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Impact of tine stiffness and operational parameters on soil disturbance profiles: moisture content, speed, depth, width, and cross-sectional analysis of furrows by duckfoot tools

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A b s t r a c t. The study aimed to elucidate the effect of tine stiffness and operational parameters, such as speed, working depth, and soil moisture, on the effectiveness of soil disturbance with duckfoot tools. The experiments were carried out with three types of duckfoots attached to tines of different stiffness (S and Vibro Crop (VCO)) working in soil with a moisture content of 10 and 14% at three depths and three movement speeds. The width and depth of furrows, disturbed soil surface areas, and the loosening coefficient were analysed. The results showed that tine stiffness had a critical impact on the shape of the furrow and the efficiency of the tools, while the depth of work had a more substantial effect on the dimensions of the furrow than the width of the duckfoots. The use of the S-spring tine reduced soil disturbance, while the rigid VCO tine led to more uniform results at greater depths, confirming the hypotheses. The developed mathematical empirical model of the surface area of the soil disturbed in the form of a second-degree polynomial reflects the nonlinear relationship with the width and depth of the furrow well. These results can help to optimise agricultural tools in precision agriculture.

K e y w o r d s: tillage tool, working element, tine, operating parameters, criteria parameters

1. INTRODUCTION

The European Union's Farm to Fork strategy aims to reduce the use of pesticides. In weed control, chemicals must be replaced mainly by mechanical means (Fishkis *et al.*, 2024). Plant cultivation tools or machines are widely used for soil treatment and inter-row tillage. The primary objectives of inter-row cultivation are shallow loosening of the soil between the rows of plants and the destruction of weeds, removal of soil crust, facilitation of water infiltration, aeration, and scarification, ensuring soil ventilation and hindering the evaporation of water from the soil (Kumagai, 2021), improving nitrogen release, covering the stems at the base of plants to enhance their growth (Jat *et al.*, 2020). This treatment also creates better conditions for plant growth and development and destroys weeds that inhibit plant growth and development while competing in their environment (Monteiro and Santos, 2022). The crust and compaction of the soil hinder access to air and inhibit the proper development of plants, while weeds, better adapted to local conditions, grow quickly (Laker and Nortjé, 2020). After cultivation treatments, plants get access to water, nutrients, and light.

The continuous development of tillage technologies, emphasising reducing their environmental impact while increasing crop productivity, requires an in-depth understanding of the mechanical interactions between soil and tillage tools. The prevailing trend of the ecosystem approach, promoting environmental protection, determines the direction of development of alternative cultivation technologies in contrast to the use of herbicides. Such non-chemical methods of plant protection include mechanical row cultivation of plants. Mechanical weed removal can be carried out in three ways: covering, cutting, and pulling out (Young and Pierce, 2014). Covering involves placing

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a layer of soil on top of the weeds to limit their growth. Cutting consists of physically cutting off some of the weeds. Uprooting is the breaking of contact between the soil and the roots of plants. Covering usually occurs during the soil preparation for sowing, and cutting and uprooting occur during cultivation and after plant emergence (Zhang and Chen, 2017).

Depending on the purpose of weeding, different tools are used. Brushes and tine harrows are effective for weeding in plant rows, and knives and duckfoots are used in inter-rows (Kouwenhoven, 1997). The effectiveness of mechanical weeding with duckfoots is influenced by several soil, plant, and technical factors reflected in the research results. Increasing the working depth did not significantly increase the disappearance of weeds, but it loosened more soil (Gürsoy and Özaalan, 2023). Expanding the working speed resulted in a reduction in weed infestation (Naruhn *et al.*, 2021). Harrowing at higher speeds and weeding did not provide more weed control but caused more soil movement (Cirujeda *et al.*, 2003). The authors also found that different types of duckfoots behaved differently regarding weeding effectiveness. The results of these studies became an additional inspiration for undertaking our research, especially regarding the assumed working parameters and the type of duckfoots.

In addition to the effectiveness of weed destruction, one of the critical indicators of the effects of the work of weeders or row cultivators is soil disturbance. Most researchers who studied weed destruction rates also studied soil disturbance (Shmulevich *et al.*, 2007). The soil disturbance determined the covering and uprooting of weeds (Pannacci *et al.*, 2017). The duckfoot cultivator is mainly used for shallow loosening, weed destruction, and soil moisture retention. Row cultivators with spring tines are particularly effective against mature weeds (Kumar *et al.*, 2023). The cultivators were more effective on clay soil than on sandy soil due to the larger knife zone in clay soil. Too much soil disturbance poses a risk of covering crops with soil. During the weeding of rapeseed plants, it was found that the use of a weeder allowed the destruction of weeds at 89% and can be used for narrow-row crops due to the slight disturbance of soil (Pullen and Cowell, 1997). Duckfoots also caused a relatively high rate of weed destruction (65-99%), but their use caused a more significant ejection of soil, which can damage plants by covering them. Cultivators generally perform best when loosening the soil with a larger inter-row width, as this reduces the risk of damaging the plants.

The literature needs to include the characteristics of soil loosening by duckfoots and the discussion on the relationship between soil loosening and types of spring tines of different stiffness. Few studies have compared different duckfoots working at different technical parameters and soil conditions. Duckfoot tools are popular with farmers who use them to amend the soil due to the width of duckfoot's wings, which move the undercut soil well between two rows of plants (Edward, 2021). Duckfoot elements in different working widths, combined with spring tines, can be used as a single tool or a section and help destroy weeds in cereals and maize, sugar beet, or vegetables (Balas *et al.*, 2022).

Developing new technical and technological solutions for primary cultivation and soil treatments, including ecological mechanical weed control treatments between plants grown in rows, is a constant challenge for researchers, developers, producers, and farmers. Preparing ridges and loosening inter-rows, optimising the soil structure for sowing and loosening only those areas of the field that require it, are indispensable in precision farming. Soil cultivation techniques and technologies should be applied to the best agricultural practices to reduce energy and fertiliser consumption. Economic and environmental considerations force farmers to work in the soil with an optimal configuration of implements to achieve the desired final soil condition (Shmulevich *et al.*, 2007). Soil cultivation research and practices are considering significant new ecological directions, as a growing awareness and understanding of agricultural sustainability and environmental protection are driving this ecological revolution (Bender *et al.*, 2016).

Research in the field of soil-tool interactions has consistently shown that the physical properties of the tool and their operation at specific operating parameters significantly affect soil mechanics (Karmakar and Kushwaha, 2006). Conversely, the soil structure influences the reactions of attachment elements of work tools. These interactions depend on the variable geometry and shape of the tool, the elasticity of the fastening component, and the expected change in the configuration of the soil structure in the loosening zone (Abo-Elnor *et al.*, 2004), such as the appearance of cracks and accumulation flow occurring at the interface between the tillage tool and the soil and between soil particles (Welsh *et al.*, 2002). Significant displacement of soil particles and the resulting redistribution of soil within the tillage layer were demonstrated (Zhang *et al.*, 2017).

A better understanding of the translocation phenomena caused by soil cultivation as a function of soil condition is needed. Regarding wide weeding implements, no indicators characterising the soil-tool relationship could be used to compare the effectiveness of soil loosening.

The literature indicates that such factors as soil moisture content, tine stiffness, speed, and depth of work play a crucial role in soil tillage efficiency and the energy required (Godwin and O'Dogherty, 2007). The interaction between tine stiffness and soil characteristics, such as moisture content, was investigated to determine their effect on furrow shape and size (Aikins *et al.*, 2023). These studies suggest that tine elasticity can lead to different furrow geometries, affecting the overall effectiveness of soil loosening and, consequently, plant growth.

Despite extensive research, there is still a clear gap in integrating individual factors into a coherent concept for assessing soil behaviour in different operating conditions with high accuracy. Most existing test methods do not comprehensively consider dynamic changes in soil properties at various moisture levels or the interactive effects of tine stiffness and working speed.

The primary scientific question that this article answers is: how do changes in tine stiffness and operating parameters affect soil loosening profiles, particularly in terms of furrow morphology, with different soil moisture contents, applied movement speed, depth, and width of duckfoot-type tools?

This research aims to develop a nuanced understanding of how tine stiffness interacts with operational parameters to influence the extent of soil disturbance. To achieve this, we will quantitatively analyse the effect of tine stiffness and operating parameters on soil furrow morphology to suggest optimal operating settings. To this end, explanatory hypotheses were formulated. The stiffness of the tines significantly affects the cross-sectional area and disturbs the loosened soil and the furrow shape, with stiffer tines producing more uniform furrow shapes at different soil moisture levels. The interaction of movement speed, working depth, width of duckfoots, and soil moisture content will significantly affect the efficiency of soil disturbance, with optimal parameters varying depending on the type and condition of the soil.

The novelty of the article is the performance of a comprehensive analysis that combines the mechanical properties of the tool with operational and environmental factors to predict soil disturbance results. By integrating empirical data, this study aims to refine existing knowledge and provide practical insights that can lead to more sustainable and efficient farming practices. In addition, this study will contribute to the ongoing discussions on precision farming by deepening the understanding of how tool design and operational strategy affect soil loosening. Understanding the interplay of tine stiffness, operating parameters, and soil conditions helps optimize agricultural practices and supports the development of sustainable farming techniques that minimise energy consumption while maximising productivity. This study aims to significantly contribute to both theoretical and practical aspects of technical and agricultural sciences.

2. MATERIAL AND METHODS

2.1. Soil properties

The study was conducted on typical soil that filled the test bin. It was a light clay sand, with a clay, dust, and sand fraction content of 2, 36, and 62%, respectively, determined with the sieve separation method. The dry soil density was 1535 ± 11 kg m^{-3}, and its compactness was determined at 486 ± 25 kPa, using a cone penetrometer with an opening angle of 30° and a base diameter of 20.27 mm, according to the ASAE S 313.2 standard (ASAE Standard, 2004). The soil was tested at two extreme moisture levels – 10% and 14% (wet basis), which allowed the maintenance treatments. Soil moisture was determined using the drying and weighing method specified by the PN-ISO 11465:1999 standard (ISO11465, 1993).

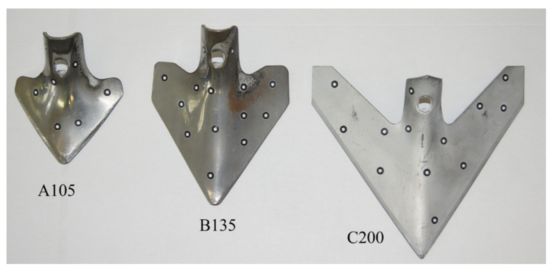
For both moisture levels, the mechanical properties of the soil were investigated using the Schulze ring-rotation apparatus at the Institute of Agrophysics of the Polish Academy of Sciences in Lublin (Schulze, 2010). The soil was preconsolidated at pressures of 10, 20, 30, 40, and 50 kPa (Stasiak *et al.*, 2008). For 10 and 14% moisture, the values of the internal friction angle were 37 and 32°, respectively, the soil-steel friction angle – 24 and 22°, cohesion – 17 and 18 kPa, adhesion – 10 and 12 kPa, and the flowability index, ff_c, was 1.50 and 1.60. According to the classification (Eurocode 1, 2006), this soil is classified as a cohesive material because the value of the ff_c is in the range of $1 < ff_c < 2$.

2.2. Test objects

Three commercial duckfoots with widths of 105, 133, and 202 mm, which were designated A105, B135, and C200, were used in the study (Fig. 1a). These elements were made of SB 27M12B boron steel, the parameters of which were verified in physicochemical tests. The duckfoots were attached to S and Vibro Crop (VCO) tines, with 5.3 and 8.3 kN m^{-1} stiffness, respectively. Although the shape and characteristic angles of the duckfoots were similar, when combined with the S and VCO tines, the clearance angles were 8 and 2°, respectively (Lisowski *et al.*, 2016).

The geometric shape of the duckfoots was mapped using a non-contact optical system based on the ATOS Triple Scan II Blue Light optical coordinate scanner from GOM and the GOM Inspect v.7.5 software (Dziubek and

a)



b)

Fig. 1. Duckfoots with glued markers for scanning a) and an example of the effect of cracked soil when the tool is stopped b).

Oleksy, 2017). The results of the measurements were compared with measurements made with a digital calliper and an optical protractor. The differences in the measurements of the area of the duckfoots were less than 3%, and in the measurements of angles – less than 2%.

2.3. Soil bin with measuring equipment

The experiments were conducted in a soil bin (Fig. 2b) at the Department of Biosystems Engineering, Institute of Mechanical Engineering of the Warsaw University of Life Sciences. The tines with attached duckfoots were installed to the frame of a tool trolley, which was pulled by two steel ropes driven by a 22.0 kW WAR 16 1M4 TF electric motor system equipped with an FUA 85A 16 1M4 TF gearbox and a V2500-0220 TFW1 inverter (Watt Drive, Austria). An optical sensor (CS3D, ZEPWN, Marki, Poland) was used to measure the trolley's speed with working elements. The working depth was determined and controlled using a laser distance meter (LDS 100-500P-S, Beta Sensorik) combined with a 3000 mm long horizontal displacement indicator with a sensitivity of 0.3163 mV V^{-1} mm^{-1} (WS12-3000-R1K-L10-M, ASM GmbH, Germany).

The same laser distance meter combined with a horizontal displacement indicator was mounted on a separate frame, which was used to measure the shape of the ridge and furrow in the cross-section to the direction of tool movement (Fig. 2b). The measurement data was stored on a computer via a high-speed digital interface board from Hottinger Baldwin DMCplus. The measurement and control system was controlled by CATMAN 2.1 software, which provided simultaneous data acquisition and motion control with a sampling rate of 50 Hz.

2.4. Measurement procedure

The soil with a depth of 0.6 m was loosened to a depth of 0.22 ± 0.02 m and then levelled and compacted with a roller weighing 360-520 kg, according to a verified procedure (Lisowski *et al.*, 2016). The shape of the soil surface before and after each series of three passes was scanned with a laser meter in three designated locations along the length of the soil bin (Fig. 2b). After the loose soil was manually removed, furrow scans were performed (Fig. 3). During the movement of the laser sensor, the signals were recorded every 1 mm. The research was conducted at three working depths of the duckfoots: 30, 50, and 70 mm and movement speeds: 0.84, 1.67, and 2.31 m s^{-1}. These variables were combined into 3 × 2 × 3 × 3 × 2 factorial experiment with three or four blocks (replications).

2.5. Criterion indicators for the assessment of the effects of soil disturbance

Based on the characteristics of the soil surface and furrow profiles, parameters and criterion indicators were determined for the assessment of the effects of soil disturbance by work elements depending on the experimental variables (Fig. 4). The following indicators were used to evaluate these effects: disturbed soil width w_d (mm), cultivated furrow width w_g (mm), furrow width w_f (mm), furrow depth d_f (mm), loosened soil area A_s (mm²), disturbed soil area A_d (mm²), and loosening coefficient *PI*, expressed as the ratio of the increase in the area of loose soil to the cross-sectional area of the furrow, $PI = 100(A_s - A_d)/A_d$ in percentage.

a)

b)

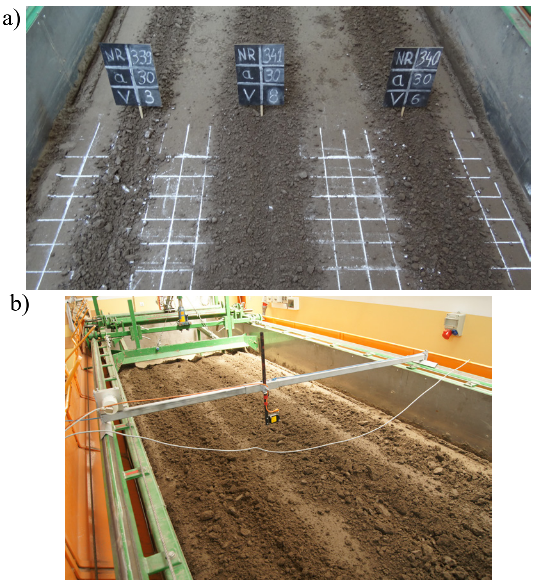


Fig. 2. Examples of effects of soil disturbance by duckfoots working at a depth of 30 mm at a speed of 0.84, 1.67, and 2.31 m s^{-1} on the soil with a moisture content of: a) 10 and b) 14% (the photo b) shows the method of measuring the soil profile before, immediately after a disturbance the soil and after removing loose soil from the furrow).

a)

b)

Fig. 3. Furrow bottom profiles after removal of loose soil in: a) triangular and b) trapezoidal shapes after work of duckfoots attached to: S-tine and VCO-tine, respectively.

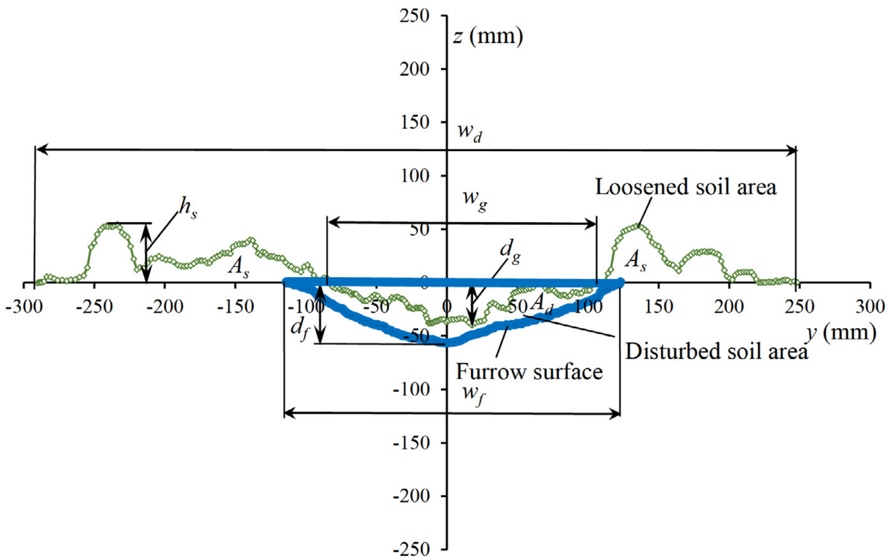


Fig. 4. Parameters used to define soil disturbance of a duckfoot tool: w_d – disturbed soil surface width, w_f – furrow width, w_g – cultivated furrow width, h_s – mound (ridge) height, d_f – furrow depth, d_g – cultivated furrow depth, A_d – disturbed soil area (surrounded by a bold line), A_s – loosened soil area.

The coordinates of the profile points of the outer surface of the soil were used to estimate the regression function, concerning which, by numerical integration, the cross-sectional area of the furrow after the removal of loose soil was calculated.

2.6. Statistical analysis

The dependent variables were checked for statistical analysis assumptions. Kolmogorov-Smirnov (K-S) tests with the Lilliefors correction (K-S-L) and the Shapiro-Wolf (S-W) test were performed to check the compliance of the distributions with the normal distribution. In addition, Levene and Brown-Forsyth tests were performed to assess the uniformity of the variance. Based on the results of the K-S test, it was found that the distributions of the variables did not deviate from the normal distribution. The results of the Levene and Brown-Forsyth tests indicate no grounds for rejecting the hypothesis of homogeneity of variance between the analysed groups.

The effect of tine type, duckfoot width, working depth, movement speed, soil moisture, and all possible interactions between these factors on the criterion indicators was evaluated based on the MANOVA analysis of variance. The statistical significance of the differences between the mean values of the parameters was assessed using Tukey's post-hoc test. The correlation relationships between factors and parameters were determined using the Pearson correlation test, with descriptors used to interpret the values of the correlation coefficients (Hopkins, 2000).

A nonlinear empirical model was developed for the identified correlations, describing the surface area of the disturbed soil, taking into account statistically significant independent variables. The Levenberg-Marquardt method was used to estimate the regression coefficients and build the regression model, considered the most effective and fastest convergent. Details of this method's algorithm are described in the literature (Moré and Sorensen, 1983). All analyses were performed at a significance level of $p \leq 0.05$ using Statistica software version 13.3.

3. RESULTS AND DISCUSSION

3.1. Width of the area of disturbed soil and cultivated furrow

Selected profiles of disturbed soil in a cross-section perpendicular to the direction of movement of the tool for various duckfoots attached to the VCO and S-tines working in soil with a moisture content of 10 and 14% at different working depths and speeds are presented in Fig. A.1–A.4 (Appendix). The figures clearly show the difference in the shape of both profiles depending on the working conditions and the elements used.

The w_d and w_g widths were statistically significantly dependent on the main factors (except for the effect of *MC* on w_d), numerous double, several triple, and occasionally quadruple interactions (Table 1). For the w_d width, there was an interaction of all five factors. The w_d and w_g widths were larger when the duckfoots with the S tine, characterised by more excellent elasticity, compared to the VCO tine were used; the relative differences were 6.5 and 41.0%, respectively (Table 2). The w_d and w_g widths were well correlated with each other (r = 0.505, Table 3). Still, the tine type had a significantly larger effect on the width of the cultivated furrow than on the width of the soil disturbance (Figs A.5 and A.6). This has a positive practical significance because using more flexible tines slightly increases the risk of covering plants with soil in the row and, at the

Table 1. Results of the analysis of variance for parameters evaluating the effects of soil disturbance by duckfoots (w) A105, B135, and C200 attached to S and VCO tines of different stiffness working in soil with moisture content (MC) of 10 and 14% at different depths (d) 30, 50 and 70 mm and to varying speeds of movement (v) 0.84, 1.67 and 2.31 m s^{-1}

Effect	w_d		w_g		w_f		d_f		A_s		A_d		PI	
	F	p	F	p	F	p	F	p	F	p	F	p	F	p
Tine	57.9	<0.001	125.6	<0.001	228.6	<0.001	207.4	<0.001	376.5	<0.001	567.7	<0.001	0.34	0.557
MC	0.3	0.608	76.4	<0.001	19.1	<0.001	12.2	0.001	3.8	0.051	25.8	<0.001	2.42	0.120
w	42.8	<0.001	64.9	<0.001	612.7	<0.001	41.6	<0.001	111.4	<0.001	262.6	<0.001	3.72	0.025
d	288.2	<0.001	24.1	<0.001	457.0	<0.001	4547.2	<0.001	1223.0	<0.001	2202.8	<0.001	20.97	<0.001
v	791.8	<0.001	203.4	<0.001	1.3	0.267	1.6	0.206	2.3	0.105	3.0	0.049	10.31	<0.001
Tine×MC	2.2	0.137	12.4	<0.001	6.9	0.009	9.1	0.003	0.0	1.000	0.6	0.455	0.11	0.743
Tine×w	6.5	0.002	8.4	<0.001	94.1	<0.001	1.3	0.272	49.0	<0.001	134.9	<0.001	6.96	0.001
MC×w	10.9	<0.001	3.2	0.043	3.3	0.037	1.3	0.281	2.7	0.067	1.8	0.170	1.01	0.365
Tine×d	5.1	0.007	3.3	0.038	4.0	0.019	32.6	<0.001	10.6	<0.001	20.8	<0.001	0.69	0.500
MC×d	4.7	0.009	10.4	<0.001	0.3	0.709	1.1	0.332	0.7	0.496	7.2	0.001	1.43	0.241
w×d	5.0	0.001	2.5	0.042	7.9	<0.001	3.8	0.005	14.0	<0.001	39.1	<0.001	1.00	0.405
Tine×v	0.0	0.995	2.8	0.062	1.9	0.151	1.2	0.308	1.4	0.238	3.2	0.041	0.24	0.785
MC×v	6.9	0.001	5.0	0.007	0.6	0.545	2.4	0.089	0.9	0.399	1.2	0.304	0.10	0.907
w×v	3.8	0.004	1.6	0.166	4.9	0.001	1.2	0.314	4.1	0.003	6.0	<0.001	0.64	0.635
d×v	11.6	<0.001	5.4	<0.001	0.7	0.594	2.8	0.026	2.5	0.045	3.7	0.006	0.29	0.884
Tine×MC×w	3.3	0.038	8.5	<0.001	2.4	0.090	5.4	0.005	4.0	0.019	0.0	0.965	4.39	0.013
Tine×MC×d	0.0	0.985	2.3	0.101	8.2	<0.001	1.5	0.220	1.5	0.220	5.0	0.007	2.64	0.073
Tine×w×d	4.4	0.002	2.7	0.029	0.6	0.668	6.5	<0.001	11.5	<0.001	21.9	<0.001	0.48	0.753
mc×w×d	3.4	0.009	0.6	0.658	3.3	0.011	10.9	<0.001	4.5	0.001	9.3	<0.001	0.92	0.452
Tine×MC×v	4.7	0.009	10.5	<0.001	0.9	0.403	1.8	0.168	0.3	0.740	2.5	0.084	1.14	0.321
Tine×w×v	5.2	<0.001	8.1	<0.001	1.5	0.204	1.2	0.318	2.8	0.024	1.2	0.331	1.23	0.297
MC×w×v	1.0	0.389	2.3	0.060	0.8	0.503	0.6	0.681	2.0	0.092	0.7	0.566	1.46	0.214
Tine×d×v	2.6	0.034	1.8	0.118	0.5	0.721	0.7	0.561	1.0	0.412	1.5	0.206	1.55	0.186
MC×d×v	1.1	0.340	0.5	0.769	3.4	0.009	0.9	0.453	0.9	0.468	1.8	0.121	0.42	0.793
w×d×v	0.7	0.714	1.1	0.329	2.4	0.013	0.6	0.752	0.8	0.567	1.5	0.149	0.89	0.527
Tine×MC×w×d	1.2	0.309	1.3	0.271	1.8	0.133	3.9	0.004	2.5	0.040	1.5	0.206	2.32	0.056
Tine×MC×w×v	6.4	<0.001	2.1	0.084	0.6	0.698	0.6	0.645	1.3	0.280	1.0	0.407	0.24	0.913
Tine×MC×d×v	0.4	0.819	1.1	0.379	0.7	0.575	1.1	0.338	1.0	0.401	1.2	0.316	1.37	0.244
Tine×w×d×v	1.5	0.137	2.9	0.004	3.4	0.001	0.6	0.792	1.7	0.093	1.9	0.061	2.15	0.030
MC×w×d×v	0.6	0.790	1.9	0.064	0.8	0.587	0.6	0.815	0.7	0.674	0.9	0.509	2.01	0.043
Tine×MC×w×d×v	3.2	0.002	0.7	0.649	1.9	0.063	1.0	0.442	1.8	0.076	1.5	0.168	2.09	0.035

w_d – the disturbed soil width, w_g – the cultivated furrow width, w_f – the furrow cut width, d_f – furrow depth, A_s – the surface area of loosened soil, A_d – the surface area of disturbed soil, PI – loosening coefficient, F – Fisher-Snedecor test parameter, p – p-value.

same time, significantly enlarges the zone of the cultivated furrow, reducing the transverse unevenness of the loosened soil (Kaczorowska-Dolowy, 2022).

The higher the soil moisture, the greater the width of the cultivated furrow with partially covered loose soil, while the extent of the soil disturbance practically did not change. In proportion to the working width of the duckfoots, the w_d and w_g values increased, and for tools A105, B135, and C200, they were 430, 462, and 487 mm for w_d and 78.2, 96.2, and 109.1 mm for w_g, respectively. The proportions of changes in these parameters decreased with the increasing width of the duckfoots and were more significant for w_d than w_g. Still, inverse standard deviations were obtained for these values, *i.e.* the disturbed soil's width was more stable than that of the cultivated furrow (Table 2).

The depth of the duckfoot's work had a much more significant effect on w_d than on w_g, confirmed by higher values of the F test (Table 1) and correlation coefficients (Table 3).

Table 2. Mean values and standard deviations for the parameters evaluating the effects of soil disturbance by duckfoots (w) A105, B135, and C200 attached to S and VCO tines of different stiffness working in soil with moisture content (MC) of 10 and 14% at various depths (d) of 30, 50 and 70 mm and to varying speeds of movement (v), v_1 = 0.84, v_2 = 1.67 and v_3 = 2.31 m s^{-1}

Factor	Level	w_d	w_g	w_f	d_f	A_s	A_d	PI (%)
		(mm)				(mm^2)		
Tine	VCO	448^{a} ±119	80.0^{a} ±55.7	221^{b} ±52	49.2^{b} ±17.5	12116^{b} ±5528	7492^{b} ±3702	67.5^{a} ±29.6
	S	477^{b} ±129	112.8^{b} ±48.9	193^{a} ±37	45.9^{a} ±15.2	9052^{a} ±4142	5575^{a} ±2652	66.7^{a} ±29.4
MC	10	464^{a} ±119	85.6^{a} ±46.0	206^{a} ±46	47.1^{a} ±16.3	10575^{a} ±5023	6472^{a} ±3269	67.8^{a} ±24.3
	14	460^{a} ±132	109.3^{b} ±61.9	208^{b} ±49	48.2^{b} ±16.7	10629^{a} ±5251	6631^{b} ±3478	66.2^{a} ±35.0
w	A105	430^{a} ±127	78.2^{a} ±38.8	170^{a} ±27	44.8^{a} ±16.2	8548^{a} ±3797	5034^{a} ±2180	72.4^{b} ±29.8
	B135	462^{b} ±127	96.9^{b} ±52.6	197^{b} ±33	49.2^{c} ±16.7	10396^{b} ±4572	6348^{b} ±2908	67.6^{ab} ±29.9
	C200	487^{c} ±115	109.1^{c} ±63.2	245^{c} ±44	48.2^{b} ±16.2	12321^{c} ±5839	7852^{c} ±3936	62.6^{a} ±28.3
d	30 mm	388^{a} ±95	83.1^{a} ±34.4	172^{a} ±35	27.5^{a} ±3.5	5307^{a} ±1593	3042^{a} ±956	77.6^{b} ±32.6
	50 mm	479^{b} ±114	98.8^{b} ±56.2	216^{b} ±40	49.0^{b} ±5.0	11075^{b} ±3098	6816^{b} ±1813	63.8^{a} ±26.6
	70 mm	520^{c} ±126	106.7^{c} ±66.9	234^{c} ±45	66.5^{c} ±6.3	15456^{c} ±4080	9803^{c} ±2769	60.1^{a} ±26.3
v	v_1	358^{a} ±76	57.5^{a} ±48.1	209^{b} ±50	47.6^{b} ±16.7	10570^{a} ±5205	6627^{b} ±3515	64.5^{a} ±25.4
	v_2	452^{b} ±81	106.1^{b} ±51.1	209^{b} ±48	48.0^{b} ±16.6	10496^{b} ±5072	6649^{b} ±3358	62.5^{a} ±28.9
	v_3	579^{c} ±100	125.3^{c} ±41.2	204^{a} ±44	47.1^{a} ±16.2	10733^{c} ±5109	6352^{a} ±3214	74.4^{b} ±32.5

a-c: different letters within a value represent a significant difference at $p < 0.05$ using Tukey's test. Other explanations as in Table 1.

Table 3. Matrix of correlation coefficient values for qualitative factors and indicators

Parameter	Tine	MC	w	d	v	w_d	w_g	w_f	d_f	A_s	A_d	PI
Tine	1.000											
MC	-0.023	1.000										
w	-0.052	-0.078^{a}	1.000									
d	0.018	-0.015	0.056	1.000								
v	0.000	-0.008	0.005	-0.001	1.000							
w_d	0.118^{a}	-0.017	0.177^{a}	0.426^{a}	0.711^{a}	1.000						
w_g	0.299^{a}	0.215^{a}	0.212^{a}	0.173^{a}	0.516^{a}	0.505^{a}	1.000					
w_f	-0.288^{a}	0.022	0.648^{a}	0.528^{a}	-0.033	0.281^{a}	0.135^{a}	1.000				
d_f	-0.099^{a}	0.032	0.057	0.950^{a}	-0.010	0.395^{a}	0.134^{a}	0.581^{a}	1.000			
A_s	-0.299^{a}	0.005	0.290^{a}	0.795^{a}	0.011	0.412^{a}	0.004	0.781^{a}	0.858^{a}	1.000		
A_d	-0.285^{a}	0.024	0.332^{a}	0.807^{a}	-0.031	0.334^{a}	0.082^{a}	0.836^{a}	0.881^{a}	0.946^{a}	1.000	
PI	-0.013	-0.027	-0.131^{a}	-0.238^{a}	0.124^{a}	0.132^{a}	-0.213^{a}	-0.304^{a}	-0.282^{a}	-0.054	-0.337^{a}	1.000

MC – soil moisture, w – the duckfoot width, d – working depth, v – movement speed, w_d – the disturbed soil width, w_g – the cultivated furrow width, w_f – the furrow cut width, d_f – furrow depth, A_s – the surface area of loosened soil, A_d – the surface area of disturbed soil, PI – loosening coefficient. [a]Statistical significance at p-value = 0.05.

A more significant amount of soil cut off by the duckfoots was more disturbed outwards, compounded by the speed of motion, as there was an interaction between depth and speed ($p<0.001$, Table 1). The movement speed had the most significant effect on the increase in w_d and w_g. These values were strongly consistent, as the values of the correlation coefficients were 0.711 and 0.516, respectively.

The effect of speed on w_d was progressive: with an increase in speed from 0.84 to 1.67 m s^{-1}, the width of w_d increased by 113 mm per unit speed, and with an increase from 1.67 to 2.31 m s^{-1}. The value of w_d increased by 198 mm (m s^{-1})$^{-1}$, which is a 75% increase. Therefore, it can be concluded that the effect of the movement speed on the disturbance of loosened soil was strongly nonlinear and similar to the quadratic model. In all combinations in which the movement speed occurred, a statistical effect of such interactions on the change in the width of the disturbed soil was found (Table 1). An almost twofold decrease in growth characterised the width of the cultivated furrow concerning the speed intervals. In the analysed range of movement speeds, the increments were 58 and 30 mm per unit of speed, respectively.

These studies are part of a wide spectrum of literature on optimising agricultural tools in terms of the effectiveness of soil loosening (Aikins *et al.*, 2020) to minimise the negative impact on plants (Mwiti *et al.*, 2023). The study results show that the width of the disturbed soil and the cultivated furrow significantly depended on the type of tines used, soil moisture, depth of work, and movement speed. Using more flexible S-tines led to a greater furrow width and soil disturbance than VCO tines, which is beneficial for agricultural practice as it reduces transverse irregularities in the soil. Vibrations of the spring tines of care tools contribute to better soil loosening, especially at greater working depths (Rahman and Chen, 2001). These studies showed that working speed has less effect on loosening efficiency than working depth, suggesting that the dynamic impact of tools on the soil can be crucial for optimising the performance of tillage tools (Mehra *et al.*, 2018). The increase in soil moisture increased the width of the cultivated furrow. At the same time, the movement speed had a progressive and non-linear effect on the width of soil disturbance, which may suggest the need to optimise the speed of tools depending on field conditions. These findings could be helpful for practitioners and designers of agricultural implements in the context of improving crop quality and work efficiency.

3.2. Width and depth of the furrow cut

Examples of furrow profiles without loose soil, left by duckfoot A105 attached to the VCO and S tines, are presented in Figs 1b and 5 and Figs 1a and 6, respectively. The shape of the furrow bottom was differentiated depending on the type of tines to which the duckfoots were attached. Duckfoots with comparable rake angles were attached to the VCO tine at a clearance angle of 2° and to the S tine at a clearance angle of 8°. The bottom of the furrow left by the duckfoot attached to the stiff tine of the VCO working at a low angle had a relatively flat shape, similar in cross-section to a trapezoid. The vibrations of the VCO tine with the higher spring stiffness of 8.3 kN m^{-1} were relatively lower than the vibrations of the spring tine S with the spring stiffness of 5.3 kN m^{-1}, which was characterised by greater compliance and more intensive vibrations in the direction of movement. The greater angle of application of the duckfoot attached to the S tine and the vibrations of the tine caused by variable soil resistance resulted in a greater inclination of the duckfoot, which led to the formation of a furrow in the shape of a triangle (Fig. 6).

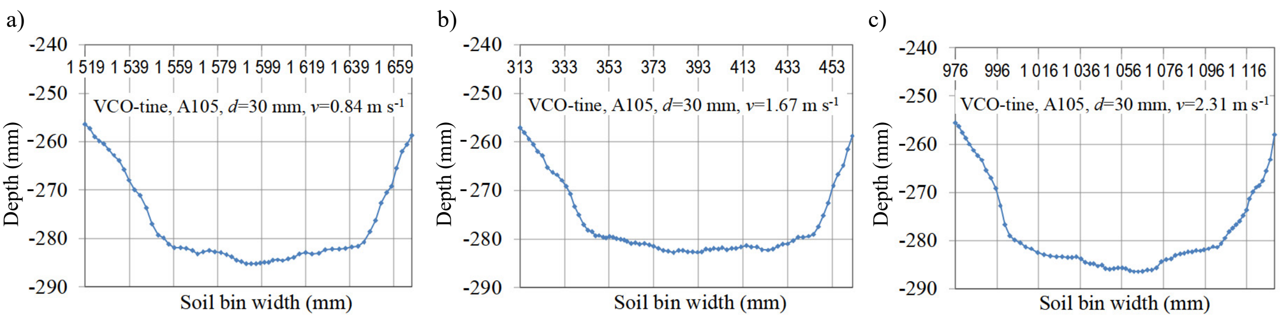


Fig. 5. Examples of profilograms of the furrow bottom surface during operation of the A105 duckfoot with a VCO tine working at a depth of 30 mm (0.03 m) at a movement speed of: a) 0.84, b) 1.67, and c) 2.31 m s^{-1} (furrow bottom cross-section similar to a trapezoid).

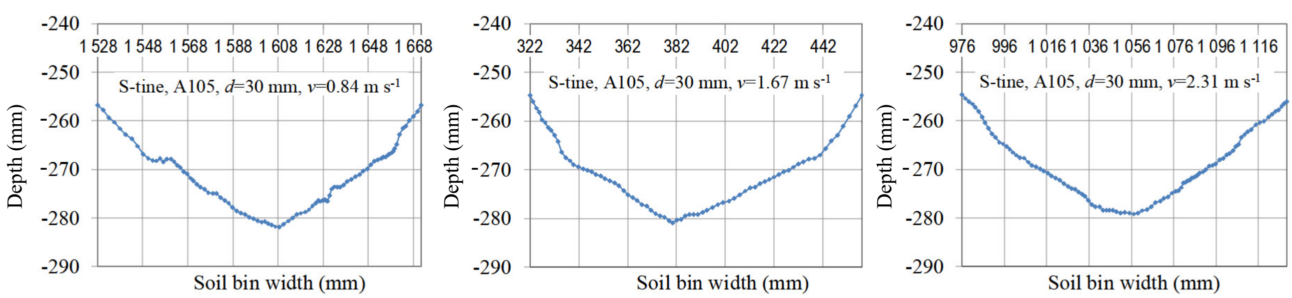


Fig. 6. Examples of profilograms of the furrow bottom surface during the operation of the A105 duckfoot with the S tine working at a depth of 30 mm (0.03 m) at a movement speed of: a) 0.84, b) 1.67, and c) 2.31 m s^{-1} (cross-section of the furrow bottom similar to a triangle).

In addition to the movement speed, other major factors had a statistically significant effect on the width and depth of the cut furrow (Table 1). The impact of these main factors was more critical on w_f and d_f than on w_d and w_g. A smaller number of interactions of factors on w_f and d_f was found than on w_d and w_g. Still, the direction of the influence was similar (Figs A.7 and A.8). The use of tines with higher elasticity reduced the furrow width by 28 mm (12.7%) and the furrow depth by 3.3 mm (6.7%). These reductions resulted from the vibrations to which the tine was subjected under the influence of soil resistance, which resulted in tine deviations and a reduction in the transverse dimensions of the furrow. With higher soil moisture, the dimensions of the furrow increased slightly: the width by 1.0% and the depth by 2.3%. When the duckfoot was pressed, the soil with a moisture content of 10% cracked in steps over short sections, forming lumps (Fig. 1b), increasing the vibration of the tines. The soil with a moisture content of 14% was cut off in the shape of longer, plastic billets, reducing the dynamics of the vibrations of the tines.

With a smaller width of the duckfoots (w), the furrow's dimensions were more significant relative to (w), especially the width of the furrow. The furrow width of the A105, B135, and C200 duckfoots was 170, 197, and 245 mm, respectively. The percentage changes in the furrow's width concerning the structural dimension of the duckfoots were 62, 48, and 22%, respectively. This may have been due to the geometry of the duckfoots and the relatively more significant influence of the nose part of the duckfoots with a smaller structural width (Fig. 1a). The nose part of the duckfoot with greater angles of sweep stem than the share rake angles of wings in the direction of movement and additionally with lateral angles of sweep stem, directly pressing on the compacted soil, caused it to crack in the direction of these angles. The range of soil cracking was similar for all three duckfoots but at a smaller width; when the proportion of wing length was smaller, the soil detachment from the ground was greater and went beyond the theoretical width of the tool. The wings of the duckfoots deformed the soil in the direction of the tool's movement, and the cut heap's cracking at the end of the wings was due to the angle of soil shearing and cohesion. Therefore, with the longer wings, the nose did not affect the range of the furrow width. Between duckfoots B135 and A105, the furrow width increased by 0.96 mm per 1 mm of duckfoot width, and between C200 and B135, the increase was 0.72 mm. Even more significant differences were found for the depth of the furrow, as these values were 0.16 mm and were close to zero between the analysed differences in the pairs of the duckfoots. The increase in the furrow dimensions decreased with the width of the duckfoots, resulting from the distribution of forces of more excellent value (Lisowski *et al.*, 2016) and increased tine vibration, leading to a shallow furrow and its width. With a lower working depth and the same cracking angles (detachment of the soil from the ground), the width of the furrow was relatively reduced. With the greater depth of work, the maximum depth of the furrow increased but remained, on average, 6% lower than the set depth, which resulted from the dynamics of vibrations and tine deviations. The depth of the furrow correlated well with its width (r = 0.581), which means that with the increasing width, cracking of the furrow and detachment of soil clods (soil wedges or soil heaps) from the side walls of the furrow, especially at the outer edge of the furrow, was observed.

The differences in the furrow width between the types of duckfoots were lower for the S flexible tine than the VCO rigid tine. When the VCO tine was in operation, minor differences in the furrow width were found for the working depth, but they were more significant for the duckfoot type (Figs A.7a, b). The stiff VCO tine, with a lower clearance angle, had a more substantial impact on the upper layers of the soil, which led to an increase in the furrow width. These results are consistent with previous studies on the effect of tillage tool geometry on furrow-cutting characteristics, which is confirmed in the literature (Lisowski *et al.*, 2016). Similar phenomena have been observed in other studies showing that the stiffness and angle of tine application can significantly affect duckfoots' work efficiency (Gautam *et al.*, 2024) and shape the furrow profile (Yazıcı, 2024).

The research showed that the width and depth of the cut furrow depended on the type of tines used, the depth of work, and soil moisture. Duckfoots attached to the rigid VCO tines created furrows with a flatter bottom, while the flexible S-tines generated furrows with a more triangular profile. The more excellent elasticity of the tines reduced the width and depth of the furrow due to the increased tool vibrations. With the greater width of the duckfoots, the percentage changes in the width of the furrow decreased, which may be due to the influence of forces acting on the tool and the geometry of the duckfoots, including the percentage share of the nose surface area.

3.3. Loosened and disturbed soil surface areas and loosening coefficient

Changes in furrow dimensions led to significant changes in loosened and disturbed soil surface areas. Still, the relationship between these fields, expressed as the loosening coefficient, was of less practical importance. Both fields, A_s and A_d, were strongly correlated, as evidenced by the high correlation coefficient r = 0.946 (Table 3). Although the soil mass from both fields was identical, because the compacted soil, cut off by duckfoots and analysed as A_d, was transformed into loosened soil, the surface area of loosened soil was 62% larger than the surface area of disturbed soil, equivalent to the cross-section of the furrow after the removal of loose soil (Fig. 4). This process results from the mechanism of work of duckfoots, which caused the expansion of the soil and increased the porosity of its structure (Gürsoy and Özaalan, 2023). Cultivation leads to an increase in soil volume and improved aeration, which has a positive effect on the development of the root system of plants and their ability to absorb nutrients (Ben-Noah and Friedman, 2018). Nevertheless, increased soil porosity also promotes the growth of weeds, which use better access to water and air, confirmed by research on soil structure and its impact on plant development (Bergmann *et al.*, 2016).

Although the A_s field was physically related to the width of the disturbed soil, their correlation was relatively weak (r = 0.412). On the other hand, fields A_s and A_d were strongly related to the dimensions of the furrow – the values of correlation coefficients concerning the width of w_f were 0.781 and 0.836, respectively, and the depth d_f were 0.858 and 0.881, respectively. These high values of the correlation coefficients, as well as the result of the F test (Table 1), indicate that the surface area of the disturbed soil was more sensitive to the factors tested than the loose soil area. The variability of the influence of operating parameters on field A_d is shown in Fig. 7 and that on-field A_s and the loosening coefficient are shown in Figs A.9 and A.10, respectively. Loosened and disturbed soils had larger areas after using the rigid VCO tine than the flexible S tine, by 33.8 and 34.4%. Because of this, the loosening coefficient did not show as much variability as one would expect.

A clear relationship between the dimensions of the furrow and the cross-sectional areas of the disturbed soil allowed the development of an empirical model in the form of a second-degree polynomial. In this model, the width of w_f was expressed by a linear and quadratic regression factor, and the depth d_f was described in the product of w_f (Fig. 8). The model has a high coefficient of determination R^2 = 71.1% and a test value of F = 22438. The surface analysis shows that the furrow dimension shows a clear synergy in the impact on the surface area of disturbed soil A_d.

When the duckfoots with the rigid VCO tine were working in the soil with 14% moisture, the field of A_d was more significant than in the soil with a moisture content of 10%, and these differences increased with working depth. The effect of the tine type on the A_d field was more significant than on the maximum furrow depth due to the simultaneous increase in the furrow width. The cross-sections of the furrow were more even when using the S tine than the VCO

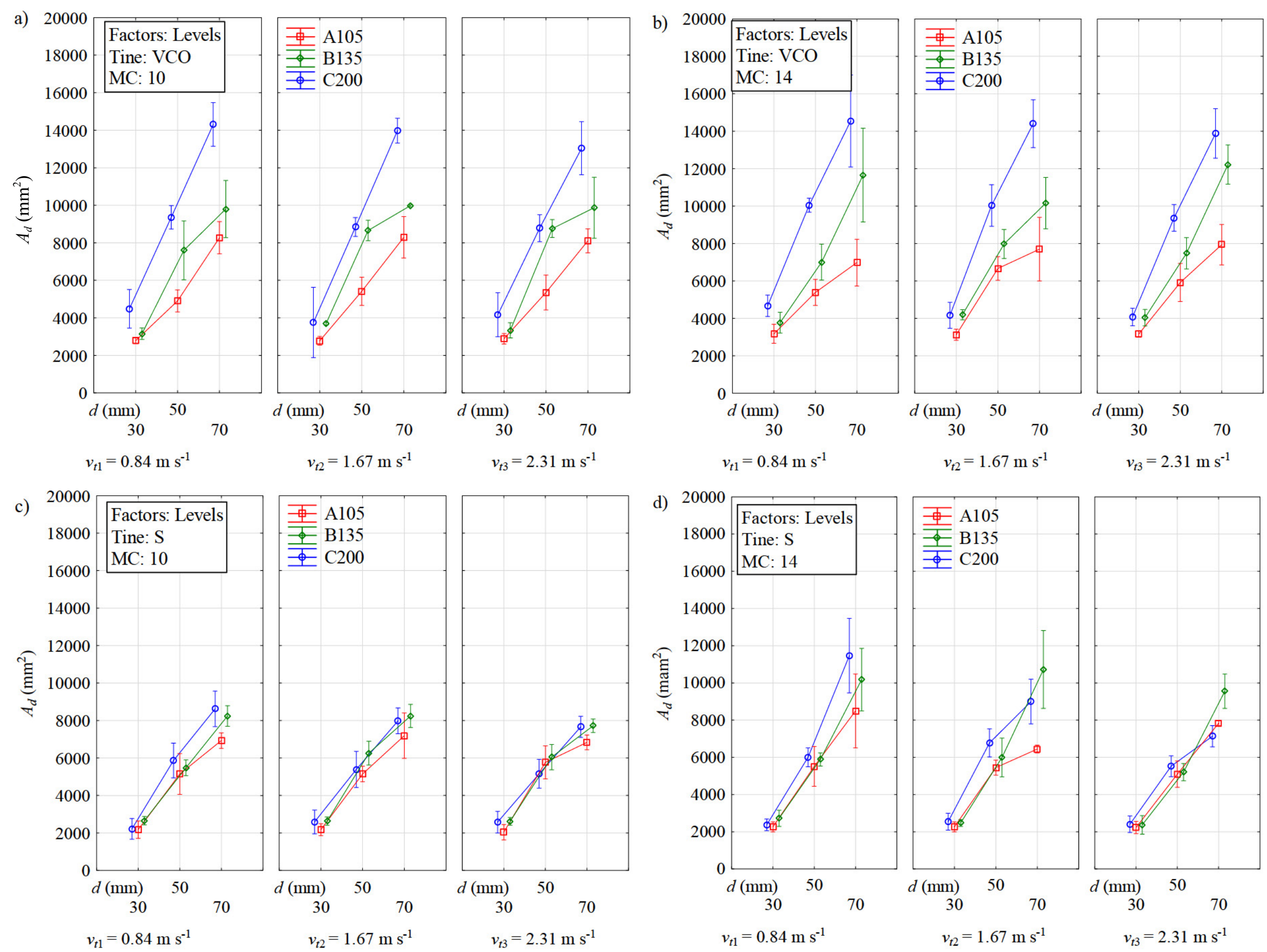


Fig. 7. Effect of depth d (30, 50, and 70 mm) and movement speed v (0.84, 1.67, and 2.31 m s^{-1}) on the surface area of disturbed soil A_d for three duckfoots A105, B135, and C200 attached to VCO-tine a), b) and S-tine c), d) working in soil with moisture content (*MC*) of: 10% a), c) and 14% b), d).

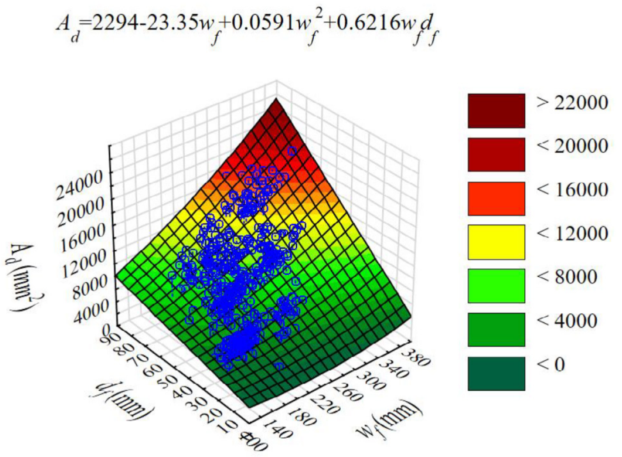


Fig. 8. Changes in the surface area of the disturbed soil A_d concerning the width w_f and the depth d_f of the furrow.

because the duckfoots attached to the VCO tine caused more rapid tearing of the soil, and larger clods were torn off from the ground. In the case of the S tine, the differences between the cross-section of the furrow decreased with increasing working depth, which is consistent with the hypothesis that the flexibility of the tine causes temporary deviations and a milder effect on the soil structure, which reduces the uprooting of large clods of soil.

To sum up, the working parameters of duckfoots, particularly the working depth and the type of tine, critically impacted the efficiency of loosening and shaping the soil structure. Duckfoots with the rigid VCO tine resulted in more soil disturbance and more tearing, which can be beneficial in some conditions. Still, the flexible S tine can provide more uniform results at smaller depths due to its more uniform action. Increasing the working depth has little effect on improving weed removal, but a higher working speed increases weed cover and reduces their survival (Pullen and Cowell, 1997). The structure of the soil after treatment is essential because, in the soil in the aggregated state with the spatial connection of the particles of the solid phase of the soil, weeds can still grow in clods of soil raised by the working elements (Bond *et al.*, 2003). Drying weeds on the soil surface is a critical factor in preventing weeds from regenerating, and moist conditions after weeding can reduce the effectiveness of weed destruction (Lejman, 2015).

The issue of improving soil structure after cultivation is significant in sustainable agriculture, where the aim is to minimise soil degradation and increase its ability to store water (Lal, 2015). Tillage tools that effectively loosen the soil improve its physical properties, such as increasing porosity, which promotes the development of the plant root system and water retention (Yang *et al.*, 2021). Studies on tools such as duckfoots have shown that the blade's shape and geometry significantly impact the efficiency of soil loosening and dispersion (Fielke, 1999). Sharper cutting edges with lower edge heights have been found to reduce tractive force and increase soil loosening efficiency, reducing energy consumption and improving soil quality (Ucgul *et al.*, 2015).

4. CONCLUSIONS

The study aimed to elucidate the effect of tine stiffness and operating parameters (speed, working depth, soil moisture) on the shape of soil disturbance profiles, in particular, the analysis of the width and depth of furrows cut by duckfoots, as well as the surface of disturbed and loosened soil and the loosening coefficient. The research was carried out on three types of duckfoots attached to tines of different stiffness (S and VCO), working in soil with a 10 and 14% moisture content at three working depths and three speeds.

The angle of application of the duckfoot had a significant impact on the shape of the cross-sectional area of the furrow. Duckfoots attached to the S (8°) flexible tine formed triangular furrows, while in combination with the VCO rigid tine (2°), the bottom of the furrow had a trapezoidal shape. The type of tine, its stiffness, and operating parameters were crucial for the effectiveness of soil disturbance. Duckfoots attached to the rigid VCO tine led to more significant soil tearing. They formed flatter furrows, while S spring tines, due to their greater flexibility, generated furrows with a more triangular cross-section, resulting in less uprooting of soil clods. Soil with a moisture content of 14% was more plastic, which resulted in less tool vibration compared to soil with a moisture content of 10%.

The results confirm that the critical factor for optimal soil disturbance is the selection of appropriate operating parameters adapted to the type of soil, its moisture, and the type of tools. The working depth had a more significant impact on furrow dimensions and loose and disturbed soil surfaces than the width of the duckfoot, which can be crucial in minimising soil damage and improving work efficiency. On the other hand, the higher movement speed of the duckfoots only increased the width of soil disturbance, which may be associated with a greater risk of covering plants with soil. The results of the research and analysis confirm the hypotheses.

The applied criterion indicators, such as the width of loosened soil disturbance (w_d), the width of the cultivated furrow (w_g), the furrow depth (d_f), and the furrow width (w_f), as well as the surface areas of the disturbed soil (A_d) and loosened soil (A_s), allowed a comprehensive assessment of the effectiveness of the work of the duckfoots. The loosening coefficient (PI) was a low-sensitivity indicator, suggesting the need to define a more integrated loosening rate. It was shown that the change in operational parameters significantly impacted these indicators, which can be helpful in precision farming.

Our practical findings suggest that the increased elasticity of the S-tines can reduce the risk of soil damage and reduce soil disturbance, promoting better plant development. VCO rigid tines, on the other hand, produce more uniform results at greater depths, which can be beneficial in certain soil conditions.

Directions for further research should include optimisation of the working parameters of tillage tools in different types of soils and studies on the influence of dynamic variables, such as working time and tool wear, on the efficiency of soil loosening. It is also worth investigating the impact of different duckfoot shapes and materials on crop efficiency, which could contribute to developing more sustainable agricultural technologies.

5. ACKNOWLEDGEMENTS

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Conflicts of interest: The authors declare that there are no conflicts of interest.

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Appendix A

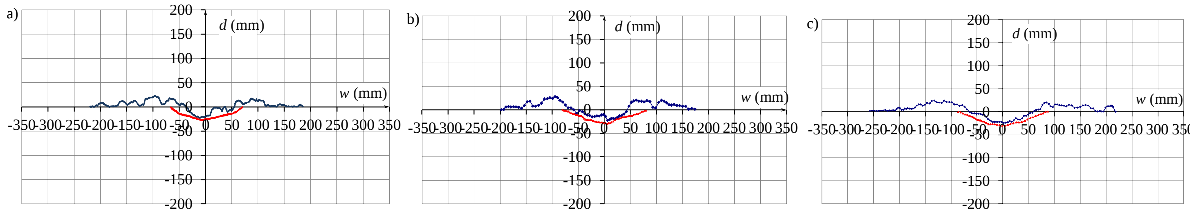

Fig. A.1. Ridge profilograms for duckfoots: a) A105, b) B135, and c) C200 attached to the S-tine working in soil with a moisture content of 10% and at a depth of 30 mm and at a movement speed of 1.67 m s^{-1} (the outer profile of loose soil is marked in the blue colour (diamond markers) and the furrow profile after removal of loose soil is marked in red (triangle markers).

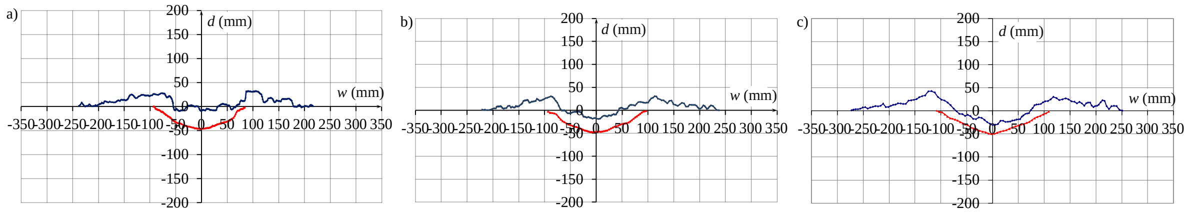

Fig. A.2. Ridge profilograms for duckfoots: a) A105, b) B135, and c) C200 attached to the S-tine working in soil with a moisture content of 10% and at a depth of 50 mm and at a movement speed of 1.67 m s^{-1} (the outer profile of loose soil is marked in the same colour (diamond markers) and the furrow profile after removal of loose soil is marked in red (triangle markers).

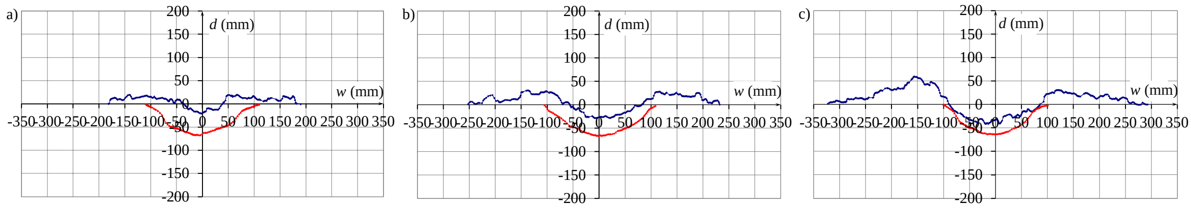

Fig. A.3. Ridge profilograms for the C200 duckfoot mounted on the S-tine working in soil with a moisture content of 10% and at a depth of 70 mm and at a movement speed of: a) 0.84 m s^{-1}, b) 1.67 m s^{-1}, c) 2.31 m s^{-1} (the outer profile of loose soil is marked in the blue colour (diamond markers) and the furrow profile after removal of loose soil is marked in red (triangle markers).

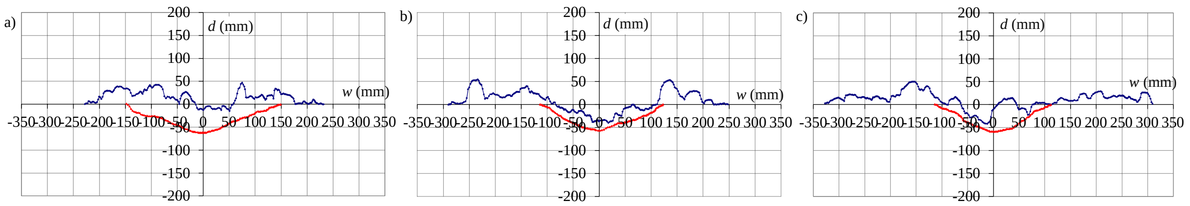

Fig. A.4. Ridge profilograms for the C200 duckfoot mounted on the S-tine working in soil with a moisture content of 14% and at a depth of 70 mm and at a movement speed of: a) 0.84 m s^{-1}, b) 1.67 m s^{-1}, c) 2.31 m s^{-1} (the outer profile of the loose soil is marked in the blue (diamond markers) and the furrow profile after removal of the loose soil is marked in red (triangle markers)).

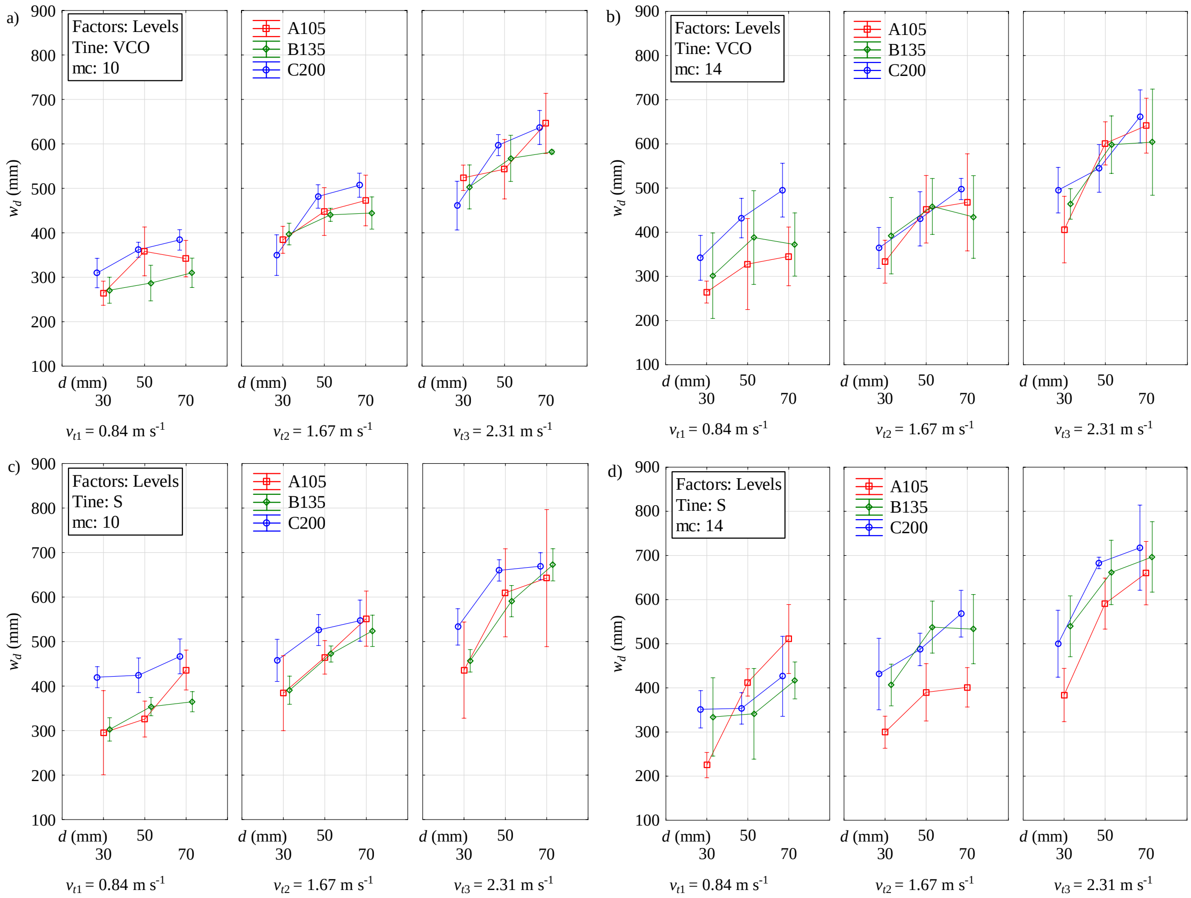

Fig. A.5. Effect of depth d (30, 50, and 70 mm) and movement speed v (0.84, 1.67 and 2.31 m s^{-1}) on the disturbed soil width w_d for three duckfoots A105, B135 and C200 attached to VCO-tine a), b) and S-tine c), d) working in soil with moisture content MC 10% a), c) and 14% b), d).

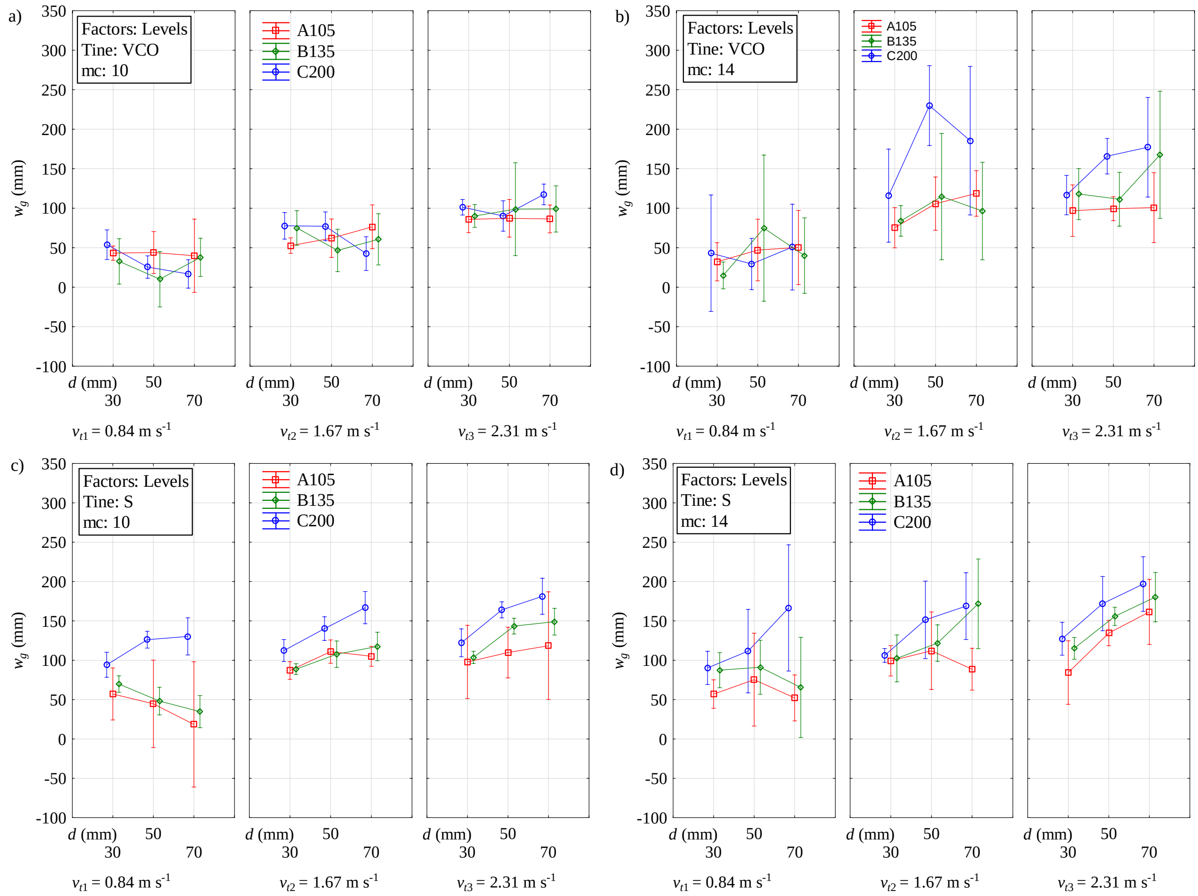

Fig. A.6. Effect of depth d (30, 50, and 70 mm) and movement speed v (0.84, 1.67, and 2.31 m s^{-1}) on the cultivated furrow width according to three duckfoots A105, B135, and C200 attached to VCO-tine a), b) and S-tine c), d) working in soil with moisture content MC 10% a), c) and 14% b), d).

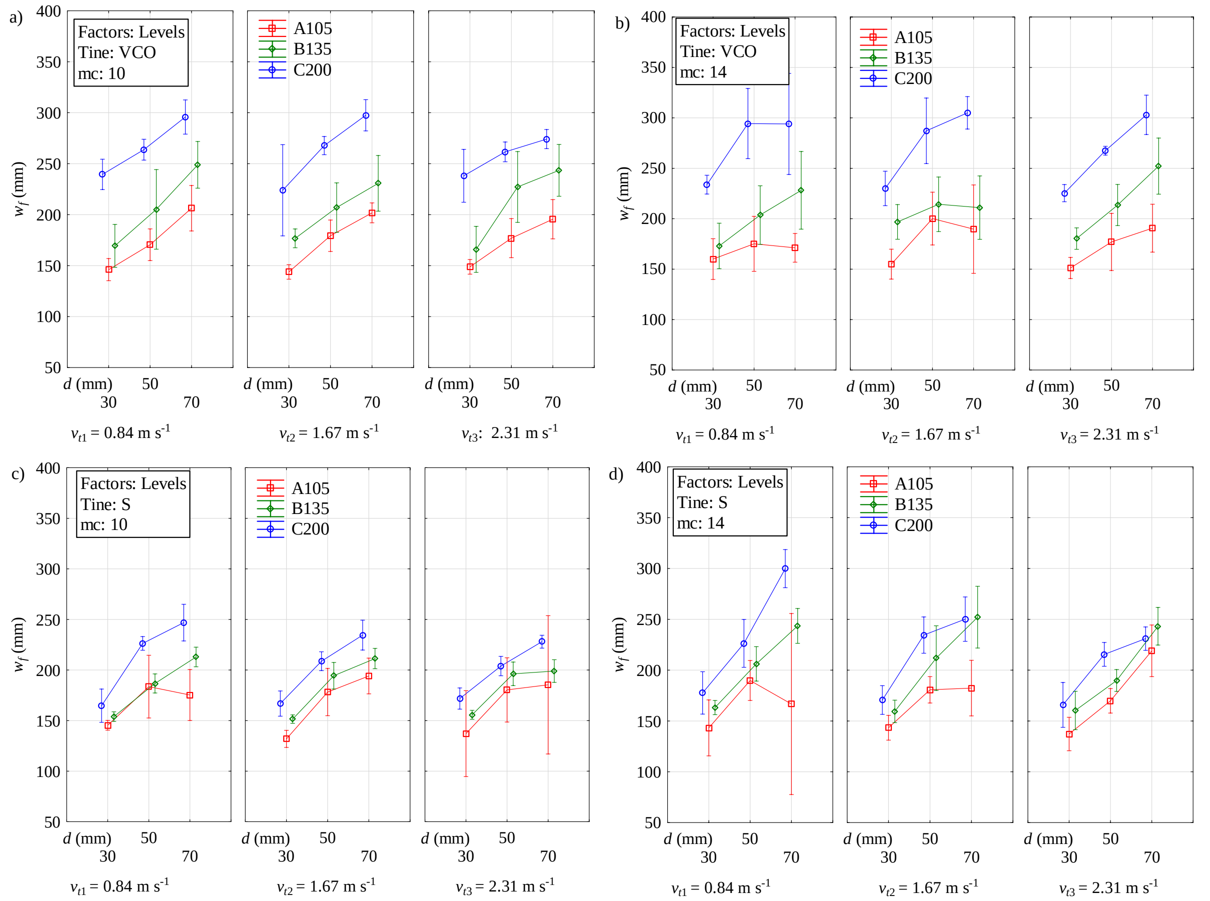

Fig. A.7. Effect of depth d (30, 50, and 70 mm) and movement speed v (0.84, 1.67, and 2.31 m s^{-1}) on furrow width w_f for three duckfoots A105, B135, and C200 attached to VCO-tine a), b) and S-tine c), d) working in soil with moisture content MC 10% a), c) and 14% b), d).

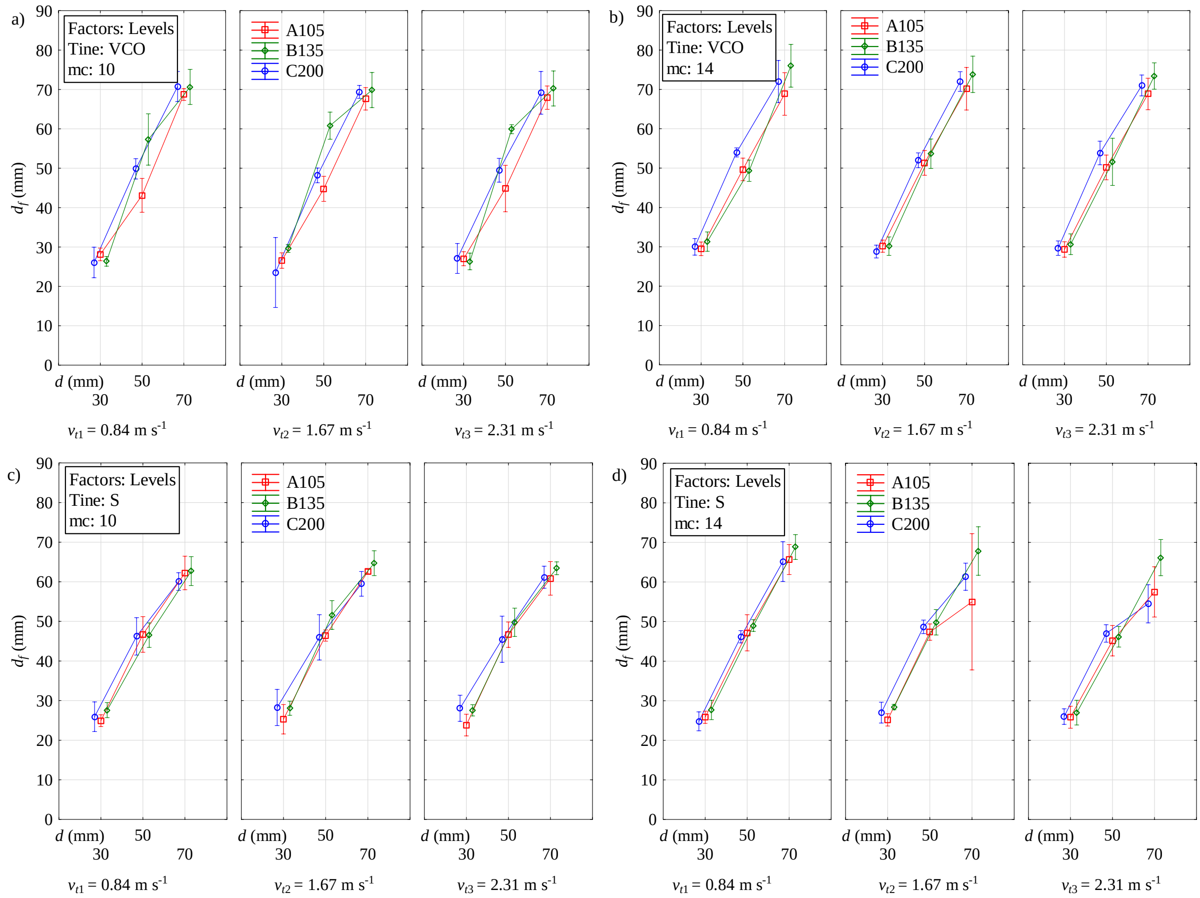

Fig. A.8. Effect of depth d (30, 50, and 70 mm) and movement speed v (0.84, 1.67, and 2.31 m s^{-1}) on furrow depth d_f for three duckfoots A105, B135, and C200 attached to VCO-tine a), b) and S-tine c), d) working in soil with moisture content MC 10% a), c) and 14% b), d).

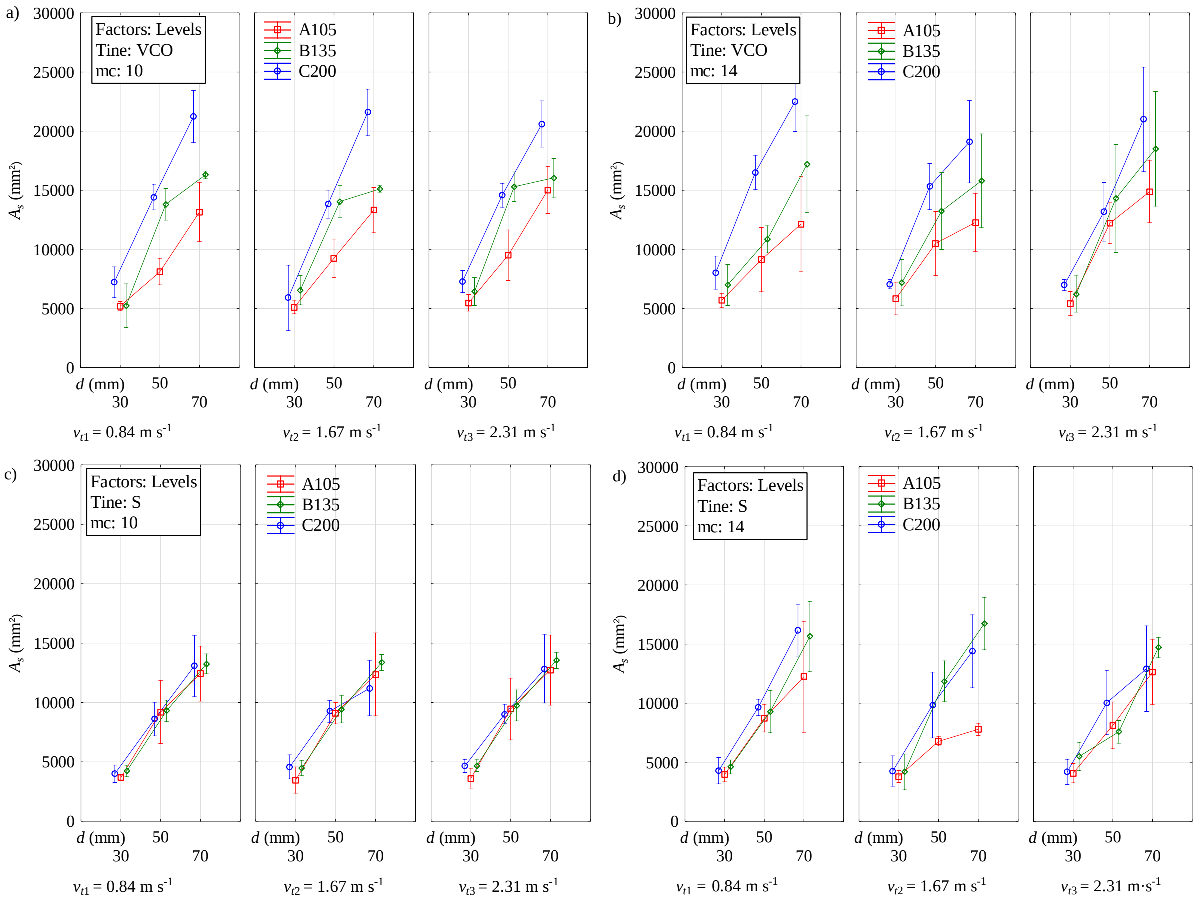

Fig. A.9. Effect of depth d (30, 50, and 70 mm) and movement speed v (0.84, 1.67, and 2.31 m s^{-1}) on the loosened soil area A_s for three duckfoots A105, B135, and C200 attached to VCO-tine a), b) and S-tine c), d) working in soil with moisture content MC 10% a), c) and 14% b), d).

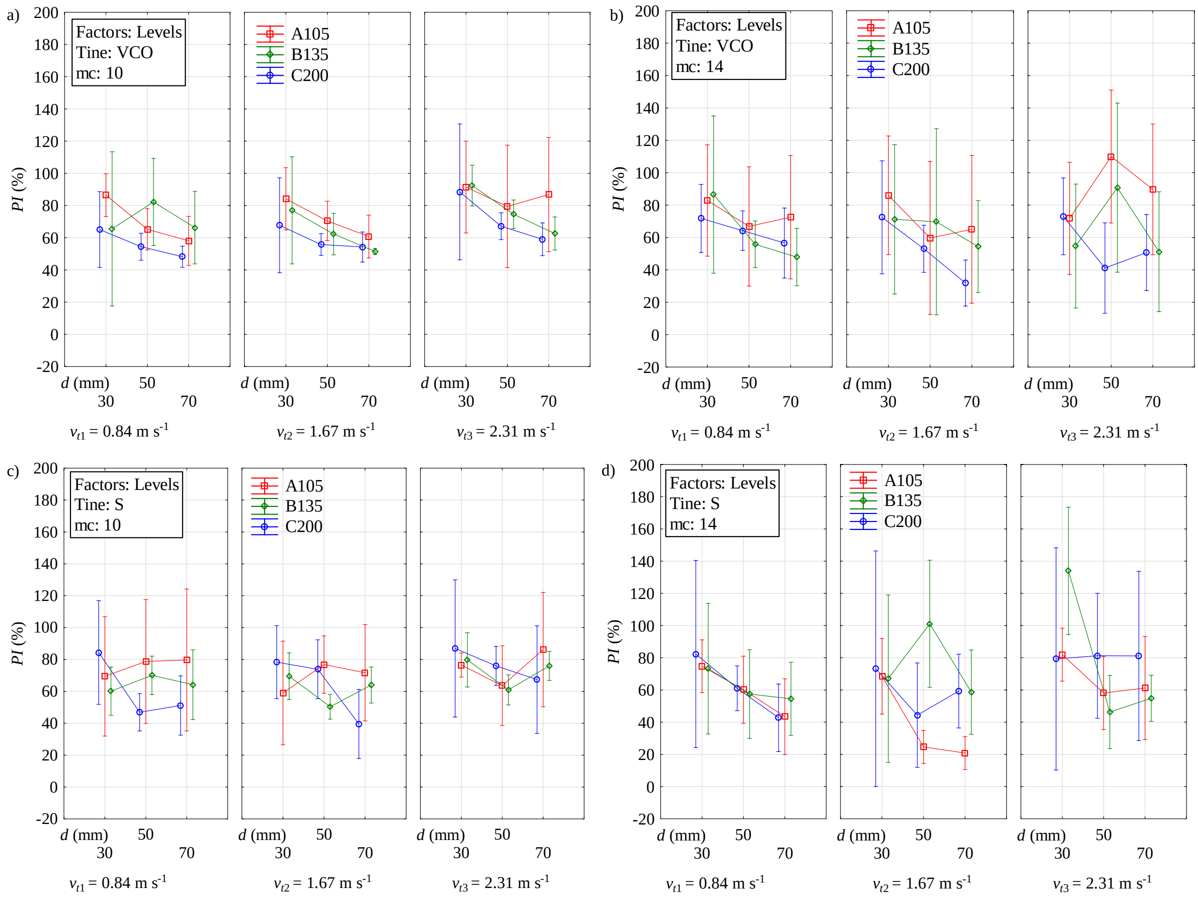

Fig. A.10. Effect of depth d (30, 50, and 70 mm) and movement speed v (0.84, 1.67, and 2.31 m s^{-1}) on the loosening index PI for three duckfoots A105, B135, and C200 attached to VCO-tine a), b) and S-tine c), d) working in soil with moisture content MC 10% a), c) and 14% b), d).