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Article

Evaluating the effects of intercrop management on weeds and soil aggregate stability during the establishment of semihardy grapevines in southern Quebec

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Abstract

Living mulches from resident vegetation or intercrops could be used to control weeds and partially alleviate soil erosion during vineyard establishment in Quebec. However, their impact on grapevine yield and fruit quality is poorly documented. Growing semihardy grapevines is a challenge in southern Quebec as winter protection is necessary. Winter protection is provided either by hilling or by geotextiles and these methods determine what type of living mulch can be grown. Annual plant species are best suited for the former method, while perennial species are compatible with the latter. The aim of this study was to evaluate the effect of two grass living mulches (annual and perennial) on weed control and diversity, soil aggregate stability, vine growth, and fruit quality in comparison with cultivation and an unmanaged (weedy) control during vineyard establishment. The cultivation treatment was the most efficient weed control method and decreased weed species richness and diversity in comparison with intercrops. Maintaining a living mulch in the interrow, however, helped preserve soil aggregate stability better than cultivation did. Vine yield and fruit quality were not affected by any interrow weed management method. Consequently, the use of living mulches is a promising alternative to cultivation in the interrow during vineyard establishment in Quebec, Canada.

Key words: viticulture, soil water erosion, aggregate stability, weed control, living mulch

Résumé

Bien que les cultures intercalaires compétitionnent avec les adventices et soient bénéfiques pour la structure du sol, leur impact sur la vigne en climat continental, où les cépages semi-rustiques doivent être protégés du gel, est peu documenté. L'implantation d'une culture intercalaire est restreinte par la protection hivernale: les espèces annuelles sont incorporées à l'automne lors du buttage, tandis que les géotextiles permettent l'utilisation d'espèces pérennes. L'objectif de cette étude est d'évaluer l'impact de deux cultures intercalaires de graminées (annuelles vs pérennes) sur l'établissement des adventices, la stabilité des agrégats du sol, la croissance et la production de la vigne comparativement au désherbage mécanique et un témoin enherbé (adventices). Le désherbage mécanique s'est avéré plus efficace et a réduit la richesse et la diversité des populations d'adventices comparativement aux couverts végétaux. Ces derniers ont toutefois davantage préservé l'intégrité physique des agrégats en comparaison, sans baisse de rendement ni qualité de la récolte. À la lumière de ces résultats, l'implantation de cultures intercalaire s'avère une alternative prometteuse au désherbage mécanique dans l'entre-rang dans les vignobles en établissement dans le Sud du Québec.

Mots-clés : viticulture, structure du sol, stabilité des agrégats, contrôle des adventices, paillis vivant

1. Introduction

The wine industry has expanded rapidly in Quebec since the 1980s. The growing popularity of local food movements, combined with marketing efforts, has resulted in a steady increase in the number of bottles of wine produced since 2010 (Keable 2019.). However, wine grape production in Quebec presents challenges. Winter frost is a major hurdle for winegrowing in Quebec as the air temperature may drop to −35 °C, below the frost tolerance threshold of the most common grapevine varieties (*Vitis vinifera* L.) (Jolivet and Dubois 2000). Hybridization with indigenous species has given rise to more winter-hardy vine cultivars while still maintaining good organoleptic characteristics for vinification. Nevertheless, winter protection remains necessary for the preferred nonhardy and semihardy grapevine varieties (Barriault 2012).

Hilling and geotextile are the two winter protection methods used. Hilling involves mounding soil over the vines by repetitive plowing before winter, and uncovering them in the spring (Dami et al. 2005). Although essential, hilling is detrimental to soil structure and enhances soil erosion by water, which is an important consideration given that many vineyards are often located on slopes (Jiang et al. 2016). Installing a geotextile fabric is an alternative method of winter protection, but it is more expensive and time consuming (Barriault 2012). Regardless of the winter protection method, weed management within and between rows is essential and challenging for winegrowers, as weed management can affect the health of the vineyard. Both chemical and mechanical weed control methods leave soil bare in the interrow, which increases soil erosion and degradation (Duran and Rodriguez 2008).

Establishing living mulches between vine rows by letting the resident vegetation grow or by growing preselected plant species as intercrops is an alternative weed control method that can limit weed establishment and promote soil conservation. Intercrops provide many ecosystem services, such as carbon sequestration and water pollution mitigation (Garcia et al. 2018). However, their adoption is limited in the hot and dry Mediterranean climate where most grapevines are grown because they could compete with the grapevine for water or nutrients, resulting in lower vine yields (Steinmaus et al. 2008). Few studies have evaluated their impact under the cooler, more humid continental climate that prevails in certain regions of North America (Devetter et al. 2015). Furthermore, the harsh winter climate in Quebec limits intercrop establishment and growth to a 6 month period, which is concurrent with grapevine growth. In addition, if the vines are hilled, the intercrop will be destroyed each fall, thereby limiting the use of perennial living mulches.

The aim of this experiment was to compare mechanical weed control with the use of intercrops during the grapevine establishment period in southern Quebec from the standpoint of weed control efficiency, plant diversity, soil aggregate stability, and fruit yield (at first commercial harvest). We hypothesized that (*i*) the weed infestation level would be greater in intercrops compared with cultivation but lower than in the unmanaged treatment, (*ii*) that soil aggregate stability would be greater in living-mulch treatments (intercrops and unmanaged, weedy treatments) than in the cultivation treatment, and that (*iii*) grapevine productivity would not be reduced by the presence of living mulches.

2. Materials and methods

2.1. Site characteristics

The experiment was conducted over three growing seasons (2018–2020) at Agriculture and Agri-Food Canada's experimental farm in Frelighsburg, QC, Canada (lat. 45°03′16.9′′N, long. 72°51′39.2′′W). This area has a continental climate characterized by cold winters and humid and warm summers (Fig. S1). The soil at the study site is part of the Blandford loam series within the Brunisolic order (41% sand, 38% loam, and 22% clay), which is typically well drained and associated with forested lands (Cann et al. 1948; Soil Classification Working Group 2002; Institut de recherche et de développement en agroenvironnement 2008).

The selected field had a slope of 2.75%, was not irrigated, and was restored from fallow. The soil was harrowed and cleared of stones before vine plantation. The study site was fertilized based on provincial recommendations (Barriault 2012): potassium sulphate (0–0–50) at 456 kg·ha^{-1}, triple superphosphate (0–46–0) at 315 kg·ha^{-1}, and sulphate of potash magnesia (0–0–22 + 21S + 11Mg) at 100 kg·ha^{-1}. Fertilization was adjusted in the following years based on the vine's response (Barriault 2012). Semihardy grapevines (cv. "Vidal") were planted on 17 May 2018 at 0.9 m spacing. Interrows were 3 m wide and oriented north×–south in the direction of the slope (Fig. S2). Vines were either cane or spur trained after planting, depending on the winter protection method used, which was specific to each treatment. The guidelines for the Gobelet system (spur-trained vines) were followed for hilled vines [cultivation, annual intercrop, and unmanaged (weedy)], whereas vines covered with a geotextile fabric during winter were double cordon trained (cane-trained vines; perennial intercrop). All vines were supported upwards by a trellis with a screw anchor end-post design. Every fall, vines were hilled or protected with a geotextile fabric in early November in preparation for vine dormancy (Table 1 and Fig. 1). Soil mounds in the vine row and the geotextile fabric were removed every spring in April. Starting in 2019, vines were pruned twice a year (spring and fall) (Table 1). Clusters were thinned in-season at bloom in 2019, leaving just the first clusters starting from the bottom to promote vegetative growth during the establishment period (Barriault 2012).

2.2. Experimental design

The experimental layout was a randomized complete block design with four treatments and four blocks (Fig. S2). A single experimental unit measured 12 m × 12 m and consisted of four vine rows with 12 vines per row. Units were secluded by a 5 m buffer alley. Treatments consisted of four interrow weed control management methods paired with a winter protection method: (1) cultivation, (2) annual intercrop, (3) perennial intercrop, and (4) unmanaged (weedy). The vines were hilled in treatments (1), (2), and (4); during hilling, the vines were buried using soil taken between the rows, killing all vegetation in the interrow. The vines were protected by a geotextile fabric in treatment (3) (Fig. 1).

A 1-m-wide strip centred under the vine row was kept weed-free throughout the experiment in all the treatments. This weeding was done using tractor-mounted finger weeders (Kult Kress, Vaihingen an der Enz, Germany) and hand weeding. Dimethenamid-P (Frontier Max®) was applied once in-row at a rate of 691 g a.i.·ha^{-1} on 21 May 2018. The product must be applied before vine bud break to avoid crop damage; however, weather conditions did not permit applications before bud break in 2019 and 2020, and thus herbicides were not used again. The cultivation treatment consisted of keeping the interrow weed-free by using a rotary cultivator three

Table 1. Main field operations in various weed management method treatments throughout the experiment.

Field operations	Weed management method treatments in which the field operation was performed	Year		
		2018	2019	2020
Dehilling	Cultivation, annual intercrop, and unmanaged (weedy)	–	29 April	7 April
Removal of geotextiles	Perennial intercrop	–	18 April	2 April
Spring pruning	All weed management methods[a]	–	25 May	9 April
Fall pruning	All weed management methods[a]	–	29 October	28 October
Seeding of annual intercrop	Annual intercrop	22 May	22 May	14 May
Seeding of perennial intercrop	Perennial intercrop	22 May	–	–
In-row weeding	All weed management methods[a]	11 June[b]	20 July	21 May
		27 June[c]	4 July	9 July
		28 June[d]	15 and 16 July	–
		6 July[d]	2 August	–
		9 July	30 September	–
		30 July	–	–
		14 August	–	–
		12 September	–	–
Rotary cultivator in the interrow	Cultivation	12 June	26 June	19 June
		30 July	10 July	15 July
		14 August	24 July	27 August
		5 September	1 October	
Living-mulch mowing	Annual intercrop, perennial intercrop, and unmanaged (weedy)	27 June	18 June	10 June
		9 July	2 July	23 June
		20 July	12 July	15 July
		30 July	24 July	7 August
		10 August	6 August	26 August
		27 August	20 August	–
		–	6 September	–
Hilling	Cultivation, annual intercrop, and unmanaged (weedy)	5 November	4 November	9 November
Installation of geotextiles	Perennial intercrop	9 November	4 November	10 November

[a]The four weed management methods were as follows: cultivation, annual intercrop, perennial intercrop, and unmanaged (weedy).
[b]All except unmanaged (weedy).
[c]Annual and perennial intercrop only.
[d]Unmanaged (weedy) only.

to four times during the growing season (Frontier RT2283 model, John Deere US, Moline, IL, USA). All intercrops were planted in a 12 m × 2 m strip at the centre of the interrow. The annual intercrop was a mixture of cultivated oats (*Avena sativa* L. cv. "Fiona") from Pedigrain (Saint-Hyacinthe, QC, Canada; 38.4 g per 1000 seeds) and Italian ryegrass (*Lolium multiflorum* Lam. cv. "Aubade") from Semican Inc. (Plessisville, QC, Canada; 4.1 g per 1000 seeds). The perennial intercrop consisted of a sward commercial mix (Common No. 1 forage seed mix) from Centre Agricole Petit Bernier Inc. (Saint-Jean-sur-Richelieu, QC, Canada) with the following grass species ratio: 20% perennial ryegrass (*Lolium perenne* L.), 15% Italian ryegrass (*L. multiflorum* L.), 30%, red fescue (*Festuca rubra* L.), and 35% Kentucky bluegrass (*Poa pratensis* L.). In 2018, both intercrop treatments underwent seed bed preparation using a rotary cultivator pass, followed by vibrating tine cultivator passes (Track Curry, MK Martin Enterprise Inc., Elmira, ON, Canada). The annual and perennial intercrop treatments were first planted on 22 May 2018 and the annual intercrop was reseeded under similar conditions in mid-to-late May in the next 2 years (Table 1).

Intercrops were seeded using a minimum-till compact drill seeder (model 3P600-1106, Great Plains Manufacturing Inc., Salina, KS, USA), with 12 units and 15 cm spacing. The annual intercrop was seeded by offsetting two subsequent seeder passes to generate alternating rows of oats and Italian ryegrass. Seeding rates were 169 $kg \cdot ha^{-1}$ (440 seeds per m^2) for oats and 17 $kg \cdot ha^{-1}$ (424 seeds per m^2) for Italian ryegrass. The perennial intercrop was seeded at a rate of 100 $kg \cdot ha^{-1}$. All the rates were adjusted based on seed germination tests done prior to seeding. In the unmanaged (weedy) treatment, weeds were left to grow only to mowing height (14 cm) to limit the invasion of perennial woody plants and to allow tractors and workers to move between the rows. All the treatments except

Fig. 1. Winter protection: hilling (top) and geotextile fabric (bottom) (Agriculture and Agri-Food Canada 2018).

cultivation were mowed five to seven times a year using a lawn tractor (ZTrak™ Z915E, John Deere US, Moline, IL, USA; Table 1), before the dispersal of seeds from weeds or intercrops. Residues were left on the ground in the interrow after mowing. Finally, pest management and disease management were identical for all units and based on standard recommendations.

2.3. Weed and intercrop sampling (2018–2020)

Weed and intercrop density, percentage cover, and shoot and root biomass data were taken using two 0.25 m^2, 50 cm × 50 cm, quadrats placed at approximately the same location (using flags located on the rows to mark the location) in the centre interrow of each experimental unit. Weed and intercrop density sorted by species was evaluated yearly in all the treatments in early June once the annual intercrop had emerged and before the first rotary cultivator pass in the cultivation treatment (Table 1 and Table S1). Intercrop density was evaluated every year in the annual intercrop and once in 2018 in the perennial intercrop (the four species in the latter crop were not distinguished) due to early tillering of the perennial grasses. Weed and intercrop cover percentages were estimated visually at intercrop emergence, before each mowing (five to seven times per year), and at the end of the growing season. Weed and intercrop species were not distinguished for cover percentage evaluation. Weed shoot biomass sorted by species and the shoot biomass of intercrop plants (all species combined) were evaluated at the end of October. Specifically, both perennial white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.) were found in plots but were pooled for analysis, owing to the difficulty of differentiating between the two at emergence and because of the time required to separate them when harvesting biomass. Shoot biomass samples were then dried at 70 °C until the weight stabilized and were weighed. Weed shoot biomass samples where $I = (1, 2, \ldots, i)$ weed species present in plots also served to evaluate weed species richness (*S*; eq. 1), relative abundance (p_i; eq. 2), and diversity (Shannon's diversity index, H'; eq. 3) based on the corresponding equations adapted from Hayek and Buzas (2010). When a plot was barren, a value of 0.0001 g·m^{-2} was recorded for the most common species [brown knapweed (*Centaurea jacea* L.), present in all blocks every year] to retain this plot in the analysis (Baumgartner et al. 2008).

(1) $S = \text{Total of } i \text{ weed species present within plot}$

(2) $p_i = \dfrac{i \text{ weed species biomass } (\text{g} \cdot \text{m}^{-2})}{\text{weed sample biomass } (\text{g} \cdot \text{m}^{-2})}$

(3) $H\prime = -\sum_{1}^{i} p_{i \times \log_{10}(p_i)}$

To evaluate root biomass (intercrops and weeds not differentiated), six core samples were taken in October (Table S1) from the middle interrow of each plot in 2019 and 2020 at two soil depths (0–15 and 15–30 cm) using a hydraulic soil corer (Giddings Machine Company, Windsor, CT, USA) with sampling tubes (diameter of 7.1 cm) mounted on a post (Multi-Pro™, Rhino Tool Company, Kewanee, IL, USA). Core samples from 2019 were kept frozen at −20 °C until evaluation in November 2020, whereas the core samples from 2020 were kept refrigerated at 4 °C. The root biomass and ash content of the core samples were determined based on protocols adapted from Beyaert and Fox (2007) and Thivierge et al. (2016). All the cores were soaked individually in a 10% *w*/*v* (g·L^{-1}) sodium hexametaphosphate solution for 16 h to disperse soil aggregates trapped within the root system before washing.

Cores were then prewashed by rinsing them through a sieve nest with 1 mm and 250 μm openings to eliminate large rock fragments and part of the soil. Subsequent root washing was conducted using a hydropneumatic elutriation washing system (Gillison's Variety Fabrication Inc., Benzonia, MI, USA) and a 760 μm sieve, with the air and water pressure set at 10 kPa and 69 PSI, respectively. After washing, the remaining root biomass was processed through a 250 μm sieve by flotation to separate roots from most other mineral and (or) organic particles that had passed through as well. The recovered root biomass was dried at 60 °C until weight stabilization. The ash content was measured by heating ground samples (1600 MiniG, SPEX SamplePrep, Metuchen, NJ, USA) to 420 °C in a muffle furnace until weight stabilization. The root biomass was corrected afterwards by subtracting the ash biomass in proportion to the sample weight (Beyaert and Fox 2007).

2.4. Soil sampling (2019–2020)

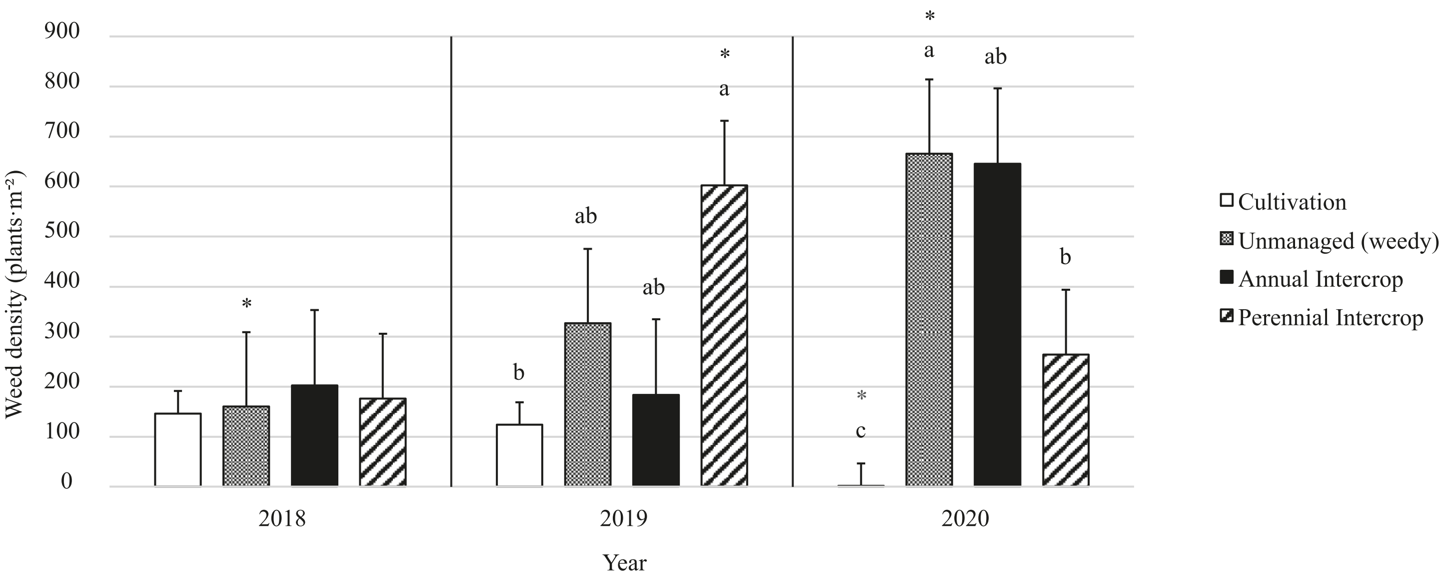
Aggregate stability to water (mean weight diameter: 0–7 cm) and soil gravimetric water content at 15–30 and 45–60 cm depths were measured (1) in spring before intercrop seeding, (2) midseason, and (3) at the end of the season in 2019 and 2020 (Table S1). Four samples were randomly collected in the interrow of each plot using a square shovel. These samples were bulked and sieved through a 6 mm mesh and then stored in rigid-wall plastic containers at 4 °C within hours of sampling. Subsamples were then processed using a custom-built wet-sieving apparatus based on the model used by Angers et al. (2007), which uses the oscillations applied to soil samples placed atop a sieve nest immersed in water to disrupt soil aggregates. The selected sieve sizes were 1, 0.50, and 0.25 mm to distinguish between classes of stability based on Le Bissonnais (2016). Samples were covered in deionized water only on the downward movement and the sieve nest was moved up and down 30 times per minute at an amplitude of 4.5 cm for 10 min. Soil-stable aggregates of each fraction (1) >2 mm, (2) 1–2 mm, (3) 0.50–1 mm, and (4) 0.25–0.50 mm were recovered into Erlenmeyer flasks and dried at 105 °C for 48 h in the first step (part one). Primary particles of each fraction were recovered in the same Erlenmeyer flasks and dried at 105 °C for 48 h in the second part of the analysis. A solution of 5% *w*/*v* (g·L^{-1}) sodium hexametaphosphate was used to facilitate the dispersion of stable aggregates and the samples were placed on a lab shaker for 10 min. The mean weight diameter and particle size of water-stable aggregates (fraction weight) were calculated according to Angers et al. (2007) and aggregate stability was determined using the classification developed by Le Bissonnais (2016). Soil gravimetric water content was evaluated by collecting one soil core at 15–30 cm and another at 45–60 cm depth in the middle interrow of each plot and on adjacent vine rows with an Edelman auger from Hoskin Scientific (Saint-Laurent, QC, Canada). These soil samples were bagged and refrigerated at 4 °C until processing, and then weighed before and after drying at 105 °C for approximately 48 h.

2.5. Vine growth, yield, and fruit quality (2018–2020)

Measurements were taken in October from three randomly selected vines per preidentified harvest row (Table S1). Every year, all leaves from the same three randomly selected grapevines were sampled a few days before senescence and dried at 70 °C until weight stabilization to determine vine leaf biomass.

Additional growth and yield variables to vine leaf biomass were measured from the same three randomly selected vines in 2019 and 2020: total vine leaf area and pruning weight. The leaf area of a subsample of 20 leaves per vine was evaluated using a planimeter to estimate the total vine leaf area. The fall

Fig. 2. Mean weed density at intercrop emergence (early June) throughout the experiment. Bars with different lowercase letters are significantly different between weed management methods and within years. Asterisks indicate significant interyear differences within weed management method. All multiple comparisons are based on Tukey's honest significant differences ($\alpha = 0.05$). Error bars indicate + standard error.



pruning weight including vine leaves was measured upwards from the first trellis wire. The vine yield and cluster number per vine were evaluated at first commercial harvest in 2020 according to the normal production cycle in Quebec vineyards (Barriault 2012). Grape must (without skin) was then extracted from a subsample of 20 berries taken randomly from 20 clusters in the harvest row. Brix measurement was performed with an optical refractometer (Reicher 13853500 High-Precision Brix Refractometer, Buffalo, NY, USA) and pH and titratable acidity were measured using a pH meter (model AR15, Fisher Scientific, Ottawa, ON, Canada).

2.6. Statistical analysis

Data analyses were conducted using the MIXED procedure in SAS University Edition 2.8.1 9.4 M6 (SAS Institute Inc. 2021). The block and sampling year were set as random effect and repeated fixed effect, respectively, for the analysis of the following variables: weed and intercrop densities, weed abundance and diversity, shoot and root biomass, grapevine leaf area, canopy biomass, and pruning weight. Only the two intercrop treatments were taken into consideration when comparing intercrop densities, intercrop cover, and intercrop shoot biomass. When soil data were analyzed, the block was treated as a random effect and the sampling event as a repeated fixed effect. For the analysis of weed and intercrop cover, the model included the block as a random effect and the sampling month × year interaction as a repeated fixed effect. All the variables were analyzed using the variance component covariance structure according to the best model fit based on the Akaike information criterion, except vegetation, intercrop, and weed cover, for which the un@ar(1) (Direct product AR[1]) covariance structure was specified. The vine yield and cluster number per vine were analysed separately with the block as a random effect and sampling year as a repeated fixed effect. For all the analyses, homogeneity of variance was verified by plotting residuals using the SGPLOT procedure. The normal distribution of residuals was assessed graphically and by performing a Shapiro–Wilk test using the UNIVARIATE procedure. The standard error of means was also calculated using the UNIVARIATE procedure. Logarithmic (weed density, annual weed biomass, pruning weight, and particle size distribution of water-stable aggregates) or square root transformations (perennial weed biomass, intercrop, and weed cover) were applied to data that did not meet these criteria, and back-transformed data were presented. The statistical significance between multiple comparisons was determined using Tukey's honestly significant difference test based on a 95% confidence interval.

3. Results

3.1. Weed and intercrop density

There was a significant effect of weed management method × year on weed density at intercrop emergence in early June ($P < 0.0001$; Fig. 2). Every year, weed density was not significantly different between the annual intercrop and unmanaged (weedy) treatments, while it was the lowest in the cultivation treatment in 2020. Weed density was also lower in the perennial intercrop treatment than in the unmanaged (weedy) treatment in 2020. In 2019, weed density was only higher in the perennial intercrop treatment relative to the cultivation treatment. Weed density remained at similar levels between years within the annual intercrop treatment, and reached its highest value in the perennial intercrop treatment in 2019 and in the unmanaged (weedy) treatment in 2020 (Fig. 2).

Intercrop density in the annual intercrop (Italian ryegrass and oats pooled together) treatment was lower in 2020 (354 plants per m^2) than in 2018 (605 plants per m^2) and 2019 (624 plants per m^2) ($P = 0.0024$; data not shown). The perennial intercrop treatment had a density of 170 plants per m^2 in 2018 (data not shown).

3.2. Weed and intercrop cover

Vegetation cover (weeds and intercrops pooled together) varied as a result of a weed management method × month × year interaction ($P < 0.0001$; Fig. 3*a*). It was consistently lower in the cultivation treatment regardless of the sampling month or year. In June 2018, vegetation cover was higher in the annual intercrop treatment (greater than 40%) but was surpassed by the unmanaged (weedy) and perennial intercrop treatments (greater than 60%) by the end of the season. Vegetation cover was greater in the perennial treatment than in the annual intercrop or unmanaged (weedy) treatment in June 2019 (40% vs. 10%, and 3%) and 2020 (90% vs. 45%, and 37%; Fig. 3*a*).

Weed cover was affected by a weed management method × month × year interaction ($P < 0.0001$; Figs. 3*b* and 4*a*). Weed cover was generally lowest in the cultivation treatment (less than 5%) than in other treatments, except in June 2018 and 2019, when the weed cover in the annual intercrop and perennial intercrop treatments was also low. In 2018, the highest weed cover values were consistently observed in the unmanaged (weedy) treatment, whereas the annual and perennial intercrop treatments had similar values (less than 20%) throughout the season. During all years, the weed cover in the unmanaged (weedy) treatment reached values above 85% in August (Fig. 3*b*). In 2019, the weed cover in the annual intercrop treatment peaked at 50% in September, while the weed cover in the perennial intercrop treatment was higher (greater than 55%) starting in July (Fig. 4*a*). In 2020, the weed cover in both intercrop treatments was high and equivalent to that of the unmanaged (weedy) treatment in August and at the end of the season (Fig. 3*b*). Moreover, the weed cover increased significantly within season in the unmanaged (weedy) and annual intercrop treatments (except for October 2019; Fig. 4*a*), reaching significantly higher values after 2018 (Fig. S3*a*). In contrast, the weed cover was significantly higher after 2018 in the perennial intercrop treatment (Fig. S3*a*) and remained approximately at the same level within season except in June 2019, with values ranging from 59% to more than 85% (Fig. 4*a*).

Finally, intercrop cover was also influenced by a weed management method × month × year interaction ($P = 0.0002$; Figs. 3*c* and 4*b*). Intercrop cover was not different between the annual and perennial Intercrop treatments except during three specific sampling months: July and August 2018 and July 2019 ($P = 0.0002$; Fig. 3*c*). Intercrop cover was constant throughout the season in the annual intercrop treatment in 2018 only (Fig. 4*b*). Perennial intercrop cover was also relatively stable throughout the season (except in June 2018 and October 2019; Fig. 4*c*) and tended to decrease in 2020 after July compared with prior years (Fig. S3*b*).

3.3. Weed and intercrop shoot and root biomass

Both total vegetation and weed shoot biomass were affected by a weed management method × year interaction (Table 2). Vegetation shoot biomass was consistently lower in the cultivation treatment but the values for the annual intercrop, perennial intercrop, and unmanaged (weedy) treatments were similar, except in 2020 when the perennial intercrop shoot biomass value was 1.49 higher than the unmanaged (weedy). Similarly, total weed shoot biomass was lowest in the cultivation treatment and the two intercrop treatments had similar values in each year. Total weed shoot biomass remained lower in the annual and perennial intercrop treatments than in the unmanaged (weedy) treatment until 2020, when both intercrop treatments had high values that were similar to that of the unmanaged (weedy) treatment. Intercrop shoot biomass did not vary between years and was 1.42 times higher in the perennial treatment than in the annual intercrop treatment (Table 2). In 2019 and 2020, annual weed shoot biomass was higher in the annual intercrop treatment compared with the perennial intercrop treatment. The shoot biomass of perennial weeds in the perennial intercrop treatment was greater than that of the annual intercrop treatment in 2019 and 2020 (Table 2).

Brown knapweed, smooth crabgrass (*Digitaria ischaemum [Schreb.]* Muhl.), witchgrass (*Panicum capillare* L.), narrow-leaved plantain (*Plantago lanceolata* L.), prostrate knotweed (*Polygonum aviculare* L.), and clovers (*Trifolium spp.* L.) represented the majority of the weed species present in the unmanaged (weedy) and annual and perennial intercrop treatments throughout the experiment (Table 3).

Weed species richness (S) and diversity (H') were both influenced by a weed management method × year interaction (Table 3). Weed species richness was lowest in the cultivation treatment except in 2020 when it was also low in the annual and perennial intercrop treatments. Weed species richness was consistently similar between the annual intercrop and unmanaged (weedy) treatments, the latter showing the highest values. Weed species diversity (Shannon's diversity H') was consistently lower in the cultivation treatment than in the other treatments except in 2020 when it was equivalent to that of the annual intercrop treatment. The highest values were recorded in the unmanaged (weedy) treatment (Table 3).

Root biomass varied between weed management methods only at depths of 0–15 cm ($P < 0.0001$) and 15–30 cm ($P = 0.0005$; Fig. 5). At a depth of 0–15 cm, root biomass was the highest in the perennial intercrop treatment and the lowest in the cultivation treatment, with intermediate values in the unmanaged (weedy) and annual intercrop treatments. At a depth of 15–30 cm, root biomass was significantly higher in the perennial intercrop treatment than in the cultivation treatment (Fig. 5).

3.4. Soil properties

There was a significant effect of a weed management method × sampling event interaction on the average size (mean weight diameter) of water-stable aggregates and on

Fig. 3. Mean vegetation (*a*), weed (*b*), and intercrop cover (*c*) before mowing through the experiment. Weed management method data were grouped by month–year for analysis. 06 = June; 07 = July; 08 = August; 09 = September; 10 = October. Bars with different lowercase letters are significantly different between weed management methods within month and year. All multiple comparisons are based on Tukey's honest significant differences ($\alpha = 0.05$). Error bars indicate + standard error.

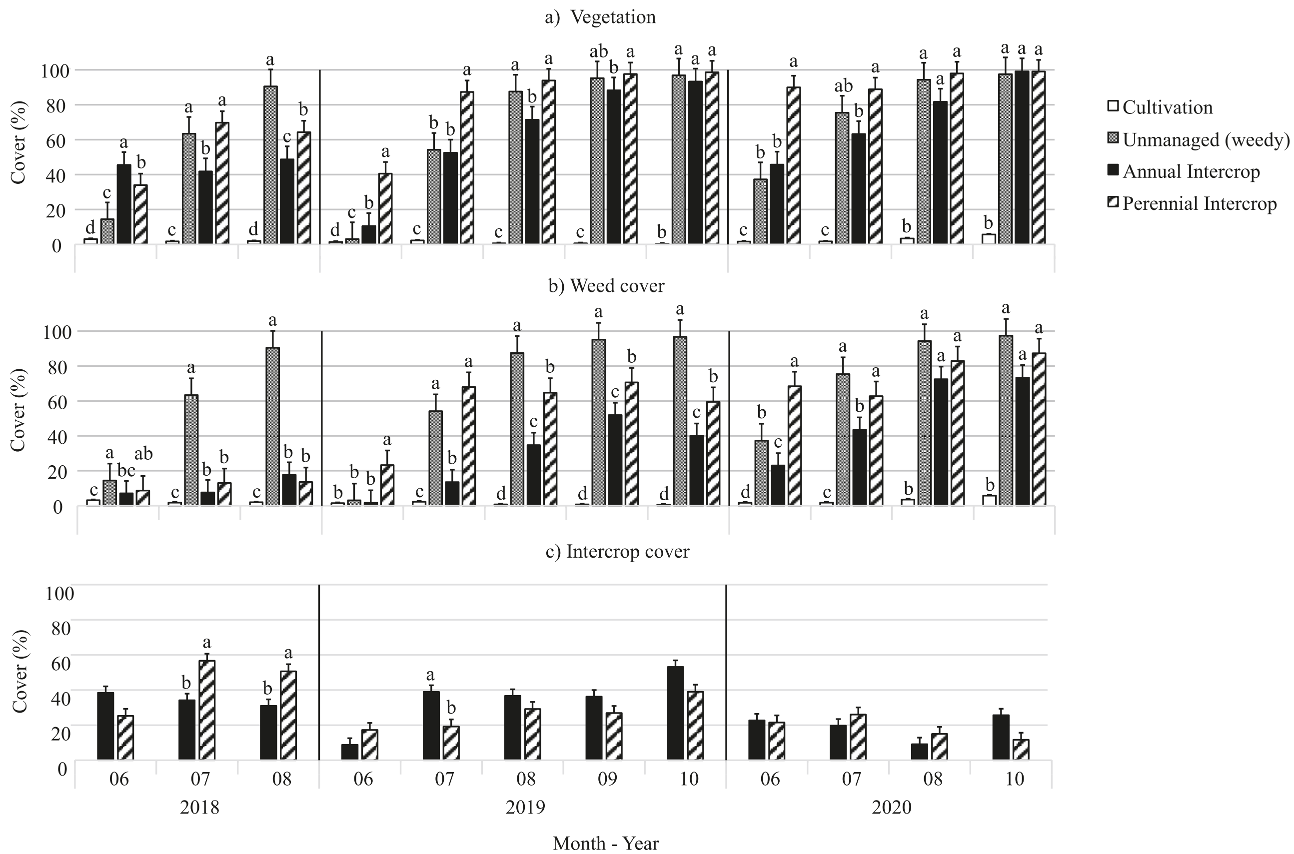


Fig. 4. Mean weed (*a*) and intercrop (*b*) cover before mowing through the experiment. Weed management method data were grouped by month–year for analysis. 06 = June; 07 = July; 08 = August; 09 = September; 10 = October. Bars with different lowercase letters are significantly different between months within year for each management method. All multiple comparisons are based on Tukey's honest significant differences ($\alpha = 0.05$). Error bars indicate + standard error.

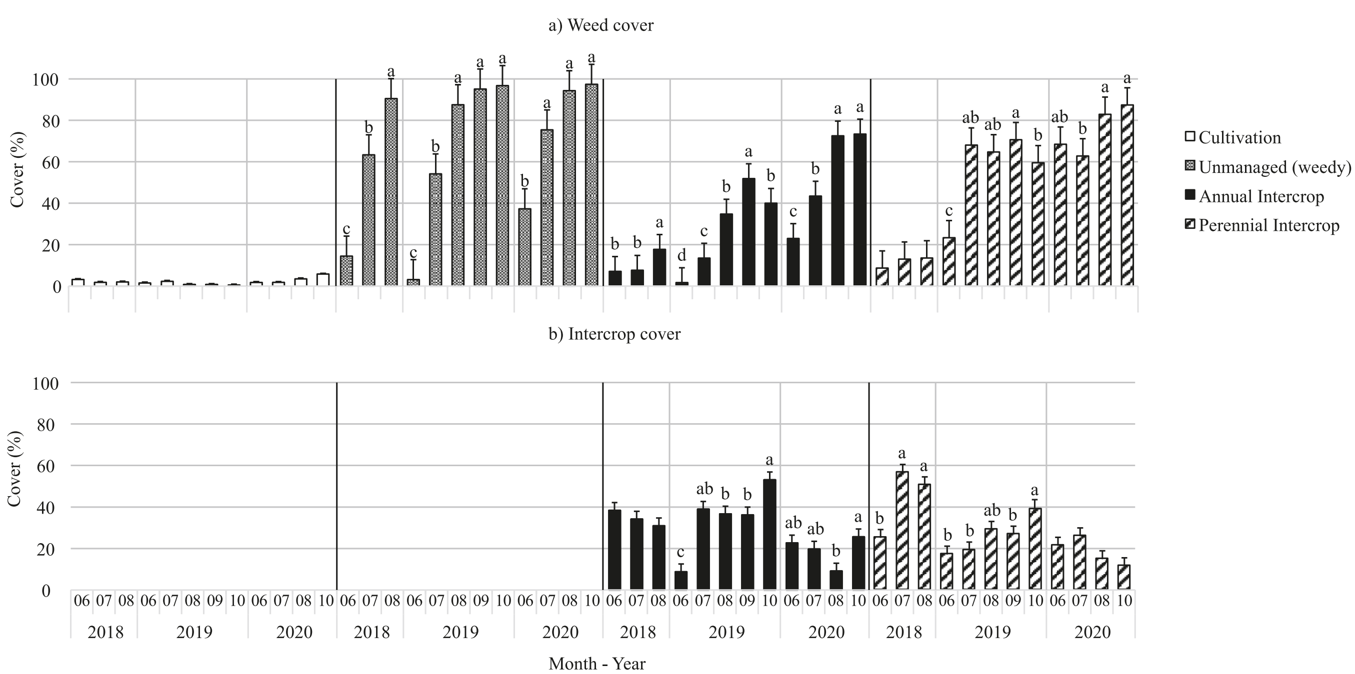


Table 2. Vegetation, intercrop, and weed shoot biomass at the end of growing seasons.

Weed management method	Vegetation shoot biomass[a] ($g{\cdot}m^{-2}$)	Intercrop shoot biomass ($g{\cdot}m^{-2}$)	Weed shoot biomass: Annual ($g{\cdot}m^{-2}$)	Perennial ($g{\cdot}m^{-2}$)	Total[b] ($g{\cdot}m^{-2}$)
Cultivation	–	–	–	–	–
Unmanaged (weedy)	–	–	–	–	–
Annual intercrop[c]	–	115.55 ± 20.03b	–	–	–
Perennial intercrop[d]	–	164.42 ± 14.84a	–	–	–
Weed management method × year					
2018					
Cultivation	0.74 ± 0.27b	–	0.05 ± 0.02c	0.69 ± 0.27c	0.74 ± 0.27b
Unmanaged (weedy)	233.24 ± 14.97a	–	74.82 ± 15.11a	157.40 ± 13.82a	233.24 ± 14.97a
Annual intercrop[c]	169.46 ± 19.59a	–	14.52 ± 6.39b	59.09 ± 20.80b	73.65 ± 24.04b
Perennial intercrop[d]	207.73 ± 8.24a	–	12.22 ± 5.30b	34.87 ± 1.83b	47.18 ± 4.71b
2019					
Cultivation	3.45 ± 3.28b	–	0.00 ± 0.00c	0.21 ± 0.12c	3.45 ± 3.28c
Unmanaged (weedy)	287.54 ± 12.84a	–	124.59 ± 21.76a	146.46 ± 18.29a	287.54 ± 12.84a
Annual intercrop[c]	239.39 ± 11.88a	–	25.04 ± 11.59b	44.34 ± 11.41b	74.89 ± 17.17bc
Perennial intercrop[d]	304.90 ± 27.40a	–	0.58 ± 0.31c	120.49 ± 16.73a	121.06 ± 16.49b
2020					
Cultivation	10.68 ± 3.75c	–	4.83 ± 1.88b	5.85 ± 2.83c	10.68 ± 3.75b
Unmanaged (weedy)	237.30 ± 17.78b	–	132.12 ± 28.42a	105.17 ± 24.38b	237.30 ± 17.78a
Annual intercrop[c]	288.81 ± 42.54ab	–	187.64 ± 57.77a	14.82 ± 5.51c	202.47 ± 55.62a
Perennial intercrop[d]	353.16 ± 14.03b	–	0.88 ± 0.37c	203.42 ± 28.29a	204.30 ± 27.94a
Source of variation	*P-values*				
Weed management method	<0.0001	0.0233	<0.0001	<0.0001	0.0001
Year	<0.0001	0.0686	<0.0001	0.2388	0.0005
Weed management method × year	0.0036	0.5701	<0.0001	<0.0001	0.0014

Note: Mean value ($n = 4$) ± standard error. Significant differences are indicated by different letters within year based on Tukey's honest significant difference ($\alpha = 0.05$).
[a]Intercrop and weed biomass pooled.
[b]Includes unknown, unidentified weeds.
[c]Italian ryegrass and oat biomass pooled.
[d]Italian and perennial ryegrass, red fescue, and Kentucky bluegrass biomass pooled.

the proportion of medium and stable (1.3–2 mm) aggregates and macroaggregates (>0.25 mm; fraction weight) (Table 4). Over the 2 year study, water-stable aggregation remained relatively constant over time within each of the living-mulch treatments, although differences between weed management methods occurred in October of both years. In October 2019, the lowest values for mean weight diameter and proportions of macroaggregates, medium aggregates, and stable aggregates were found in the cultivation treatment. In October 2020, the mean weight diameter as well as the proportions of macroaggregates and medium and stable aggregates were higher in the perennial intercrop treatment than in the cultivation treatment (Table 4).

Soil gravimetric water content did not vary among the weed management methods ($P > 0.05$), regardless of soil depth or field sampling spot (in-row or interrow). It varied only between sampling events ($P < 0.01$) and was generally the lowest in August (Fig. S4).

3.5. Vine growth, yield, and fruit quality

Vine leaf biomass just like vine leaf area was affected by single weed management ($P < 0.0001$) and year ($P < 0.0001$) effects (Table 5). Vine leaf biomass and leaf area were both lower in the intercrop treatments than in the cultivation treatment, and higher in 2019 than in 2020, regardless of treatment. There was a single-year effect on pruning weight, which significantly decreased year after year in all the treatments ($P < 0.0001$; Table 5). Vine yield ($P = 0\ 2563$), cluster number ($P = 0.3363$), Brix ($P = 0.3850$), pH ($P = 0.7592$), and titratable acidity ($P = 0.3250$) were not affected by the weed management method in 2020 (Table 5).

Table 3. The richness, diversity, and relative abundance of the most frequent weed species.

Weed management method × year	Weed species richness (S)	Weed species diversity (H')	Weed species relative abundance (p_i) CENJA (%)	DIGIS (%)	PANCA (%)	PLALA (%)	POLAV (%)	TRFG[a] (%)
2018								
Cultivation	4 ± 1b	0.46 ± 0.04b	30	0	0	27	0	1
Unmanaged (weedy)	13 ± 0a	0.81 ± 0.02a	28	0	10	7	12	4
Annual intercrop	10 ± 2a	0.58 ± 0.11ab	49	0	4	15	9	5
Perennial intercrop	10 ± 1a	0.64 ± 0.06a	41	0	6	15	12	7
2019								
Cultivation	1 ± 0c	0.00 ± 0.00c	6	0	0	0	0	0
Unmanaged (weedy)	15 ± 15a	0.87 ± 0.02a	12	2	24	9	10	4
Annual intercrop	13 ± 13a	0.86 ± 0.08a	11	9	8	13	11	4
Perennial intercrop	7 ± 7b	0.40 ± 0.03b	36	0	0	9	0	49
2020								
Cultivation	5 ± 1b	0.29 ± 0.07c	0	8	14	4	0	0
Unmanaged (weedy)	12 ± 1a	0.73 ± 0.11a	17	24	16	6	3	12
Annual intercrop	9 ± 2ab	0.39 ± 0.10bc	2	73	7	3	1	1
Perennial intercrop	8 ± 1b	0.46 ± 0.01b	41	0	0	1	0	46
Source of variation	*P-values*							
Weed management method	<0.0001	<0.0001	–	–	–	–	–	–
Year	0.6132	0.0097	–	–	–	–	–	–
Weed management method × year	0.0026	0.0004	–	–	–	–	–	–

Note: Mean value ($n = 4$) ± standard error. Significant differences are indicated by different letters within year based on Tukey's honest significant difference ($\alpha = 0.05$). EPPO codes represent these weed species: brown knapweed (CENJA), smooth crabgrass (DIGIS), witchgrass (PANCA), narrow-leaved plantain (PLALA), prostrate knotweed (POLAV), and clovers (TRFG).
[a]White and red clover biomass were pooled for analysis.

Fig. 5. Mean root biomass (ash-free) at 0–15 cm (*a*) and 15–30 cm (*b*) soil depth in weed management method before hilling. Root biomass data from 2019 and 2020 were pooled by weed management method for presentation. Bars topped with different letters are significantly different between weed management methods within soil depth. All multiple comparisons are based on Tukey's honest significant differences ($\alpha = 0.05$). Error bars indicate + standard error.

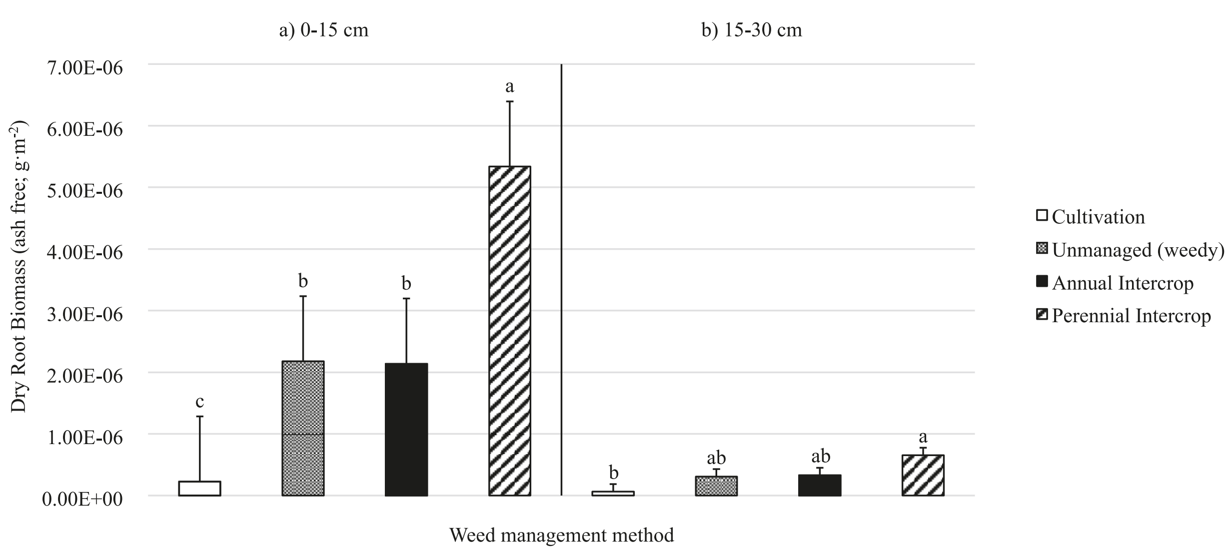


Table 4. Mean water-stable aggregate characteristics (2019–2020).

Weed management method × sampling	Mean weight diameter (mm)	Particle size distribution: Medium, stable aggregates > 1 mm (%)	Particle size distribution: Macro aggregates > 0.25 mm (%)
May 2019			
Cultivation	2.03 ± 0.06	51.43 ± 1.77	84.53 ± 2.87
Unmanaged (weedy)	2.01 ± 0.06	50.82 ± 1.90	84.39 ± 1.79
Annual intercrop	2.14 ± 0.15	55.22 ± 4.85	85.13 ± 2.93
Perennial intercrop	1.83 ± 0.08	45.22 ± 2.40	80.61 ± 3.82
August 2019			
Cultivation	1.79 ± 0.16	44.44 ± 4.91a	78.48 ± 2.75
Unmanaged (weedy)	1.60 ± 0.08	38.29 ± 2.75a	76.22 ± 1.30
Annual intercrop	1.97 ± 0.24	50.36 ± 7.69a	80.84 ± 3.61
Perennial intercrop	1.65 ± 0.11	39.90 ± 3.47a	76.05 ± 1.43
October 2019			
Cultivation	1.59 ± 0.15b	39.40 ± 4.61b	68.86 ± 3.01b
Unmanaged (weedy)	2.23 ± 0.10a	58.16 ± 3.38a	87.65 ± 1.72a
Annual intercrop	2.48 ± 0.07a	65.77 ± 2.53a	93.15 ± 0.48a
Perennial intercrop	2.22 ± 0.15a	57.58 ± 4.93a	88.48 ± 2.96a
May 2020			
Cultivation	2.20 ± 0.13	57.23 ± 4.07	87.24 ± 1.98
Unmanaged (weedy)	2.08 ± 0.22	53.14 ± 7.24	86.30 ± 3.17
Annual intercrop	2.32 ± 0.13	60.96 ± 4.09	89.06 ± 2.50
Perennial intercrop	2.39 ± 0.18	63.77 ± 5.77	88.97 ± 3.50
August 2020			
Cultivation	1.39 ± 0.06	31.53 ± 2.33b	73.94 ± 0.89
Unmanaged (weedy)	1.80 ± 0.10	45.26 ± 3.39ab	77.80 ± 1.41
Annual intercrop	1.90 ± 0.07	47.75 ± 2.18a	82.59 ± 1.96
Perennial intercrop	1.88 ± 0.08	47.42 ± 2.51ab	80.16 ± 2.29
October 2020			
Cultivation	1.55 ± 0.14b	37.80 ± 4.42b	68.52 ± 3.09a
Unmanaged (weedy)	1.91 ± 0.18ab	48.94 ± 5.80ab	75.17 ± 3.83ab
Annual intercrop	1.77 ± 0.21ab	44.79 ± 6.27ab	71.77 ± 5.80ab
Perennial intercrop	2.10 ± 0.10a	54.77 ± 3.24a	81.35 ± 2.01a
Source of variation	*P*-values		
Weed management method	0.0009	0.0007	0.0004
Sampling	<0.0001	0.0001	<0.0001
Weed management method × sampling	0.0027	0.0316	0.0009

Note: Mean value ($n = 4$) ± standard error. Significant differences are indicated by different letters within sampling event (month–year) based on Tukey's honest significant difference ($\alpha = 0.05$).

4 Discussion

4.1. Weed control and weed community composition

As predicted, intercrops did not outperform cultivation as a weed management method but still provided significant weed control as measured by weed biomass in at least 2 years out of 3 relative to unmanaged interrows, thus confirming our first hypothesis. Results show that both annual and perennial intercrops did not prevent weed establishment during the study, but prevented weed growth during the first 2 years. The weed density generally increased, except in the cultivated treatment, where most weeds did not grow to maturity, whereas the seedbank was replenished in the other treatments despite regular mowing. Weed emergence may have been curbed only by the dense cover of perennial weeds in 2020 as perennial plant species can effectively limit the

Table 5. Mean vine yield, cluster number, fruit quality, and vine growth at the end of the season.

Weed management method	Vine yield[a] (kg per vine)	Cluster number[a] (no. per vine)	Fruit quality: Brix[a] (°)	pH[a]	Titratable[a] acidity (gL^{-1})	Vine growth: Pruning weight[b] (g per vine)	Vine leaf biomass (g per vine)	Leaf area[b] (m^2 per vine)
Cultivation	1.38 ± 0.31	13 ± 3	17.7 ± 0.5	3.37 ± 0.04	7.84 ± 0.24	1 766 ± 242	252 ± 46a	4.65 ± 0.69a
Unmanaged (weedy)	1.22 ± 0.29	13 ± 2	16.0 ± 1.2	3.33 ± 0.03	7.09 ± 0.22	1 249 ± 183	184 ± 38ab	3.25 ± 0.48ab
Annual intercrop	1.33 ± 0.18	12 ± 1	16.8 ± 0.6	3.33 ± 0.07	7.51 ± 0.27	1 187 ± 147	182 ± 32b	3.08 ± 0.39b
Perennial intercrop	2.43 ± 0.80	20 ± 5	16.1 ± 0.5	3.31 ± 0.03	7.63 ± 0.36	1 078 ± 340	137 ± 24b	2.31 ± 0.34b
Year								
2018	–	–	–	–	–	–	57 ± 6c	–
2019	–	–	–	–	–	1 703 ± 181a	313 ± 24a	4.29 ± 0.37a
2020	–	–	–	–	–	938 ± 103b	196 ± 19b	2.35 ± 0.24b
Source of variation	*P-values*							
Weed management method	0.2563	0.3363	0.3850	0.7592	0.3250	0.0793	0.0009	0.0026
Year	–	–	–	–	–	0.0014	< 0.0001	< 0.0001
Weed management method × year	–	–	–	–	–	0.6043	0.1589	0.5338

Note: Mean value ($n = 4$) ± standard error. Significant differences are indicated by different letters within column based on Tukey's honest significant difference ($\alpha = 0.05$).
[a]2020 only.
[b]2019 and 2020 only.

weed density in pastures (Wardle et al. 1992; Demjanova et al. 2009; Meiss et al. 2010; Luna et al. 2020).

Although deep tillage such as mouldboard ploughing can normally bury weed seeds deeper in the soil and thus reduce weed germination and emergence during the subsequent growing season (Rahman et al. 2000; Cordeau et al. 2020), ploughing to a depth of 30 cm (hilling and dehilling every year) did not reduce the weed density in the hilled treatments where weeds were only mowed. This is probably because the first 30 cm top soil layer could still hold a lot of weed seeds despite repeated ploughing as reported by Vasileiadis et al. (2007) and that seeds do not become deeply buried during the growing season. Weed seeds were buried in the soil mound on the vine row during winter, only to be redistributed in the interrows and rows in the spring.

The perennial intercrop treatment did prevent weed establishment during the third year, as mentioned above, but allowed for significantly higher weed cover in June (mostly brown knapweed, clovers, and prostrate knotweed). This is most likely attributable to management techniques, such as seeding date, mowing height, and fertilization, which failed to promote the competitiveness of the species in the perennial grass mixture. Mowing alone will not prevent weed establishment, even if the cut is done higher (14 cm vs. <5 cm; Busey 2003). Typical grass management techniques, such as reapplication of fertilizers, interseeding, or chemical weed control are often required to replenish grass cover, thus limiting weed establishment (Christians et al. 2017). This intensive management is however contrary to the idea that intercrops have to be low maintenance to remain cost effective for winegrowers. Finally, seeding the perennial intercrop prior to the experiment in August or September 2017 would probably have allowed a more rapid establishment in 2018 and increased intercrop competitivity (Reicher et al. 2000).

Our results also demonstrated that living-mulch management affects weed community assembly within a short period of time (first 3 years) (Ryan et al. 2010; Sanguankeo and León 2011; Steenwerth et al. 2016). Smith (2006) and Cordeau et al. (2017), among others, showed that soil tillage is an important driver of weed community assembly. Lower plant species richness and diversity are generally associated with soil tillage used for weed control, as observed in our cultivated treatment (Bàrberi and Mazzoncini 2001; Hyvönen and Salonen 2002; Ngouajio and McGiffen 2002; Mas and Verdú 2003; Moonen and Bàrberi 2004; Baumgartner et al. 2008). Furthermore, annual weeds are usually associated with tilled annual intercrops (Tuesca et al. 2001; Chauhan et al. 2006) and they became dominant in our annual intercrop in 2020. Drier weather conditions during the spring of 2020 may also have promoted the proliferation of smooth crabgrass, which is known for its tolerance to dryness owing to its C_4-type photosynthesis (Dore and McNeill 1980; Turner et al. 2012). Smooth crabgrass proliferation increased weed cover in August and decreased weed species diversity in 2020.

The decrease in weed species richness and diversity in the perennial intercrop relative to the control and the annual intercrop is in accordance with the conclusions of Jiang et al. (2008), who reported lower plant species richness and density in no-till vineyards compared with hilled vineyards. This lower diversity coincides with the predominance of perennial weeds such as brown knapweed and clovers in the perennial intercrop. Perennial weeds are typically more persistent under perennial intercrop management because they benefit from the absence of soil disturbance, which leaves their root systems and underground plant propagation asexual organs intact. Mowing is thus mostly ineffective for weed species that grow near the ground, which explains how brown knapweed, prostrate knotweed, narrow-leaved plantain, and clovers came to be the most common weed species in these vegetated treatments (Gago et al. 2007; Jiang et al. 2008). Although the cultivation treatment was hilled, the frequent rotary cultivator passes kept weed infestation levels low and thus weed species richness and diversity always remained inferior compared with the perennial intercrop treatment.

4.2. Soil conservation

As expected, maintaining living mulches in the interrow preserved the short-term physical integrity of soil aggregates to a greater extent than did mechanical weeding throughout the season, thus confirming our second hypothesis. This difference at the end of the season seems to be the net result of the positive influence of groundcover root systems and the negative effect of repeated cultivation on aggregate stability. Although this improvement is transient because groundcover dies off and aggregate stability is susceptible to soil wetting–drying cycles occurring between seasons, the groundcover is effective during the fall when erosion from rainfall is important (Le Bissonnais 2016mulch shoot biomass and mowing residues were incorporated into the soil only once a year, during fall hilling, in the annual intercrop and unmanaged treatments, compared with the three to four passes of a rotatory cultivator made in the cultivation treatment each year. The fact that the root biomass and mean weight diameter were constantly higher in the perennial intercrop treatment in October suggests that root-derived carbon from rhizodeposition had more of an effect than the decomposition of fresh material from shoot biomass by soil fauna and microorganisms in terms of mitigating aggregate breakdown (Bronick and Lal 2005). The higher proportions of stable aggregates and macroaggregates relative to sample weights in October also support this idea. We observed no short-term benefit from the use of the perennial intercrop compared with our annual intercrop on soil water-stable aggregation. This is likely because the selected annual and perennial intercrop species had similar functional traits, such as root architecture, whereas higher plant species diversity can increase the benefits of intercropping on soil properties, including aggregation, through the positive influence of complementary root traits (Gould et al. 2016; Saleem et al. 2020).

Soil tillage was detrimental to soil structure, as observed by Jiang (2010) in vineyards. Tillage for mechanical weed control is associated with the loss of particulate organic matter (POM), a primary source of organic carbon metabolized into binding agents contributing to aggregate cohesion (Six et al. 1998, 1999). The idea that tillage limits the benefits of intercropping has been documented in vineyards growing in a Mediterranean climate. For example, a study conducted by Belmonte et al. (2018) in the Napa Valley of California showed that tillage limited the long-term capacity of an annual intercrop to accumulate soil organic carbon, thus preventing aggregate stability improvement in comparison to a no-till system (lower POM). Garcia et al. (2019) showed how aggregate stability rapidly degraded with the introduction of tillage even though intercropping had been done for years.

4.3. Vine growth, yield, and fruit quality

Vine leaf biomass was higher in the cultivation treatment than in the intercrops but berry yield and quality were equivalent. This indicates that intercrops competed with grapevines for the available resources at the beginning of the season (Jackson 2008), but not enough to cause yield loss or differences in fruit quality. Similar results were observed in semipermanent and permanent intercrops established in North American vineyards (Ingels et al. 2005; Smith et al. 2008; Steinmaus et al. 2008; Sweet and Schreiner 2010).

However, we acknowledge that the yield and fruit quality comparisons between the perennial intercrop and other treatments are imperfect because the vines did not have the same training and winter protection. This may have caused variations in bud fruitfulness and in the microclimate within the vine canopy during grape maturation (Greven et al. 2014; Provost and Barriault 2019).

Yield and soil gravimetric water content results indicated that there was limited competition for water between intercrops and vines. Although no vine water status analyses were conducted, monthly cumulative precipitation (yearly totals averaged 113.3 cm) likely provided a sufficient supply of water. Hartwing and Ammon (2002) found that competition for water in vineyards would be low if the average annual rainfall exceeded 110 cm. Vine response to intercrops is tempered in a cooler and humid climate compared with areas where water is scarcer (Tesic et al. 2007). In addition, intercrop management by mowing or destroying annual intercrops before vine budbreak can help mitigate competition between intercrops and vines (Garcia et al. 2018). Studies in North American vineyards also demonstrated that weeding on the row limits competition by intercrops by preventing the establishment of interrow crops on the trellis (Baumgartner et al. 2007; Olmstead et al. 2012). Whether this conclusion also applies to weeds left to grow in the interrow in the long term remains to be tested.

5. Conclusions

Our results confirmed our three hypotheses: (*i*) weed infestation in intercrops was intermediate between the cultivation and unmanaged (weedy) treatments; (*ii*) soil aggregate stability was greater in living mulches than in cultivation at the end of the season; and (*iii*) living mulches did not affect grapevine productivity. Growing intercrops during the establishment period of grapevines in southern Quebec did not compromise yield and fruit composition at the first commercial harvest (third year) and this approach limited weed growth during the first 2 years. Soil aggregate stability in the interrow and species richness were higher under living mulches (intercrops, resident vegetation) compared with repetitive interrow weed control based on cultivation. Although these are encouraging results from the perspective of sustainable winegrowing in the province of Quebec, further research is needed to evaluate the long-term effects of these practices. These results also raise the question of whether intercropping should be recommended over living mulches of resident vegetation, considering the costs associated with crop seed purchasing and buying or renting a planter, not to mention the time required to plant crops and (or) manage a perennial turfgrass that becomes dominated by perennial weeds. Although the living-mulch option would decrease costs, leaving the interrow unmanaged, except for mowing, could increase the soil weed seed bank or vegetative underground structures (if the interrow is never disturbed) on the row. This could possibly make weed control in this zone more challenging over time and cause further issues as certain weed species could be potential hosts for vine pests and pathogens.

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Competing interests

The authors have declared that no competing interests exist.

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Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/CJPS-2021-0213.

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