12th INTERNATIONAL SCIENTIFIC CONFERENCE
RURAL DEVELOPMENT 2025
RESILIENCE TO GLOBAL CHANGE
1-3rd October, 2025, Vytautas Magnus University Agriculture Academy, Lithuania

VYTAUTAS MAGNUS UNIVERSITY AGRICULTURE ACADEMY

Proceedings of the 12th International Scientific Conference Rural Development 2025

Edited by assoc. prof. dr. Judita Černiauskienė

ISSN 2345-0916 (Online)

Article DOI: https://doi.org/10.15544/RD.2025.026

THE INFLUENCE OF HERBICIDE APPLICATION TIME AND HARROWING ON WEEDINESS AND ECONOMIC EFFICIENCY OF WINTER WHEAT

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A two-factor field experiment was conducted in 2023–2024 on the farm of farmer Algirdas Aukselis in Joniškis district. Experimental treatments: Factor A – herbicide application time: 1) not applied (N), 2) only in autumn (A), 3) only in spring (S), 4) in autumn and spring (A+S); and Factor B – crop harrowing: 1) not harrowed, and 2) harrowed (H). With dicotyledonous weeds prevailing in the winter wheat crop, the herbicide DIFLANIL 500 SC (0.2 L ha^{-1}, active ingredient diflufenican) was used for autumn spraying. In spring, a mixture of HERBISTAR 200 EC (0.6 L ha^{-1}, active ingredient fluroxypyr) and AXIAL 50 EC (0.6 L ha^{-1}, active ingredient pinoxaden) herbicides was sprayed. It was found that the time of herbicide application and harrowing had a significant impact on the weediness of the crop. When spraying with herbicides, weediness of winter wheat crops in autumn decreased by 52.7–66.6 % compared to unsprayed fields. Spring harrowing significantly (1.3–1.7 times) reduced the weediness of crops. During spring harrowing, the efficiency of herbicide spraying reached 45.0–47.5 %. When applying a combined weed control strategy – spraying with herbicides (S+A, and S) together with harrowing, a greater effect on total profit was found compared to herbicides used separately at different times. Harrowing of crops increased total profit from EUR 16.0 ha^{-1} (in unsprayed fields) to EUR 228.0 ha^{-1} (in fields sprayed in autumn and spring).

Keywords: *winter wheat; use of herbicides; harrowing; crop weediness; total profit*

INTRODUCTION

Weeds are considered undesirable plants in agriculture, as they reduce crop yields by competing for water, light, nutrients, and space (Roslim et al., 2021). US scientists have found that winter wheat yield losses due to weeds can range from 3 to 34 %, with an average loss of about 26% of total production. Therefore, weeds often cause minor or major economic damage (Flessner et al., 2021). To avoid such economic losses, it is necessary to identify the predominant weeds in the field and select appropriate control measures. Various preventive, mechanical, biological, and chemical control measures are available (Pala, Mennan, 2021). Herbicides are the most widely used group of pesticides in agriculture worldwide, used to inhibit the growth and development of weeds in order to remove unwanted plants from various crops (Mauser et al., 2023). Compared to other weed control measures, the use of herbicides saves time and labor costs, as it eliminates the need for physical labor or large amounts of fuel to mechanically work the soil with agricultural implements (Mesnage, Zaller, 2021). Weed control with herbicides was found to be much cheaper and to yield 3–4 times greater net benefits than mechanical weed control. However, despite the economic benefits, chemical weed control with herbicides can harm nature, microorganism populations, and human health. Improper use of herbicides can cause phytotoxicity to crops and contribute to weed resistance to herbicides (Rahman, 2016). Due to the long-term use of herbicides, many weeds become resistant to them or the weed flora is replaced by alien weeds (Sanbagavalli et al., 2020). Therefore, farmers need to look for sustainable weed management solutions that would increase crop yields without negatively impacting the environment and ecosystems. For example, conventional weed control measures such as tillage – mechanical control, crop density formation, intercropping, crop rotation, and other measures – remain effective and environmentally friendly to this day (Bajwa et al., 2019).

One effective measure for controlling weediness in crops is harrowing. Harrowing crops is most commonly used in organic farming, but has recently become widespread in conventional farming as an alternative to herbicides (Berge et al., 2023). Harrowing as a mechanical control measure is valued for its effectiveness and impact on higher yield potential. K. Jabran et al. (2017) state that inter-row cultivation and crop harrowing are the two most important mechanical weed control strategies. Under favorable weather conditions, weeds grow very quickly in cultivated fields, and their abundance can significantly reduce yields. To effectively control their spread, spring-loaded harrows are most commonly used in various field and garden crops. These harrows can be particularly effective in cereal crops, as their effectiveness often ranges from 10 to 80% (Samuel et. al, 2022). To achieve maximum weed control efficiency during harrowing, it is recommended to destroy weeds during the cotyledon stage (Hussain et al., 2018). However, the optimal period for using this tool is limited, as it is determined by local weather and soil conditions (DLG Organic Farming Committee et al., 2022; Samuel et. al, 2022). Under optimal conditions (properly selected harrowing time, favorable environmental conditions, smooth soil surface), harrowing can achieve an effect equivalent to that of herbicide use. Under unfavorable environmental conditions, harrowing often does not ensure the same effectiveness as the use of herbicides. Therefore, to achieve greater efficiency, it is important to combine weed control measures using both mechanical and chemical methods (Naruhn et al., 2021).

The aim of the experiment was to determine the effect of harrowing and herbicide application at different times on the weediness, productivity, and economic efficiency of winter wheat crops.

RESEARCH METHODS

A two-factor field experiment was conducted in 2023–2024 on the farm of Algirdas Aukselis in the village of Šimkūnai, Joniškis district (56° 10' 59.56“, 23° 26' 27.82”). Experimental treatments: Factor A – herbicide application time: 1) not applied, 2) only in autumn, 3) only in spring, 4) in autumn and spring; and Factor B – crop harrowing: 1) not harrowed, and 2) harrowed. In autumn, when dicotyledonous weeds spread, the winter wheat crop was sprayed with the herbicide DIFLANIL 500 SC (active ingredient diflufenican) 0.2 L ha^{-1}, and in spring, HERBISTAR 200 EC (active ingredient fluroxypyr) 0.6 L ha^{-1} and AXIAL 50 EC (active ingredient pinoxaden) 0.6 L ha^{-1} herbicide mixture according to the research scheme. Part of the crop was only harrowed in spring, during the tillering stage of winter wheat. The winter wheat variety ‘Etana’ was sown across the entire experimental field at a seed rate of 3.7 million ha^{-1}. Sowing was carried out with a Väderstad Super Rapid 400 C seed drill, with 12.5 cm row spacing and a depth of 3 cm. During sowing, $N_{14}P_{14}K_{21}$ fertilizer was applied locally at a rate of 160 kg ha^{-1}. In the spring, after vegetation renewal, all fields were fertilized with liquid nitrogen N_{32} (KAS) fertilizer (200 L ha^{-1}), and after a week, the crop was harrowed with ecological harrows. When weeds emerged, a mixture of herbicides was sprayed according to the research scheme. Later, ammonium sulfate was applied at a rate of 120 kg ha^{-1}. At the end of April, a growth regulator and microelements were applied, followed by ammonium nitrate (150 kg ha^{-1}) five days later. At the flag leaf formation stage, at the end of May, an additional 80 kg ha^{-1} of ammonium nitrate was applied. The experiment was conducted in four replicates. The gross plot size was 350 m^2, the net plot size was 200 m^2.

The pH of the field soil in the experiment was 6.8±0.2, the humus content was 4.09±0.54 %, the mobile potassium content was 450±39 mg kg^{-1}, and the mobile phosphorus content was 558±43 mg kg^{-1}.

The field experiment determined the density, weediness, and grain yield of winter wheat in five permanent locations in each replication. Winter wheat crop density was determined 6 times: after germination (BBCH 10-11), at the end of the vegetation in autumn (BBCH 25-27), at the beginnig of vegetation in spring (BBCH 25-27), before harrowing (BBCH 26-28), after harrowing (BBCH 26-28) and productive steams before harvesting (BBCH 80-83). Weed infestation of winter wheat was also determined 6 times: before herbicide spraying in autumn (BBCH 20–21), at the end of the vegetation in autumn (BBCH 25–27), before harrowing in spring (BBCH 26–28), after harrowing (BBCH 26–28), after herbicide spraying in spring (BBCH 30–31) and before harvesting (BBCH 87–88). The number of plants and weeds was determined in 0.25 m^2 plots, then converted to pcs. m^{-2}. Winter wheat yield was determined by sampling plants at four locations per 1 m^2 and threshing them with a laboratory thresher Wintersteiger LD 350.The economic assessment of the weed control measures applied was performed based on 2024 prices, assessing the monetary value of the additional yield obtained and the costs incurred for herbicides, their spraying, and crop harrowing. A two-factor analysis of variance was used for the statistical evaluation of the experimental data, using the ANOVA analysis module from the SELEKCIJA software package (Raudonius, 2017).

RESEARCH RESULTS AND DISCUSSION

Seed germination is influenced by seed quality, sowing technology parameters, and various physical, chemical, and biological factors (Chaichi et al., 2022; Wesołowska et al., 2022; Šerá, Hnilička, 2023). Plants can be affected by various abiotic factors: drought, excess moisture, extreme temperatures, chemicals, heavy metals, and nutrient deficiencies or excesses, which often harm plants, i.e., disrupting seed germination and reducing their germination energy (Kumar et al., 2020; Das, Biswas, 2022). Temperature and moisture are considered to be the main factors influencing seed germination (Khaeim et al., 2022). After evaluating the germination of winter wheat, no significant differences were found between the fields, but it can be noted that not all of the seeds sown germinated. The seed rate for winter wheat was 3.7 million ha^{-1} or 370 pcs. m^{-2}, but the number of germinated plants in the fields ranged from 338.4 to 360.0 pcs. m^{-2} (Table 1). The field germination rate of seeds was 91.2–97.3 %. According to A. A. Šiuliauskas (2015), when farming intensively on medium-yield soils, the optimal number of germinated winter wheat seedlings after sowing should be 280–300 pcs. m^{-2}. Therefore, it can be said that the density of the winter wheat crop was in line with the recommendations of scientists. Scientists also claim that each wheat plant should have formed 3–4 side shoots by autumn, and the crop should have accumulated 300–350 sum of active temperatures. However, for the crop to successfully overwinter, it is recommended to form a crop density that does not exceed 1200 shoots m^{-2} at the end of the vegetation period in autumn (Šiuliauskas, 2015; Duchovskis et al., 2024). By the end of the vegetation period in autumn, winter wheat plants had formed 1036.8–1096.8 shoots m^{-2}, but no significant differences were found between the experimental fields, even though the number of dicotyledonous weeds was reduced by autumn spraying in the respective fields. The tillering coefficient of winter wheat was 3.02–3.14. Good tillering of plants in autumn was due to a sufficiently long and warm autumn, as the sum of active temperatures was 441.7 °C.

Based on practical recommendations and research, winter wheat overwintering is considered successful if at least 260 plants m^{-2} or at least 70 % of the crop remains in the spring. A particularly high degree of overwintering is considered to be when more than 80 % of plants remain (Voloschuk et al., 2021). In this experiment, after assessing the density of the winter wheat crop in the spring after the renewal of vegetation, it was found that the number of shoots ranged from 834.0 to 881.6 m^{-2}, and overwintering reached 79.2–83.4 %. A slightly better (1.5–3.4 percentage points) overwintering percentage was found in fields that had been sprayed with herbicides in the autumn and where dicotyledonous weeds had been controlled. Before crop harrowing, the plants were still bushy, and the number of shoots increased by 5.4–8.6 %.

Harrowing is considered an effective weed control measure, but its effectiveness depends on many factors, the most important of which are weed species composition, crop development, harrowing time, and weather conditions (Špokienė, Jodaugienė, 2009). Harrowing not only destroys weeds but also causes mechanical damage to cultivated plants. The literature usually states that when harrowing a cereal crop once, up to 8–11 % of plants may be damaged, and when harrowing twice, the damage may be even greater, i.e., 17–32 % (Pilipavičius et al., 2010). According to V. Pilipavičius (2010), damage during harrowing, when the amount of uprooted plants does not exceed 5 %, is considered insignificant. After harrowing winter wheat crops at the end of the tillering stage, very good results were achieved, as the number of shoots in the harrowed fields decreased by only 1.6–3.0 % and ranged from 868.0 to 908.0 pcs. m^{-2}. Later, as the crop grows and develops, some of the stems are reduced. According to various sources, the optimal density of winter wheat before harvesting should be such that there are about 600 productive stems per square meter (Šiuliauskas, 2015; Petrychenko et al., 2021). After assessing the density of the winter wheat crop (number of productive stems) before harvesting, it was found that it ranged from 535.2 to 647.2 pcs. m^{-2}. Significantly denser crops (14.8–17.4 %) and fewer reduced stems (5.3–9.8 %) were found in fields that were sprayed only in spring, or both autumn and spring, regardless of whether the crop was harrowed or not, compared to unsprayed and unharrowed fields.

Table 1. The influence of herbicide application time and harrowing on winter wheat crop density, pcs. m^{-2}

Experimental variants	Germination BBCH 10–11	At the end of the vegetation BBCH 25–27	At the beginning of the vegetation BBCH 25–27	Before harrowing BBCH 26–28	After harrowing BBCH 26–28	Productive stems BBCH 80–83
N	348.0 a	1057.6 a	838.0 a	897.2 a		551.2 a
N+H	341.6 a	1041.6 a	834.0 a	891.2 a	868.0 a	541.6 a
A	349.6 a	1052.0 a	860.4 b	922.2 ab		535.2 a
A+H	340.0 a	1036.8 a	864.8 b	916.0 ab	888.8 a	604.0 ab
S	360.0 a	1059.2 a	840.8 a	913.5 a		637.6 b
S+H	338.4 a	1045.6 a	843.2 a	916.0 a	900.8 a	632.8 b
A+H	346.4 a	1084.0 a	879.2 b	948.6 b		632.8 b
A+S+H	347.6 a	1096.8 a	881.6 b	929.6 b	908.0 a	647.2 b

Note: means of variants without the same letters differ significantly at a 95% confidence level; N – herbicides not used, A – sprayed with herbicides in autumn, S – sprayed with herbicides in spring, H – harrowed in spring

Various agronomic factors are important for assessing the yield and yield potential of winter wheat, including the use of herbicides and mechanical tillage. Proper application of these measures can improve plant growth conditions, reduce weed competition, and optimize crop structure elements (Wesołowska et al., 2022; Duchovskis et al., 2024). The warming climate, especially in autumn, and early sowing lead to the proliferation of monocotyledonous weeds (field bentgrass, cheatgrass, and black-grass) and the use of herbicides in autumn. In the early stages of development, agricultural plants are most sensitive to weed competition because their poorly developed aboveground parts are unable to suppress weeds growing in the crop. Although weeds that germinate in spring are often suppressed by the crop, in sparse crops, they can compete with the crop. Therefore, autumn is the right time to control weeds (Špokienė, Jodaugienė, 2009; Weed control in .., 2020). In the autumn of 2023, weediness was recorded in those fields where herbicide had been used in the autumn (R). It was found that the two most common types of short-lived weeds were *Lamium purpureum* L. and *Stellaria media* L., and that weediness in the fields did not differ significantly. Therefore, the herbicide DIFLANIL 500 SC (active ingredient diflufenican), which destroys dicotyledonous weeds, was selected. In unsprayed fields (N; N+A; P and P+A), both dicotyledonous and monocotyledonous weeds grew intensively until the end of the winter wheat vegetation period (Table 2).

In the fields sprayed in autumn (A; A+H; A+S; A+S+H), after controlling dicotyledonous weeds, monocotyledonous weeds grew intensively, so the total number of weeds at the end of the winter wheat vegetation period in the autumn was higher than before the use of herbicides, but significantly lower (1.5–3.6 times) compared to the unsprayed fields. In spring, when winter wheat vegetation resumed, the total number of weeds was found to be even higher. The weed count in fields that were not sprayed in the autumn (N; N+H; S; S+H) increased by 1.5–1.6 times, while in fields that were sprayed in the autumn, it increased by 2.2–2.5 (A+S; A+S+H) to 3.0–3.1 (A; A+H) times. The main reason is that weeds, especially *Apera spica-venti*, germinate even at low positive temperatures in late autumn or even in warmer winters (Scherner et al., 2017; Harrington et al., 2019; Auškalnienė et al., 2020). *Apera spica-venti* accounted for 48.1–74.9 % in unsprayed fields and even 76.7–96.6 % in fields sprayed in autumn.

Table 2. The influence of herbicide application time and harrowing on winter wheat crop weediness, pcs. m^{-2}

Experimental variants	Before herbicide spraying in autumn BBCH 20–21	At the end of the vegetation BBCH 25–27	Before harrowing BBCH 26–28	After harrowing BBCH 26–28	After herbicide spraying in spring BBCH 30–31	Before harvesting BBCH 87–88
N	79.2 a	287.2 b	450.0 b		450.0 c	383.2 g
N+H			443.2 b	353.4 b	353.4 c	222.4 e
A		96.0 a	286.7 a		286.7 bc	334.4 f
A+H			296.7 a	180.0 a	180.0 ab	186.4 d
S	88.0 a	262.0 b	400.1 b		223.4 bc	107.2 ab
S+H			419.9 b	273.3 ab	143.4 ab	68.8 a
A+H		136.0 a	343.4 a		163.3 ab	121.0 bc
A+S+H			296.7 a	206.8 ab	110.0 a	59.0 a

Note: means of variants without the same letters differ significantly at a 95% confidence level; N – herbicides not used, A – sprayed with herbicides in autumn, S – sprayed with herbicides in spring, H – harrowed in spring.

Under favorable weather conditions, weeds germinate quickly in crops, which can significantly reduce plant yield. Therefore, harrowing is particularly effective in the early stages of plant development, before weeds have become established (Hussain et al., 2018). Spring harrows are most commonly used to control weeds effectively. Under optimal conditions, their effectiveness in cereal crops can reach up to 80 % (Samuel et. al, 2022). Once the soil reached physical maturity, winter wheat fields were harrowed according to the research plan. A single harrowing reduced weed infestation in the crop by 20.3 to 39.3 %. *Apera spica-venti* decreased the most in fields that were not sprayed in the autumn, from 32.1 to 41.5 %, while in fields that were sprayed in the autumn, it decreased from 9.7 to 11.1 %. Such uneven destruction of *Apera spica-venti* was also due to intra-species competition, as weediness was higher in autumn crops without herbicide use. Weeds competed not only with cultivated plants, but also with each other, so they were less well established and more vulnerable during harrowing.

After the use of herbicides in spring, it was found that the highest weed infestation in winter wheat crops was in unsprayed (450.0 pcs. m^{-2}) or only harrowed crops (353.4 pcs. m^{-2}), while the lowest weed infestation was found in crops that were sprayed in the autumn and spring and harrowed (110.0 pcs. m^{-2}). Similar trends were observed before harvesting. The highest weed infestation in winter wheat crops was found in unsprayed crops (383.2 pcs. m^{-2}), while the lowest was found in crops sprayed in autumn and spring and in harrowed crops (59.0 pcs. m^{-2}). Various studies also confirm that the use of herbicides significantly reduces weed infestation and increases productivity. However, the use of herbicide mixtures and mechanical measures is usually more effective than individual herbicides (Gurmanchuk et al., 2021).

Significantly higher winter wheat yields were obtained by spraying crops with herbicides in autumn and spring (8.1 t ha^{-1}) or only in spring (8.3 t ha^{-1}). When these variants were additionally harrowed, the yield was significantly higher – 9.2 and 8.8 t ha^{-1}, respectively. The lowest winter wheat grain yield was obtained when the crops were not sprayed or were sprayed only in the autumn, and only dicotyledonous weeds were destroyed, 5.5 and 5.7 t ha^{-1}, respectively (Aukselis, Jodaugienė, 2025). The winter wheat yield increase ranged from 0.1 t ha^{-1} (without herbicide application and with harrowing) to 3.7 t ha^{-1} (with herbicide application in autumn and spring and with harrowing) (Table 3).

Table 3. Economic assessment of weed control measures applied

Experimental variants	Yield increase t ha^{-1}	Grain price EUR t	Yield increase value EUR	Total cost of herbicide spraying and harrowing EUR ha^{-1}	Gross profit EUR ha^{-1}
1. Herbicides not used (comparative variant)	-	-	-	-	-
2. Herbicides not used, harrowed in spring	0.1	212.0	21.2	5.2	16.0
3. Herbicides applied in autumn	0.2	212.0	42.4	13.0	29.4
4. Herbicides applied in autumn, harrowed in spring	1.1	212.0	233.2	18.2	215.0
5. Herbicides applied in spring	2.8	212.0	593.6	37.8	555.8
6. Herbicides applied in spring, harrowed in spring	3.3	212.0	699.6	43.0	656.6
7. Herbicides applied in autumn and spring	2.6	212.0	551.2	50.8	500.4
8. Herbicides applied in autumn and spring, harrowed in spring	3.7	212.0	784.4	56.0	728.4

The highest yield increase was observed when winter wheat was sprayed in spring, and both autumn and spring (EUR 593.6 and EUR 551.2, respectively), and when these sprayings were combined with harrowing (EUR 699.6 and EUR 784.4, respectively). When assessing the gross profit from herbicide use, the highest profit (EUR 555.8 ha^{-1}) was obtained by spraying winter wheat crops in spring with a mixture of HERBISTAR 200 EC and AXIAL 50 EC herbicides. After a comprehensive assessment of weed control measures (herbicides and harrowing), the highest gross profit (EUR

728.4 ha^{-1}) was obtained by spraying winter wheat crops in autumn with the herbicide DIFLANIL 500 SC 0.2 L ha^{-1} and in spring with a mixture of the herbicides HERBISTAR 200 EC 0.6 L ha^{-1} and AXIAL 50 EC 0.6 L ha^{-1}, using crop harrowing.

CONCLUSIONS

The timing of herbicide application had no significant effect on crop density in the autumn until the end of winter wheat vegetation. Winter wheat overwintered better, and the crop was denser in fields that were sprayed in the autumn. When the crop was harvested, the number of shoots decreased by only 1.6–3.0 % and ranged from 868.0 to 908.0 per m². A significantly higher (14.8–17.4 %) number of productive stems formed in fields that were sprayed only in spring or in autumn and spring, regardless of whether the crop was harrowed or not, compared to unsprayed and unharrowed fields.

The timing of herbicide application and crop harrowing had a significant effect on crop weediness. When herbicides were sprayed in the autumn, the weediness of winter wheat crops decreased by 52.7–66.6 % compared to unsprayed fields. Spring harrowing significantly reduced (1.3–1.7 times) weed infestation in the crop. The effectiveness of spring herbicide spraying reached 45.0–47.5 %. Before harvesting, the highest weed infestation was found in unsprayed (N) and only autumn-sprayed (A) fields, while the lowest was found in spring-sprayed (S) or autumn- and spring-sprayed (A and S) fields.

After a comprehensive assessment of weed control measures (timing of herbicide application and harrowing), the highest total profit (EUR 728. 4 ha^{-1}) was obtained by spraying winter wheat in autumn with the herbicide DIFLANIL 500 SC 0.2 L ha^{-1} and in spring with a mixture of HERBISTAR 200 EC 0.6 L ha^{-1} and AXIAL 50 EC 0.6 L ha^{-1} herbicides, using crop harrowing.

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