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Influence of Forecrop on Soil Quality Estimated on the Basis of the Growth and Development of Faba Bean and Biochemical Properties of the Soil

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Abstract: Proper crop rotation determines soil fecundity, which is pertinent for successor crops. With this problem in mind, a study was performed to evaluate the interference of spring wheat (*Triticum aestivum* L. subsp. *aestivum*), winter wheat (*T. aestivum* L. subsp. *aestivum*), maize (*Zea mays* L.), and winter rape (*Brassica napus* L.) as forecrops on the increase in faba bean (*Vicia faba* L.) and the biochemical and physicochemical properties of the soil. Tests with faba bean were performed in pots in the vegetation hall. The pots were filled with soil from under the abovementioned four plant species, and faba bean was grown. Soil unsown with faba bean was also tested to measure the rhizosphere effect. At the beginning of the experiment, and after its completion, enzymatic and physicochemical analyses of the soil were performed. On the 120th day of the study, faba bean was harvested and biometry was performed. The forecrop substantially influenced the biometric features of the faba bean and the biochemical activity of the soil. Faba beans grown in soil under spring wheat and winter wheat had the highest seed yield, while those grown in soil under the winter rape had the lowest yield. The geometric mean of the enzyme activity index was only significantly positively correlated with the number of faba bean seeds and the soil pH, as well as with the seed dry matter yield and the faba bean plant height. Faba bean cultivation increased the soil biochemical activity. The values of the biochemical and physicochemical parameters of the unsown soil were lower compared to the soil sown with faba bean. The conducted research can help to estimate the changes occurring in arable soils and maintain their stability thanks to the use of appropriate bioindicators, which are the soil enzymes. Moreover, the use of a diversified crop rotation in soil cultivation can provide a lot of information about its function, which can ultimately be used for planning the plant rotation, leading to the improvement of the soil structure and fertility, as well as its protection.

Keywords: faba bean; forecrop; soil enzymes; soil health; soil quality index; sustainable agriculture

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1. Introduction

Human activity has a very strong impact on soil processes, which is particularly noticeable in agroecosystems [1,2]. Hence, agricultural production should take account of sustainable development so as to minimize soil degradation. Soil is the cornerstone of food production, which provides it with a superior role to play in sustainable land management [3,4]. Its quality means, primarily, its ability to preserve plant productivity. It is evaluated based on soil properties like, the enzymatic activity, the contents of micro- and macro-elements, the contents of C and N, humidity, the pH, the soil structure and texture, and also the population numbers and activities of the soil microorganisms [5]. These parameters enable the observation of changes triggered in the soil environment by anthropogenic activity and natural conditions [6–8]. The purpose of plant production is to achieve the maximal mass and quality of the crop yield, usually by means of appropriate cultivation practices, which most often lead to an increase in soil fertility. However, im-

proper land management may hamper the functioning of agroecosystems by, among other things, suppressing the biological activity of the soil [9–11].

Due to their sensitivity to varying environmental factors, soil enzymes are well-proven reliability indicators in soil quality diagnosis. They perfectly indicate whether the course of biochemical reactions proceeding in the soil environment has been correct or somehow disrupted [12–15]. Given their prompt reactions and heightened sensitivity to modifications in the soil conditions induced by arable land management, enzymes have been deemed sensitive and reliable indicators of soil usability for performing ecological functions [16–21]. There are many enzymes, e.g., urease, alkaline phosphatase, acid phosphatase, arylsulfatase, β-glucosidase, cellulase, and invertase, in the soil that increase the rate of chemical reactions, as well as biological and biochemical processes. Soil enzymes are implicated in the circulation of elements and the conversations concerning SOM (soil organic matter), which has a huge role in plant development. They are mainly responsible for the synthesis of proteins and nucleic acids, the hydrolysis of nitrogen compounds, the degradation of amino acids, and the metabolism of organic phosphorus species [22,23]. These processes result in the release of elements and ions that become accessible to plants, which is of vital importance to farming production [5]. Bogati et al. [24] demonstrated that extracellular enzymes synthesized by live microorganisms and endoenzymes secreted after their death play important functions in the soil environment, as they enable the release of bioavailable carbon and other biogenic elements, thereby affecting the control of the succession and stabilization of biotic soil communities [25,26]. The synthesis and secretion of enzymes responsible for organic material degradation in the soil strongly depend on the availability and quality of the substrates, which, in turn, are affected by the species abundance and productivity of the plants [27]. Enhanced plant productivity may contribute to the increased carbon content of the soil by producing litter from the plant shoots and roots and releasing root secretions, thereby increasing the substrate availability and enzyme activity [28]. Plant roots produce secretions that include various organic compounds that are used by the rhizosphere microbiota as a source of carbon and energy. These compounds include, among others, phenols, saccharides, organic acids, sterols, and vitamins [29].

It is essential to evaluate the dependence between soil biochemical and physicochemical properties, crop yields, and soil cultivation systems so to evaluate the impact of agriculture on the functioning and productivity of soil ecosystems. Extending the knowledge about the response of these parameters to diversified soil management is deemed necessary because they are the indicators of the qualities and fertility of agricultural soils, which are, in turn, pivotal to sustainable land management. Modern agricultural challenges force the search for innovative solutions that will not only increase plant yields, but also contribute to maintaining long-term soil quality. One of the main tools contributing to the achievement of these goals is proper soil tillage planning with the use of appropriate plants and the estimation of the soil fertility based on biochemical and physicochemical indicators [30].

Holatko et al. [31] reported that the varied use of a suitable forecrop is a desirable practice in crop production, which not only leads to increased crop yields but is also related to sustainability. An example is growing wheat after maize or legumes [32,33]. This forecrop has a beneficial effect on plant growth through the improved yield [34], increased nutrient use efficiency, soil aggregation [34], and the number and diversity of soil microorganisms [35,36]. Fabaceae plants have an important function in crop rotation because they not only enhance the soil fertility and quality but also eliminate weeds, pathogens, and pests. In addition, they help to improve the soil structure, increase the biodiversity, and accelerate nitrogen and phosphorus immobilization in the soil environment [4,37,38]. In their study, Faligowska et al. [39] proved that legumes as a forecrop increased the efficiency of all post-harvest crops in the rotation. The rotation conducted in the 2012–2018 field experiment included the following crops: legumes and spring barley, winter rape, spring wheat, and winter wheat. The study by Szymanska et al. [40] also showed that legumes

had a beneficial effect on the growth and development of spring barley, winter triticale, and winter rape.

Soil use has a meaningful influence on the microbiological, biochemical, and chemical processes in the soil, as it modifies the quantity and quality of its organic matter [41,42]. An experiment carried out by Błońska et al. [43] showed differences in the soil biochemical properties, with the lowest dehydrogenases and urease activities found in the agriculturally cultivated soils and enhanced activities of these enzymes—in the pasture and forest soils. This relationship is related to the high SOM content and the respective C:N ratio. In turn, Danuoras et al. [44] reported that landforms, plant biodiversity, and humus content play a crucial role in the soil biochemical activity in grasslands and forests.

The present study aimed to assess the impact of the forecrops (spring wheat, winter wheat, maize, winter rape) and soil use (unsown soil and sown soil) on the soil quality as assessed by its biochemical activity and physicochemical properties during the growth of faba bean. The following hypotheses were proposed: (a) the type of forecrop affects the yielding of faba bean; (b) the type of forecrop modifies the biochemical, chemical, and physical properties of the soil; and (c) soil use modifies its biochemical and physicochemical properties.

2. Materials and Methods

2.1. Soil Material

Soil was brought in from the Krzyżanowo village (eastern part of the Pomeranian Province, Poland NE, 54.0242°N, 19.1216°E). This area belongs to the Vistula Marshland, a macroregion—Gdansk Coast, and subprovince—South Baltic Coast. In line with the IUSS Working Group [45] classification, the soil was categorized as Fluvisols. The soil was collected from an arable field, from the topsoil and humus layer (layer depth from 0 to 20 cm), where the following crops were grown: spring wheat (SW)—*Triticum aestivum* L. subsp. *aestivum* "*Tybalt*" cultivar, winter wheat (WW)—*Triticum aestivum* L. subsp. *aestivum* "*Apostel*" cultivar, maize (M)—*Zea mays* L. "*SY Calo*" cultivar, and winter rape (WR)—*Brassica napus* L., "*Kuga* F1" cultivar. The crops were amended with the following fertilizer doses (per pure compound in kg ha^{-1}): SW and WW—198 kg N, 60 kg P and 90 kg K; M—310 kg N, 62 kg P and 93 kg K; and WR—264 kg N, 80 kg P and 120 kg K. Table 1 presents the soil physicochemical properties, whereas Table 2 collates data on the soil enzymatic activity.

Table 1. Physicochemical properties of the soil used in the experiment.

Soil Properties	Unit	Forecrop (Fc)			
		Spring Wheat (SW)	**Winter Wheat (WW)**	**Maize (M)**	**Winter Rape (WR)**
Soil type		Silty loam clay (Slc)	Silty loam clay (Slc)	Silty loam clay (Slc)	Silty loam clay (Slc)
		Particle-size distribution			
Clay (<0.002 mm)	%	1.000 ± 0.026	1.000 ± 0.010	2.000 ± 0.021	1.000 ± 0.030
Silt (0.02–0.05 mm)		69.000 ± 2.082	65.000 ± 1.000	69.000 ± 1.732	61.000 ± 2.517
Sand (0.0–2.0 mm)		30.000 ± 1.528	34.000 ± 2.517	29.000 ± 2.082	38.000 ± 2.646
		Chemical properties			
pH	1 Mol KCl dm^{-3}	6.233 ± 0.058	6.367 ± 0.058	6.233 ± 0.058	5.933 ± 0.058
Hydrolytic acidity (HAC)	mMol^{+} kg^{-1} d.m. soil	26.750 ± 0.433	18.750 ± 0.750	21.250 ± 0.433	28.000 ± 0.433
Sum of exchangeable bases (EBC)		238.000 ± 2.00	298.000 ± 2.00	386.667 ± 2.309	210.000 ± 2.00
Sorption capacity (CEC)		264.750 ± 2.385	316.750 ± 1.250	407.917 ± 2.554	238.000 ± 2.385
Base saturation (BS)	%	89.896 ± 0.090	94.080 ± 0.260	95.645 ± 0.076	88.236 ± 0.089
Organic carbon content (C_{org})	g kg^{-1} d.m. soil	18.220 ± 0.023	18.770 ± 0.018	17.170 ± 0.013	18.290 ± 0.012
Total nitrogen content (N_{tot})		2.460 ± 0.009	2.630 ± 0.004	2.625 ± 0.006	2.745 ± 0.004
C:N ratio		7.406 ± 0.009	7.137 ± 0.035	6.541 ± 0.060	6.663 ± 0.035

Table 2. Enzymatic properties of the soil (kg^{-1} d.m. soil).

Forecrop (Fc)	Dehydrogenases (Deh) µMol TFF	Catalase (Cat) Mol O_2	Alkaline Phosphatase (Pal)	Acid Phosphatase (Pac)	β-Glucosidase (Glu)	Arylsulfatase (Aryl)	Urease (Ure) mMol $N\text{-}NH_4$	Geometric Mean of Enzyme Activities (GMea)
			mMol PNP					
SW	22.161 ± 0.363	0.592 ± 0.004	4.587 ± 0.230	6.359 ± 0.101	0.518 ± 0.003	0.520 ± 0.021	1.044 ± 0.021	1.951 ± 0.001
WW	12.056 ± 0.872	0.622 ± 0.004	6.419 ± 0.144	6.340 ± 0.252	0.430 ± 0.00 9	1.280 ± 0.032	1.278 ± 0.021	2.153 ± 0.002
M	12.172 ± 1.320	0.624 ± 0.002	4.928 ± 0.166	6.940 ± 0.089	0.448 ± 0.002	0.757 ± 0.018	0.731 ± 0.086	1.813 ± 0.002
WR	20.112 ± 0.810	0.554 ± 0.004	4.408 ± 0.083	7.202 ± 0.022	0.475 ± 0.005	0.542 ± 0.022	1.317 ± 0.065	1.981 ± 0.001

Explanations of forecrops can be found in Table 1.

2.2. Experiment Establishment and Design

The soil was collected from plots where SW, WW, M, and WR were cultivated, and then transported to the greenhouse of the Educational and Experimental Station in Olsztyn (NE Poland, Central Europe). The vegetation pot experiment was conducted for 120 days, from May to September 2021. Before the pot experiment, the collected soil batches were passed through a screen, and then 5 kg portions of each soil type were weighed into plastic pots (7 dm^3 in volume) in 6 replications. The experiment was carried out in two variants: with samples of the soil without seeding plants (unsown—Us) (3 repetitions), and with the samples of soil sown (Ss) with faba bean (Fb)—*Vicia faba* L. (3 repetitions). All soil samples were fertilized with identical doses of P and K (per pure compound), i.e., a P dose of 91.65 mg kg^{-1} in the form of KH_2PO_4 and a K dose of 36.14 mg kg^{-1} in the form of KH_2PO_4 + KCl. In the second mentioned variant, Fb of the "*Albus*" cultivar was sown in each pot (10 seeds per pot), and then the soil was brought to a constant humidity (50% of the capillary volume of water). At the sprouting phase of Fb (developmental phase 0), the plants were thinned, and 5 plants were left in each pot. The soil moisture was monitored throughout the experimental period and kept at a stable level (water losses were replenished 3 times a day with deionized water). Over the experimental period, the conditions in the greenhouse were as follows: the mean air humidity—70.0%, the mean air temperature—16.8 °C, and the mean day length—10.2 h. On the day of harvest, faba bean was analyzed for biometric parameters, and the soil material was collected for enzymatic and physicochemical analyses. The soil material was collected from each pot (3 repetitions) separately for each combination (forecrop—Fc and soil use—Su). From each combination, the soil from the 3 pots was combined and thoroughly mixed. Moist soil was collected for the microbiological and enzymatic analyses into sterile plastic bags in the amount of 700 g. In turn, the soil intended for the physicochemical analyses was air-dried, sieved through a screen, and then placed in plastic bags (weight of the soil sample was 700 g). Enzyme activity assay was performed on the samples of moist soil, and physicochemical activity assay was performed on the samples of air-dry soil. A schematic diagram of the vegetation pot experiment is presented in Figure 1.

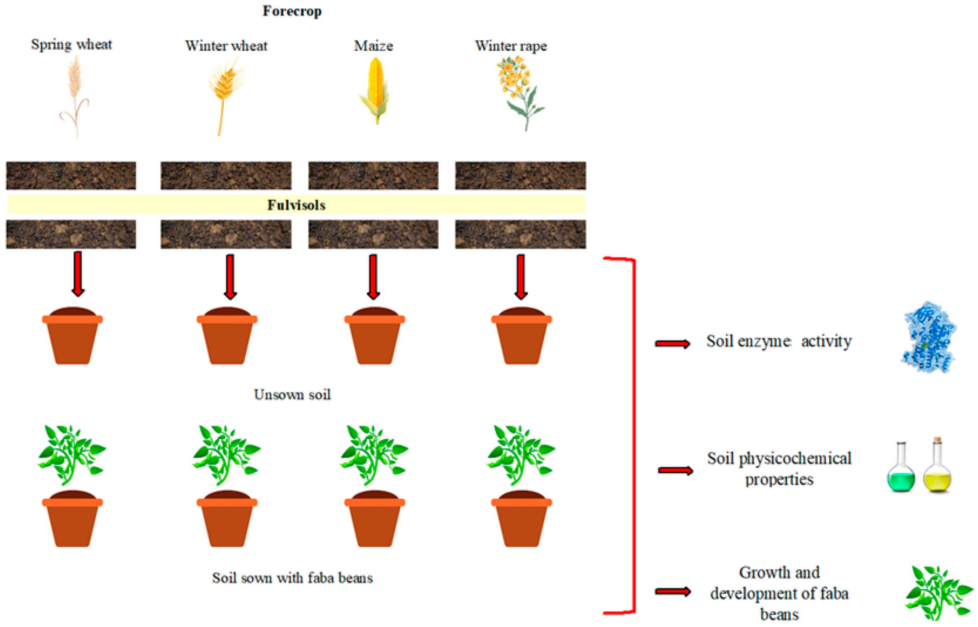


Figure 1. Schematic diagram of the vegetation pot experiment.

2.3. Biometry of Faba Bean

The plants were harvested on day 120 of the experiment, at the BBCH 99 developmental stage (harvested product), according to the BBCH scale (Biologische Bundesantalt, Bundessortenamt und Chemische Industrie). The plant biometry was performed for the plants from each pot sown with Fb (each pot contained 5 plants, giving a total of 15 plants):

- Stem length—SLe (cm);
- Number of pods per plant—PNu;
- Number of seeds per pod—SNu;
- Dry matter yield of: seeds—YDMSe, leaves—YDMLe, stems—YDMSt and siliques—YDMSi (g d.m. per plant).

In addition, the leaf greenness index (SPAD) was determined on two dates using a chlorophyll meter when Fb was at the following developmental stages:

- BBCH 32—2 visibly extended internodes;
- BBCH 79—nearly all pods have reached the final length.

2.4. Physicochemical Analysis of the Soil

Basic physicochemical analyses of the soil were carried out before the establishment of the experiment (soil samples collected from the crop field) and after the Fb harvest (after 120 days of the experiment). Before the physicochemical analyses, the soil material was air-dried and sieved through a screen. The soil samples were determined for the following:

- Particle size distribution—with the laser diffraction method;
- pH—with the potentiometric method;
- HAC and EBC—with the Kappen method;
- C_{org} and N_{tot}—using a Vario Max Cube CN analyzer (Elementar Analysen-systeme GmbH, Germany).

The listed physicochemical features were determined as described in the publication by Wyszkowska et al. [46].

2.5. Enzymatic Analysis of the Soil

The enzymatic analysis of the soil conducted on the day the experiment was established and on day 120 of the experiment included determinations of activities of the following: Deh with 3% $C_{19}H_{15}ClN_4$ [47] as a substrate; Cat—3% H_2O_2 [48]; Pal and Pac—0.115 M

$O_2NC_6H_4OP(O)(ONa)_2 \times 6H_2O$; Aryl—0.02 M $C_6H_4KNO_6S$; Glu—0.025 M $C_{12}H_{15}NO_8$; and Ure—10% CH_4N_2O [49]. The method for determining the enzymatic activity was described in the papers by Kucharski et al. [50] and Wyszkowska et al. [46]. All enzymatic analyses were conducted in 3 repetitions for each experimental variant with the Us and Ss with Fb. The results of the soil enzyme activity determination were then used to compute the GMea based on the equation posited by Paz-Ferreiro et al. [51]:

$$GMea = (Deh \times Cat \times Pal \times Pac \times Aryl \times Glu \times Ure)^{1/7}$$

The rhizosphere effect (R:S), a ratio of the enzyme activity in the SS with Fb to that in the Us, was computed as well.

2.6. Statistical Analysis of the Results

The research results were subjected to 2-way analysis of variance (ANOVA; I: forecrop—Fc, II: soil use—Su) at $p = 0.05$, using Statistica 13.3 package [52]. The following analyses were conducted:

- Homogeneous groups (2-way analysis, Tukey *t*-test $p = 0.05$)—computed separately for each enzyme and each physical and chemical property of the soil;
- Percentage of the observed variability (η^2) — determined for enzyme activity and soil chemical properties;
- PCA (principal component analysis)—conducted for enzyme activity and soil physicochemical properties;
- Pearson's linear correlations ($p = 0.05$) between soil biochemical parameters and soil chemical properties — presented as a heat map.

3. Results

3.1. Biometric Traits of Faba Bean

The growth of faba bean (Fb) followed different patterns on the soils with various crops grown as the forecrop (Fc) (Figure 2, Table 3). Fb developed the longest stems (SLe) when grown after winter wheat (WW) (94.943 cm). The highest number of pods (PNu) per plant was noted when it was grown after spring wheat (SW) (6.120 pods per plant, on average), whereas the highest number of seeds (SNu) per pod—when it was cultivated after maize (M) (1.885 seeds per pod, on average). The dry matter yield of seeds (YDMSe) per pod was the highest in the Fb grown after WW (4.099 g seeds per pod, on average). The dry matter content of the individual morphological parts of the Fb was found to depend on the Fc, so its YDMSe was the highest when it was grown after WW (4.099 g d.m. plant^{-1}, on average), whereas the dry matter yield of leaves (YDMLe), dry matter yield of stems (YDMSt), and dry matter yield of siliques (YDMSi)—when it was grown after SW (2.489, 3.554, and 2.213 g d.m. plant^{-1}, on average, respectively).

Figure 2. Faba bean at BBCH 63 (flowers open 3 racemes per plant). Explanations of the abbreviations can be found in Section 2.

Table 3. Biometry of the faba bean.

Fc	Stem Length (cm)	Pod Number (Plant^{-1})	Seed Number (Pod^{-1})	Dry Matter Yield Of			
				Seeds	Leaves	Stems	Silique
				g d.m. Plant^{-1}			
SW	93.880 ± 1.339 ^{a}	6.120 ± 0.676 ^{a}	1.708 ± 0.071 ^{b}	3.915 ± 0.712 ^{a}	2.489 ± 0.144 ^{a}	3.554 ± 0.279 ^{a}	2.213 ± 0. 092 ^{a}
WW	94.943 ± 4.253 ^{a}	5.300 ± 0.817 ^{ab}	1.782 ± 0.075 ^{b}	4.099 ± 1.018 ^{a}	1.993 ± 0.340 ^{ab}	3.488 ± 0.338 ^{a}	2.157 ± 0.395 ^{a}
M	92.307 ± 2.451 ^{b}	4.967 ± 1.054 ^{ab}	1.885 ± 0.078 ^{a}	3.714 ± 0.496 ^{ab}	2.168 ± 0.51 7 ^{ab}	3.242 ± 0.554 ^{b}	2.075 ± 0.372 ^{b}
WR	89.783 ± 3.172 ^{c}	4.233 ± 0.446 ^{c}	1.810 ± 0.044 ^{a}	3.408 ± 0.915 ^{b}	1.860 ± 0.421 ^{b}	2.976 ± 0.804 ^{c}	1.739 ± 0.455 ^{c}
p-value	0.072	0.004	0.044	0.508	0.052	0.008	0.029

Explanations of the abbreviations can be found in Section 2. Homogeneous groups marked with letters (a–c) were calculated separately for each parameter.

It was also observed that, by modifying the physicochemical features of the soil, the Fc had an immediate impact on the leaf greenness index (SPAD) of the Fb (Figure 3), which was the highest when it was grown after WW (34.944), whereas the lowest—when it was cultivated after winter rape (WR) (28.023). At both analyzed developmental stages of Fb, i.e., at 2 visibly extended internodes (BBCH 32) and when nearly all pods had reached final length (BBCH 79), the SPAD value was the highest in the variant with WW used as the Fc (39.537 and 30.350, respectively).

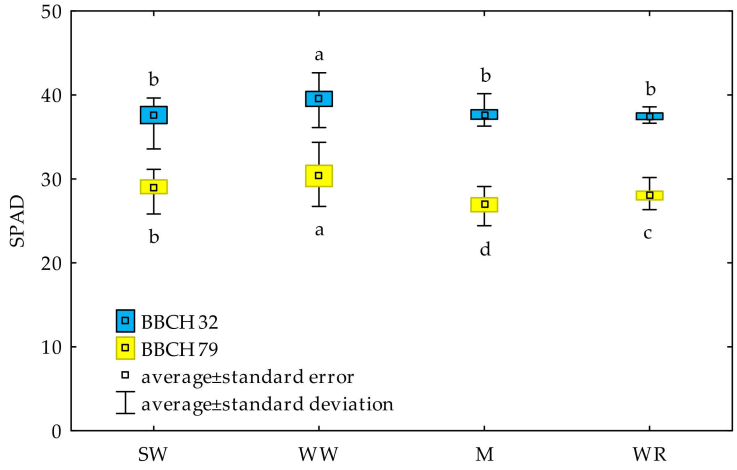


Figure 3. Leaf greenness index of the faba bean. Explanations of the abbreviations can be found in Section 2. Homogeneous groups marked with letters (a–d) were calculated separately for each phase of bean development.

3.2. Biochemical Properties of the Soil

The statistical analysis demonstrated (Figure 4) that activity of the soil enzymes was significantly affected by the sowing of the soil with Fb (Ss), i.e., by 84.63% (dehydrogenases—Deh) to 99.87% (catalase—Cat). The Fc and the interactions of the analyzed factors affected enzyme activity to a small extent. The values of the geometric mean of enzyme activities (GMea) were most strongly influenced by the soil use (η^2 = 90.69%).

After the Fb harvest (120 days), unsown soil (Us) collected after M cultivation exhibited the highest activity of Deh (13.537 µMol TFF), Cat (0.591 Mol O_2), and arylsulfatase—Aryl (0.384 mMol PNP); that collected after SW cultivation exhibited the highest activity of acid phosphatase—Pac (5.603 mMol PNP), whereas the soil after SW cultivation showed the highest activity of alkaline phosphatase—Pal (3.877 mMol PNP), *β*-glucosidase—Glu (0.403 mMol PNP), and urease—Ure (0.892 mMol N-NH_4). The Ss with Fb after M cultivation exhibited the highest activity of Deh (19.249 µMol TFF), Cat (0.651 Mol O_2), and Aryl (0.438 mMol PNP); the soil after SW cultivation as the Fc—the highest activity of Glu (0.582 mMol PNP); the soil cultivated after WW—the highest activity of Pal (5.663 mMol PNP) and Ure (1.245 mMol N-NH_4); and the soil after WR cultivation—the highest activity of Pac (6.648 mMol PNP). Activities of the soil enzymes were, indeed, lower in the Us

with respect to the Ss with Fb, i.e., Deh activity was lower by 15.80% to 71.13%, Cat activity by 7.98% to 12.82%, Pal activity by 5.29% to 41.46%, Pac activity by 2.05% to 37.53%, Glu activity by 1.92% to 42.78%, Aryl activity by 12.33% to 30.50%, and Ure activity by 23.91% to 52.54%. Also, the values of GMea indices were significantly higher in the Ss than Us. The highest value of the GMea index was determined in the Ss with Fb after M cultivation (GMea = 1.853), and the lowest one—in the Us collected also after M cultivation (GMea = 1.210). The GMea value determined for the Us collected after SW cultivation decreased 1.3 times, after WW—1.2 times, after M—1.5 times and after WR—1.4 times, in comparison to the Ss with Fb (Table 4).

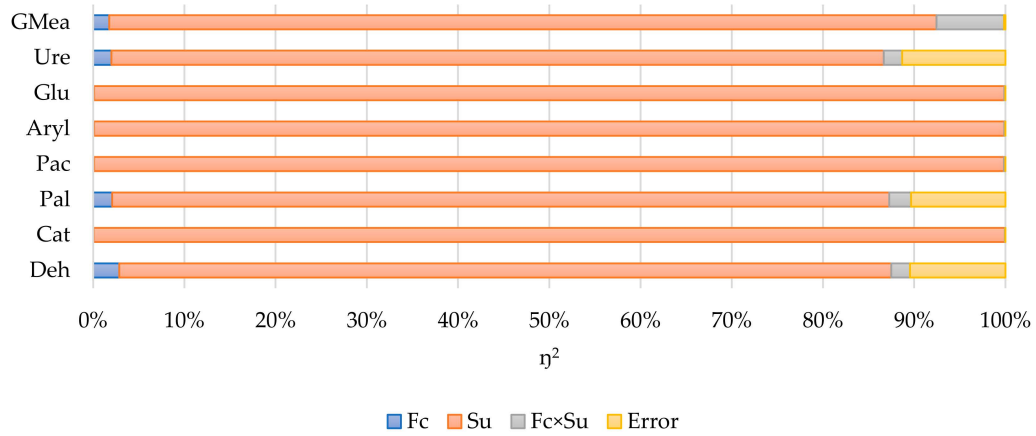


Figure 4. The percentage of variability observed (η^2) in the soil biochemical parameters. Explanations of the abbreviations can be found in Section 2. Variable factors: Fc—forecrop, Su—soil use, Fc×Su—interaction of factors.

Table 4. Soil enzymatic activity (kg^{-1} d.m. soil).

Fc	Deh µMol TFF	Cat Mol O_2	Pal	Pac	Glu	Aryl	Ure mMol N-NH_4	GMea
			mMol PNP					
Us								
SW	13.537 ± 1.118 ^{d}	0.551 ± 0.004 ^{d}	3.309 ± 0.018 ^{f}	5.603 ± 0.157 ^{d}	0.333 ± 0.006 ^{g}	0.303 ± 0.004 ^{e}	0.420 ± 0.018 ^{g}	1.286 ± 0.009 ^{f}
WW	8.375 ± 0.598 ^{f}	0.588 ± 0.004 ^{c}	3.877 ± 0.102 ^{d}	3.898 ± 0.039 ^{h}	0.408 ± 0.029 ^{e}	0.350 ± 0.007 ^{d}	0.892 ± 0.018 ^{b}	1.378 ± 0.002 ^{e}
M	5.558 ± 0.538 ^{g}	0.591 ± 0.007 ^{bc}	2.647 ± 0.056 ^{g}	4.816 ± 0.049 ^{e}	0.403 ± 0.014 ^{e}	0.384 ± 0.014 ^{c}	0.589 ± 0.034 ^{d}	1.210 ± 0.017 ^{g}
WR	15.023 ± 0.733 ^{c}	0.531 ± 0.003 ^{e}	2.486 ± 0.156 ^{h}	4.153 ± 0.027 ^{g}	0.380 ± 0.006 ^{f}	0.330 ± 0.035 ^{e}	0.498 ± 0.017 ^{f}	1.262 ± 0.008 ^{f}
Ss								
SW	17.408 ± 0.490 ^{b}	0.632 ± 0.004 ^{a}	3.494 ± 0.128 ^{e}	5.720 ± 0.103 ^{c}	0.582 ± 0.001 ^{a}	0.436 ± 0.028 ^{a}	0.552 ± 0.018 ^{e}	1.632 ± 0.022 ^{d}
WW	12.273 ± 0.062 ^{e}	0.639 ± 0.004 ^{a}	5.663 ± 0.069 ^{a}	4.375 ± 0.093 ^{f}	0.416 ± 0.003 ^{d}	0.411 ± 0.011 ^{b}	1.245 ± 0.017 ^{a}	1.702 ± 0.010 ^{c}
M	19.249 ± 0.775 ^{a}	0.651 ± 0.004 ^{a}	4.004 ± 0.033 ^{c}	6.421 ± 0.028 ^{b}	0.430 ± 0.015 ^{c}	0.438 ± 0.007 ^{a}	1.241 ± 0.017 ^{a}	1.853 ± 0.010 ^{a}
WR	17.842 ± 0.838 ^{b}	0.607 ± 0.007 ^{b}	4.247 ± 0.001 ^{b}	6.648 ± 0.135 ^{a}	0.533 ± 0.002 ^{b}	0.412 ± 0.007 ^{b}	0.792 ± 0.017 ^{c}	1.764 ± 0.004 ^{b}
				p-value				
Fc	0.064	<0.001	0.086	<0.001	<0.001	<0.001	0.042	<0.001
Su	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Fc×Su	0.032	<0.001	0.043	<0.001	<0.001	<0.001	0.023	<0.001

Explanations of the abbreviations can be found in Section 2. Homogeneous groups marked with letters (a–h) were calculated separately for each enzyme.

Furthermore, the conditions developed in the soil after SW cultivation promoted, to the greatest extent, the activities of Cat (R:S = 1.148), Aryl (R:S = 1.439), and Glu (R:S = 1.750); those developed in the soil after M cultivation—the activities of Deh (R:S = 3.494) and Ure (R:S = 2.108), whereas those found after WR cultivation—the activities of Pal (R:S = 1.712) and Pac (R:S = 1.601) (Figure 5).

The principal component analysis (PCA) results demonstrated (Figure 6) that the parameters such as the pH value, the sorption capacity (CEC) of the soil, and the total nitrogen content (N_{tot}) were negatively correlated with the PC1, explaining 51.90% of the total variability, and that the activities of Deh and Pac, the hydrolytic acidity (HAC), and the ratio of organic carbon to total nitrogen content (C:N ratio) were negatively correlated with the PC2, explaining 29.93% of the total variability.

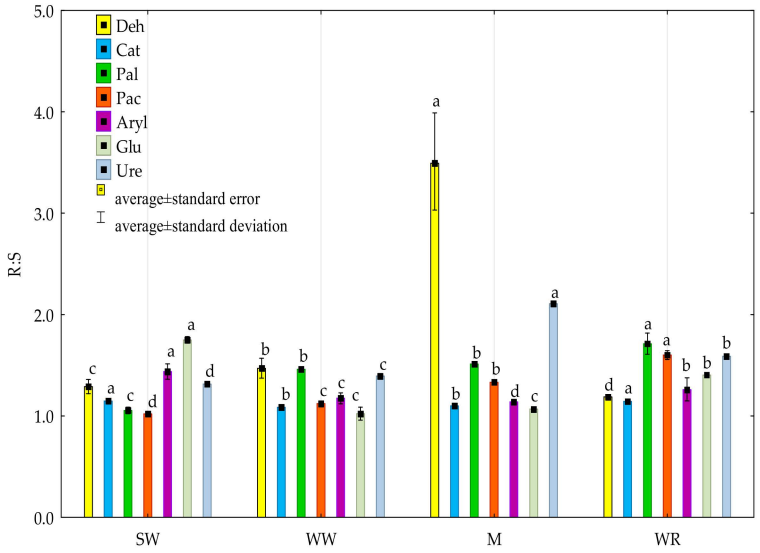
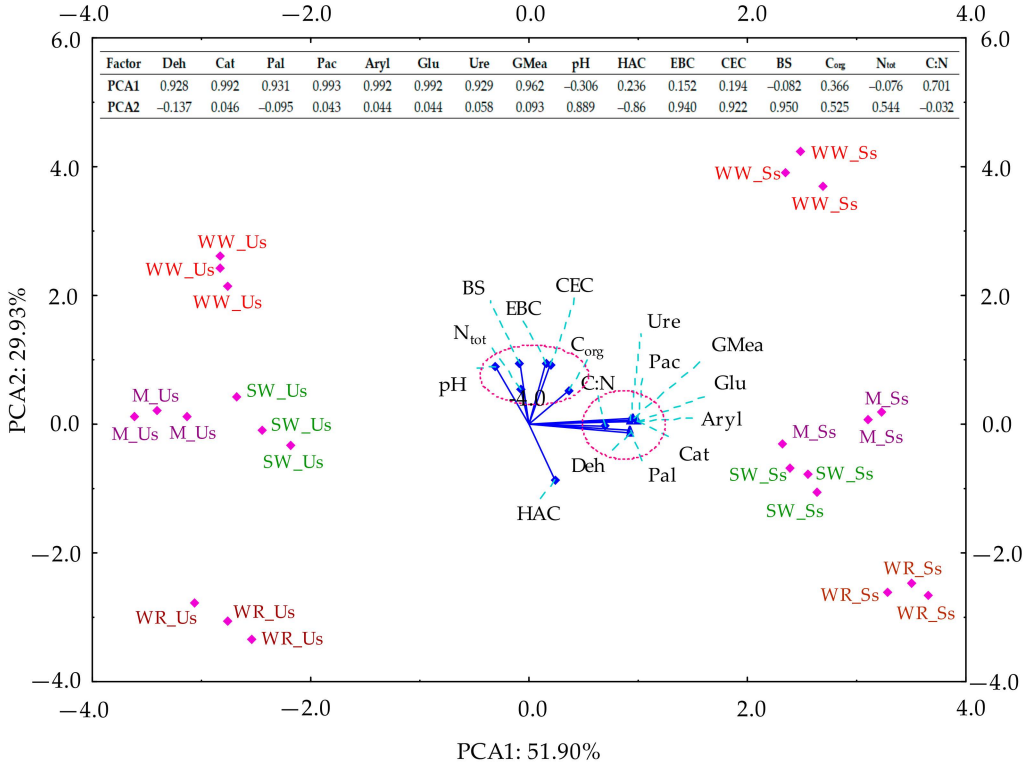


Figure 5. The rhizosphere effect (R:S) on the soil enzymatic activity. Explanations of the abbreviations can be found in Section 2. Homogeneous groups, marked with letters (a–d), were compared between soil use methods separately for each enzyme.



Factor	Deh	Cat	Pal	Pac	Aryl	Glu	Ure	GMea	pH	HAC	EBC	CEC	BS	C_{org}	N_{tot}	C:N
PCA1	0.928	0.992	0.931	0.993	0.992	0.992	0.929	0.962	−0.306	0.236	0.152	0.194	−0.082	0.366	−0.076	0.701
PCA2	−0.137	0.046	−0.095	0.043	0.044	0.044	0.058	0.093	0.889	−0.86	0.940	0.922	0.950	0.525	0.544	−0.032

Figure 6. PCA of the soil biochemical and chemical parameters. Explanations of the abbreviations can be found in Section 2.

The enzyme activity and GMea index were significantly positively correlated with the C:N, whereas the organic carbon content (C_{org})—with the Ure activity. The remaining physicochemical parameters of the soil had no significant impact on the activity of the soil enzymes (Figure 7).

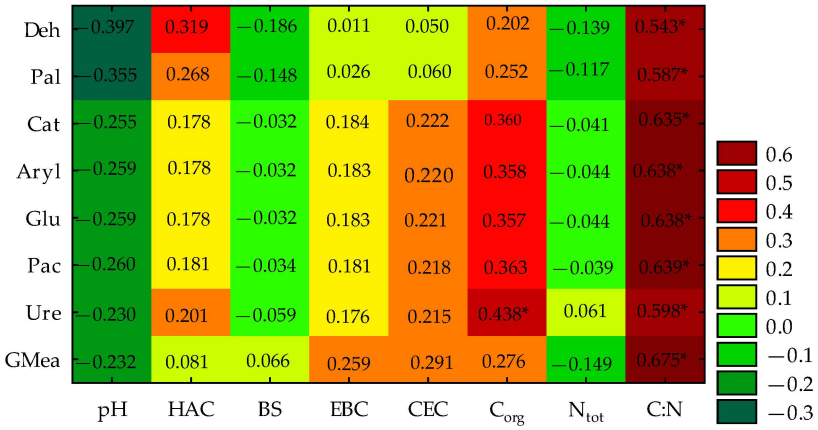


Figure 7. The interaction of soil enzyme activity and soil physicochemical properties, n = 24, *—significant differences at $p = 0.05$. Explanations of the abbreviations can be found in Section 2.

3.3. Physicochemical Properties of the Soil

The physicochemical properties of the soil (Figure 8) were most strongly modified by the Fc, as indicated by the percentage of the observed variability (η^2) which ranged from 87.79% (pH) to 98.55% (base saturation—BS). The contents of C_{org} and N_{tot}, as well as the C:N ratio in the soil, were most strongly modified by the interactions of Fc (η^2 reached 44.22%, 47.88%, and 19.57%, respectively). The soil use had the strongest impact on the C:N value (η^2 =39.46%), whereas its effect on the remaining analyzed soil properties was less pronounced and ranged from 2.92% (HAC) to 13.28% (C_{org}).

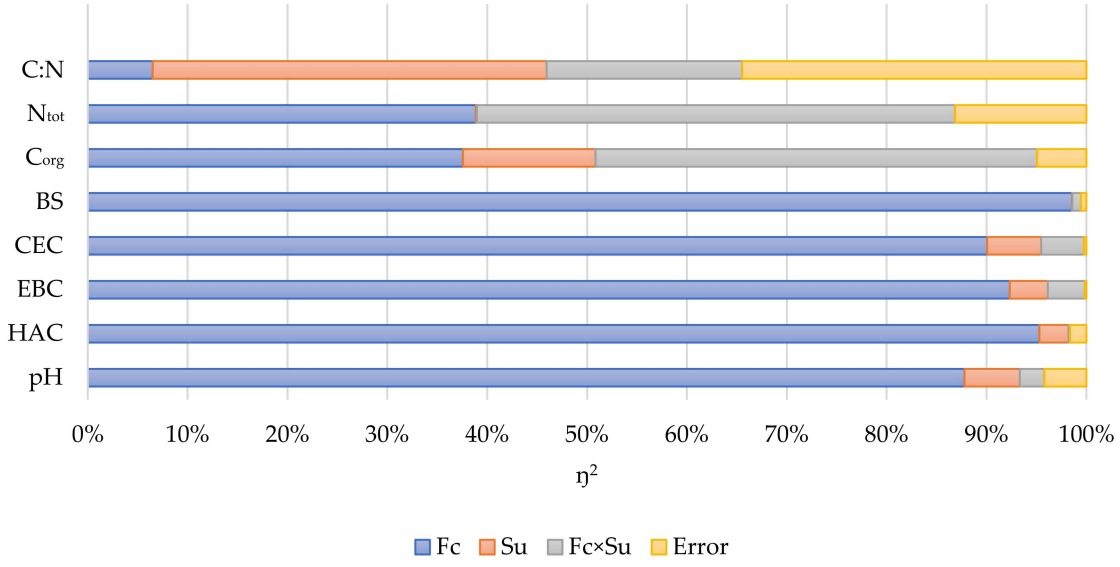


Figure 8. The percentage of variability observed (η^2) in the physicochemical properties of the soil. Explanations of the abbreviations can be found in Section 2.

The pH of the Us soil collected after SW, WW, M, and WR cultivation ranged from 5.833 to 6.333, whereas that of the Ss with Fb—from 5.633 to 6.333. Considering the soil use (Su), it was found that the pH values were higher and the HAC values were lower in the Us compared to the Ss with Fb. In turn, the C:N ratio was higher in the Ss with Fb than in the Us. The Ss with Fb after WW cultivation had the most beneficial values of pH, HAC, the sum of exchangeable base (EBC), CEC, and BS. Opposite observations were made for the Ss with Fb after WR cultivation, i.e., its pH, EBC, CEC, and BS values were the lowest, whereas the HAC value was the highest (Table 5).

Table 5. Physicochemical properties of the soil (kg^{-1} d.m. soil).

Fc	pH	HAC	EBC	CEC	BS (%)	C_{org}	N_{tot}	C:N
		$mmol^{(+)}$ kg^{-1} d.m. Soil				g kg^{-1} d.m. Soil		
				Us				
SW	6.167 ± 0.058 ^{b}	27.750 ± 0.750 ^{b}	240.000 ± 2.000 ^{d}	267.750 ± 1.750 ^{d}	89.635 ± 0.299 ^{c}	20.090 ± 0.230 ^{a}	2.540 ± 0.090 ^{a}	7.914 ± 0.190 ^{ab}
WW	6.333 ± 0.58 ^{a}	19.250 ± 0.433 ^{e}	300.667 ± 2.082 ^{b}	319.917 ± 1.665 ^{b}	93.982 ± 0.165 ^{a}	18.770 ± 0.180 ^{c}	2.415 ± 0.035 ^{bc}	7.773 ± 0.038 ^{ab}
M	6.167 ± 0.058 ^{b}	21.750 ± 0.750 ^{cd}	228.000 ± 2.000 ^{e}	249.750 ± 2.750 ^{e}	91.293 ± 0.204 ^{b}	19.030 ± 0.130 ^{bc}	2.520 ± 0.060 ^{ab}	7.555 ± 0.232 ^{b}
WR	5.833 ± 0.058 ^{c}	29.250 ± 0.750 ^{b}	212.000 ± 2.000 ^{f}	241.250 ± 1.750 ^{f}	87.875 ± 0.336 ^{e}	17.700 ± 0.120 ^{d}	2.265 ± 0.035 ^{d}	7.816 ± 0.174 ^{ab}
				Ss				
SW	6.067 ± 0.058 ^{b}	29.250 ± 0.750 ^{b}	236.000 ± 2.000 ^{d}	265.250 ± 2.750 ^{d}	88.974 ± 0.168 ^{d}	19.430 ± 0.060 ^{b}	2.455 ± 0.015 ^{ab}	7.915 ± 0.024 ^{ab}
WW	6.333 ± 0.058 ^{a}	20.250 ± 0.750 ^{de}	334.000 ± 2.000 ^{a}	354.250 ± 2.750 ^{a}	94.285 ± 0.167 ^{a}	20.260 ± 0.360 ^{a}	2.525 ± 0.005 ^{ab}	8.024 ± 0.158 ^{a}
M	6.033 ± 0.058 ^{b}	23.250 ± 0.750 ^{c}	256.000 ± 2.000 ^{c}	279.250 ± 2.462 ^{c}	91.675 ± 0.222 ^{b}	18.775 ± 0.325 ^{c}	2.330 ± 0.020 ^{cd}	8.058 ± 0.070 ^{a}
WR	5.633 ± 0.058 ^{d}	31.250 ± 0.433 ^{a}	217.333 ± 1.155 ^{f}	248.583 ± 1.588 ^{e}	87.429 ± 0.094 ^{c}	19.405 ± 0.085 ^{b}	2.405 ± 0.025 ^{bc}	8.069 ± 0.119 ^{a}
				p-value				
Fc	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.046
Su	<0.001	<0.001	<0.001	<0.001	0.053	<0.001	0.032	<0.001
Fc×Su	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	0.023

Explanations of the abbreviations can be found in Section 2. Homogeneous groups denoted by letters $^{(a–f)}$ were calculated separately for each physicochemical parameter of the soil.

3.4. Relationships between the Studied Soil Parameters

Based on the calculated correlation coefficients (Table 6), there were significant positive correlations between the GMea and SNu; soil pH and SLe and YDMSe, C_{org} and N_{tot}; SLe and YDMSe and YDMSt; as well as YDMSt and YDMSi. In turn, significant negative correlations were found between forecrop (Fc) and PNu and YDMSt; Deh and $C_{org;}$, Aryl and Ure, HAC, and BS.

Table 6. Interactions between the studied soil properties and plant biometry.

Variable	Fc	Deh	Cat	Pal	Pac	Aryl	Glu	Ure	GMea	pH	HAC	EBC	CEC	BS	C_{org}	N_{tot}	C:N	SLe	PNu	SNu	YDMSe	YDMLe	YDMSt	YDMSi
Fc	1.000																							
Deh	0.350	1.000																						
Cat	−0.438	−0.065	1.000																					
Pal	0.083	−0.873	0.100	1.000																				
Pac	0.609	0.940	−0.340	−0.738	1.000																			
Aryl	−0.214	0.393	−0.610	−0.713	0.394	1.000																		0.801 ÷ 1.00
Glu	−0.394	0.652	0.578	−0.753	0.355	0.200	1.000																	0.601 ÷ 0.800
Ure	0.269	−0.326	0.602	0.672	−0.323	−0.997 *	−0.174	1.000																0.401 ÷ 0.600
GMea	0.752	0.474	0.245	0.004	0.532	−0.568	0.119	0.629	1.000															0.201 ÷ 0.400
pH	−0.716	−0.667	0.753	0.505	−0.869	−0.521	0.104	0.465	−0.305	1.000														0.01 ÷ 0.200
HAC	0.227	0.571	−0.784	−0.695	0.679	0.903	0.054	−0.874	−0.220	−0.837	1.000													–0.200 ÷ 0.00
EBC	−0.337	−0.860	0.528	0.865	−0.903	−0.750	−0.350	0.698	−0.117	0.867	−0.909	1.000												−0.400 ÷ −0.201
CEC	−0.346	−0.883	0.494	0.874	−0.918	−0.726	−0.379	0.671	−0.153	0.861	−0.889	0.999 *	1.000											−0.600 ÷ −0.401
BS	−0.309	−0.663	0.745	0.734	−0.769	−0.854	−0.107	0.817	0.095	0.885	−0.991 *	0.952	0.937	1.000										−0.800 ÷ −0.601
C_{org}	−0.331	−0.964 *	−0.178	0.777	−0.861	−0.158	−0.731	0.091	−0.617	0.496	−0.331	0.694	0.726	0.441	1.000									−1.00 ÷ −0.801
N_{tot}	−0.542	−0.913	−0.133	0.614	−0.875	0.010	−0.559	−0.083	−0.787	0.552	−0.254	0.625	0.659	0.377	0.967 *	1.000								
C:N	0.911	0.094	−0.120	0.393	0.314	−0.597	−0.438	0.639	0.840	−0.364	−0.196	0.054	0.038	0.111	−0.173	−0.420	1.000							
SLe	−0.859	−0.654	0.649	0.380	−0.873	−0.295	0.146	0.232	−0.518	0.969 *	−0.676	0.764	0.766	0.746	0.534	0.642	−0.576	1.000						
PNu	−0.989 *	−0.208	0.470	−0.218	−0.492	0.263	0.523	−0.310	−0.695	0.657	−0.168	0.230	0.234	0.238	0.186	0.413	−0.927	0.803	1.000					
SNu	0.722	0.362	0.305	0.121	0.419	−0.669	0.063	0.723	0.992 *	−0.202	−0.335	0.011	−0.025	0.215	−0.526	−0.708	0.859	−0.429	−0.679	1.000				
YDMSe	−0.832	−0.705	0.623	0.442	−0.905	−0.325	0.077	0.261	−0.517	0.973 *	−0.696	0.802	0.804	0.769	0.586	0.680	−0.538	0.997 *	0.766	−0.422	1.000			
YDMLe	−0.821	0.230	0.281	−0.638	−0.048	0.573	0.736	−0.592	−0.583	0.264	0.223	−0.235	−0.233	−0.182	−0.190	0.067	−0.929	0.447	0.889	−0.627	0.389	1.000		
YDMSt	−0.972 *	−0.486	0.567	0.113	−0.742	−0.016	0.315	−0.043	−0.659	0.859	−0.445	0.540	0.544	0.522	0.416	0.589	−0.790	0.954 *	0.943	−0.601	0.936	0.687	1.000	
YDMSi	−0.914	−0.334	0.761	0.041	−0.635	−0.152	0.495	0.106	−0.441	0.880	−0.547	0.526	0.518	0.593	0.208	0.372	−0.693	0.931	0.912	−0.385	0.903	0.683	0.962 *	1.000

Explanations of the abbreviations can be found in Section 2. n = 12, *—significant differences at $p = 0.05$.

4. Discussion

4.1. The Influence of Forecrop on the Faba Bean Biometry

Every plant needs appropriate nourishing compounds for its normal development. However, the substances found in soil often fail to cover plant demands for nutrients that would ensure the desired yield amount and quality. For this reason, soil cultivation should make it rich in nutrients available to plants [53]. Hence, the use of appropriate forecrop (Fc) as an additional nutritional source for the crops plays an important role in agriculture [54,55]. The study conducted by Pszczółkowska et al. [56] showed that the Fc had a strong impact on winter wheat (WW) yielding, as its seed yield was observed to increase when it was grown after faba bean (Fb) and blue lupine. In this study, the number of seeds (SNu), dry matter yield of leaves (YDMLe), dry matter yield of stems (YDMSt), and dry matter yield of siliques (YDMSi) were the most positively affected by spring wheat (SW) used as Fc. In turn, the stem length (SLe) and the dry matter yield of seeds (YDMSe) were the most positively affected by winter wheat (WW) used as Fc. These correlations might have been due to the beneficial physicochemical effect of WW which endowed the soil properties which promoted Fb growth and development. The Ss with Fb after WW cultivation had the highest pH value, the sum of exchangeable bases (EBC), the sorption capacity (CEC), the base saturation (BS), and the organic carbon content (C_{org}), which could increase Fb biomass. The soil cultivated after SW as the Fc also had high contents of C_{org} and total nitrogen content (N_{tot}). Faligowska et al. [39] reported that crop yielding might be determined by residues of N and C left after the cultivation of other crops (Fc). These authors found legumes to be appropriate Fc for the cultivation of winter rape (WR) and WW. In our research, the contents of C_{org} and N_{tot}, as well as the ratio of organic carbon to total nitrogen content (C:N ratio) were, probably, the major factors determining Fb growth and development on the soils where other various crops had been earlier cultivated. As indicated by Kimbirauskiene et al. [57], the Fc, following a period as well as intensive and reduced soil tillage systems, may strongly affect the N-fixing capability and yield of legumes, including Fb. The chlorophyll content of leaves is an indicator of the satisfactory condition and health of a plant. Insufficient contents of nutrients may reduce the chlorophyll content of young plants and, consequently, deteriorate their quality [58]. Plant yielding is determined by photosynthesis, the rate of which is strongly affected by N, i.e., its low level decreases chlorophyll content and suppresses nitrate reductase activity in a plant, thereby impeding the course of photosynthesis [59]. In the present study, Fb photosynthesis was stimulated to the greatest extent in the soil with WW used as the Fc, as indicated by the leaf greenness index (SPAD) value. In turn, Wanic and Treder [60] observed that WR used as the Fc had a more beneficial effect on the course of photosynthesis of common wheat and spelt compared to field pea, spring barley, and wheat.

4.2. The Influence of Forecrop on the Biochemical Properties of the Soil

The soil enzymes are one of the most activated organic components of the plant rhizosphere. They are biologically active substances that exhibit catalytic properties, which are released mainly from the cells of soil microorganisms but also from plant root secretions and during the degradation of plant and animal residues [61,62]. Through their active involvement in biochemical processes, the soil enzymes effectively aid the metabolic processes in the soil and serve an important function in the circulation of elements and the flow of energy. Enzyme activity is indicative of the intensity and course of biological processes in the soil, as well as the health of soil ecosystems [63]. Activities of all soil enzymes analyzed in the present study were higher in the soil sown (Ss) with Fb than in the bare soil (Us), which suggests that the plant root secretions have a strong impact on the biochemical parameters of the soil. Plant interactions with soil enzymes are determined by the chemical composition of their root secretions, which may vary greatly across plant genera, species, and cultivars [3,64,65]. Woźniak et al. [66] reported that legumes had a more beneficial impact on the soil enzymes compared to cereals. In turn, Meena and Rao [67] reported that soil tillage systems and the extent of soil coverage by vegetation

significantly affected soil properties as well as soil organic matter (SOM) content, thereby contributing to changes in the soil quality and fertility. The biological functions of the soil are also influenced by crop genus or cultivar. Soil enzyme activity is regulated by the availability of C sources and SOM degradation, and may be suppressed due to the intensive soil tillage disrupting its structure [68–70].

The analyzed enzymes are key indicators of soil health due to their deep involvement in the processes ongoing in the soil. The enzyme activity is strictly linked to the biomass of microorganisms and the C_{org} content of the soil [67,69]. The enzymes belonging to the group of oxidoreductases, i.e., dehydrogenases (Deh) and catalase (Cat), are often used as indicators of the biological properties of soil because the activity of Deh indicates the intensity of soil microbiota respiration, whereas Cat degrades toxic hydrogen peroxide to water and molecular oxygen [5]. In the present study, the highest activities of Deh and Cat were determined in the Ss with Fb after maize (M) cultivation, which could be due to the greater availability of SOM derived from plant residues and root secretions [70], as well as to the quantity and quality of M root secretions, which had a stimulating effect on the diversity and activity of soil microorganisms. These enzymes are considered indicators of the intensity of soil microbial metabolism, and their activities strongly correlate with the content of SOM in the soil [71]. Noteworthy is also a group of enzymes which aid the nutrient uptake from organic compounds, like arylsulfatase (Aryl), which is involved in the hydrolysis of S-containing organic compounds to produce SO_4^{2-} [9]. This process enriches the soil with easily available S compounds, which in turn improves crop yielding. In this experiment, the highest Aryl activity was determined in the Ss with Fb after SW and M cultivation. Ure is another important soil enzyme as it participates in urea hydrolysis, which makes it indispensable in providing crops with available nitrogen compounds. Its activity depends on multiple factors, like soil pH, soil type, the abundance of nutrients, and the land management system [8]. The highest Ure activity in the soil from under WW and M crops may have been related to the physicochemical properties of the soil, including, in particular, its pH, C_{org}, and N_{tot} contents and C:N ratio, which strongly affect the activity of the analyzed enzyme. The beneficial effect of the Fc after WW and M on urease (Ure) activity may be due to an increase in the content of N-NH_4^+ ions in the soil. SOM represents a source of energy and offers a suitable environment for the growth of microorganisms that catalyze the activity of extracellular enzymes, including Ure [72]. In addition, these soils were reported to have high values of the sorption capacity (CEC), which may have contributed to the binding of Ure by soil colloids [73]. In our study, its highest activity was determined in the soil sown with Fb after WW and M cultivation, which indicates that the availability of SOM derived from Fb root secretions could enhance the activity of soil microorganisms and, by this means, contribute to increased Ure activity [74,75]. The mineralization of organic P proceeds, among others, in the presence of alkaline phosphatase (Pal) and acid phosphatase (Pac), which make it available to plants. In the present study, the activity of Pal was the highest in the Ss with Fb after WW cultivation, whereas that of Pac—in the Ss with Fb after M. The activities of both these enzymes could be due to the nutrient content and SOM content of the soil, as well as the structure of microbial communities [7,8]. These enzymes are also involved in the degradation of C_{org}, e.g., cellulose or lignin. In turn, β-glucosidase (Glu) is a reliable indicator of the N-free metabolism of organic compounds [76]. Its highest activity determined in the soil from under the SW crop may be related to the availability of the substrate, which contributes to its production yield and rate. It was also likely that the soil from under the SW crop was rich in carbohydrates that were used by microorganisms, producing large amounts of Glu, as a source of nutrients. This, in turn, may have promoted the synthesis of this enzyme in the soil ecosystems, leading to a significant increase in its activity [66,77]. Beyond that, the rate of enzymatic reactions is linked to the soil pH, which is responsible for the ionization state of the enzyme active centers. A change in the content of H^+ ions may trigger changes in the content of inhibitors or activators in the soil, thereby affecting the availability of substrates [77]. The present study showed that its activity was the highest in the Ss with Fb after SW cultivation. In general, Glu activity is associated with

SOM degradation in the soil, which provides nutrients to plants and, thus, increases Glu secretion to the soil environment [66]. This enzyme is, therefore, deemed a reliable index of early changes in the soil conditions and the SOM metabolism in the soil. In addition, Glu activity is positively correlated with the soil fertility, the contents of available N and P, and microbiological activity of the soil [78]. Positive correlations were observed between the C:N ratio and activities of the analyzed enzymes, which implies that the SOM availability is the key indicator of their activity. Kwiatkowski et al. [79] also noted a positive correlation between these parameters. The activity of the soil enzymes could have been due to the content of SOM provided by, among others, the grown crops. Jurado et al. [80] reported that the C:N ratio established the course and intensity of the SOM conversion in the soil. In the present study, the geometric mean of enzyme activities (GMea), determined based on the enzymatic activity, was the highest in the soil cultivated after M (GMea = 1.853). The values of this index in this soil reflected the higher activities of most analyzed soil enzymes, i.e., Deh, Cat, Pac, and Aryl, compared to the other soil types. The GMea index is based on the activity of many soil enzymes; hence, it is very sensitive to any changes in the soil environment. In addition, its values are related to the physical and chemical properties of the soil. In our study, the soil from under M cultivation showed higher GMea index values compared to the other soil types, indicating an improvement in the soil conditions. The highest value of the GMea index in the soil after M cultivation was determined for Deh, Cat, Pal, and Aryl [51,81].

4.3. The Influence of Forecrop on the Physicochemical Properties of the Soil

An important factor affecting the quality and amount of crop yield is the soil affluence in nutrients, which in turn greatly affects its physical and chemical properties [82]. In this experiment, the soils collected after SW, WW, M, and WR cultivation differed in their physicochemical properties, which was also reflected in their enzymatic activity and Fb yielding. Woźniak et al. [66] emphasized that both soil use (Su) and Fc led to modifications in the physical and chemical properties of the soil. They also noted a higher content of C_{org} and pH value in the soil from under the wheat crop compared to the soil from pea cultivation, as well as an opposite correlation in the case of the N_{tot} content. In the present study, the unsown soil (Us) cultivated after SW as the Fc showed the highest values of C_{org}, N_{tot}, and C:N, whereas that cultivated after WW had the highest values of pH, EBC, CEC, and BS. In turn, the Ss with Fb after WW cultivation had the highest values of pH, EBC, CEC, BS, C_{org}, and N_{tot}. The secretions of plant root systems are connected to the species and cultivar of plants, which modify the physicochemical properties of the soil, especially in the rhizosphere, which is diverse in terms of soil microbial species. Such a relationship may have occurred in the soil from under SW and WW crops, which translated into the changes observed in the soil physicochemical properties [81,83]. Haruna et al. [84] reported that wheat cultivation could improve the soil structure and increase the contents of N and SOM, which was related to root density. In turn, Wang et al. [82] emphasized that SOM affected soil quality by improving its structure and water-holding capacity and, thereby, enhancing its bioactivity. Such conditions of the soil can be achieved by, among other things, using the Fc.

5. Conclusions

The Fc was found to strongly affect Fb growth as well as the enzymatic and physicochemical properties of the soil. The soil under SW and WW produced the highest yield of Fb seeds, whereas the lowest YDMSe was recorded in the soil under WR. In addition, the soil from under WW had the highest dry matter yield of faba bean leaves, stems, and siliques (YDMLe, YDMSt, and YDMSi). The highest SPAD was recorded for the Fb grown in the soil after SW, and the lowest one—for that grown in the soil after WR. On the grounds of the rhizosphere effect, it was found that the Us from under the SW crop showed the highest activities of Cat, Aryl, and Glu, and the soil from under the M crop had the highest activities of Deh and Ure, whereas the soil from under the WR crop had the highest activities of

Pal and Pac. The Ss with Fb after SW cultivation had the highest values of pH, EBC, CEC, BS, C_{org}, and N_{tot}, whereas the Ss with Fb after WR as the Fc showed the most beneficial ratio of C_{org} to N_{tot}. It was found that WW as the Fc exerted the most positive effect on the physicochemical properties of the soil, which could contribute to slightly better soil conditions for the Fb development than in the case of SW, M, and WR. The parameters determined in the study are very useful in evaluating soil fertility and quality, particularly for agricultural purposes.

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Abbreviations

SW—spring wheat; WW—winter wheat; M—maize; WR—winter rape; Fc—forecrop; Su—soil use; Fc×Su—interaction of factors; Us—unsown soil; Ss—sown soil; Deh—dehydrogenases; Cat—catalase; Pal—alkaline phosphatase; Pac—acid phosphatase; Aryl—arylsulfatase; Glu—β-glucosidase; Ure—urease; GMea—geometric mean of enzyme activities; pH—soil acidity/alkalinity; HAC—hydrolytic acidity; EBC—sum of exchangeable bases; CEC—sorption capacity; BS—base saturation; C_{org}—organic carbon content; N_{tot}—total nitrogen content; C:N—ratio of organic carbon content to total nitrogen content; SLe—stem length; PNu—pod number; SNu—seed number; YDMSe—dry matter yield of seeds; YDMLe—dry matter yield of leaves; YDMSt—dry matter yield of stems; YDMSi—dry matter yield of siliques; BBCH 32—2 visibly extended internodes; BBCH 79—nearly all pods have reached final length.

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