-0.94	0.97	0.88	-0.84	0.89	0.82	0.21	-0.07	-0.72	0.68	0.64	-0.73	0.58	0.67	0.12
2		-0.01	-0.12	-0.39	0.37	-0.27	-0.34	0.37		0.68	-0.54	-0.44	0.44	-0.51	-0.45	0.49
3			-0.87	-0.76	-0.86	-0.77	-0.73	0.27			-0.75	-0.61	-0.74	-0.61	-0.52	0.41
4				0.81	-0.83	0.81	0.77	-0.36				0.96	-0.69	0.60	0.52	-0.24
5					-0.71	0.90	0.98	0.93					-0.73	0.88	0.92	0.90
6						-0.78	-0.55	-0.70						-0.49	-0.22	0.04
7							0.82	0.55							0.52	0.04
8								0.02								-0.48

Note: Significant at the significance level 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 – rverage root penetration depth (ARPD, 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}).

the factor of precipitation (d_{xy}=1.44–4.41%) and of medium strength for the factor of average daily temperature (d_{xy}=13.69–24.01%). Based on this, given the nature of the calculation of the SRL and the above dependencies, the factor response to the hydrothermal regime of the RMD was higher than that of the RLD. This indicated that oilseed radish is characterized by the preservation of the corresponding rates of linear and fractal growth of the root system under changes in hydrothermal conditions of vegetation with a more significant decrease/increase in the corresponding mass of branches based on the nature of the dependence for SRL index. This character proved the adaptive property of oilseed radish to intensify branching of the root system with a decrease in their total mass, while increasing the amount of precipitation and increasing the average daily temperature. In view of this, the presence of an adaptive mechanism of growth and root system formation characteristic of wild cruciferous species (Kashyap et al., 2023) was confirmed the same nature of formation in oilseed radish. It was also determined that the intensity of development of the root of oilseed radish (according to RLD, RMD criteria) is determined by such indicators as SH (inverse dependence at d_{xy}=53.29–59.29% for spring and d_{xy}= 27.04–37.21% for summer sowing) and WRS (direct dependence at d_{xy}=52.29–65.61% for spring and d_{xy}=27.04–36.00% for summer sowing).

For the SRL indicator, an increase in density will contribute to its growth, and an increase in soil moisture reserves will lead to its decrease. The relatively low levels of dependencies indicated the heterogeneity of the influence of soil moisture and its density on the formation of the RLD and RMD parameters separately. Given the ratio of the sum of the modules of the correlation coefficients for RLD and RMD parameters at the level of 1.23 for spring and 1.11 for summer sowing in oilseed radish, the formation of morphometric parameters of the root system were less adaptive than the formation of its weight characteristics in relation to environmental and soil parameters. As a result, a more significant reduction in the linear dimensions of the root system and its distribution in the soil profile than in the root mass should be expected with increasing environmental depressivity, primarily in the moisture regime against the background of increasing soil hardness. This is consistented with the data comparing the nature of the distribution of roots in the soil profile for spring (Figure 3 a) and summer sowing (Figure 3 b). The obtained values of dependence from the standpoint of hydrothermal conditions for the average root penetration depth (ARPD) confirmed the previously made conclusions that the root system of oilseed radish under the deficit of soil moisture was able to form an adaptive growth of the root system to optimize the moisture supply of plant growth processes. This is consistented with the direct nature of the dependence of this indicator on the average daily air temperature (t_{av}) at d_{xy} 13.69% and 19.36% for spring and summer sowing and the inverse nature of the dependence on the amount of Pr at d_{xy} 53.29% and 70.56%, respectively. Based on this, the root system of oilseed radish demonstrated a certain moisture tropism noted as a process in the studies of Kemper (2024), forming a more compact root system with sufficient moisture supply at moderate air temperatures and a more diffuse one with a moisture deficit and intensive increases in air temperature. This feature maked it possible to grow oilseed radish as a green manure crop and under conditions of unstable moisture in accordance with the criteria of conformity (Deus et al., 2022). It was confirmed the system of regression equations (Table 8).

In particular, the statistical evidence of the formative role of the amount of precipitation during the growing season and the inverse formative role of the average daily air temperature with an average level of the multiple regression coefficient of 0.783 (in the statistical correction (adj.) 0.667 at $p<0.001$) for the formation of the same indicators RBY, RLD, RMD and ARPD was proved. The direct formative role of the factor water reserves in the soil (WRS) and the inverse formative role of the factor soil hardness (SH) with an average level of the multiple regression coefficient of 0.790 (in the statistical correction (adj.) 0.670 at $p<0.001$) for the formation of the values of the same indicators was also proved. The most stable factor system for the influence on the main indicators of morpho- and bioproductivity of the root system at the three-factor level of comparison in combination of Pr, SH and WRS with an of multiple regression coefficient of 0.890 (in statistical correction (adj.) 0.746 at $p<0.001$) was determined.

From the standpoint of the established values and direction of dependencies of the formation of the root system of oil radish by basic characteristics (RLD, RMD, SRL, ARPD) depending on SH, it can be predicted that under the conditions of unstable moisture intensity of radial and vertical development of the root system for other types of soils (in particular, chernozems and sod soils, for which the level of threshold density is significantly lower than for gray forest soils in the range of 18–37% (according to Sanchez et al. (1982)) will be significantly higher. In addition, morphogenesis in the profile of such soils will be intensified under the regime of their moisture in the gradation below the optimal level. At the same time, the adaptive mechanism of formation of the root system of oil radish in the form of intensive branching of the radial root system

Table 8. Regression dependencies of the intensity of oilseed radish root system development depending on hydrothermal growing conditions and individual soil characteristics (average data for 2014–2024)

Qualitative indicator*	Equation of dependence	Parameters of Eqs.			Statistical evaluation of components				
		x	*y*	z	Multiple *R*	Multiple $R^2_{(adj.)}$	*F*	*df1, df2*	*p*
SH	$7.37-0.04x+1.67y$	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	0.701	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	0.492	11.163	2.190	<0.01
RMD	$0.132+0.00018x-0.0069y$				0.682	0.409	8.269	2.190	<0.05
SRL	$143,23+0.286x+8.492y$				0.603	0.545	4.892	2.190	<0.05
RBY	$-1.99-0.0084x+0.086y$	Soil hardness (SH, kg cm^{-2})	Water reserves in the soil (WRS, mm	–	0.859	0.612	26.950	2.190	<0.01
ARPD	$108.21-1.153x-0.236y$				0.556	0.309	3.687	2.190	<0.05
RLD	$0.577-0.017x+0.012y$				0.727	0.578	11.623	2.190	<0.01
RMD	$0.005+0.00011x+0.00058y$				0.690	0.518	8.612	2.190	<0.05
SRL	$260.54+1.516x+0.474y$				0.597	0.318	3.125	2.190	<0.05
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
ARPD	$293.71-0.40x-11.91y+0.009z+0.0004x^2+0.20y^2+0.0001z^2$				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	0.644	8.971	6.150	<0.01

Note: *decoding of indicators in the description of Table 6.

and their elongation in vertical orientation with increasing soil density against the background of decreasing soil moisture supply will predictably have higher levels of manifestation. This is proved by the signs of the argument functions (SH and WRS) of the regression equations for RMD and SRL indicators. These features confirm the higher levels of efficiency of oil radish use as a green manure at different sowing dates for the zone of distribution of black soil and sod groups for climate zones Cfa–c/Dfa–b (according to Köppen-Geiger climate classification).

CONCLUSIONS

It was proved that oilseed radish formed on soils of medium fertility potential on an unfertilized background under conditions of unstable moisture for 11 years of evaluation in spring and summer sowing root mass bioproductivity of 8.45 and 5.26 t ha^{-1} in wet and 1.77 and 1.19 t ha^{-1} in dry matter, respectively.

It has been defined that the root system of oilseed radish according to the basic criteria of spatial development and weight distribution in the soil profile formed adaptive morphotype, which ensured active interaction of the system of four-level root branches with the soil profile 60–80 cm deep in spring and 40–60 cm in summer sowing of green manure, which is consistented with the classification of its suitability for bioorganic green manure systems with an active influence on the agrophysical parameters of the soil profile.

According to the results of correlation and regression analysis the following factors determining root biomass yield (RBY) during the spring sowing period were established in ascending order: average daily temperature (t_{av}) < soil hardness (SH) < water reserves in the soil (WRS) < total precipitation during the growing season (Pr) < root mass density (RMD) < root length density (RLD). For the summer sowing period, a similar series was as follows: average daily temperature (t_{av}) < root mass density (RMD) < root length density (RLD) < total precipitation during the growing season (Pr) < soil hardness (SH) < water reserves in the soil (WRS).

The ability of the root system of oilseed radish to adaptive mechanism of soil deepening with additional branching under the deficit of atmospheric and derived soil moisture was proved.

REFERENCES

1. Atkinson D., Dawson L.A. (2000). Root Growth: Methods of Measurement. In: Smith K.A. *Soil and Environmental Analysis. 2nd Edition*. CRC Press.
2. Boter M., Pozas J., Jarillo J.A., Piñeiro M., Pernas M. (2023). Brassica napus roots use different strategies to respond to warm temperatures. *International Journal of Molecular Sciences, 24*(2), 1143. https://doi.org/10.3390/ijms24021143
3. Bublitz T.A., Kemper R., Müller P., Kautz T., Döring T.F., Athmann M. (2022). Relating profile wall root-length density estimates to monolith root-length density measurements of cover crops. *Agronomy, 12*, 48. https://doi.org/10.3390/agronomy12010048
4. Cutforth H.W., Angadi S.V., McConkey B.G., Miller P.R., Ulrich D., Gulden R., Volkmar K.M., Entz M.H., Brandt S.A. (2013). Comparing rooting characteristics and soil water withdrawal patterns of wheat with alternative oilseed and pulse crops grown in the semiarid Canadian prairie. *Canadian Journal of Soil Science, 93*, 147–160. https://doi.org/10.4141/cjss2012-081
5. Deus T.R.V. de, Giongo V., Salviano A. M., Santana M. da S., Silva V.C., da Santos T.C. dos (2022). Selection of green manures to provide ecosystem services in a semi-arid environment. *Revista Brasileira de Ciências Ambientais, 57*(3), 409–421. https://doi.org/10.5327/Z2176-94781268
6. Dharmasri L.C., de Jong E., Cowell L.E. (1993). *Effective rooting depth of mustard under dryland conditions*. Dept. of Soil Science, University of Saskatchewan., Repository for Research (http://hdl.handle.net/10388/10502), 233–238.
7. Diggle A.J. (1988). ROOTMAP – a model in three-dimensional coordinates of the growth and structure of fibrous root systems. *Plant and Soil, 105*(2), 169–178. https://doi.org/10.1007/bf02376780
8. dos Santos Nascimento G., de Souza T.A.F., da Silva L.J.R. (2021). Soil physico-chemical properties, biomass production, and root density in a green manure farming system from tropical ecosystem, North-eastern Brazil. *Journal of Soils and Sediments, 21*, 2203–2211. https://doi.org/10.1007/s11368-021-02924-z
9. Dowd T.G., Li M., Bagnall G.C., Johnston A., Topp C.N. (2022). Root system architecture and environmental flux analysis in mature crops using 3D root mesocosms. *Frontiers Plant Science, 13*, 1041404. https://doi.org/10.3389/fpls.2022.104140
10. Faye A., Laplaze L., Sine B., Chopart J.L. (2022). RACINE2.2: A software application for processing and mapping spatial distribution of root length density and potential root extraction ratio from root counts on trench profiles. *Methods in Molecular Biology, 2395*, 247–258. https://doi.org/10.1007/978-1-0716-1816-5_12

11. Gan Y.T., Campbell C.A., Janzen H.H., Lemke R., Liu L.P., Basnyat P., McDonald C.L. (2009). Root mass for oilseed and pulse crops: Growth and distribution in the soil profile. *Canadian Journal of Plant Science*, *89*, 883–893. https://doi.org/10.4141/CJPS08154
12. Gardner A.S., Maclean I.M.D., Gaston K.J. (2020). A new system to classify global climate zones based on plant physiology and using high temporal resolution climate data. *Journal of Biogeography, 47*, 2091–2101. https://doi.org/10.1111/jbi.13927
13. Gentsch N., Riechers F., Boy J., Schwenecker D., Feuerstein U., Heuermann D., Guggenberger G. (2024). Cover crops improve soil structure and change organic carbon distribution in macroaggregate fractions. *Soil, 10*, 139–150. https://doi.org/10.5194/soil-10-139-2024
14. Hudek C., Putinica C., Otten W., De Baets S. (2022). Functional root trait-based classification of cover crops to improve soil physical properties. *European Journal of Soil Science, 73*(1), e13147. https://doi.org/10.1111/ejss.13147
15. Jabbari H., Khosh kholgh Sima N.A., Akbari G.A., Allahdadi I., Shiranirad A.H. Hamed A. (2016). Study of root system relationship with water relations in Rapeseed under drought stress conditions. *Journal of Crops Improvement, 18*(1), 1–19. https://doi.org/10.22059/jci.2016.56544
16. Kaletnik H., Pryshliak V., Pryshliak N. (2020). public policy and biofuels: energy, environment and food trilemma. *Journal of Environmental Management and Tourism, 104*(36), 479–487. https://doi.org/10.14505/jemt.v10.3(35).01
17. Kashyap A., Kumari S., Garg P., Kushwaha R., Tripathi S., Sharma J., Gupta N.C., Kumar R.R., Yadav R., Vishwakarma H. (2023). Indexing resilience to heat and drought stress in the wild relatives of rapeseed-mustard. *Life. 13*(3), 738. https://doi.org/10.3390/life13030738
18. Kemper R. (2024). *Root growth of sole and mixed cover crops in organic farming. Dissertation for the attainment of the degree Doctor of Agricultural Sciences*. Institute of Crop Science and Resource Conservation. Department of Agroecology and Organic Farming. Bonn.
19. Kou X, Han W., Kang J. (2022). Responses of root system architecture to water stress at multiple levels: A meta-analysis of trials under controlled conditions. *Frontiers Plant Science, 13*, 1085409. https://doi.org/10.3389/fpls.2022.1085409
20. Kucerik J., Brtnicky M., Mustafa A., Hammerschmiedt T., Kintl A., Sobotkova J., Alamri S., Baltazar T., Latal O., Naveed M., Malicek O., Holatko J. (2024). Utilization of diversified cover crops as green manure-enhanced soil organic carbon, nutrient transformation, microbial activity, and maize growth. *Agronomy, 14*(9), 2001. https://doi.org/10.3390/agronomy14092001
21. Kutschera L., Lichtenegger E., Sobotik M. (2009). *Würzelatlas der Kulturpflanzen gemässigter Gebiete mit Arten des Feldgemüsebau*es. Frankfurt am Main : DLG-Verlag.
22. Lohosha R., Palamarchuk V., Krychkovskyi V. (2023). Economic efficiency of using digestate from biogas plants in Ukraine when growing agricultural crops as a way of achieving the goals of the European Green Deal. *Polityka Energetyczna, 26*(2), 161–182. https://doi.org/10.33223/epj/163434
23. Lohosha R., Palamarchuk V., Krychkovskyi V., Kolisnyk O., Vasyliev O. (2025). Specifics of cultivation, productivity, and energy efficiency of miscanthus giganteus for solid biofuel production *Polityka Energetyczna, 28*(1), 99–112. https://doi.org/10.33223/epj/196384
24. Lutkovska S., Kaletnik G. (2020). Modern organizational and economic mechanism for environmental safety. *Journal of Environmental Management and Tourism, XI, 3*(43), 606–612. https://doi.org/10.14505/jemt.11.3(43).14
25. Maan C., ten Veldhuis M.-C., van de Wiel B.J.H. (2023). Dynamic root growth in response to depth-varying soil moisture availability: a rhizobox study. *Hydrology and Earth System Sciences, 27*, 2341–2355. https://doi.org/10.5194/hess-27-2341-2023
26. Marcinkevičienė A., Velička R., Raudonius S., Kosteckas R. (2013). The relationship between root biomass and productivity of spring oilseed rape (*Brassica napus* L.) as influenced by crop density and fertilization. *Zemdirbyste-Agriculture, 100*(1), 39–44.
27. Pimentel M.L., Reis I.M.S., Romano M.L.P.C., de Castro J.S., Vildoso C.I.A., Gasparin E., Sia E.F. de, de Sousa L.S. (2023). Green manure, a sustainable strategy to improve soil quality: A case study in an oxisol from Northern Brazil. *Australian Journal of Crop Science, 17*(6), 488–497. https://doi.org/10.21475/ajcs.23.17.06.p3832
28. Razanov S., Ovcharuk V., Krasnyak O., Bakhmat M., Bakhmat O. (2021). Agroecological assessment of green manures grown from winter grain harvest lost in the conditions of the right-bank Forest-steppe of Ukraine. *International Journal of Ecosystems and Ecology Science, 11*(4), 895–902. https://doi.org/10.31407/ijees11.429
29. Rouse A. (2019). *A geotechnical approach to root anchorage modelling in wheat, oats and oilseed rape. PhD thesis doctor of philosophy*. College of Engineering and Physical Sciences University of Birmingham.
30. Sanchez P.A., Cuoto W., Boul S.W. (1982). The fertility capability soil classification system; interpretation application and modification. *Geoderma, 27*, 238–309.

https://doi.org/10.1016/0016-7061(82)90019-2

31. Schnepf A., Huber K., Landl M., Meunier F., Petrich L., Schmidt V. (2018). Statistical characterization of the root system architecture model CRootBox. *Vadose Zone Journal, 17*, 1–11, 170212. https://doi.org/10.2136/vzj2017.12.0212
32. Shoaib M., Banerjee B.P., Hayden M., Kant S. (2022). Roots' drought adaptive traits in crop improvement. *Plants, 30*, 11(17), 2256. https://doi.org/10.3390/plants11172256
33. Shukla D., Trivedi P.K., Sahi S. (2023). A simple protocol for mapping the plant root system architecture traits. *Journal of Visualized Experiments, 192*, e64876. https://doi.org/10.3791/64876
34. Talgre L. (2013). *Biomass production of different green manure crops and their effect on the succeeding crops yield A Thesis of the degree of Doctor of Philosophy in Plant Production*. Tartu. Estonian University of Life Sciences.
35. Tsytsiura Y. (2024 a). Evaluation of ecological adaptability of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) biopotential realization in the system of criteria for multi-service cover crop. *Journal of Ecological Engineering, 25*(7), 265–285. https://doi.org/10.12911/22998993/188603
36. Tsytsiura, Y. (2024 b). Potential of oilseed radish (*Raphanus sativus* l. var. *oleiformis* Pers.) as a multi-service cover crop (MSCC). *Agronomy Research, 22*(2), 1026–1070. https://doi.org/10.15159/AR.24.086
37. Tsytsiura, Y. (2024 c). Potential of the proline-fluorescent method for assessing plant drought tolerance on the test object of oilseed radish. *AgroLife Scientific Journal, 13*(2), 274–290. https://doi.org/10.17930/AGL2024225
38. Wahlström E.M., Hansen E.M., Mandel A., Garbout A., Kristensen H.L., Munkholm L.J. (2015). Root development of fodder radish and winter wheat before winter in relation to uptake of nitrogen. *European Journal of Agronomy, 71*, 1–9. https://doi.org/10.1016/J.EJA.2015.07.002
39. Wong K.M., Griffiths M., Moran A., Johnston A., Liu A.E., Sellers M.A., Topp C.N. (2024). Cover crop cultivars and species differ in root traits potentially impacting their selection for ecosystem services. *Plant and Soil, 500*, 279–296. https://doi.org/10.1007/s11104-023-06431-7