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Research article

Timing of Primary Soil Tillage as a Determinant of Soybean (*Glycine max* L.) Productivity

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ABSTRACT

Timing of primary soil tillage is a key agronomic practice influencing soybean (Glycine max L.) yield and seed quality. Soil physical properties, root development, and nutrient availability are affected by tillage timing, which can interact with cultivar characteristics and environmental conditions. A field experiment was conducted over two growing seasons (2023–2024) near Bačka Topola. Three tillage timings (autumn, winter, spring) and three soybean cultivars ('NS Atlas', 'NS Hogar', 'Rubin') were tested in a three-factorial design with three replications. Grain yield and thousand-seed weight were measured at harvest. Statistical analysis was performed to assess the main effects and interactions of year, cultivar, and tillage timing. Tillage timing significantly affected both grain yield and thousand-seed weight. Autumn tillage consistently produced the highest yield and heaviest seeds, while spring tillage resulted in the lowest values. Cultivar differences were present, with Rubin performing best, but the effect of tillage timing was more pronounced. Interactions between the year, cultivar, and tillage timing highlighted the influence of environmental conditions on yield formation. Timely primary tillage, particularly in autumn, enhances soil structure, root development, and water-nutrient use efficiency, leading to higher yields and improved seed quality. Optimal tillage timing, combined with cultivar selection, is essential for achieving stable and high soybean production under variable agroecological conditions.

Key words: *agroecological conditions, cultivar, yield, soil tillage, soybean, thousand-seed weight*

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INTRODUCTION

Soybean (*Glycine max* L.) is one of the most important field crops in modern agricultural production. Due to the high protein and oil contents of its seeds, as well as its wide range of applications in human nutrition, livestock production, and various sectors of the food and processing industries, soybean holds substantial economic importance worldwide. (FAO, 2023). In addition, this crop plays an important agroecological role in crop rotation, as it contributes to soil nitrogen enrichment and fertility improvement through symbiosis with Rhizobium bacteria (Salvagiotti et al., 2008). Stable and high soybean yields are conditioned by the interaction of numerous factors, among which agroecological conditions and applied cultivation technology are particularly important (Miladinov et al., 2020).
Soil tillage represents one of the fundamental cultural practices in the production of field crops (Đukić et al., 2019). Its role lies in creating favorable physical, chemical, and biological soil properties that enable unobstructed plant

growth and development. Properly performed primary tillage contributes to improving soil structure, increasing porosity and aeration, as well as better moisture accumulation and retention in the soil (Lal, 2004). Simultaneously, tillage affects the distribution of plant residues, microbial activity, and the dynamics of organic matter mineralization, which has a significant impact on nutrient availability for plants (Six et al., 2006).

In soybean cultivation technology, particular attention should be paid to the timing of primary soil tillage. The timing of tillage can significantly influence soil conditions before sowing, as well as the conditions in which the initial stages of plant growth and development will occur (Giller et al., 2009). Differences in tillage timing may lead to changes in soil water-air regime, degree of compaction, and the rate of surface layer warming, which can affect seed germination, root system development, and subsequent vegetation (Zapata et al., 2021). Therefore, choosing the optimal time for primary tillage is an important component of modern soybean production technology (Đukić et al., 2023).

Soybean yield is a complex trait influenced by a large number of interrelated factors. Yield formation is determined by yield components such as plant density, number of pods per plant, number of seeds per pod, and seed weight. Each of these components can be affected by the genetic characteristics of the cultivar, agroecological conditions during the growing season, and applied agrotechnical measures (Vogel et al., 2021).

Thousand-seed weight is one of the key yield components and an important indicator of seed size and quality. This trait is determined at standard seed moisture and is frequently used as an indicator of production success (Wei and Molin, 2020). Its value is influenced by several factors, including the genetic characteristics of the cultivar, water and nutrient availability during seed filling, and conditions prevailing in the final stages of vegetation. Moreover, the applied cultivation technology, including soil tillage, can indirectly affect seed weight formation through its impact on plant growth and development (Chiluwal et al., 2022).

Research on the influence of specific cultural practices on yield components is of great importance for improving soybean cultivation technology and achieving stable and economically viable production (Mamlić et al., 2024). In particular, it is important to evaluate how different timings of primary soil tillage can affect yield and its components in this crop.

Although numerous studies have investigated the role of soil tillage in crop production, the optimal timing of primary tillage is still insufficiently defined, especially under variable agroecological conditions. Most research has focused on the type and intensity of tillage, whereas little attention has been given to the timing of operations and its interaction with cultivar characteristics and climatic conditions. Inconsistent results indicate the need for comprehensive studies on the effects of tillage timing in interaction with genotype and year-to-year climatic variability. The objective of this study was to determine the effect of primary soil tillage timing on soybean yield and thousand-seed weight, as well as the stability of these effects across different cultivars and growing seasons. The working hypothesis was that earlier tillage, particularly in autumn, creates more favorable soil conditions, leading to higher yield and improved seed quality.

MATERIAL AND METHODS

Local conditions

The study on the effect of primary soil tillage timing on soybean yield and thousand-seed weight was conducted over two growing seasons, 2023 and 2024, at an experimental plot in Bačka Topola (latitude 45°46′ N, longitude 19°42′ E, northern Vojvodina). The soil is chernozem with good structure, pH 7.0–7.5, and a humus content of 2.1 %, providing favorable conditions for plant growth and good fertility.

The main meteorological parameters during the soybean growing period are presented in Figure 1. The average air temperature during the growing period (April–September) in 2023 was 19.8 °C, whereas in 2024 it was 22.1 °C. Both values were higher than the long-term average (18.3 °C). In 2023, the mean monthly air temperatures in June (21.4 °C), July (24.7 °C), August (23.7 °C), and September (21.4 °C) were above the long-term averages. The air temperature in April (10.5 °C) was below the long-term average (11.8 °C), while in May (17.2 °C) it was approximately equal to the long-term value (17.0 °C). In 2024, the mean monthly air temperatures during the entire growing period were higher than the long-term averages. The highest temperatures were recorded during the summer months, with values of 24.3 °C, 26.9 °C, and 27.5 °C in June, July, and August, respectively. The total precipitation during the growing period in 2023 was 385.9 mm, slightly above the long-term average (366.1 mm). In 2024, 317.5 mm of precipitation was recorded, which is below the long-term average. In 2023, lower precipitation occurred in June and the first two decades of July, while in 2024, precipitation deficits were observed during the last decade of June, July, August, and the first decade of September.

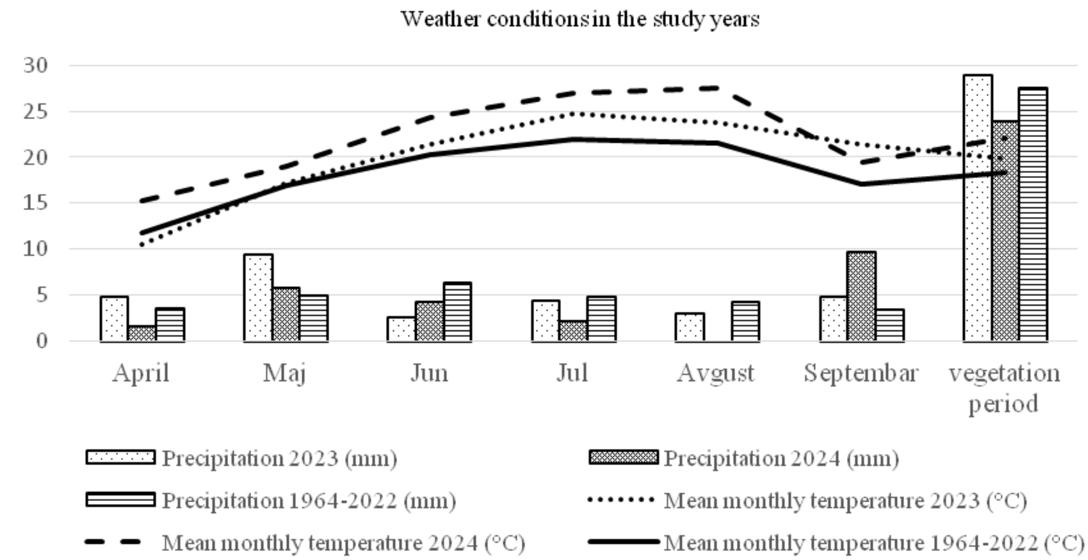

Figure 1. Weather conditions in the study years (RHZS, 2026)

Experimental design

The experiment was arranged as a three-factorial field trial with three replications. The factors studied were the timing of primary soil tillage, soybean cultivar, and year of study. Three tillage treatments were applied:

i) autumn tillage (25–31 October): the soil is tilled just before winter, allowing it to rest during the cold months and accumulate moisture.

ii) winter tillage (10–20 December): the soil is cold and mostly frozen or wet during this period; tillage is performed when the soil begins to "rest" after the first colder months.

iii) spring tillage (10–20 March): tillage is carried out shortly before sowing, when the soil has warmed up and dried after winter.

The tillage depth was 25 cm, and the same machinery was used in all treatments: John Deere 6110D tractor with a four-furrow Vogel & Noot plow. Two to three days before sowing, the soil was further prepared using a seedbed cultivator to create optimal conditions for sowing.

Three soybean cultivars with different lengths of the growing season were used:

'NS Atlas' (maturity group 0) – sowing density 500,000 plants/ha,

'NS Hogar' (maturity group I) – sowing density 450,000 plants/ha,

'Rubin' (maturity group II) – sowing density 400,000 plants/ha.

Sowing was carried out in mid-April in both growing seasons directly into the prepared furrows. Standard agronomic practices commonly applied in soybean production in Vojvodina were followed, including weed control through mechanical and chemical means and monitoring for diseases and pests according to local recommendations. Growth and development phenophases were monitored and scored according to the BBCH scale (Meier, 2001).

Harvesting was performed at the stage of technological maturity. Seed moisture was determined, yield was recalculated to a standard moisture content of 13 %, and expressed per unit area, while thousand-seed weight was determined on representative seed samples. The results were subjected to analysis of variance for the three-factorial experiment, and differences between mean values were tested using the LSD test at 5 % and 1 % probability levels. Statistical analysis was performed using Statistica 13.0, and the results are presented in tabular form.

RESULTS AND DISCUSSION

Effect of primary soil tillage timing, cultivar, and year on soybean grain yield

The effect of year, cultivar, and primary soil tillage timing on soybean grain yield is presented in Tables 1 and 2. The results indicate that the year of study had a significant effect on soybean yield. The average grain yield in 2023 was 2,899 kg ha^{-1}, whereas in 2024 it was 1,883 kg ha^{-1}, with statistically significant differences between the two years. The higher yield achieved in 2023 can be attributed to more favorable meteorological conditions during the growing season, primarily due to greater precipitation and its more even distribution compared to 2024.

Table 1. Effect of year, cultivar and soil tillage timing and their interactions on soybean grain yield (kg ha⁻¹)

Year (A)	Cultivar (B)	Soil tillage (C)			Average (A x B)	Average (A)
		Autumn	Winter	Spring		
2023	NS Atlas	3127	3090	2869	3029	2899
	NS Hogar	2896	2888	2742	2842	
	Rubin	2928	2931	2624	2828	
	Average (A x C)	2984	2970	2745**	-	
2024	NS Atlas	1872	1711	1588	1724	1883
	NS Hogar	2108	1994	1645	1916	
	Rubin	2319	2109	1597	2008	
	Average (A x C)	2100**	1938	1610	-	

LSD	A	A x B	A x C
5%	78.3	163.5	99.0
1%	118.6	217.9	133.8

Legend: Values represent mean soybean grain yield (kg ha⁻¹). A – year; B – cultivar; C – soil tillage timing. Mean (A × B) – average yield of cultivars within each year; Mean (A) – average yield across cultivars for each year; Mean (A × C) – average yield of soil tillage timings within each year. LSD values are provided for factors A, B, C and interactions A × B and A × C at the 5% and 1% significance levels. Values marked with * and ** indicate significant differences at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Meteorological conditions during the growing period are one of the key factors affecting soybean yield formation. In particular, the amount and distribution of precipitation during flowering, pod formation, and seed filling stages are crucial, as water deficit in these phases can reduce the number of pods per plant and limit seed filling, thereby decreasing total yield (Rotundo and Westgate, 2009). Inter-annual climatic variability is recognized as a major cause of soybean yield fluctuations (Mamlić et al., 2025; Guo et al., 2022; Odey et al., 2022).

Analysis of the interaction between year and soil tillage timing (A × C) showed a consistent trend in both years. In 2023, the lowest yield was recorded under spring tillage (2,745 kg ha⁻¹), while autumn and winter tillage achieved higher yields (2,984 kg ha⁻¹ and 2,970 kg ha⁻¹, respectively). A similar pattern was observed in 2024, with the highest yield obtained under autumn tillage (2,100 kg ha⁻¹) and the lowest under spring tillage (1,610 kg ha⁻¹). This indicates that earlier tillage promotes favorable soil moisture conditions and a more stable environment for plant growth, whereas late tillage may lead to soil compaction and weaker root development (Triplett and Dick, 2008; Toliver et al., 2012).

Analysis of cultivar effects showed that the average soybean yields varied within a relatively narrow range. The lowest average yield was obtained for 'NS Atlas' (2,376 kg ha⁻¹), while the highest yield was recorded for 'Rubin' (2,418 kg ha⁻¹). 'NS Hogar' achieved an average yield of 2,379 kg ha⁻¹. No statistically significant differences were found among the tested cultivars, indicating a similar production potential under the given agroecological conditions. These results suggest that the cultivars exhibited relatively uniform production characteristics, and that their genetic yield potential was not significantly differentiated under the applied management practices (Cober and Morrison, 2010; Morsy et al., 2018).

The timing of primary soil tillage had a significant effect on soybean grain yield. The highest average yield was obtained with autumn tillage (2,542 kg ha⁻¹), followed by winter tillage (2,454 kg ha⁻¹), while the lowest yield was observed with spring tillage (2,171 kg ha⁻¹), with statistically significant differences among treatments.

Higher yields achieved with autumn and winter tillage can be explained by the fact that timely soil preparation improves soil structure, increases water retention, and ensures favorable aeration, supporting the development of a stronger root system and more efficient utilization of water and nutrients during the growing season (Đukić et al., 2023; Verhulst et al., 2011; Govaerts et al., 2005). In contrast, delayed spring tillage is usually performed when the soil is already warmer and drier, which may reduce moisture in the topsoil, hinder uniform soil preparation, and negatively affect early plant growth and yield formation (Weidhuner et al., 2026; Brezinščak and Bogunović, 2021; Faligowska et al., 2025; Du et al., 2009).

Table 2. Mean soybean yield depending on cultivar and soil tillage timing (kg ha⁻¹)

Cultivar (B)	Soil tillage (C)			Average (B)
	Autumn	Winter	Spring	
NS Atlas	2500**	2400*	2229	2376
NS Hogar	2502**	2441**	2194	2379
Rubin	2624**	2520**	2111	2418
Average (C)	2542	2454	2171	-

LSD	B	C
5%	95.3	58.9
1%	127.3	78.4

Legend: Values represent mean soybean grain yield (kg ha⁻¹). B – cultivar; C – soil tillage timing. Mean (B) – average yield of each cultivar across soil tillage treatments; Mean (C) – average yield of soil tillage timings across cultivars. LSD values are provided for factors B and C at the 5% and 1% significance levels. Values marked with * and ** indicate significant differences at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Mean values of soybean grain yield indicate that yield varied depending on the combination of cultivar and soil tillage timing. The lowest yields were consistently observed under spring tillage for all cultivars. For 'NS Atlas', yield under spring tillage was 2,229 kg ha⁻¹, compared to 2,500 kg ha⁻¹ and 2,400 kg ha⁻¹ under autumn and winter tillage, respectively. A similar trend was observed for 'NS Hogar' and 'Rubin', with 'Rubin' achieving the highest yield under autumn tillage (2,624 kg ha⁻¹). These results suggest that the effect of soil tillage timing on yield was consistent across cultivars, emphasizing the importance of proper selection of primary tillage timing in soybean production. Timely tillage ensures favorable soil conditions, including improved soil water-air relations and nutrient availability, which directly contribute to higher yields (Księżak and Bojarszczuk, 2023; Gawęda et al., 2014).
Overall, the results indicate that year had the strongest influence on soybean yield, followed by soil tillage timing, while cultivar had no significant effect. The statistically supported interactions (A × B and A × C) further confirm the stability of the tillage effect across years and cultivars, highlighting the importance of timely soil management for achieving stable and high soybean yields.

Effect of primary soil tillage timing, cultivar, and year on soybean thousand-seed weight
The effect of year, cultivar, and primary soil tillage timing on soybean thousand-seed weight is presented in Tables 3 and 4. The results showed that the year of study had a significant effect on seed weight. The average thousand-seed weight in 2023 was 156.29 g, while in 2024 it was 149.64 g, with statistically significant differences between years. Higher values in 2023 can be attributed to more favorable meteorological conditions during the seed-filling period, which allowed better accumulation of water and nutrients in the seeds.

Table 3. Effect of year, cultivar and soil tillage timing and their interactions on soybean thousand-seed weight (g)

Year (A)	Cultivar (B)	Soil tillage (C)			Average (A x B)	Average (A)
		Autumn	Winter	Spring		
2023	NS Atlas	152.80	149.70	145.40	149.30	156.29*
	NS Hogar	170.30	166.40	153.70	163.47	
	Rubin	160.80	158.00	149.50	156.10	
	Average (A x C)	161.30	158.03	149.53**	-	
2024	NS Atlas	144.30	141.60	136.30	140.73	149.64
	NS Hogar	152.60	150.20	138.90	147.23	
	Rubin	171.20	162.50	149.20	160.97	
	Average (A x C)	156.03	151.43*	141.47**	-	

LSD	A	A x B	A x C
5%	6.84	7.24	7.05
1%	3.80	4.17	4.02

Legend: Values represent mean thousand-seed weight (g). B – cultivar; C – soil tillage timing. Mean (B) – average thousand-seed weight of each cultivar across soil tillage treatments; Mean (C) – average thousand-seed weight for each soil tillage timing across cultivars. LSD values are provided for factors B and C at the 5% and 1% significance levels. Values marked with * and ** indicate significant differences at $P \leq 0.05$ and $P \leq 0.01$, respectively.

The measurements of thousand-seed weight were carried out at the stage of technological maturity (R8) according to the Fehr and Caviness (1977) growth stage scale for soybean, ensuring consistency and comparability of results. Differences in thousand-seed weight among cultivars and tillage timings may be explained by variations in soil conditions, root development, and water-nutrient availability during the seed-filling phase.

Meteorological conditions during the seed-filling period are one of the key factors affecting thousand-seed weight. More favorable conditions in 2023 allowed better accumulation of water and nutrients, resulting in higher seed weight.

Considering the cultivar effect, thousand-seed weight ranged from 145.02 g for 'NS Atlas' to 158.53 g for 'Rubin', while 'NS Hogar' showed an average value of 155.35 g. Differences between 'NS Atlas' and the other two cultivars were statistically significant, whereas 'Rubin' and 'NS Hogar' did not differ significantly. These results indicate that later-maturing cultivars may have a higher potential for producing heavier seeds under the given agroecological conditions (Ngalamu et al., 2013).

The analysis of the effect of primary soil tillage timing showed that the highest thousand-seed weights were achieved with autumn tillage (158.67 g), while the lowest was observed under spring tillage (145.50 g). Winter tillage resulted in an average of 154.73 g. Differences between autumn and spring tillage, as well as between winter and spring tillage, were statistically significant.

Considering the interaction of year and tillage timing, in 2023, the lowest thousand-seed weight was recorded for spring tillage (149.53 g), while autumn and winter tillage achieved higher values (161.30 g and 158.03 g, respectively). In 2024, the highest seed weight was obtained with autumn tillage (156.03 g), while spring tillage produced the lowest value (141.47 g), and winter tillage was intermediate (151.43 g).

These results indicate that timely primary tillage significantly contributes to increased seed weight, likely due to improved soil water-air regime and more efficient nutrient use during seed filling (Licht and Al-Kaisi, 2005).

Table 4. Mean soybean thousand-seed weight depending on cultivar and soil tillage timing (g)

Cultivar (B)	Soil tillage (C)			Average (B)
	Autumn	Winter	Spring	
NS Atlas	148.55	145.65	140.85**	145.02
NS Hogar	161.45	158.30	146.30**	155.35**
Rubin	166.00	160.25*	149.35**	158.53**
Average (C)	158.67	154.73*	145.50	-

LSD	B	C
5%	6.29	6.91
1%	3.24	3.86

Legend: Values represent mean soybean thousand-seed weight (g). B – cultivar; C – soil tillage timing. Mean (B) – average thousand-seed weight (g) of each cultivar across soil tillage treatments; Mean (C) – average thousand-seed weight (g) of soil tillage timings across cultivars. LSD values are provided for factors B and C at the 5% and 1% significance levels. Values marked with * and ** indicate significant differences at $P \leq 0.05$ and $P \leq 0.01$, respectively.

Mean thousand-seed weight indicates that the lowest values were consistently observed under spring tillage for all cultivars. For 'NS Atlas', spring tillage produced 140.85 g, compared to 148.55 g and 145.65 g under autumn and winter tillage. For 'NS Hogar', autumn tillage produced 161.45 g, while spring and winter tillage achieved 146.30 g and 158.30 g. 'Rubin' showed the highest weight under autumn tillage (166.00 g), with spring tillage producing 149.35 g.

These findings clearly show that timely autumn tillage significantly increases yield and thousand-seed weight for all the tested cultivars. This can be explained by optimal root system development and more efficient accumulation of water and nutrients during seed filling (Egli, 2013). Conversely, spring tillage reduces yield and seed weight, likely due to poorer soil structure and limited moisture availability during critical growth stages (Franzluebbers, 2002).

The results also indicate that the genetic traits of cultivars determine the potential for yield and seed weight, but cannot compensate for unfavorable agrotechnical or climatic conditions. The interaction of year and tillage timing highlights the importance of climatic factors, while the interaction with cultivar confirms that timely autumn tillage consistently improves productive traits of all cultivars, in line with studies emphasizing the role of genotype-environment interactions for yield stability (Hatfield et al., 2011).

Therefore, the selection of optimal tillage timing should be planned according to local agroecological conditions to maximize seed quality and yield stability. These findings emphasize the importance of an integrated approach in soybean cultivation, where timely agrotechnical practices and cultivar choice synergistically enhance production efficiency.

CONCLUSIONS AND RECOMMENDATIONS

The agroecological conditions of northern Vojvodina, particularly the variable distribution of precipitation and temperature fluctuations, have a decisive impact on the effectiveness of primary soil tillage and the final soybean yield. The results of this study clearly indicate that autumn tillage is the only strategy that provides optimal conditions for plant growth and development, directly contributing to higher yields and better seed quality.

In contrast, spring tillage, conducted at an unfavorable time, leads to a dramatic reduction in yield and seed weight because the soil is not adequately prepared, moisture is limited, and root system development is compromised. Winter tillage provides intermediate results, but does not match the efficiency of autumn tillage.

These findings clearly demonstrate that delays in primary soil tillage or inadequate planning pose a direct risk of substantial yield losses, regardless of the genetic potential of the cultivars. Therefore, for stable, economical, and sustainable soybean production in northern Vojvodina, primary soil tillage should be scheduled in autumn, in combination with standard agronomic practices, to maximize yield and seed quality.

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