

The influence of different methods of under-vine management on the structure of vegetation and the qualitative parameters of the grapes in the Moravian wine region

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ABSTRACT

The present article explores the importance of vineyard soil management. Studies on under-vine management have yielded a wide range of results, with some indicating potential benefits for vine growth and productivity. However, the methods of under-vine management and their specific effects on vineyard parameters require further research. The aim of this study is to evaluate the relationships existing between the different types of management of under-vine areas and the vegetation grown in this zone and to determine the effects of under-vine management on the yield and quality of Traminer grapevines. By examining various approaches, the research aims to provide insights into the optimising of vineyard management methods to achieve enhanced biodiversity and grape quality in this specific geographical context. The findings indicated that management of the under-vine area can impact the composition of plants, grape yield and quality. Under-row management had an effect on the number of plant species and their composition. The highest weight of bunches was found in MIX (a species from the Fabaceae family), while the lowest was found in the MECH treatment (bare soil). MULCH, MONO and MIX consistently had higher yeast assimilable nitrogen (YAN) in grapes than other treatments. In many of the evaluated parameters, the influence of the seasons was evident.

Keywords: Fabaceae, grape quality, soil vegetation cover, sustainable viticulture, vine yield

INTRODUCTION

The global vineyard surface area in 2021 was estimated to be 7.3 million ha, of which the European Union has a 45% share (OIV, 2022). As a result, the wine sector represents a significant segment of EU agriculture. According to Oberč and Schnell (2020), within the EU

Common Agricultural Policy for the period 2021–2027, there are three environmental objectives: climate change action, environmental care and preserving landscapes and biodiversity. The EU is now firmly committed to sustainable agriculture. The European Green Deal

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aims to expand sustainable practices, such as precision agriculture, organic farming, agroecology, and so on. It pays particular attention to managing and storing carbon in the soil and establishing better nutrient management to improve water quality and reduce emissions in agriculture.

Vineyard soil belongs to the most eroded land type. The soils are frequently poor in organic matter and are with limited plant cover (García-Díaz et al., 2016; Rodrigo-Comino et al., 2020). However, cover crops in permanent cultures can provide multiple potential ecosystem services (Novara et al., 2018). Many authors focus on the diversification of vegetation in agroecosystems due to its impact on ecosystem services (e.g., maintaining crop yields and soil fertility and natural enemies support) (Ragasová et al., 2019; Teixeira et al., 2021). Cover crops can lead to higher carbon and nitrogen content in the soil and improve the soil's biological activities, including those that are earthworm-related (Gabriel et al., 2016; Saleem et al., 2020). Organic carbon in vineyard soil increases under this management because it increases carbon inputs and reduces organic matter mineralisation (García-Díaz et al., 2016). Cover-cropped soils have greater microbial biomass than disked or berm soils (Muhammad et al., 2021). Generally, cover crops can also improve the hydraulic properties of the soil and the environmental sustainability (Haruna et al., 2022). However, cover crops in vineyards can have a potentially negative effect on vigour and yield, which could be caused by water and nutrient competition (Gómez, 2017). Cover crops can not only positively influence runoff reduction but also increase evapotranspiration at the same time. Therefore, cover crops affect both ecosystem services with an opposite effect; there is a strong interaction between the two ecosystem services, as the runoff reduction could significantly increase water storage of the soil, leading to competition with the main crop and reducing yield (Novara et al., 2021). However, Delpuech and Metay (2018) reported that cover crops in one inter-row out of two can bring ecosystem service (e.g. soil protection) without significantly decreasing the grape yield, even in a dry Mediterranean region.

A large number of research studies have focused on inter-row vegetation. Several studies devoted to under-vine vegetation have already been published; however, findings are often inconsistent. Jordan et al. (2016) reported that under-vine cover crops had no effects on vine growth, yield or juice characteristics when compared with conventional herbicide use in the under-vine row. In contrast, Karl et al. (2016) stated that under-vine cover crops could limit vine vigour relative to conventional practices and that herbicide use promoted higher yields without sacrificing fruit quality. Abad et al. (2020) stated that under-vine cover crops in a semi-arid climate reduced the vegetative growth and increased water deficit slightly with no changes in yield or grape composition. Regarding soil parameters, Marks et al. (2022) reported that cover crops in the under-vine area have the potential to sequester carbon in vineyard

soils. Cabrera-Pérez et al. (2023) noted that mulching the under-vine zone is the most efficient method to control weeds in irrigated vineyards. Chou et al. (2018) investigated the impact of under-vine management on soil's microbial pool and fruit-associated microbial composition.

From the review published by Vanden Heuvel and Centinari (2021), it is evident that many under-vine species can improve several parameters of soil health, although long-term effects are still unknown. The effects of under-vine species on vine growth and productivity remain less predictable, but some similarities in vine responses have been identified across studies.

In this study, we evaluate the influence of different management practices of the under-vine zone on non-crop vegetation and grape quality. The under-vine area is a specific zone of the vineyard that creates conditions for direct and rapid interactions between the grapevines and the immediate surroundings; the relationships between the grapevines and other types of plants can also quickly manifest here. To unravel these interactions, the following objectives were set: (i) to evaluate the relationships between different management methods of under-vine areas and the vegetation growing in this zone, (ii) to determine the effect of under-vine management methods on the yield and (iii) to determine the effect of under-vine management methods on the quality of grapevines.

MATERIALS AND METHODS

Study area and experimental design

Field experiments were conducted at the experimental vineyard of the Faculty of Horticulture, Mendel University in Lednice, vineyard track Na Valtické (48.788380, 16.796148), for two consecutive growing seasons (2021 and 2022). The average temperature of this location is 9°C, and the average annual precipitation is 516.6 mm. Climate conditions for both growing seasons are recorded in Figure 1. Both experimental years were below normal precipitation. The soil is sandy-loam with 20%–24% clay particles. Initial soil analysis (at a depth of 30 cm) showed the following parameters: pH 7.5; Nmin 18.2 mg · kg⁻¹; P 51.7 mg · kg⁻¹; K 266.8 mg · kg⁻¹; Ca 6687 mg · kg⁻¹ (April 2021). Grapevines of the Traminer variety were planted in 2014 with a spacing of 2.20 m × 0.9 m using the Rhine-Hessian training system and horizontally balanced canes. Disease was controlled using integrated protection systems. Vegetation in the inter-rows was mowed or mulched three times per year.

The experimental design of 6 treatments, 3 replications and 15 vines available per replicate is described in Tables 1 and 2 and Figure 2.

Under-vine vegetation assessment

Geospatial assessment of vegetation

Geospatial assessment was carried out in the second year of the experiment. On a sunny day on 3 October 2022, flights were conducted with the Phantom

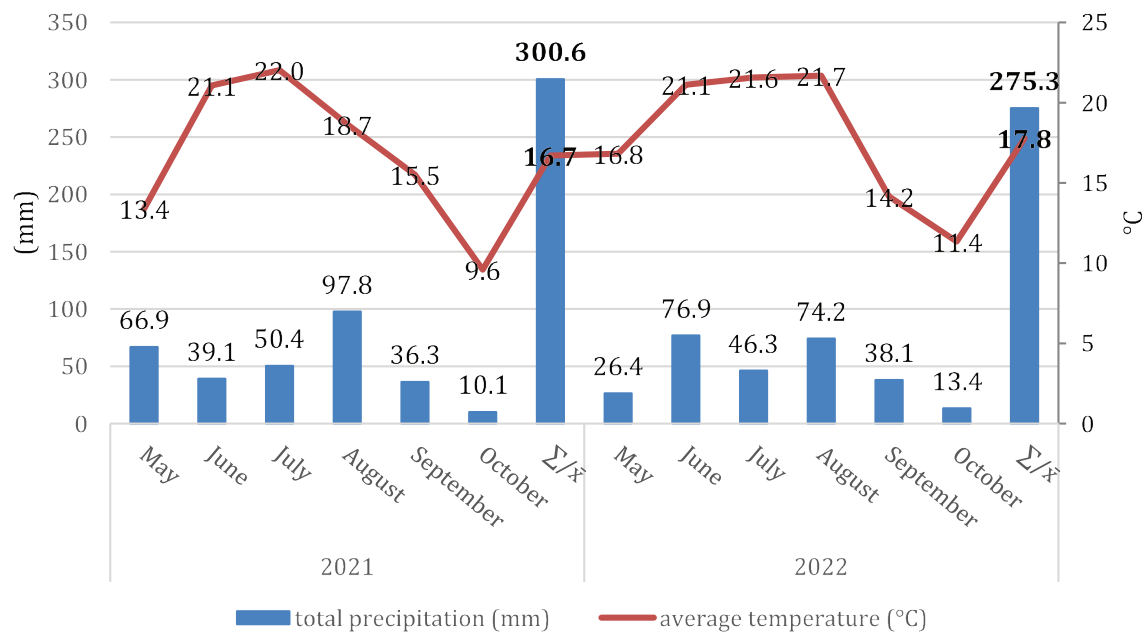


Figure 1. Meteorological conditions of the experimental site.

Table 1. Treatment description.

Abbreviation	Treatment	Description
MECH	Bare soil cultivated mechanically	Weed control in the under-vine area was carried out by using a mechanical blade weeder (three times per year)
HERB	Bare soil with herbicide application	Weed control in the under-vine area was carried out by applying herbicide (Glyphosate) at a rate of 4 L · ha ⁻¹ on the following dates: 31/04, 17/06, 12/08 in 2021 and 13/04, 29/06, 4/08 in 2022
TEX	Textile mulch	The under-vine belt was covered by black woven agrotexile (90 g) made of polypropylene with UV stabilisation with a width of 60 cm
MULCH	Green mulch – mowed grass	Under-vine area with a width of 60 cm was covered with a layer of cut grass at a height of 30 cm during June every year
MONO	Cover crop – monoculture	Microclover (<i>Trifolium repens</i> ‘Pipolina’) were sown manually on 07/04 2021 at a seed rate of 15 kg · ha ⁻¹ on a 60 cm-wide strip in the under-vine area
MIX	Cover crop – a mixture of plants	Plants from the Fabaceae family were sown manually on 07/04 2021 on a 60 cm-wide strip in the under-vine area, as shown in Table 2

Table 2. Species composition of treatment MIX.

Species	Variety	Seed rate kg · ha ⁻¹	% share in mixture	Final seed rate kg · ha ⁻¹
<i>Trifolium repens</i> L. f. <i>silvestre</i>	Luke	15	35	5.25
<i>Lotus corniculatus</i> L.	Leo	15	10	1.5
<i>Medicago lupulina</i> L.	Ekola	15	50	7.5
<i>Anthyllis vulneraria</i> L.	Pamír	15	5	0.75

4 Multispectral drone (DJI, China) to analyse the quality of plant vegetation in the under-vine areas. Unmanned aerial vehicle (UAV) multispectral imagery is a promising method for monitoring plant health

(Fernández-Guisuraga et al., 2018; Fawcett et al., 2020; Lee et al., 2022). The principle of the method consists of combining the separate acquisition of the red and near-infrared spectra, where there are differences



Figure 2. Different under-vine treatments. (MECH, bare soil cultivated mechanically; HERB, bare soil with herbicide application; TEX, under-vine belt covered by black woven agrotextile; MULCH, green mulch – mowed grass; MONO, cover crop – monoculture; MIX, cover crop – mixture of plants).

in the health status of the vegetation. Radiation in the red spectrum is absorbed, while radiation in the near-infrared spectrum is reflected; the more prosperous the vegetation, the greater the contrast between the absorbed red and the reflected near-infrared spectrum. One of the most frequently used indices for determining vegetation vitality is the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974).

According to the formula $NDVI = (NIR - Red) / (NIR + Red)$, NDVI was calculated based on acquired images from an optical camera mounted on a DJI Phantom Multispectral UAV with the following ranges: blue (B) – $450 \text{ nm} \pm 16 \text{ nm}$; green (G) – $560 \text{ nm} \pm 16 \text{ nm}$; red (R) – $650 \text{ nm} \pm 16 \text{ nm}$; red edge (RE) – $730 \text{ nm} \pm 16 \text{ nm}$; and near-infrared (NIR) – $840 \text{ nm} \pm 26 \text{ nm}$.

Multispectral images were processed in QGIS software (Open Source Geospatial Foundation). Images of individual bands were georeferenced and the NDVI index was calculated in the second step. The images were further reclassified into three classes (in the intervals -1 to 0.1 ; 0.1 to 0.2 ; 0.2 to 1) using the ‘reclassify by table’ tool, and the area that represents samples was extracted from the raster. Finally, the ratio between NDVI classes in individual samples was calculated. The typical range of NDVI for green vegetation is 0.2 – 0.9 (Weier and Herring, 2000). According to Antognelli (2018), the $NDVI < 0.1$ can be classified as bare soil and 0.1 – 0.2 as almost absent canopy cover. Based on these interpretations, our research methodology defines that category 1 means no vegetation, and categories 2 and 3 mean vegetation cover.

Phytosociological and botanical assessment of vegetation

The under-vine vegetation was evaluated according to Braun-Blanquet (1964) three times from July to September in every season. Each plot for the phytosociological surveys had a width and length of $0.6 \text{ m} \times 15 \text{ m}$. The present plant species were identified, and the coverage of the present species was estimated. Taxonomic nomenclature of plants follows Kaplan et al.

(2019). The plant species were divided into groups according to families and the presented relationship to the vine.

Yield and analytical parameters of grapes

The grape harvest was performed on 7 October 2021 and 30 September 2022. The sampling of bunches for uvological analysis took place according to the International Union for the Protection of New Varieties of Plants (UPOV) methodology (UPOV, 2008), where 10 bunches were taken randomly from 5 grapevine plants. Uvological analysis includes evaluation of number of bunches per vine, weight of bunches per vine, bunch weight, berry weight, number of berries in a cluster and rachis weight. For uvological data, hanging digital scales and laboratory digital scales (Kern) were used to determine the weight parameters.

High-performance liquid chromatography (HPLC, Shimadzu, Japan) was used for the analytical evaluation of the grapes, where the content of fermentable monosaccharides in the must (glucose + fructose) and the content of the main must acids (tartaric, malic and citric) were analysed. The total acid content in the must was determined by the titration method. A handheld refractometer (Atago, Japan) ($^{\circ}\text{Brix}$) was used to determine the sugar content of the must. The pH of the must was verified by using a pH metre WTW (Xylem Analytics, USA). Yeast assimilable nitrogen (YAN) in the must was determined using the Miura One instrument (TDI, Spain).

Statistical methods

Data from phytosociological relevés were analysed using Canoco 5 software (Biometris, Wageningen University and Research Centre, Wageningen, the Netherlands; University of South Bohemia in České Budějovice, České Budějovice, Czech Republic) for multivariate analysis of ecological data. Canonical correlation analysis (CCA) was selected as a statistical method as well. The statistical significance of the results

was calculated with the Monte-Carlo permutation test (999 permutations) (Ter Braak and Šmilauer, 2018). Botanical assessment, as well as yield and analytical parameters, were evaluated using an analysis of variance (ANOVA) with Statistica 12 (TIBCO Software Inc., Palo Alto, USA). Significant differences were calculated using Fisher's least significant difference (LSD) test at a significance level of $p \leq 0.05$, where different letters denote significant differences.

RESULTS

Under-vine vegetation assessment

Geospatial assessment of vegetation

Under-vine vegetation assessment was analysed according to the distribution of NDVI using a geospatial approach (Figure 3). Three groups of surface coverage were defined: (i) no vegetation (red); dry vegetation; (ii) green vegetation with a lower chlorophyll content (yellow) and (iii) green vital vegetation (green). A low NDVI value points to the absence of vegetation or sparse vegetation, where the reflectance of the soil is significant; conversely, a high NDVI value corresponds to dense vegetation. Figure 3 shows an actual image of under-vine vegetation for each location and an image with NDVI distribution. It is evident that in the treatments MECH, HERB and TEX, there is predominantly a red colour, indicating coverage without vegetation (NDVI value of <0.1). In the MONO and MIX treatments, green and yellow dominate, suggesting that most of the surface was covered with green vegetation. Figure 4 shows the total coverage in the under-vine area as the sum of NDVI categories 2 and 3.

Green vegetation surface cover based on multispectral analysis shows that covering in TEX (textile mulch), HERB (application of herbicides) or MECH (mechanical cultivation) limits the occurrence of plants in the under-vine area. Green vegetation coverage with these treatments varied between 1.9% and 5.1% (Figure 4). It can also be concluded that variants MIX and MONO with purposefully sown plant species had the highest proportion of vegetation coverage, 69% and 75%, respectively. MULCH treatment was covered with mowed grass; however, some proportion of plant vegetation was present here (26%). The results of geospatial vegetation assessment show the total soil cover by plants regardless of species composition. The following qualitative analysis of vegetation addresses this issue.

Phytosociological and botanical assessment of vegetation

Based on a phytosociological survey (Figure 5), it can be concluded that the coverage proportion (2-year average) of selected plant groups and families varied between treatments and between assessment dates.

Relative coverage of species from the Fabaceae family was the greatest in MONO and MIX treatments. Species from the Poaceae family were present in all treatments, with the majority in the TEX and HERB treatments. Noxious weeds prevailed in the MULCH treatment. The graph shown in Figure 5 demonstrates the percentage proportion of coverage of selected plant groups (Fabaceae, Poaceae, noxious weeds and the rest of the dicotyledonous plants) within overall green vegetation surface cover that differs for each treatment (Figure 4).

The multivariate analysis of the data (Figure 6) supported the previous findings. Results of the CCA analysis indicate that representatives of the Fabaceae family have the strongest link to the MONO and MIX treatments. The greatest coverage of noxious weeds is strongly connected with the MULCH treatment. The diversity of noxious weeds in other treatments was similarly low. Representatives of the Poaceae family were mainly present in the HERB and TEX variants, with the greatest coverage found in the TEX treatment (Figure 6).

The botanical assessment showed a number of statistical differences between the treatments (Figure 7). Significant differences were primarily found between treatments TEX (both years) and MULCH (2022), representing the lowest number of species in the under-vine area and MONO (both years) and MIX (2021) with the highest number of species. Similarly, the number of species in MECH (2021) and HERB (2022) was significantly higher than in treatment TEX (Figure 7A).

The number of botanical families varied between five and seven for most treatments; only in the TEX treatment, three families were present on average. The only statistical differences were found between the TEX treatment as the lowest and MONO and MECH (2021) as the highest in the number of families (Figure 7B).

The higher proportion of Fabaceae corresponds to the MONO and MIX treatments where these species were sown. During the 2nd year, the number of Fabaceae species in the under-vine area remained essentially unchanged compared to the first year. In other treatments, there was always only one representative of this plant family (Figure 7C).

The occurrence of grasses (Poaceae family) was influenced by the type of treatment, with the lowest number found in MULCH (2022). In the HERB treatment, there were significant differences between experimental years (Figure 7D).

The occurrence of noxious weeds varied between two and four for most of the treatments. The lowest occurrence of noxious weeds was in the treatment TEX (Figure 7E).

The correlation between green vegetation surface cover based on multispectral analysis and number of species was not statistically significant ($p = 0.76$). This may indicate the fact that the coverage in the under-vine area can be independent of how many plant species are present.

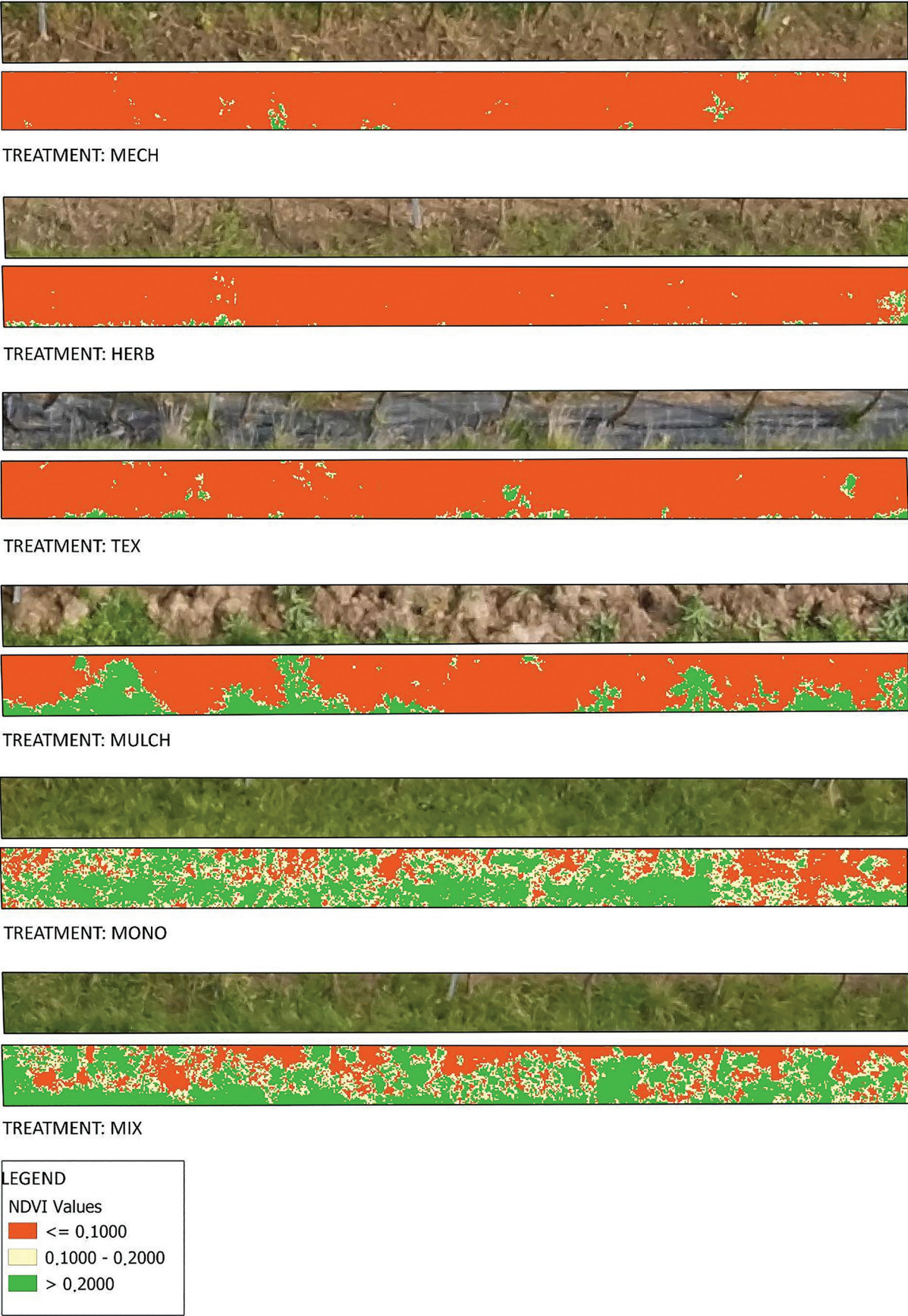


Figure 3. Graphical evaluation of NDVI in different treatments. NDVI, normalized difference vegetation index.

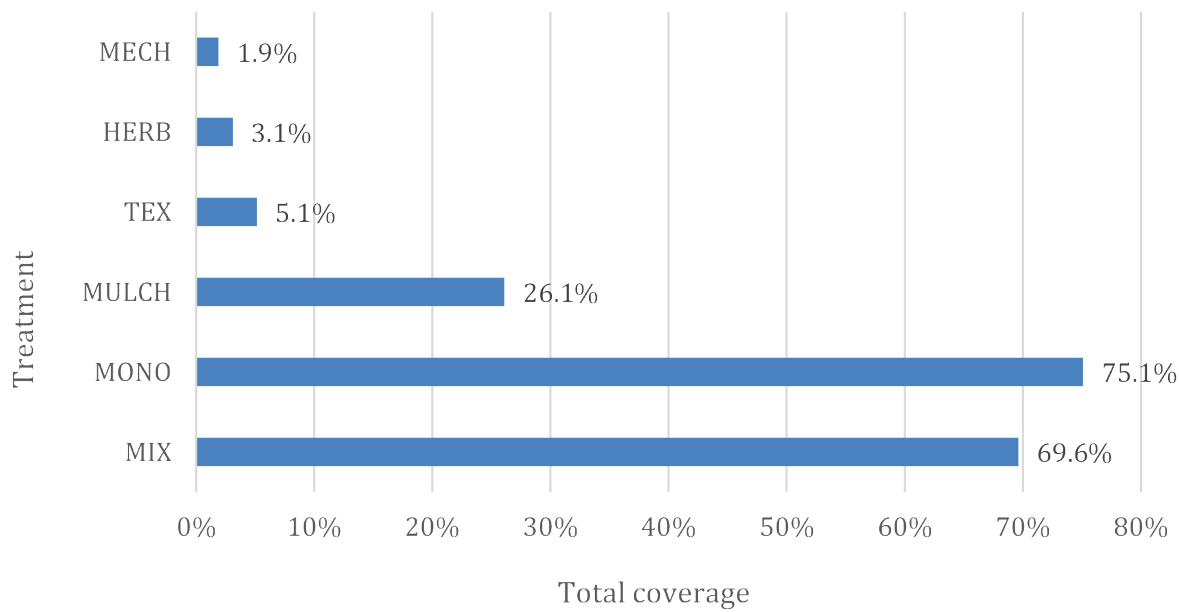


Figure 4. Under-vine area covered by green vegetation (2022).

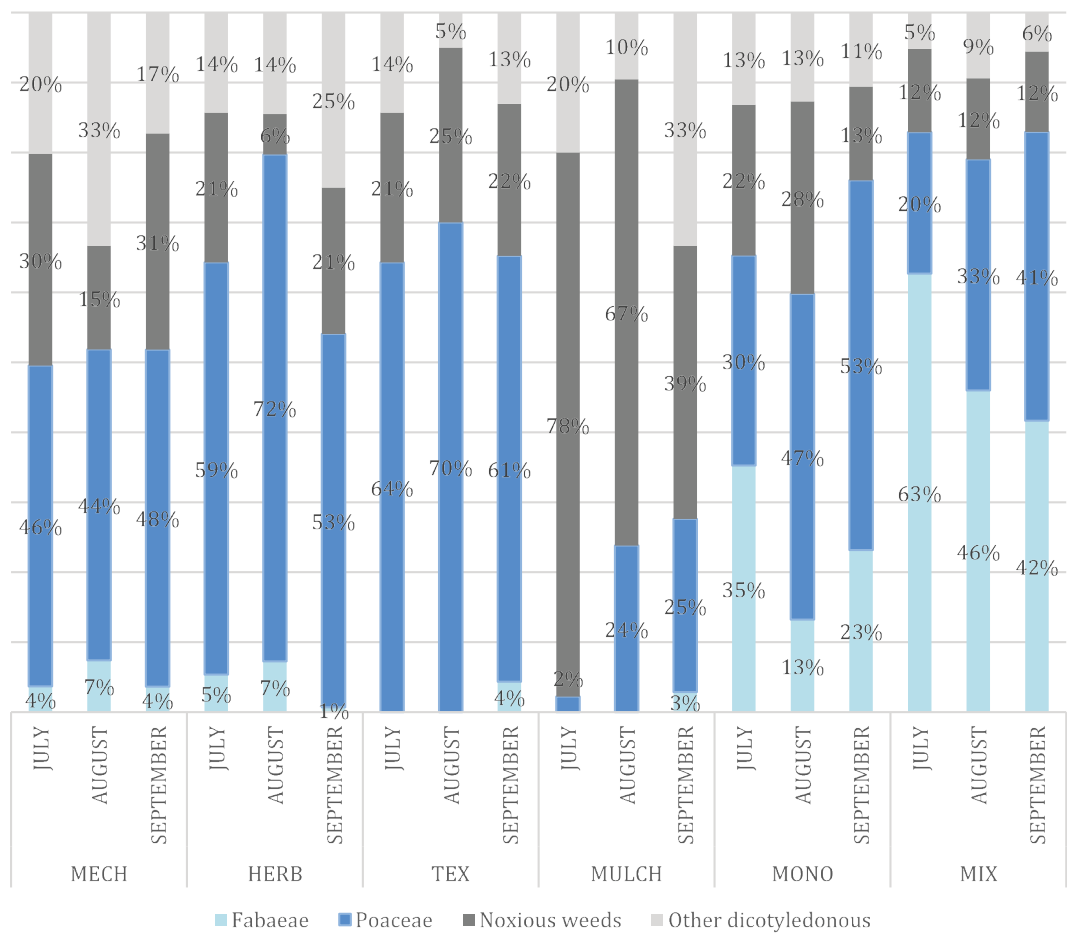


Figure 5. Ratio (2-year average) of selected plant groups coverage (Fabaceae, Poaceae, noxious weeds and the rest of dicotyledonous) per three evaluation terms.

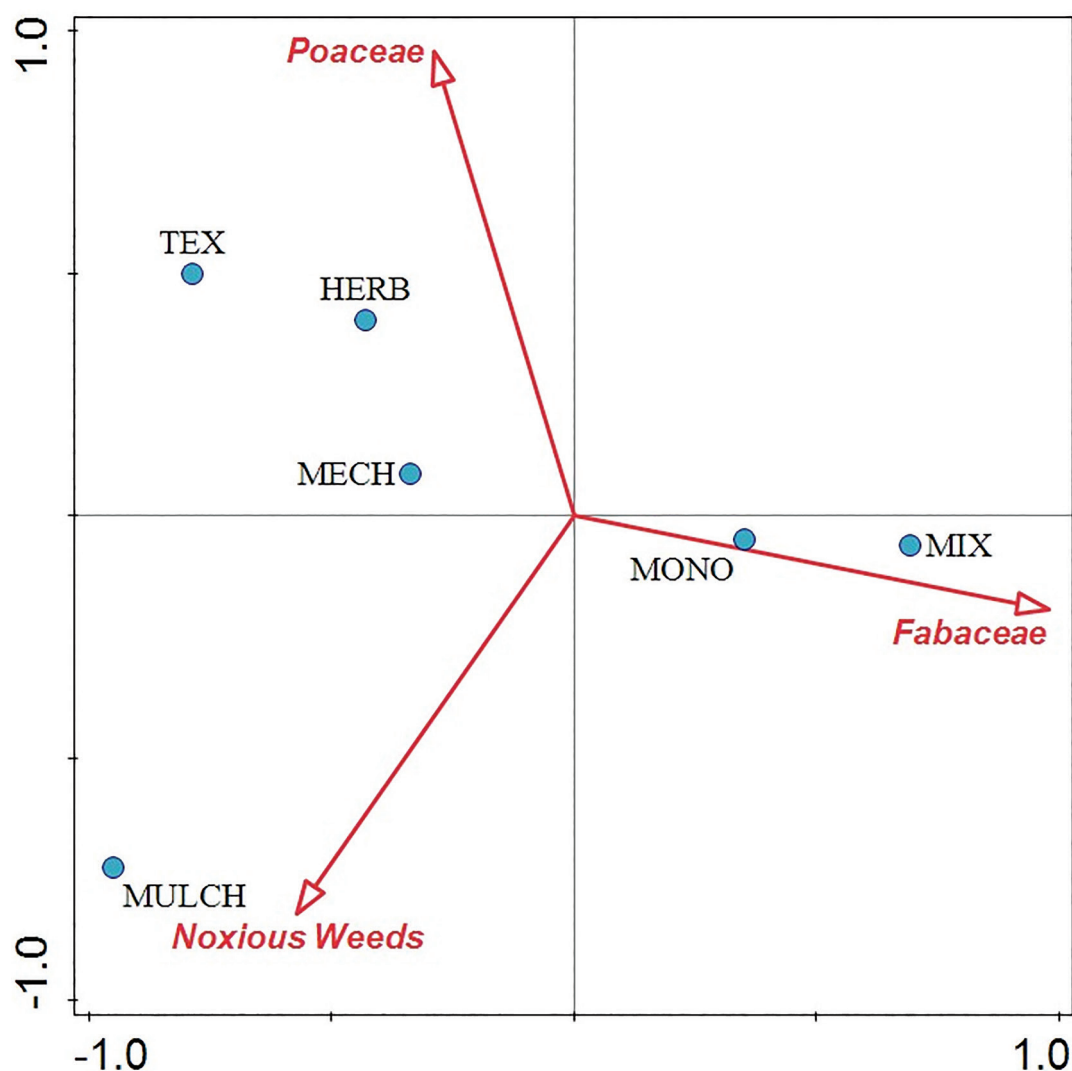


Figure 6. Ordination diagram of CCA, describing the distribution of three categories of plant species and their coverage in the six different treatments (pseudo-F = 10.1, $p = 0.002$). CCA, canonical correlation analysis.

Based on a detailed botanical survey, the following results about vegetation cover are reported in Table 3. For more details, see Supplementary Table 1.

Yield and analytical parameters of grapes

Statistical evaluation of the yield parameters is shown in Table 4. Based on the ANOVA, the effect of treatment, year and interactions can be indicated for some evaluated parameters. The number of bunches per vine varied between treatments and years. Generally, a higher number was found in the vines of MONO and MIX treatments, with a significant difference in 2022. The highest average weight of bunches per vine was identified in the treatment MIX in 2022, and in 2021, it was among the highest. The MONO treatment was also one of the highest values, but not always with statistical evidence. The lowest weight of bunches per vine was found on the traditionally mechanically treated vines (MECH) in both years. The highest bunch weight (the largest bunches) was found on vines with the MIX treatment in 2022. The differences between the other

treatments were mostly not significant. Berry weight was highest in the vines with MECH treatment in 2021; however, in 2022, it was the lowest. The number of berries in a cluster ranged from 66 (MECH 2021) to 188 (TEX 2022). In most cases, the number of berries was higher in the second year (2022). A similar trend in the difference between years can be observed in rachis weight, with the lowest in MECH (2021) and the highest in MIX (2022), as shown in Table 4.

A summary of the qualitative parameters is shown in Table 5, with statistical differences indicated. Using ANOVA, we identified the influence of treatment, year and their interactions on certain assessed parameters. YAN varied between years and treatments, with the highest for MULCH in 2021 ($244 \text{ mg} \cdot \text{L}^{-1}$) and the lowest for MECH in 2022 ($119 \text{ mg} \cdot \text{L}^{-1}$). Except for the HERB treatment, the measured values in 2021 were significantly higher than in 2022. During both years, the grapes from the treatments MULCH, MONO and MIX were consistently higher in YAN content compared to the rest of treatments (HERB, MECH and TEX).

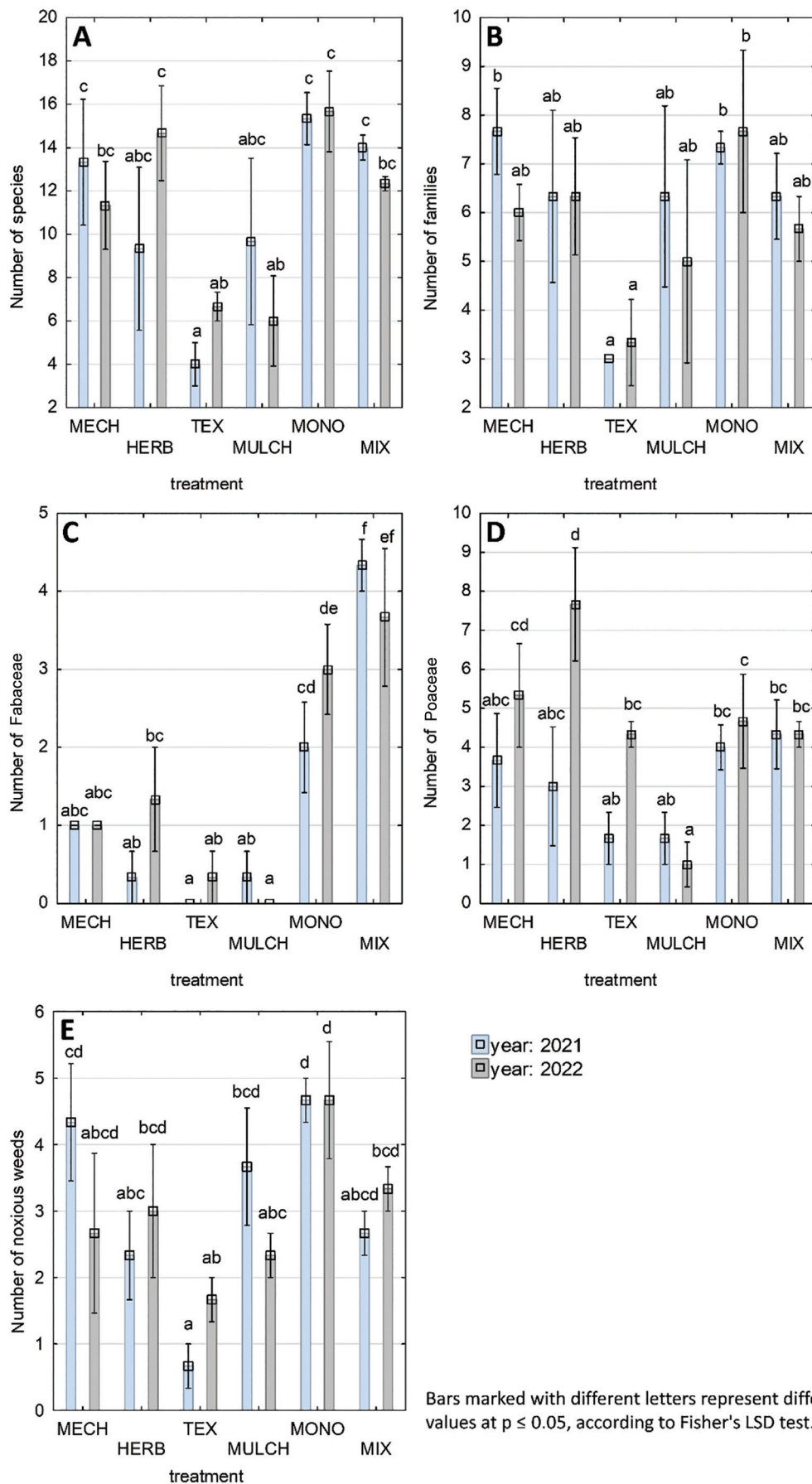


Figure 7. Botanical assessment of vegetation (A – number of species; B – number of families; C – number of Fabaceae; D – number of Poaceae; E – number of noxious weeds). LSD, least significant difference.

Table 3. Species identification in different treatments.

Treatment	Predominant species in the vegetation cover
MECH	<i>Bromus hordeaceus</i> L., <i>Convolvulus arvensis</i> L., <i>Amaranthus retroflexus</i> L., <i>Taraxacum</i> sect. <i>Taraxacum</i> , <i>Lolium perenne</i> L., <i>Setaria pumila</i> , <i>Cirsium arvense</i> (L.) Scop., <i>Hordeum murinum</i> L., <i>Chenopodium album</i> L.
HERB	<i>Bromus hordeaceus</i> L., <i>Setaria verticilata</i> (L.) P. Beauv., <i>Lolium perenne</i> L., <i>Setaria pumila</i> (Poir) Roem. et Schult., <i>Convolvulus arvensis</i> L., <i>Portulaca oleracea</i> L., <i>Setaria viridis</i> (L.) P. Beauv., <i>Digitaria sanguinalis</i> (L.) Scop., <i>Echinochloa crus-galli</i> (L.) P. Beauv., <i>Amaranthus retroflexus</i> L., <i>Cirsium arvense</i> (L.) Scop., <i>Taraxacum</i> sect. <i>Taraxacum</i> .
TEX	<i>Lolium perenne</i> L., <i>Convolvulus arvensis</i> L., <i>Bromus hordeaceus</i> L.
MULCH	<i>Cirsium arvense</i> (L.) Scop., <i>Convolvulus arvensis</i> L., <i>Bromus hordeaceus</i> L., <i>Amaranthus retroflexus</i> L., <i>Stellaria media</i> (L.) Vill.
MONO	<i>Lolium perenne</i> L., <i>Trifolium repens</i> L., <i>Cirsium arvense</i> (L.) Scop., <i>Amaranthus retroflexus</i> L., <i>Setaria viridis</i> (L.) P. Beauv., <i>Chenopodium album</i> L., <i>Bromus hordeaceus</i> L., <i>Medicago lupulina</i> L., <i>Taraxacum</i> sect. <i>Taraxacum</i> , <i>Convolvulus arvensis</i> L., <i>Setaria verticilata</i> (L.) P. Beauv., <i>Lotus corniculatus</i> L.
MIX	<i>Trifolium repens</i> L., <i>Lolium perenne</i> L., <i>Anthyllis vulneraria</i> L., <i>Medicago lupulina</i> L., <i>Lotus corniculatus</i> L., <i>Amaranthus retroflexus</i> L., <i>Bromus hordeaceus</i> L., <i>Chenopodium album</i> , <i>Setaria viridis</i> , <i>Setaria verticilata</i> , <i>Taraxacum</i> sect. <i>Taraxacum</i> , <i>Convolvulus arvensis</i> L.

Table 4. Selected yield and uvological parameters.

Year	Treatment	Number of bunches per vine (pcs)	Weight of bunches per vine (kg)	Bunch weight (g)	Berry weight (g)	Number of berries in a cluster (pcs)	Rachis weight (g)
2021	MECH	16.4 ± 1.5 abc	1.7 ± 0.1 a	103.0 ± 12.5 ab	1.7 ± 0.3 d	66.6 ± 13.7 a	4.0 ± 0.1 a
	HERB	19.8 ± 1.9 d	2.1 ± 0.1 bc	115.2 ± 8.3 ab	1.1 ± 0.1 abc	95.8 ± 6.8 cd	6.0 ± 0.7 b
	TEX	18.8 ± 0.8 cd	1.9 ± 0.04 ab	97 ± 6.3 a	1.4 ± 0.4 bc	76.4 ± 12.4 ab	4.1 ± 0.3 a
	MULCH	18.8 ± 2.5 cd	2 ± 0.2 ab	110.1 ± 4.3 ab	1.2 ± 0.4 abc	84 ± 18.9 bc	4.6 ± 0.1 a
	MONO	20.2 ± 1.8 d	2.4 ± 0.1 d	120.9 ± 3.7 ab	1.0 ± 0.2 ab	117.0 ± 3.1 e	6.3 ± 0.2 bc
	MIX	19.2 ± 3.1 d	2.3 ± 0.1 cd	119.2 ± 12.2 ab	1.1 ± 0.1 abc	107.0 ± 3.9 de	7.0 ± 0.1 c
2022	MECH	15.0 ± 2.3 a	1.8 ± 0.2 a	112.8 ± 7.3 ab	1.0 ± 0.1 a	121.6 ± 10.4 e	6.8 ± 0.5 bc
	HERB	15.2 ± 2.8 a	2.5 ± 0.3 d	162.6 ± 23.1 c	1.3 ± 0.2 abc	154.2 ± 12.5 f	6.8 ± 0.5 c
	TEX	16.0 ± 2.3 ab	2.3 ± 0.3 cd	139.5 ± 25.6 bc	1.0 ± 0.4 a	188.0 ± 14.6 h	9.2 ± 0.7 d
	MULCH	14.0 ± 0.7 a	2.5 ± 0.04 d	173.8 ± 45.3 c	1.4 ± 0.2 cd	161.0 ± 13.3 fg	9.4 ± 0.5 d
	MONO	19.8 ± 2.9 d	2.4 ± 0.3 d	122.3 ± 29.3 ab	1.0 ± 0.2 ab	117.0 ± 11.5 e	6.0 ± 0.5 b
	MIX	18.4 ± 1.8 bcd	3.2 ± 0.3 e	215.9 ± 84.2 d	1.4 ± 0.3 c	173.0 ± 16.3 gh	9.7 ± 1.8 d

Values in each column followed by different letters are significantly different at $p \leq 0.05$, according to Fisher's LSD test. LSD, least significant difference.

Sugar content varied between $204.6 \text{ g} \cdot \text{L}^{-1}$ (MULCH 2021) and $243.7 \text{ g} \cdot \text{L}^{-1}$ (HERB 2021). In 2021, the grapes from the treatments MULCH, MONO and MIX had significantly lower sugar content compared to grapes from treatments MECH, HERB and TEX. A similar tendency was observed in 2022, but not always with statistical differences.

Acid content was significantly lower in 2022 compared to 2021. The grapes from the MULCH treatment showed the highest value of acid content in 2021 ($9.3 \text{ g} \cdot \text{L}^{-1}$), while the lowest was in 2022 ($4.18 \text{ g} \cdot \text{L}^{-1}$). Treatment of the under-vine area with artificial cover (TEX, MULCH, MONO, MIX) indicated

a higher acid content than those without cover (MECH, HERB). This relationship was observed in only 2021.

Selected acids (malic, tartaric and citric) generally had a higher value in 2021 than in 2022; malic acids were significantly different between years. Malic acid reached its highest content in the grapes from the MULCH treatment for both years. The results for the other acids did not show a clear tendency in relation to the treatment.

Grapes from vines with MULCH treatment in 2021 and 2022 reached similar pH values that varied between 3.38 and 3.86, respectively. The results do not show a clear influence of the treatment.

Table 5. Analytical parameters of grapes.

Year	Treatment	YAN (mg · L ⁻¹)	Sugar content (glucose + fructose) (g · L ⁻¹)	Acid content (g · L ⁻¹)	Malic acid (g · L ⁻¹)	Tartaric acid (g · L ⁻¹)	Citric acid (g · L ⁻¹)	pH
2021	MECH	211.7 ± 4.3 cd	240.6 ± 4.0 fg	7.2 ± 0.1 c	3.6 ± 0.1g	7.6 ± 0.03 ef	0.25 ± 0.01 f	3.5 ± 0.03 bc
	HERB	150.4 ± 3.5 b	243.7 ± 1.0 g	6.9 ± 0.7 c	3.1 ± 0.2 f	7.4 ± 0.5 de	0.18 ± 0.02 c	3.6 ± 0.1 c
	TEX	221.8 ± 4.7 d	238.0 ± 2.9 fg	8.2 ± 0.2 d	3.7 ± 0.05 h	8.2 ± 0.01 h	0.22 ± 0.01 de	3.5 ± 0.02 abc
	MULCH	344.4 ± 14.2 f	204.6 ± 8.9 a	9.3 ± 0.7 e	5.9 ± 0.1 k	8.3 ± 0.1 h	0.24 ± 0.02 ef	3.4 ± 0.1 a
	MONO	268.9 ± 2.0 e	207.8 ± 3.1 ab	8.5 ± 0.4 d	4.8 ± 0.02 j	7.9 ± 0.01 fg	0.23 ± 0.01 def	3.5 ± 0.01 abc
2022	MIX	278.7 ± 1.1 e	208.9 ± 2.3 ab	8.7 ± 0.2 d	4.3 ± 0.03 i	8.1 ± 0.1 gh	0.21 ± 0.01 d	3.4 ± 0.03 ab
	MECH	119 ± 1.8 a	227.9 ± 1.8 de	4.2 ± 0.1 ab	0.6 ± 0.04 a	7.5 ± 0.04 de	0.10 ± 0.01 a	3.8 ± 0.2 ef
	HERB	162.1 ± 5.4 b	221.06 ± 3.4 cd	4.6 ± 0.4 ab	1.1 ± 0.03 c	6.7 ± 0.3 b	0.15 ± 0.01 b	3.6 ± 0.1 c
	TEX	152.4 ± 6.5 b	232.5 ± 10.2 ef	4.7 ± 0.1 b	0.8 ± 0.01 b	7.3 ± 0.01 cd	0.10 ± 0.01 a	3.5 ± 0.01 abc
	MULCH	218 ± 12.8 d	210.7 ± 2.0 ab	4.2 ± 0.02 a	1.7 ± 0.01 e	7 ± 0.02 c	0.15 ± 0.01 b	3.9 ± 0.02 f
	MONO	201 ± 4.6 c	216.1 ± 3.0 bc	4.2 ± 0.01 ab	0.8 ± 0.03 ab	7.5 ± 0.02 de	0.10 ± 0.01 a	3.6 ± 0.02 cd
	MIX	214.1 ± 11.4 d	220.9 ± 7.8 cd	4.7 ± 0.1 ab	1.3 ± 0.02 d	6.3 ± 0.1 a	0.11 ± 0.01 a	3.7 ± 0.01 de

Values in each column followed by different letters are significantly different at $p \leq 0.05$, according to Fisher's LSD test. LSD, least significant difference; YAN, yeast assimilable nitrogen.

DISCUSSION

Under-vine vegetation assessment

Although the coverage of the under-vine area according to drone geospatial assessment was low, a higher number of species in the MECH and HERB treatments (identified by phytosociological survey) indicates that direct sowing of cover crop species (MIX treatment) does not necessarily mean the absolute highest number of plant species will be found (Figure 6A).

According to the results of this study, a significant decrease in the number of plant species was found on the TEX-treated under-vine row. The conditions of this treatment were unfavourable for most of the species. Besides the growth space limitation of the textile used, the black geotextile mulch also increases the soil temperature (Wang et al., 2021). Similarly, growth space for most of the plants was limited by using grass mulch (MULCH). In addition, McMillen (2013) demonstrated that a 15 cm thin layer of cut grass could conserve a considerable amount of water, especially right after irrigation. Mulches can provide adequate weed control, however, and create a favourable habitat for voles and rodents (Nagy et al., 2010). From the perspective of overall vegetation coverage, the MECH, HERB and TEX variants were at a similar level, whereas the MULCH variant exhibited a higher degree of plant coverage. According to Cabrera-Pérez et al. (2022), effectivity of various types of mulches (straw of species *Medicago sativa*, *Festuca arundinacea*, *Hordeum vulgare* or chopped pine wood of *Pinus sylvestris*) to control weed coverage differed throughout the years and season. All types of mulches effectively control weeds (<20% of weed coverage) during the first year of the experiment when the mulch coverage remains over 75% of the total soil coverage.

The number of species did not differ significantly within the rest of the treatments. However, a notable species composition change occurred. Under-row treatments, MECH, MULCH and HERB were dominated by annual grass species (*Bromus hordeaceus*, *Digitaria sanguinalis*, *Echinochloa crus-galli*, *Hordeum murinum*, *Setaria pumila* and *Setaria viridis*), annual dicotyledonous species (*Amaranthus retroflexus*, *Chenopodium album* and *Portulaca oleracea*) and species that are difficult to control (*Cirsium arvense*, *Convolvulus arvensis* and *Taraxacum* sect. *Taraxacum*). Consistently, according to Mairata et al. (2023), proportion of noxious weeds (incl. *C. album*, *C. arvense*, *C. arvensis*, *Lactuca seriola* and *Sonchus oleraceus* etc.) was higher on herbicide and tillage treated under-vine than on the under-vines covered with several types of organic mulches. In the study by Cabrera-Pérez et al. (2022), the predominant species on herbicide control was *Conyza bonariensis* representing 60%–85% of weed cover during summer, confirming its difficulty to control with glyphosate herbicide. Species composition in the treatments MIX and MONO was markedly higher in

the number of sown species (*Trifolium repens*, *Anthyllis vulneraria*, *Medicago lupulina* and *Lotus corniculatus*) and perennial grass species (*Lolium perenne*). Under-row management affected the number of plant species and species composition. Various plant species compositions can lead to a shift in the function of the ecosystem that can cause a response in the grapevine plants (García et al., 2018). The sowing of selected plant species in a grapevine under-row can affect the composition and coverage rate of particular species. Specifically, such a change was evident in the coverage rate increase of the Fabaceae family species. In the 2-year experiment, Abad et al. (2020) reported results confirming higher rate of clover species (*Trifolium fragiferum*) and suppression of noxious weed *C. arvensis* occurrence in the under-vine with sown cover crop (clover) than in the tilled under-vine, especially in the second year of succession of cover crop. In the study from semi-arid climate vineyard (Mediterranean) during the first year, the under-vine cover of species *Plantago lanceolata* had higher effectivity to control noxious weeds than *Festuca ovina* cover. However, during the second and third year, both under-vine cover crops showed sufficient ability to suppress weeds without the need for mechanical or chemical control, reducing costs and damage to vines (Guerra et al., 2022).

Furthermore, scanning the surface of the under-vine area using a multispectral drone was a quick method to determine the degree of soil coverage by vegetation. This can be a faster way to assess a large area compared to a traditional phytosociological survey.

The use of different methods of under-vine management led to specific changes in the composition of the plant vegetation. However, the influence of this management on the qualitative parameters of production remains an important question.

Yield and analytical parameters of grapes

The number of berries in a cluster was likely affected most by weather conditions. During the 2022 season, the temperatures were higher; moreover, in the 2021 season, a higher rainfall amount during the grapevine bloom period (May 2021) appeared (Figure 1). According to a study by Zhu et al. (2020), rainfall during the bloom of grapevines has a negative effect on berry and bunch mass. The rainfall during the post-flowering period was higher in the 2022 season (June 2022) (Figure 1). Post-flowering rainfall was found to have a strong positive effect on berry and bunch mass (Zhu et al., 2020). Aside from treatment, the yield parameters were higher in the 2022 season, assuming those parameters mainly depend on factors such as rainfall amount and distribution, temperature and pest and disease pressure during growth (Medrano et al., 2015; Zhu et al., 2020). However, in the treatments with cover crops (MONO and MIX in 2021 and MIX in 2022), the weight of grapes per vine was significantly higher compared to the rest of the treatments. As mentioned

above, the rainfall amount and sufficient soil moisture were significant factors affecting the yield (Medrano et al., 2015; Zhu et al., 2020). Although cover crops may be considered water competition for the grapevines (Medrano et al., 2015), the cover crop root system maintained good soil structure, improved infiltration of the rainfall water (Li et al., 2004; Pingping et al., 2013) and affected the microclimate in the vineyard (Peng et al., 2022). Rainfall water runoff in the bare soils (tillage or herbicide application) can cause a significant decrease in soil moisture (Ben-Salem et al., 2018; Marqués et al., 2020). Research conducted by Chou and Vanden Heuvel (2018) showed that yield per vine was not reduced by any of the under-vine cover crops in a mature, cool-climate vineyard. These findings came from areas with a precipitation amount between 286 mm and 400 mm per season (May–October), which is comparable to the conditions at the location of the vineyards in this study (Figure 1). According to these authors, not only nutrient or water competition but also other mechanisms, such as microbial or allelopathic effects of under-vine cover crops, should be examined to explain the effect of under-vine management on vine vigour. The availability of nutrients in the soil may directly affect the growth of the grapevine. The use of legume cover crops (Fabaceae) increased the supply of nitrogen in the root zone (Tribouillois et al., 2015; Xie et al., 2015). Moreover, legume crops in under-vine areas may increase the soil N content in the long term (Chou and Vanden Heuvel, 2018). Different findings were also discovered. For example, white clover in under-vine areas reduced vine vegetative growth in the short term (Karl et al., 2016). According to Kesser et al. (2023), no significant impact of under-vine spontaneous vegetation with domination of grass species was found on grapevine yields. In the study of Burg et al. (2022), the yield of grapevines increased from 6% to 19% in vineyards treated with cereal straw mulch or compost mulch applied in inter-rows compared to control (bare soil).

It is well known that nitrogen, as the main plant growth element, has a direct impact on the yield parameters of many horticulture and agriculture crops (Torres-Olivar et al., 2014; Sun et al., 2023). The presence of cover crop vegetation in under-row areas affects the microbial activity in the soil, which can lead to various effects, such as an increase in nutrient availability for the plants or may affect the occurrence of pests and diseases (Kim et al., 2020; Gao et al., 2022). For example, biofumigation with white mustard plants has the potential to enhance the control of black-foot disease in grapevines (Berlanas et al., 2018). In contrast, according to a study by Castillo et al. (2007), grass cover crops may act as a host for soilborne pathogens and nematodes in the vineyards.

Mulching also had a significant impact on local soil and microclimate properties. For instance, according to Zhang et al. (2020), grass mulch increases the water-holding capacity of the soil and reduces the topsoil

and canopy temperature. Besides other benefits of using organic mulches in vineyard, Dami et al. (2023) reported as well effective winter protection of grafts unions comparable to conventionally soil hilling, moreover provided effective weed suppression. The release of nutrients, namely nitrogen, during grass mulch decomposition may be an additional benefit. Reported results on this issue are contradictory. In the study by Valenzuela-Solano and Crohn (2006), high rates of nitrogen released by grass clippings mulch were reported, while in other studies, a decrease in nitrogen content due to the use of grass or straw mulch was found (Brunetto et al., 2011; Qin et al., 2022).

Sugars increase the fullness, texture and extract of the resulting wine; a low level of these sugars reduces the alcohol content so that bitterness and acidity dominate. Similarly, yeast activity requires monosaccharides (fructose and glucose) where healthy and well-ripened berries reach values of $200\text{--}250\text{ g} \cdot \text{L}^{-1}$ (Dequin et al., 2017; Oláhné Horváth et al., 2020). All values in this experiment are within the recommended range. In the MULCH, MONO and MIX variants, the sugar content was lower, while the nitrogen content in grapes was higher compared to other treatments. Contrarily, according to Burg et al. (2022), using a cereal straw mulch in inter-row increased sugar content in inter-rows. The accumulation of nitrogen in grapes is dependent on the availability of nitrogen in the soil (Havlin et al., 2022). It might be assumed that if there were higher nitrogen content available in the soil, higher vegetative growth could be expected, as was reported by Chang and Kliewer (1991), who stated that excessive nitrogen could lead to excessive vegetative growth of grapes. Higher vegetative growth can, therefore, lead to delayed maturation, resulting in a generally lower sugar content (Thomidis et al., 2016; Muscas et al., 2017).

The natural occurrence of assimilable nitrogen in grapes is $100\text{--}500\text{ mg} \cdot \text{L}^{-1}$ and is necessary for the reproduction and activity of yeast, while the ideal concentration is in the range of $190\text{--}200\text{ mg} \cdot \text{L}^{-1}$ (Hernández-Orte et al., 2011). A higher level of YAN is desirable for aromatic wines due to the higher need for N during fermentation (Palomo et al., 2006). The highest level of YAN in this trial was detected in the treatments MULCH, MONO and MIX. The effect of the year can also be noted. In 2022, when the season was warmer and with less precipitation (Figure 1), YAN reached lower values than in 2021. This fact was already described by Baroň (2011), who expected that in the regions with a colder climate, the contents of ammonia ions in grapes would be increased. Higher YAN in the MULCH treatment could be attributed to the gradual decomposition of the mulched grass, during which nutrients for growth, especially nitrogen, are released. YAN content was also higher in the MONO and MIX treatments. This fact can be attributed to the higher proportion of leguminous plants (Figure 7C), which could have ensured a higher supply of available nitrogen

for the plants due to nitrogen-fixing bacteria. Longa et al. (2017) explained that green manure, composed mainly of the Fabaceae family, enhances the diversity of microorganisms in the soil, particularly bacteria associated with the nitrogen cycle. However, Zanzotti and Mescalchin (2019) reported that although there were variations in nitrogen release patterns from the soil, the YAN content in the musts remained largely unaffected. They found that nitrogen dynamics in the soil varied depending on the year and weather conditions. Pérez-Álvarez et al. (2015) suggested that nutrient competition begins in the soil, spreads to vegetative tissues later and then finally to grapes. This indicates that the positive or negative influence of under-vine management on YAN may appear relatively late. Chou and Vanden Heuvel (2018) reported that under-vine cover crops had little impact on harvest parameters, including titratable acidity, pH or YAN. In their study, they recommended that in order to have sufficient YAN in grapes, nitrogen adjustment may be required regardless of under-vine cover crops. Competing relationships can also be examined. Reduced YAN has been found in studies under competitive cover crops (Gouthu et al., 2012). More recent research from Spangenberg and Zufferey (2023) shows that YAN concentrations decrease much more severely due to the competition between cover crops and vines for nitrogen, rather than as an effect of different soil moisture conditions (seasonal effect). In their experiment, YAN also decreased in the case of cover crop with a grass-dominated mixture. Therefore, we can suggest that cover crop containing leguminous species might be more effective.

Even if this experiment shows certain relationships between grass mulch (MULCH), leguminous sowing (MONO, MIX) and higher YAN content, other factors must also be considered (e.g., temperature, growing stages, etc.).

Winemakers are interested in sufficient acids; the value for dry white wine in cool-climate regions is recommended to be a minimum $4\text{ g} \cdot \text{L}^{-1}$ (Ribéreau-Gayon et al., 2006). From this point of view, the acid content was sufficient for all treatments. The effect of floor management on acid content was mentioned by Reeve et al. (2016), who stated that treatment with grass caused lower titratable acids compared to treatment that was free of vegetation by tilling in some years. Ground mulch has been reported to decrease titratable acidity and pH (Guerra and Steenwerth, 2011), which was not in line with our findings. From our research, it follows that all variants with covered soil (MULCH, MONO, MIX) reached higher titratable acids in 2021. In the following year, however, the difference was no longer evident. Similar results were reported by Wang et al. (2020) who stated, that compared to clean tillage, grass cover increased titratable acid. However, mulching with black plastic film significantly decreased it.

No clear effect of year or treatment was found in the pH assessment, so this parameter was influenced by other factors.

Currently, there is an effort to focus on the non-production functions of agriculture and the protection of the agroecosystems. There are a number of technological measures that prevent soil erosion, increase organic matter in the soil or support the biodiversity of plants and animals in the agroecosystem. However, some measures may have a different impact on the yield or quality parameters of grapes, which may mean that given measures are not adopted by growers. Therefore, it is essential to test the given measures in specific growing and climatic conditions. Owing to different compositions of vegetation, we have the opportunity to influence the ecosystem functions of vegetation in vineyards. It is necessary to pay increased attention to the selection of species and varieties for sowing in the under-vine area. Species and varieties should not compete with grapevines, should tolerate drought well and produce less biomass.

CONCLUSIONS

During a 2-year experiment conducted in the Moravian wine region, it was found that management of under-vine areas can influence plant composition of cover crops (number of plant species and botanical families, number of Poaceae, Fabaceae and noxious weeds) as well as grape yield and certain quality parameters. Under-row management affected the number of plant species and species composition. A notable reduction in the number of plant species was observed in the variants treated with TEX and MULCH. In both years, the MONO and MIX treatments retained the highest percentage of representatives from the Fabaceae family. The results of yield and analytical parameters also demonstrated the impact of weather conditions, which varied in the observed years. Yield parameters showed variability, and the influence of treatment, year and their interaction was identified. In 2022, the treatment MIX exhibited the highest average bunch weight per vine, and in 2021, it was one of the highest. Conversely, the traditional mechanical treatment (MECH) had the lowest bunch weight per vine in both years. The measured values of assimilable nitrogen were significantly higher in most treatments in 2021. In each year, it was evident that the MULCH, MONO and MIX treatments consistently had higher YAN content compared to the other treatments. The sugar content in the MULCH, MONO and MIX variants was significantly lower compared to MECH, HERB and TEX in 2021. The total acid content was significantly lower during 2022 compared to 2021. Malic acid reached its highest content in the MULCH treatment in both years. Other results did not show a clear influence of the treatments.

The influence of under-vine management on selected parameters often varies in different years with varying weather patterns. In the context of climate change, this question will become increasingly relevant. From our results, it is apparent that a key indicator for evaluating the effect of under-vine management should be the

stabilisation of quantitative and qualitative indicators. Although it seems that a number of analytical parameters could be mainly influenced by the course of the growing season, partial results indicate the potential influence of under-vine management, which could be further studied.

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AUTHOR CONTRIBUTIONS

T.K. and J.W. – research concept and design. T.K., J.W., L.N.R., R.S., V.F., J.S. and E.H. – data collection. T.K., J.W., R.S., L.N.R. and J.S. – analysis and interpretation of results. T.K., L.N.R. and J.W. – preparing a draft text. All authors reviewed the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPLEMENTARY MATERIALS

Supplementary Table 1. Coverage rate of each plant species in six under-vine treatments during three evaluation terms (July, August and September) in years 2021 and 2022.

Family	Species	Category*	JULY 2021						AUGUST 2021						SEPTEMBER 2021					
			MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX
Amaranthaceae	<i>Amaranthus blitoides</i>	1																		
	S. Watson																			
	<i>Amaranthus retroflexus</i> L.	2	10			7	15	4		2	1		15	20	4	3	1	3	10	7
	<i>Atriplex patula</i> L.	2																		
	<i>Chenopodium album</i> L.	3	6	1		2	6	5	1	1			15	15	4	1		3	15	10
Apiaceae	<i>Chenopodium hybridum</i> L.	2																		
	<i>Daucus carota</i> L.	2																		
	<i>Artemisia vulgaris</i> L.	3																1		
Asteraceae	<i>Cirsium arvense</i> (L.) Scop.	3	1			10	12					1	5		5			15	5	
	<i>Conyza canadensis</i> (L.) Cronq.	2							1											
	<i>Crepis biennis</i> L.	2																		
	<i>Crepis tectorum</i> L.	2																		
Asteraceae	<i>Erigeron annuus</i> (L.) Pers.	3																		
	<i>Senecio vulgaris</i> L.	1																		
	<i>Sonchus oleraceus</i> L.	1																1		
	<i>Taraxacum officinale</i> (L.) Weber ex F. H. Wigg.	3	5			5	3	7	1	1			4	2	4	1		1	1	4
Brassicaceae	<i>Tragopogon pratensis</i> L.	2				1														
	<i>Tripleurospermum inodorum</i> (L.) Sch.Bip.	3					1						2		1				1	
	<i>Capsella bursa-pastoris</i> L.	1	1				2	1		1				1	3	4		3		
	<i>Sinapis alba</i> L.	1																		
Caryophyllaceae	<i>Thlaspi arvense</i> L.	1																		
	<i>Arenaria serpyllifolia</i> L.	1	1				1						2							
	<i>Stellaria media</i> (L.) Vill.	1	1															6		
Convolvulaceae	<i>Convolvulus arvensis</i> L.	3	1			2		2	1	1	1	1	2	1	8	3	2	8	4	

(Continued)

Supplementary Table 1. Continued

Family	Species	Category*	JULY 2021						AUGUST 2021						SEPTEMBER 2021					
			MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX
Fabaceae	<i>Anthyllis vulneraria</i> L.	1						5						10						10
	<i>Lotus corniculatus</i> L.	2						3						5						7
	<i>Medicago lupulina</i> L.	2	1					5	1				4	8		1		1		5
	<i>Onobrychis viciifolia</i> Scop.	1																		
	<i>Trifolium pratense</i> L.	1																		1
	<i>Trifolium repens</i> L.	1					10	40					8	40	1		3		20	70
	<i>Vicia tetrasperma</i> (L.) Schreb.	1																	1	
Geraniaceae	<i>Erodium cicutarium</i> (L.) L'Hér.	2													1					
	<i>Geranium pusillum</i> Brum. fil.	2	1				1	1							1				1	
Lamiaceae	<i>Lamium amplexicaule</i> L.	1																		
	<i>Lamium purpureum</i> L.	1																1		
Plantaginaceae	<i>Plantago major</i> L.	1											1							
	<i>Veronica polita</i> Fries.	1			1								1							
Poaceae	<i>Bromus hordeaceus</i> L.	2	2				3	6			1		2	3	10	11	3	18		5
	<i>Bromus japonicus</i> Thunb.	2																		
	<i>Bromus tectorum</i> L.	2																		
	<i>Digitaria sanguinalis</i> (L.) Scop.	2							2					5	3	2	2			4
	<i>Echinochloa crus-galli</i> (L.) P. Beauv.	2														1			1	
	<i>Elytrigia repens</i> (L.) Nevski	3													1					
	<i>Festuca rubra</i> L.	2																	10	
	<i>Hordeum murinum</i> L.	2												1						
	<i>Lolium perenne</i> L.	2	3				3	4					3	3				3	6	6
	<i>Panicum miliaceum</i> L.	3																		
	<i>Poa annua</i> L.	1																		
	<i>Setaria pumila</i> (Poir.) Roem. et Schult.	2	6	1											1				55	15
	<i>Setaria verticillata</i> (L.) P. Beauv.	2							1	5			10	12	6	12		2	4	
	<i>Setaria viridis</i> L.	2			1	1	8	4	2				12	10		4	1			

(Continued)

Supplementary Table 1. Continued

Family	Species	Category*	JULY 2021						AUGUST 2021						SEPTEMBER 2021					
			MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX
Polygonaceae	<i>Polygonum vulgare</i> L.	2	5	1	1	1	3	3	1	4		1	2		2	2	1	1	7	4
Portulacaceae	<i>Portulaca oleracea</i> L.	2		1																
Resedaceae	<i>Reseda lutea</i> L.	1														8	1	3		
Rosaceae	<i>Rosa canina</i> L.	3																		
Solanaceae	<i>Datura stramonium</i> L.	3																		
	<i>Solanum nigrum</i> L.	2								1			1			1				
Violaceae	<i>Viola arvensis</i> Murray	1																		
Amaranthaceae	<i>Amaranthus blitoides</i> S. Watson	1																		
	<i>Amaranthus retroflexus</i> L.	2							5			1				6		1		
	<i>Atriplex patula</i> L.	2																		
	<i>Chenopodium album</i> L.	3					1						2	2					2	
	<i>Chenopodium hybridum</i> L.	2																		
Apiaceae	<i>Daucus carota</i> L.	2																1		
Asteraceae	<i>Arenaria vulgaris</i> L.	3																		
	<i>Cirsium arvense</i> (L.) Scop.	3	8	1	1	8	8	1				8	8	2		10	1	10		4
	<i>Conyza canadensis</i> (L.) Cronq.	2																		
	<i>Crepis biennis</i> L.	2																		
	<i>Crepis tectorum</i> L.	2																		
	<i>Erigeron annuus</i> (L.) Pers.	3																		
	<i>Senecio vulgaris</i> L.	1																1		
	<i>Sonchus oleraceus</i> L.	1																		
	<i>Taraxacum officinale</i> (L.) Weber ex F. H. Wigg.	3	2	4		3	5	6					3		7	4		4		3
	<i>Thlaspi arvense</i> L.	2																		
	<i>Tripleurospermum inodorum</i> (L.) Sch.Bip.	3	1				2						3							
Brassicaceae	<i>Capsella bursa-pastoris</i> L.	1	1	1											1	3		3	2	
	<i>Sinapis alba</i> L.	1																		
	<i>Thlaspi arvense</i> L.	1													3				1	
Caryophyllaceae	<i>Arenaria serpyllifolia</i> L.	1		1			2						2							
	<i>Stellaria media</i> (L.) Vill.	1													2	7		6	1	2

(Continued)

Supplementary Table 1. Continued

Family	Species	Category*	JULY 2021						AUGUST 2021						SEPTEMBER 2021					
			MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX
Convolvulaceae	<i>Convolvulus arvensis</i> L.	3	5	4	2	5	3	2	1	1	4	4	7	4	4	8	2	3	1	7
Fabaceae	<i>Anthyllis vulneraria</i> L.	1					15	15											6	
	<i>Lotus corniculatus</i> L.	2					8	8						11					12	
	<i>Medicago lupulina</i> L.	2	3	2			10	25		2			3	7					7	
	<i>Onobrychis viciifolia</i> Scop.	1												1						
	<i>Trifolium pratense</i> L.	1																		
	<i>Trifolium repens</i> L.	1		1			45	20	1	3			10	6					10	10
	<i>Vicia tetrasperma</i> (L.) Schreb.	1					2								3	1			2	
Geraniaceae	<i>Erodium cicutarium</i> (L.) L'Hér.	2							2											
	<i>Geranium pusillum</i> Brum. fil.	2	2	3			1	1							1	1	1	2	1	
Lamiaceae	<i>Lamium amplexicaule</i> L.	1														1		2	1	
	<i>Lamium purpureum</i> L.	1																		
Plantaginaceae	<i>Plantago major</i> L.	1																		
	<i>Veronica polita</i> Fries.	1																	1	
Poaceae	<i>Bromus hordeaceus</i> L.	2	15	10	3		15	10	2	2	2	1	4	1	12	12	1			2
	<i>Bromus japonicus</i> Thunb.	2			1					1	1									
	<i>Bromus sterilis</i> L.	2																		
	<i>Bromus tectorum</i> L.	2		3			2	1							5					
	<i>Digitaria sanguinalis</i> (L) Scop.	2		2					1	2						5			4	
	<i>Echinochloa crus-galli</i> (L.) P. Beauv.	2	2	1	1		1		2	10										
	<i>Elytrigia repens</i> (L.) Nevski	3	4													4				
	<i>Festuca rubra</i> L.	2																		
	<i>Hordeum murinum</i> L.	2	2	2			3	1							10		1			
	<i>Lolium perenne</i> L.	2	8	4	3		20	13	4	5	6	3	55	35		15	4	3	40	55
	<i>Panicum miliaceum</i> L.	3		2																
	<i>Poa annua</i> L.	1													1					
	<i>Setaria pumila</i> (Poir.) Roem. et Schult.	2	5	4			1			10				2					6	
	<i>Setaria verticillata</i> (L.) P. Beauv.	2	2	2						5	2					8	2		3	7
	<i>Setaria viridis</i> L.	2	1	2			1			8	2		2	2					7	4

(Continued)

Supplementary Table 1. Continued

Family	Species	Category*	JULY 2021						AUGUST 2021						SEPTEMBER 2021					
			MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX	MECH	HERB	TEX	MULCH	MONO	MIX
Polygonaceae	<i>Polygonum vulgare</i> L.	2																	1	1
Portulacaceae	<i>Portulaca oleracea</i> L.	2								2										
Resedaceae	<i>Reseda lutea</i> L.	1																		
Rosaceae	<i>Rosa canina</i> L.	3											1							1
Solanaceae	<i>Datura stramonium</i> L.	3																		
	<i>Solanum nigrum</i> L.	2																		
Violaceae	<i>Viola arvensis</i> Murray	1		2																

*Category: 1: non-dangerous weed; 2: dangerous weed; 3: highly dangerous weed.