Peter Berk[1], Denis Stajnko[1], Andrej Paušič[1], Mario Lešnik[1] **Original scientific paper**

Effectiveness and environmental effect of alternative weed control in vineyard

Abstract
In the presented research, we tested two alternative concepts for controlling weeds under the vines as a counterweight to the glyphosate-based herbicide approach: control with plant extract-based organic fertilizer Stopeco with herbicidal action and mechanical control with the help of a combined tool consisting of rotary star tiller and finger weeder. A comparative analysis among the tested methods was done on fuel consumption, carbon footprint, grape yield, economic feasibility and environmental effect. The smallest environmental footprint was estimated for three-times application of organic fertilizer Stopeco (7.50 gha anno^{-1}), followed by two-times glyphosate application (7.79 gha anno^{-1}) and four times mechanical weed control (8.09 gha anno^{-1}). However, Stopeco can be environmentally friendly from an eco-toxicological point of view. The biggest GWP emissions (990.91 kg CO_2eq) and CO_2 emissions (381.92 kg CO_2) were again established for mechanical weeding and the smallest for glyphosate application (762.22 kg CO_2eq and 351.46 kg CO_2). Considering the economic feasibility, both alternative weed control methods were comparable to the glyphosate-based herbicide because the financial benefit amounted to 1933 EUR per ha at mechanical weeding, 1085 EUR per ha at glyphosate-based herbicide, and organic fertilizer 989 EUR per ha, respectively.
Keywords: *glyphosate, vineyard, weed control, rotary star tiller (Rollhacke)*

Introduction

The control of weeds in vineyards in the area under the vines using herbicides is currently relatively easy, efficient, and cheap. Chemical agents for controlling weeds under vines in vineyards include various herbicides, adapted to specific types of weeds and environmental conditions. Glyphosate-based herbicides are currently the most widely used herbicides in the European Union (EU) and have been in use for several decades on one hand, and are slowly being withdrawn from viticultural use on the other hand (Poje et al., 2022) despite the fact that the active substance glyphosate meets the criteria for extending the approval from article 4 of Regulation (EC) 1107/2009, (2009). Herbicides based on glyphosate can be replaced with other herbicides, which are less efficient and need to be used more frequently than glyphosate. Herbicides may not be used by winegrowers engaged in organic grape production. Suppression of weeds under the vines in the vineyard can also be carried out through alternative mechanical tools, installed via a three-point hydraulic coupling on the tractor. It is also necessary to highlight the fact that more and more grape growers do not use herbicides, and yet they are not official organic grape growers (Poje et al., 2022). The reason is to be found in the fact that

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grape growers in conventional grape production stopped the use of glyphosate to protect the environment in which they live and for better promotion of their wines with less PPP residues at marketing. The third reason is due to the financial subsidies provided by the state through the Ministry of Agriculture, Forestry, and Food for abandoning herbicide use.

Modern grape growers perform the environmental environmentally harmful control of weeds (use of mechanical tools such as undercutters, weeders, stringers, ploughs, and mechanical rotating wheels with rotary action, (Berk et al., 2023; Manzone et al., 2020) and thermal control of weeds under vines (e.g. fire, hot foam) (Morselli et al., 2022). Additionally, it is considered as an alternative method such as mulching (use of under-vine mulchers) and cover crop growing ("living mulch" with various ground cover forming plants where we do not mechanically cultivate the soil and vegetation). One of the alternative approaches is the use of organic or biological preparations based on acetic acid, pelargonic acid, essential oils of citrus fruits, bacteria, salts (Berk et al., 2021), and organic mulches ("dead mulch") as an alternative to conventional under-vine weed management (Cabrera-Pérez et al., 2022). More and more different modulating practical mechanical tools are appearing in the market, which combine several operations of mechanical weed suppression under vines. All of the listed methods for controlling weeds under vines belong to the so-called low-risk plant protection methods.

The aim of our research was to test whether the use of glyphosate for weed control in the vineyards can be replaced by mechanical weeding or the application of organic fertilizer with herbicidal action and to check if two alternative methods have the same economic feasibility and are also more sustainable in terms of environmental footprint.

Materials and methods

Vineyard features and trial design

The experiment was carried out in the vineyard owned by agricultural holding Greif, Fram, Slovenia ''46°27'10.3" N, 15°38'19.8" E (Figure 1). The 3-years old vineyard was planted with «Sauvignon Blanc» grape variety and grafted on the 'Kober 5BB' rootstock. The inter-row distance between vines is 2.50 m, and the training form is a double Guyot (two spars with up to ten buds) with two plugs (three or more buds), where the height of the grapevine trunk is 0.90 m, and the average distance between the grapevines is 1.70 m. The inclination of the vineyard terrain was 0%. The weed population under vines was predominantly composed of the fallowing species: *Chenopodium album, Amaranthus retroflexus, Elymus repens, Sonchus asper, Ranunculus repens, Potentilla repens, Gallinsoga parviflora, Lolium perenne, Poa annua, Rumex obtusifolius, Cerastium arvense, Capsella bursa pastoris, Polygonum lapathyfolium, Echynochloa cruss gallii, Convolvulus arvensis* and *Digitaria sanguinalis*.

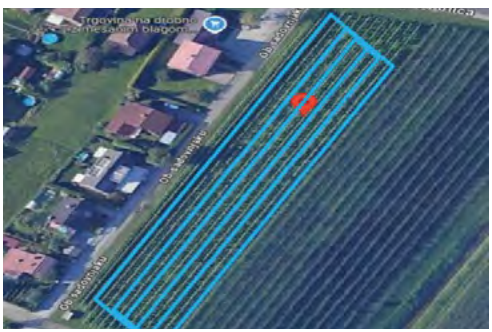

Figure 1. Arial view of the experimental vineyard under "Sauvignon blanc"

Slika 1. Pogled iz zraka na pokusni vinograd sorte "Sauvignon blanc"

The field trial was organized in a randomized block design with plots repeated for times. The whole trial plot consisted of seven 120.00 m long rows. All evaluations were performed only in the middle of rows. Three different weed control methods were carried out several times during the growing season to analyze the effect of the control measures on the amount and quality of grape yield: a) glyphosate, b) mechanical weeding, c) organic fertilizer Stopeco with herbicidal action, d) mechanical weeding, e) weed free control (manually) and f) non-treated-weeded (control).

For statistical evaluations, the analysis of variance (ANOVA) was performed, and the post-hoc Tukey HSD test ($p<0.05$) was used to separate the means of all studied parameters. We used IBM SPSS statistical software, version 28 (www.ibm.com/products).

Equipment for mechanical weeding

For mechanical weeding under vine stocks, we used a modular system consisting of the following components: a Fendt 211 F tractor, a rotary star tiller “Rollhacke” and a finger weeder “Fingerhacke” (Braun Maschinenbau GmbH; Germany) (Figure 2). The Fendt 211 F vario narrow track tractor (111 KM/ 82 KW) is equipped with the intuitive “FendtONE control concept”.

The mechanical tools were installed on both lateral sides, between the tractor axles. One of the characteristics of the tested mechanical tool is that in addition to surface vegetation cutting and pulling out (weed control), it also cultivates soil to an 0.08 m depth. A mechanical tool rotates due to the movement of the tractor and soil resistance. The working efficiency of the tool depends largely on the appropriate driving speed of the tractor. A mechanical tool needs hydraulic energy support, hydraulic cylinders for lifting, a tilt adjustment, and an offset from the trunks of the vine. The optimum performance of a rotary star tiller is at higher driving speeds, which should be between 7 kmh^{-1} and 12 kmh^{-1}. The tool pulls weeds out of the soil more intensively at higher speeds and replaces them in the interrow space.

The mechanical tool finger weeder with a combination of a rotary star tiller enables a very efficient mechanical weeding under the vine (Figure 2). We used a finger weeder with a diameter of 0.54 m. The shape and position of the teeth allow the finger weeder to work more externally than the fixed rotary star tiller disc, guaranteeing better towing in all types of soils and more effective grubbing.

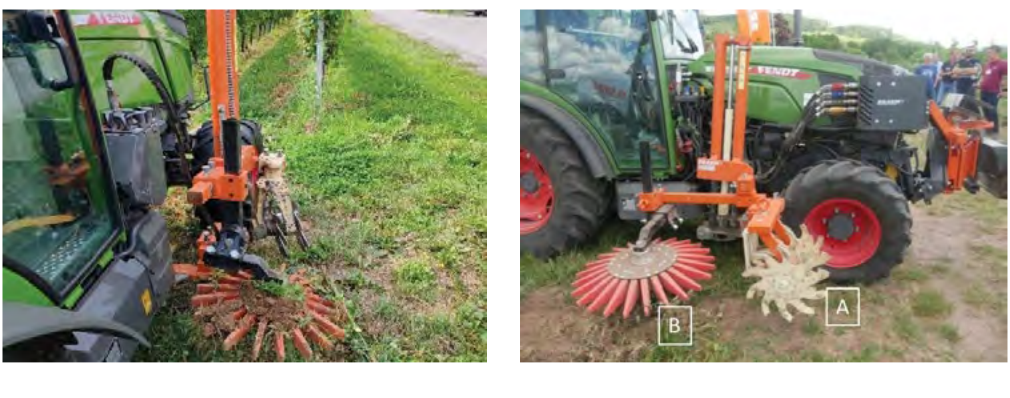

Figure 2. Mechanical weed control with a rotary star tiller (A) and finger weeder (B)
Slika 2. Mehaničko suzbijanje korova s rotacijskom zvjezdastom frezom (A) i prstastom plijevicom (B)

Figure 3. The layout of the under-vine stripe areas after being treated with Boom efekt herbicide (left), rotary star tiller (Rollhacke) (middle), Stopeco fertiliser (right) (May 5th)
Slika 3. Raspored površina podloznih pruga nakon tretiranja herbicidom Boom efekt (lijevo), zvjezdastom frezom (Rollhacke) (sredina), gnojivom Stopeco (desno) (5. svibnja)

Tested products for weed control
The systemic glyphosate-based herbicide Boom efekt (Albaugh TKI Slovenia; 48.3% of glyphosate in the form of isoprophyl amine salt) was used two times at rate 4 Lha^{-1} and the organic fertiliser Stopeco at rate 5 Lha^{-1} was used three times, respectively. Stopeco is a natural liquid organic-mineral N-P-Fe fertilizer made from plant extracts of ginger, soy, and others with added iron oxide (Hortis Eu; Moga Slovenia). Substances from the fertilizer disturb several enzyme systems and metabolisms of nutrients in weeds causing strongly retarded growth of weeds.

The working speed of the tractor with cruise control was fixed at 9 kmh^{-1} whenever applying the rotary star tiller and finger weeder, while for chemical weed control, the speed of the tractor was set to 6 kmh^{-1}. In the field trial, the herbicide was applied to a 0.60 m treated strip with special nozzles mounted at both sides of the interrow mulcher. Assuming the inter-row distance is 2.50 m, we treated only 24% of the entire vineyard soil surface, so the corrected quantity amounts to 0.96 Lha^{-1} of glyphosate and 1.20 Lha^{-1} of Stopeco, respectively.

Determination of grape yield
At the end of the growing season, we randomly selected 10 grapevines in the middle of the plots (a total of 40 grapevines for one trial replication). All picked grape clusters from 10 randomly chosen grapevines were weighed in the vineyard. Before weighing, we checked for the presence of diseased berries and removed them all before weighing the cluster mass. Only a very small proportion of berries were diseased because we had a very intensive spraying program with excellent disease and pest control.

Life cycle analysis performance
Calculation of the environmental footprint (global hectares – gha anno^{-1}) and global warming potential (GWP (kgCO_{2eq})) was done using the free code program SPI on Web® (Kettl, 1996). In accordance with the guidelines presented by Moidl et al. (2008), we first entered the data on the machinery tools/herbicides used in each under-vine stripe area treatment system and then evaluated the life cycle parameters of individual process chains. Besides the environmental footprint, we have estimated also the calculations of CO_2 and GWP emission per hectare through the entire life cycle for a specific process.

We did a simplified economic cost-benefit analysis of different weed control methods. The following price values were used to calculate costs and value of yield: 1 kg of grapes 0.90 EUR, 1 L of preparation Stopeco 19.00 EUR, 1 L of preparation Boom efekt 16.00 EUR, cost of 1 h of tractor driver activity 9.50 EUR, cost of 1 h of tractor + sprayer system operation at double-sided spraying of herbicide 37.00 EUR, cost of 1 h of tractor operation at double-sided under-row cultivation with rotary star tiller and finger weeder 48.00 EUR.

Results and discussion

Fuel consumption and footprint parameters
The data on different weed control operations are presented in Table 1, which clearly shows varying time and fuel consumption for individual mechanical and chemical weed control operations under the vines. In total, during the grape growing season, we carried out 4 mechanical weeding operations according to the appearance and growing stage of weeds. On average, for one mechanical weeding pass, 132 minutes were spent per hectare, whereby the fuel consumption amounted to 4.20 Lha^{-1}, so for a total of four passes per season, 528 minutes and 16.80 Lha^{-1} were spent. On the contrary, we applied the organic fertilizer Stopeco three times during the growing season and glyphosate-based herbicide “Boom efekt” two times. The cumulative fuel consumption per season during the application of organic fertilizer amounted to 6.61 Lha^{-1}, and 518 minutes were needed, while for the application of glyphosate-based herbicide, it amounted to 2.94 Lha^{-1} and 347 minutes, respectively. Subsequently, there was the lowest fuel consumption per season for glyphosate-based herbicide applications.

Table 1. Data on mechanical and chemical weed control operations
Tablica 1. Podaci o mehaničkim i kemijskim postupcima suzbijanja korova

Treatment	Date	Quantity per hectare and working speed	Time consumption (min ha^{-1})	Fuel consumption (Lha^{-1})
Glyphosate	May 5th 2024 July 3rd 2024	4 Lha^{-1}, 6 kmh^{-1} 4 Lha^{-1}, 6 kmh^{-1}	172 175	1.42 1.52
Stopeco	April 17th 2024 June 6th 2024 July 15th 2024	5 Lha^{-1}, 6 kmh^{-1} 5 Lha^{-1}, 6 kmh^{-1} 5 Lha^{-1}, 6 kmh^{-1}	171 174 173	2.13 2.20 2.28
Rotary star tiller + finger weeder	May 20th 2024 June 10th 2024 July 15th 2024 August 26th 2024	9 kmh^{-1} 9 kmh^{-1} 9 kmh^{-1} 9 kmh^{-1}	132 133 135 129	3.70 3.80 4.70 4.60
Weed free control (manually)	May 20th 2024 June 10th 2024 July 15th 2024 August 26th 2024			

Results of analysis of environmental footprint parameters

Table 2 shows differences in the environmental effects of the three tested weed control systems. The results in global hectares represent the annual amount of biologically productive land that is necessary to assimilate the CO_2 emissions produced in all processes needed for the weed control of the 1 ha vineyard area. Figure 4 depicts the largest environmental footprint (7.79 gha anno^{-1}), which is related to two-fold systemic glyphosate-based herbicide applications. The main footprint represents the 2.85 gha anno^{-1} footprint needed for the life cycle of 1.92 L of glyphosate (Figure 4, left). The significant effect of glyphosate on the environmental footprint was also estimated by Stajnko (2017) for arable land production, meaning that synthetic products affect the world's natural resources most. This was for 3.85% less than the environmental footprint when using mechanical weeding with a combination of rotary star tiller and finger weeder (8.89 gha anno^{-1}) and for 3.86% more than for biological herbicide Stopeco (8.09 gha anno^{-1}), respectively.

The inside of CO_2 emissions shows the most favorable result for organic fertilizer application (341.42 kg CO_2), followed by glyphosate-based herbicide (351.46 kg CO_2) and mechanical weeding (381.92 kg CO_2), respectively. Concerning the GWP emissions, the worst result was estimated when using mechanical weeding (990.91 kg CO_{2eq}), followed by the organic fertilizer Stopeco (940.06 kg CO_{2eq}) and glyphosate (762.22 kg CO_{2eq}). Stopeco can be environmentally friendly from the eco-toxicological point of view, but it is obviously less favorable in terms of environmental effects.

Table 2. Environmental effect of different weeding methods for 1 ha of vineyard
Tablica 2. Ekološki učinak različitih metoda plijevljenja za 1 ha vinograda

	Weeding method		
Environmental Effect	Mechanical weeding rotary star tiller (4-times)	Organic fertiliser (3-times)	Glyphosate-based herbicide (2-times)
Footprint (gha anno^{-1})	8.09	7.50	7.79
CO_2 emission (kg CO_2)	381.92	341.42	351.46
GWP (kg CO_{2eq})	990.91	940.06	762.22

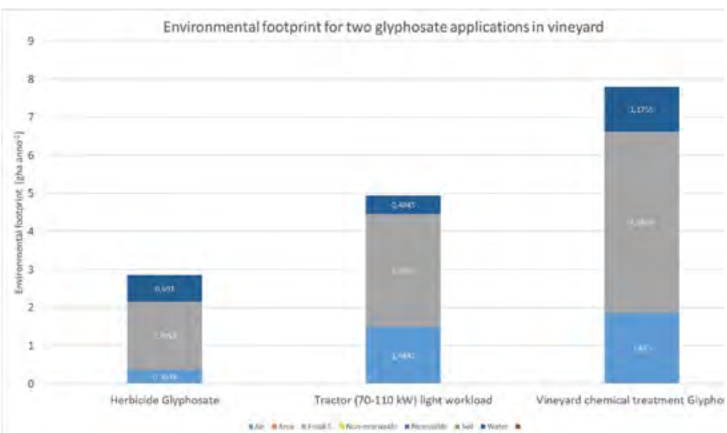

Figure 4. The environmental effect of environmental footprint for two glyphosate applications (right) including two most important processes (left, middle)
Slika 4. Ekološki učinak na okoliš za dvije primjene glifosata (desno) uključujući dva najvažnija procesa (lijevo, sredina)

There are not many sources in the literature describing the parameters of the ecological effects of different weed control techniques in stripe areas under vines. We found a study similar to ours (Gagliardi et al., 2023). In terms of total field time for weed control execution per hectare, fuel consumption, and CO_2 emissions, the single use of rotary star tiller 'Rollhacke' and finger weeder recorded intermediate values equal to 3.85 h ha^{-1}, 15.29 kg ha^{-1}, and 48.72 CO_2 kg ha^{-1}, respectively. In the mentioned study, researchers obtained very similar results to ours by conducting that mechanical weeding represents a sustainable weed control strategy, as we did in our study.

Evaluation of grapes yield and quality

Table 3. Evaluation of yield quality and quantity
Tablica 3. Ocjena kvalitete i količine prinosa

Trial variant:	Total yield ($kgha^{-1}$ ± SE)	TSS ± SE (° Brix)	The sum of titratable acids (gL^{-1} ± SE)	YAN (mgL^{-1} ± SE)
Boom efekt 2x	15132 ± 1704.1 a	21.94 ± 1.20 a	8.82 ± 0.58 a	144.3 ± 12.40 a
Stopeco 3x	15097 ± 1608,5 a	21,98 ± 1,70 a	8,83 ± 0,97 a	154,6 ± 11,70 a
Rollhacke 4x	16075 ± 1732,1 ab	22,73 ± 1,48 a	8,48 ± 0,95 a	143,7 ± 9,05 a
Non-treated weedy control	13832 ± 1135,1 c	20.54 ± 1.95 a	8.62 ± 0.85 a	127.2 ± 12.07 b
Weed free control	16907 ± 1090.5 a	21.63 ± 1.80 a	8.41 ± 0.95 a	147.2 ± 10.15 a

[a,b,c,] Means marked with the same letters at individual parameters do not differ statistically significantly according to the Tukey HSD test (P<0.05). YAN – yeast available nitrogen. TSS – total content of soluble solids.

Table 3 presents the data on yield and must quality. As seen, the weed control significantly increased the yield on all treatments when compared to non-treated weedy control. Weeds decreased yield from 16907 $kgha^{-1}$ in weed-free control to 13832 $kgha^{-1}$ in weedy control (approx. 18% yield reduction). Weed control methods didn't significantly influence the must quality parameters such as TSS and YAN values.

Results of economic feasibility evaluation

Table 4 presents the results of the economic feasibility evaluation. We can see that all three weed control methods were highly feasible. The highest value of increased yield was achieved at weed control with Rollhacke (2018.7 $EURha^{-1}$). Maybe there is a certain beneficial effect of soil aeration besides weed control. The use of rotary star tiller (Rollhacke) also provided the highest economic benefit (1933 $EURha^{-1}$). We can conclude that both alternative methods, organic fertilizer with herbicidal action and mechanical weeding, are economically equivalent to the use of the glyphosate-based herbicide. We must consider a very high yield in particular growing season. In vineyards with lower yielding potential, the benefit of alternative weed control methods probably would be at a lower level when compared to glyphosate-based herbicide treatment.

Table 4. A simple feasibility analysis of three weed control methods
Tablica 4. Jednostavna analiza izvedivosti tri metode suzbijanja korova

Trial variant:	Total yield ($kgha^{-1}$)	Increase in yield ($kgha^{-1}$)*	Value of increased yield ($EURha^{-1}$) (A)	Cost of weed control ($EURha^{-1}$) (B)	Benefit A-B ($EURha^{-1}$)
Boom efekt 2x	15132	1300	1170	84.7	1085.34
Stopeco 3x	15097	1265	1138.5	149.3	989.19
Rollhacke 4x	16075	2243	2018.7	85.6	1933.14
Non-treated control	13832	0	0	0	0
Weed free control	16907	3075	2767.5	/	/

*Comparison to non-treated weedy control.

Conclusions

The field experiment showed that the tested alternative methods of weed control are comparable to control using glyphosate-based herbicide in terms of the effectiveness of weed suppression and the amount of grape yield. The economic analysis of the use of two alternative methods showed that the mechanical method is economically competitive to glyphosate-based herbicide use because the costs of weed control are not significantly higher than the costs of the glyphosate-based herbicide control. In the case of the use of organic fertilizer, the cost is higher in comparison to applying glyphosate because of a higher product costs and due to more applications per season. Analysis of footprint parameters shows that mechanical control has a less favourable environmental footprint than chemical control, either with the herbicide glyphosate or organic fertilizer with herbicidal action. The highest amount of CO_2 as well as GWP emissions was released while using a rotary star tiller four times a season, showing that the environmental impact of food production is also a very important indicator in guiding farmland management. Considering the mentioned fact, the most sustainable approach would be one application of glyphosate at the beginning of the season, and two passes with rotary star tiller ‘Rollhacke’’ tool per season later in the summertime.

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Izvorni znanstveni rad

Učinkovitost i ekološki učinak alternativnog suzbijanja korova u vinogradu

Sažetak

U ovom istraživanju testirali smo dva alternativna pristupa suzbijanju korova kod uzgoja vinove loze kao zamjenu za herbicid na bazi glifosata: suzbijanje korova organskim gnojivom Stopeco na bazi biljnih ekstrakata s herbicidnim djelovanjem te mehaničko suzbijanje pomoću kombiniranog alata koji se sastoji od rotacijske zvjezdaste freze i prstaste pljevačice. Provedena je usporedna analiza testiranih metoda u pogledu potrošnje goriva, ugljičnog otiska, prinosa grožđa, ekonomske isplativosti i utjecaja na okoliš. Najmanji ekološki učinak zabilježen je kod trostruke primjene organskog gnojiva Stopeco (7,50 gha/god), zatim kod dvostruke primjene glifosata (7,79 gha/god) i četverostrukog mehaničkog suzbijanja korova (8,09 gha/god). Međutim, Stopeco može biti ekološki prihvatljiv s ekotoksikološkog stajališta. Najveće emisije stakleničkih plinova (990,91 kg CO_2eq) i emisije CO_2 (381,92 kg CO_2) ponovno su zabilježene kod mehaničkog uklanjanja korova, dok su najmanje emisije zabilježene kod primjene glifosata (762,22 kg CO_2eq i 351,46 kg CO_2). Što se tiče ekonomske isplativosti, obje alternativne metode suzbijanja korova bile su usporedive s herbicidom na bazi glifosata, s financijskom koristi od 1933 EUR po hektaru kod mehaničkog uništavanja korova, 1085 EUR po hektaru kod primjene glifosata i 989 EUR po hektaru kod primjene organskog gnojiva.

Ključne riječi: *glifosat, vinograd, suzbijanje korova, rotacijska zvjezdasta freza (Rollhacke)*