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Using Mulch for Agroecological Pest Management in Potatoes—Slowed Population Growth of *Leptinotarsa decemlineata*

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ABSTRACT

Even in organically managed potato fields, *Leptinotarsa decemlineata* is frequently controlled using chemical pesticides. Mulching presents a promising alternative for suppressing egg deposition and larval populations of *L. decemlineata*. We evaluated its effects through three field trials, each replicated four times, comparing unmulched control plots (a) with plots mulched using grass-clover (b) or triticale-vetch (c). In 2020 and 2021, larvae and their developmental stages were monitored twice weekly on 30 marked potato plants per plot, whereas in 2022, observations occurred three times over the season on 16 plants per plot. To investigate potential microclimatic changes induced by mulching, temperature loggers were positioned 15 cm above the canopy and underground. Across all mulched treatments, larval numbers were reduced on average by 65%, and advanced larval stages appeared later and in smaller numbers than in unmulched plots. In 2022, the emergence of a second-generation adult population of *L. decemlineata* was observed, with densities in mulched plots reduced by approximately 90%. During warm and hot conditions, canopy temperatures in mulched plots were substantially higher than in unmulched plots, often exceeding the optimal range for *L. decemlineata* development. Overall, mulching appears to delay or decrease adult beetle immigration and may slow egg and larval development.

Keywords: Chrysomelidae, Conservation biocontrol, Organic agriculture, Pest management, Regenerative agriculture

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Introduction

The genus *Leptinotarsa* encompasses 41 species, all of which are specialized herbivores. These beetles belong to the family Chrysomelidae, commonly known as leaf beetles, a group of phytophagous Coleoptera [1]. Among them, the Colorado potato beetle (CPB), *Leptinotarsa decemlineata* (Say), first described by Thomas Say, ranks as one of the most significant pests affecting potato crops globally. In central Europe, adult beetles that overwinter in the soil typically emerge between late May and June. Following initial feeding on host plants and sexual maturation, females lay eggs in clusters of approximately 30 over several weeks. Larvae hatch within 5–10 days and progress through four instars. Upon completing feeding, CPB larvae burrow into the soil to pupate. Depending on climate conditions, a second generation may occasionally appear; otherwise, adults remain in the soil to overwinter [1, 2]. With ongoing climate change, the likelihood of CPB completing two generations per growing season in central Europe is expected to increase [3].

In organic potato production, management of CPB relies primarily on preventive strategies complemented by biopesticide applications. Standard preventive practices include crop rotation with a minimum four-year gap between potato plantings and maintaining at least 500 meters from prior potato fields. When infestation surpasses

the damage threshold—defined as one egg mass or an average of 10 larvae per plant—organically approved insecticides such as azadirachtin (neem) or spinosad are applied, targeting early larval stages [4]. *Bacillus thuringiensis* var. *tenebrionis* (B.t.t.) is no longer authorized for CPB control in Germany.

Several studies conducted throughout the 20th and 21st centuries have reported that mulching can reduce CPB populations across all life stages, including eggs, larvae, and adults [5–8]. However, the mechanisms driving this effect remain unclear. Junge *et al.* (2022) summarized six main hypotheses that may partially explain the suppressive effects of mulch on CPB [2]: (i) mulch may disrupt visual cues used by CPB for orientation [9]; (ii) CPB rely initially on visual orientation and later on olfactory cues to locate host plants, which could be interfered with by volatile compounds from mulch [10]; (iii) mulch may act as a physical barrier, hindering beetle movement compared to bare soil [8]; (iv) mulch insulates the soil, slowing spring warming and delaying potato plant development, with larger unmulched plants appearing more attractive to CPB [11]; (v) differences in mineral content between organically and conventionally fertilized potatoes—such as higher boron and lower zinc in organic leaves—may reduce CPB development, supporting the mineral balance hypothesis, which suggests that phytophagous insects prefer plants offering certain nutrients [12, 13]; (vi) mulched plots have been shown to harbor higher numbers of natural CPB predators, including larvae of *Chrysopa* spp. (Chrysopidae), ladybug larvae (Coccinellidae), predatory bugs, and ground beetles, which can feed on CPB eggs and larvae [4, 5, 14]. These mechanisms are not mutually exclusive and may act synergistically.

In six field trials conducted from 2014 to 2019, Junge *et al.* (2022) reported that mulching significantly reduced initial adult infestations (–24 percent), egg masses (–27 percent), and larvae (–75 percent) [2]. Although the data suggested that larval development was delayed in mulched plots, this aspect was not the primary focus. Winkler *et al.* (2024) observed similar trends, reporting fewer larvae early in the season in mulched plots and higher numbers of L3 and L4 larvae in unmulched plots later in the season [15]. In this study, we present detailed three-year trials investigating the effects of nutrient-rich transferred mulch on CPB population development.

The study aimed to answer several questions: (i) Do CPB females lay fewer eggs on mulched potatoes compared to unmulched ones? (ii) Is there a difference in larval development of CPB between mulched and unmulched potato plants? If either of these hypotheses is supported, (iii) does this subsequently influence the timing and size of a potential second CPB generation? Mulch can strongly modify the microclimate by cooling the soil and potentially reducing air moisture through its hygroscopic properties, which could differentially affect CPB development [16]. Optimal CPB development occurs between 27°C and 31°C, though this range varies among populations [17]. Exposure to higher temperatures, even briefly—35°C or 39°C—can increase egg mortality and reduce fecundity, while prolonged exposure to 8°C for ten days can extend egg development from four to fifteen days [18, 19]. To assess the potential impact of these microclimatic changes, we recorded temperatures both 15 cm above the soil within the potato canopy and 15 cm below the soil surface, alongside relative humidity in the canopy. Based on these measurements, we further investigated (iv) whether any observed alterations in CPB development could be attributed to the microclimatic effects induced by mulching.

Materials and Methods

Experimental site and design

Field experiments were carried out over three consecutive years (2020–2022) at the University of Kassel's experimental farm in Neu-Eichenberg, North Hesse, Germany (51°22'51" N, 9°54'44" E), situated at 223 m above sea level. The site has been organically managed since 1988. Historical climate data (1991–2020) indicate a mean annual temperature of 9.3°C and yearly precipitation of 663 mm. Potatoes were cultivated within a six-year crop rotation established in 2005 on a haplic luvisol, with main plots of 15 × 50 m replicated four times, under non-inversion tillage since 2015. The pre-crop was winter wheat, followed by cover crops. For the purposes of these trials, plots sown with vetch (2020–2021) or a triticale-vetch mix (2022) were selected. Cover crops were terminated shortly before planting the potato variety 'Laura' at a density of ~40,000 tubers per hectare in 0.75 m ridges on 22 April 2020, 3 May 2021, and 3 May 2022.

Each experimental plot measured 4.5 × 12 m and was arranged in a split-plot design within the larger main plots. Mulch treatments were applied in three separate strips, while the cover crop assignment was randomized across these strips. Plot borders included the outer 0.75 m rows and two rows on either side of the 15 × 50 m main plots. Control plots without mulch received 100 kg N/ha as hair meal pellets (Provita), whereas mulched plots were covered with approximately 50 t/ha of freshly cut and chopped (~5 cm) grass-clover or triticale-vetch mulch

applied shortly before plant emergence (19 May 2020, 9 June 2021, and 25 May 2022). The applied mulches had C:N ratios ranging from 21 to 43, providing 160–250 kg N/ha, with an estimated 0–50% inorganic N release during the growing season [20].

Potato development was tracked by counting the number of stems per plant on 29 June 2020 (BBCH 65, flowering), 27 July 2021 (BBCH 70), and 25 July 2022 (BBCH 71, fruit formation). Leaf nitrogen content was determined by collecting one leaflet from 30 plants per plot on 24 July 2020 (BBCH 81, fruit ripening), 28 July 2021, and 27 July 2022 (BBCH 70, fruit development), analyzed by NovaCropControl (Netherlands). Tubers were hand-harvested from 8 m of two adjacent ridges per plot, weighed, and extrapolated to yield per hectare.

Microclimate and weather monitoring

An on-site automated weather station continuously recorded standard meteorological parameters. In addition, temperature and relative humidity were monitored at two positions: 15 cm above the soil within the potato canopy and 15 cm below the ridge surface, for both unmulched control and triticale-vetch mulch plots. Aboveground sensors were mounted on rods secured in the soil and shielded from rain. All measurements were logged at 30-minute intervals throughout the potato growing season.

*Monitoring of *leptinotarsa decemlineata**

In 2020 and 2021, CPB populations were assessed twice per week on 30 designated potato plants per plot (one complete 9 m row; **Table 1**) starting from the first egg mass detection until no further eggs or larvae were observed and second-generation adults were absent. In 2022, three observation rounds were carried out on 16 selected plants per plot, representing the first and last eight plants within a row. The survey recorded the number of egg masses and total eggs per plant, with all four larval stages recorded individually.

Table 1. Number of assessments done for Colorado potato beetles, potato yield and mean number of stems per plant as well as N-contents in potato leaves in the unmulched control, plots with grass clover and triticale vetch mulch application.

Year	Cover crop	Mulch treatment	Plants /Plot	No. of assessments	Yield (t/ha)	Mean no. of stems/plant	N in potato leaves (ppm)
2020	Vetch	Unmulched control	30	13 (10 June	30.9	4.0	1351.2
		Grass clover mulch		2020–23 July	27.4	3.7	3005.2
		Triticale-vetch mulch		2020)	30.4	3.8	2953.6
2021	Vetch	Unmulched control	30	10 (22 June	49.8	7.4	3185.1
		Grass clover mulch		2021–28 July	50.2	6.5	3367.5
		Triticale-vetch mulch		2021)	53.4	6.9	2124.4
2022	Triticale-vetch	Unmulched control	16	3 (13 June	23.8	4.7	3526.5
		Grass clover mulch		2022–26 July	21.3	4.3	3037.8
		Triticale-vetch mulch		2022)	20.4	4.1	2844.4

Note: Summary of the experimental setup and assessments conducted during the 2020, 2021, and 2022 observational seasons. Potato tuber yield is presented as total yield, including all size classes. The mean number of stems per potato plant is reported \pm standard deviation (SD). Specific dates of CPB assessments can be found in the Supporting Information.

^a Nitrogen content was determined via plant sap analysis: on 24 July 2020 at BBCH 81 (fruit ripening, when *Phytophthora infestans* caused severe damage), on 28 July 2021, and on 27 July 2022 (both at BBCH 70, fruit ripening, with low or no occurrence of *P. infestans* in 2021 and 2022, respectively).

Data processing and statistical analysis

Counts of insects in field studies often exhibit overdispersion and an excess of zeros, which was also observed in this study. To account for these characteristics, data were analyzed using Generalized Linear Models (GLMs) appropriate for the underlying distributions [21]. For each CPB life stage (eggs, larval instars 1–4, and adults) across the experimental years, four candidate models were compared using the Akaike Information Criterion (AIC) to identify the best-fitting model: Poisson, negative binomial, zero-inflated Poisson, and zero-inflated negative binomial. Analyses were conducted using the MASS, pscl, and stats packages in R. Pairwise comparisons were performed via Tukey's test using the emmeans package. All statistical analyses were performed in R version 4.3.2.

Results and Discussion

No significant differences in gross tuber yield or stem number per potato plant were observed between treatments (**Table 1**). Leaf nitrogen content was significantly higher in mulched plots compared to unmulched controls only in 2020, while no significant differences were detected in 2021 or 2022.

Weather conditions and microclimate

The 2020 growing season was relatively cool, with dry spells in April and July. In 2021, the season began with a cool spring but transitioned into warm, adequately hydrated conditions. In contrast, 2022 was marked by extreme heat and pronounced drought (**Table 2**).

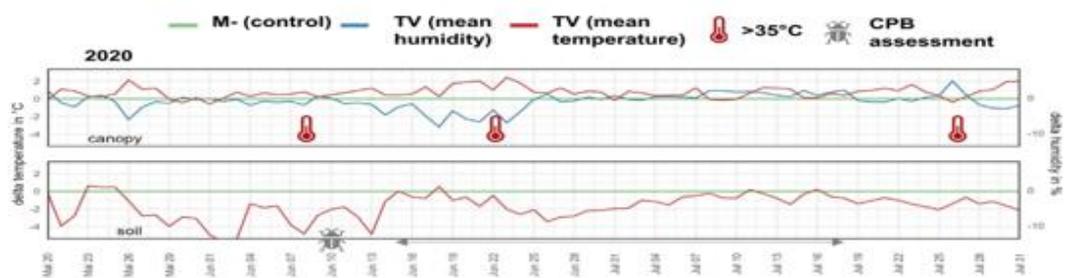
In triticale-vetch mulched plots, canopy relative humidity during nighttime hours (23:00–04:00) in mid-June to mid-July 2020 was up to 25 percentage points lower than in unmulched plots, where humidity commonly approached 100%. A similar pattern occurred in 2022 but was absent in 2021 (data not shown).

Daytime temperatures (11:00–16:00) in mulched plots were up to 2.5°C higher within the canopy and up to 4.5°C lower in the potato ridges compared to unmulched plots (**Figure 1**). Across all three years, temperatures frequently exceeded the CPB optimal range of 27°C and even the critical threshold of 35°C reported by Liao *et al.* (2022) [18], coinciding with peak egg presence in the first generation (June 2020–2022) and during the second generation in July 2022 (**Figures 1 and 2**).

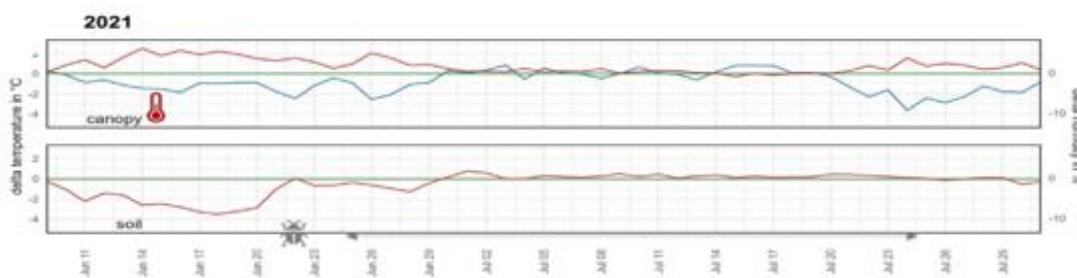
In 2020, canopy temperatures in mulched plots surpassed 35°C for approximately 12 hours, compared to 9 hours in unmulched plots. Ridge temperatures were consistently lower in mulched plots than in unmulched plots (**Figure 1**).

The 2021 season had few temperature extremes, yet during the critical egg development period in June, canopy temperatures exceeded 35°C for 24 hours in mulched plots and 17 hours in unmulched plots, with peaks of 42°C and 39°C, respectively (**Figure 1**). Potato ridge temperatures reached 25°C for roughly a week, but mulched plots were up to 3°C cooler during day and night. Canopy temperatures in mulched plots were up to 2°C higher during daytime (**Figure 1**).

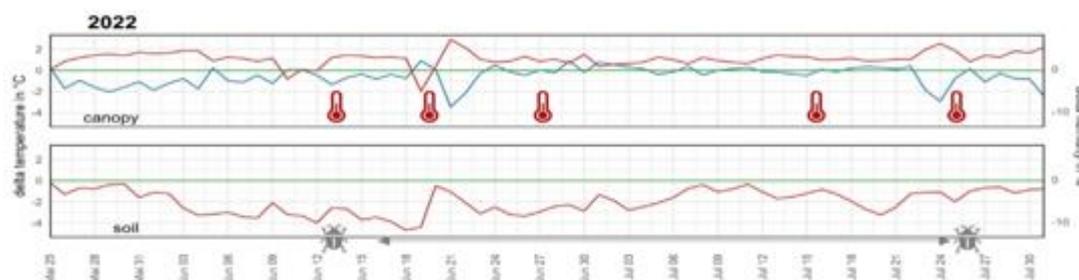
During the exceptionally hot and dry 2022 season, daytime canopy temperatures exceeded 35°C for 30 hours in June and 39 hours in July in mulched plots, versus 27 and 25 hours, respectively, in unmulched plots, coinciding with development of the second-generation eggs (**Figures 1 and 2**). Maximum temperatures reached 42°C in mulched plots and 39°C in unmulched plots. Ridge temperatures regularly reached 30°C during the day, dropping by 10–15°C at night. Mulched ridges were consistently cooler by up to 4.5°C throughout June and July, and canopy temperatures at night were up to 2°C lower. Relative humidity was occasionally higher in mulched plots.



a)



b)



c)

Figure 1. Differences in mean temperature (red line) and mean humidity (blue line) between triticale-vetch (TV) mulched plots and unmulched control plots (M-, green line) during 11 AM to 4 PM. Panels display data for (a) 2020, (b) 2021, and (c) 2022. Recording started after each year's mulch application. Temperatures were measured every 30 minutes both 15 cm below the potato ridge and 15 cm above the soil surface. Red symbols indicate temperatures exceeding 35°C for at least 4 hours per day over a week. Grey arrows along the x-axis show the timing of field assessments for each year. Beetle icons indicate the start of a beetle generation (note: a second generation was observed in 2022).

Table 2. Monthly mean temperature and precipitation in Neu-Eichenberg, North Hesse, for the months of April to July 2020 to 2022 as well as the annual mean temperature and total annual precipitation (right column) and the long-term average (below).

Year	April	May	June	July	Annual mean temperature and total precipitation
2020	9.1	11.2	16.0	17.1	10.3 °C
	11.0	43.9	89.4	38.0	671.3 mm
2021	5.7	10.5	18.4	17.7	9.3 °C
	40.2	51.2	78.1	86.9	576.0 mm
2022	7.7	14.1	17.8	18.7	10.4 °C
	44.4	26.4	28.3	37.7	410.4 mm
1991–2020	8.9	13.0	16.0	18.1	9.3 °C
	38	61	66	71	662.2 mm
Temperature Deviation	> +2°C	> +1°C	< +1°C and > -1°C	< -1°C	< -2°C
Precipitation Deviation	> +50%	+25%	< +25% and > -25%	< -25%	< -50%

Note: The deviations from the long-term average (1991–2020) are coloured according to the colour scale below.

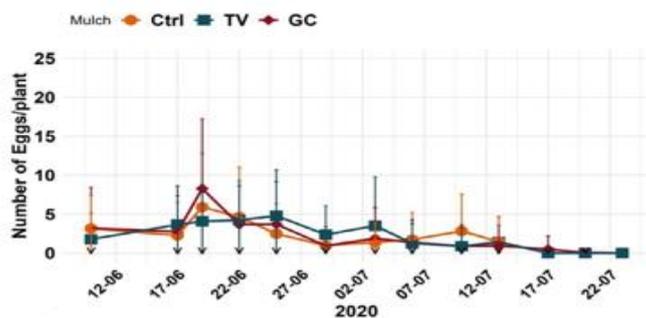
Initial infestation and population development

The first CPB egg masses appeared on 10 June 2020 and 13 June 2022, coinciding with the potato growth stage BBCH 24 (lateral shoots forming). In 2021, heavy rainfall delayed the first survey until 22 June, at BBCH 27. Across the three years, initial egg counts suggested that pest pressure increased annually (**Figure 2**).

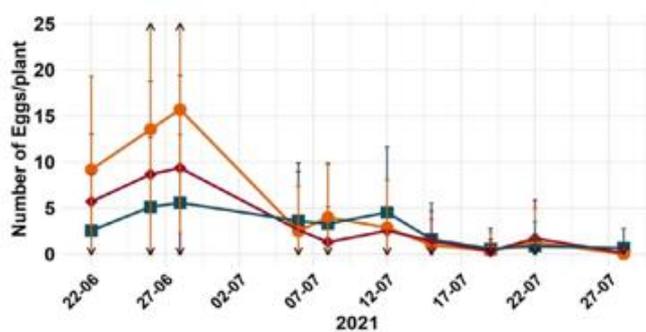
In 2020, unmulched plots had the greatest proportion of plants with egg masses (19%), followed by grass-clover mulch (13%), while triticale-vetch mulch showed the fewest (10%) (**Figure 2a**). Egg numbers remained low overall and no consistent seasonal pattern was observed. In 2021 and 2022, unmulched control plots again had the highest early-season egg presence (25% in 2021, 64% in 2022), with grass-clover mulch intermediate (15% in 2021, 31% in 2022) and triticale-vetch mulch lowest (7% in 2021, 11% in 2022) (**Figures 2b and 2c**). While these differences were not statistically significant (**Figure 3**), a clear tendency was seen: unmulched plots initially hosted more eggs, whereas later in 2021 and during the second generation in 2022, egg distribution became more even, with triticale-vetch mulch occasionally exceeding other treatments (**Figure 2**).

For larval stages observed twice weekly in 2020 and 2021, all stages consistently showed significantly higher numbers in unmulched controls compared with both mulch treatments (**Figure 3**). Differences between mulch types were rare and inconsistent.

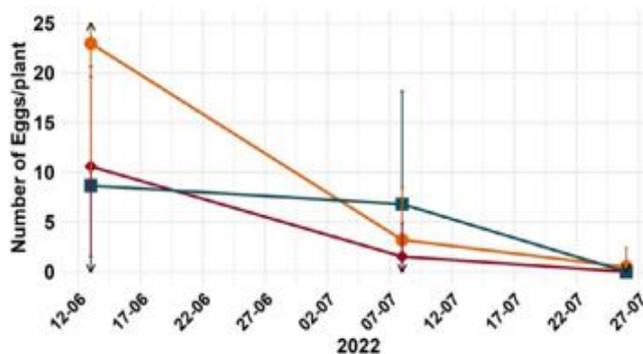
By 26 July 2022, at BBCH 69 (end of flowering), second-generation adults were recorded in substantial numbers. Across all mulched plots, adult counts per plant were roughly one-tenth of those in unmulched plots ($p < 0.001$) (Figure 4).



a)



b)



c)

Figure 2. Average number of *Leptinotarsa decemlineata* eggs recorded in 2020 (a), 2021 (b), and 2022 (c) across plots without mulch (M-), with grass-clover mulch (GC), and with triticale-vetch mulch (TV). Sample size per plot was 30 plants in 2020 and 2021, and 16 plants in 2022 \pm standard error (SE). Black arrows indicate cases where the SE exceeds the plot boundaries.

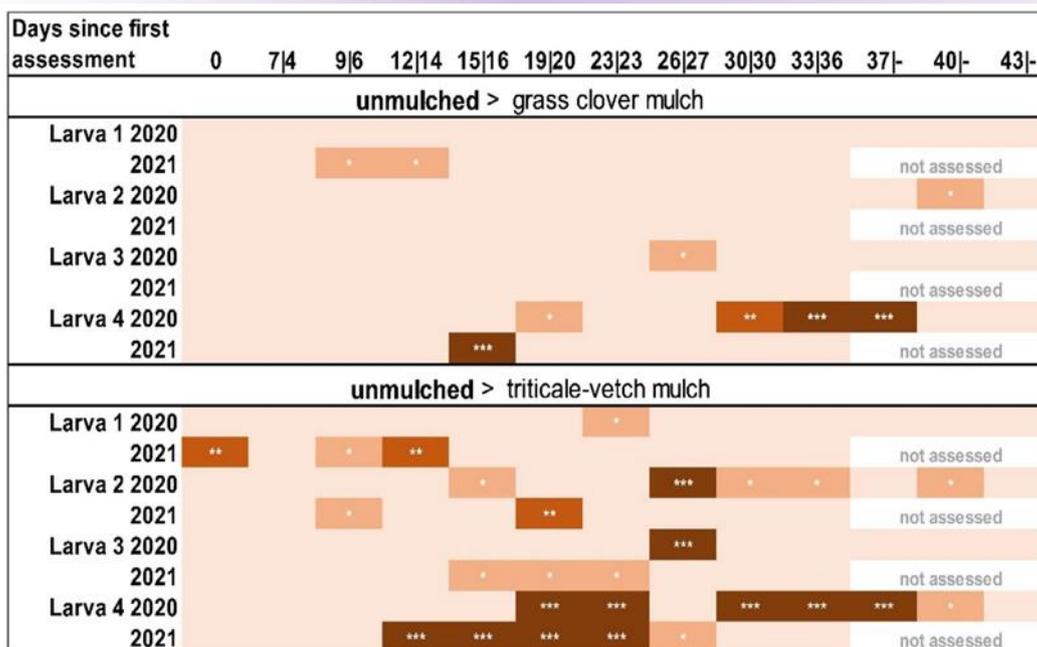


Figure 3. Outcomes of statistical analyses comparing the counts of Colorado potato beetle (CPB) larvae across all developmental stages (larval stages one to four) in unmulched control plots versus plots covered with either grass-clover mulch (top) or triticale-vetch (TV) mulch (bottom). Significant differences between treatments are denoted as $p < 0.001$ ‘’, $p < 0.01$ ‘’, and $p < 0.05$ ‘’ (GLM followed by Tukey’s post-hoc test).

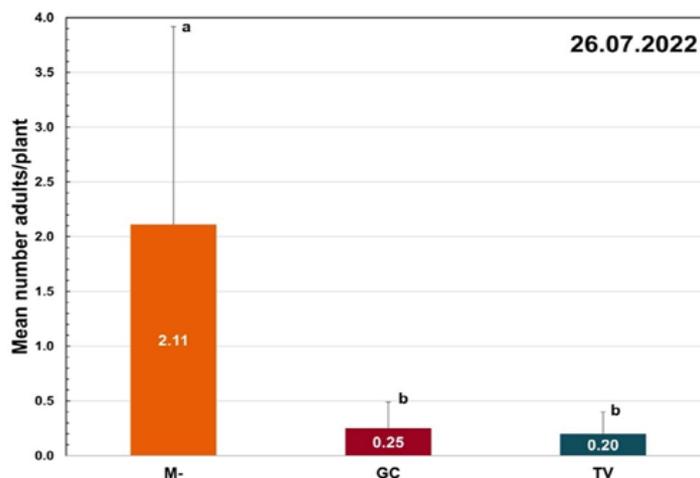


Figure 4. Average counts of second-generation *Leptinotarsa decemlineata* adults in 2022, including standard errors, in plots without mulch (M-), with grass-clover (GC), and triticale-vetch (TV) mulch. Each plot included 16 sampled plants and four replicates.

Larval development dynamics of CPB

In 2020 and 2021, detailed monitoring of all four larval stages showed that unmulched plots consistently harbored the highest mean larval density per plant, exceeding 6 larvae/plant in 2020 and 5 larvae/plant in 2021 (Figure 5). Conversely, plots covered with triticale-vetch mulch exhibited the lowest larval abundance. Notably, fourth-instar larvae emerged earlier and in larger numbers in the unmulched plots during both years.

Peak larval infestation aligned with the potato flowering stage, identified at the 6th assessment (three weeks post initial infestation) in 2020 (BBCH 69) and 2021 (BBCH 63). At these points, control plots contained approximately 4.5 total offspring per plant, of which 78% were larvae, while the remaining portion was still in the egg stage. Mulched plots, in contrast, had 2.6–3.8 offspring per plant, with larvae representing only 39% in 2020 and 52% in 2021. Triticale-vetch mulch plots, in particular, retained a larger fraction of unhatched eggs than the other treatments (Table 3).

In 2022, observations at the second assessment (BBCH 66) presented a different pattern. The triticale-vetch

treatment showed the highest total offspring number (9 per plant), while grass-clover plots recorded the lowest (2.8 per plant). Interestingly, grass-clover plots had the largest proportion of larvae (45%) compared with 25% in the other two treatments, indicating faster larval development despite lower overall offspring counts (**Table 3**).

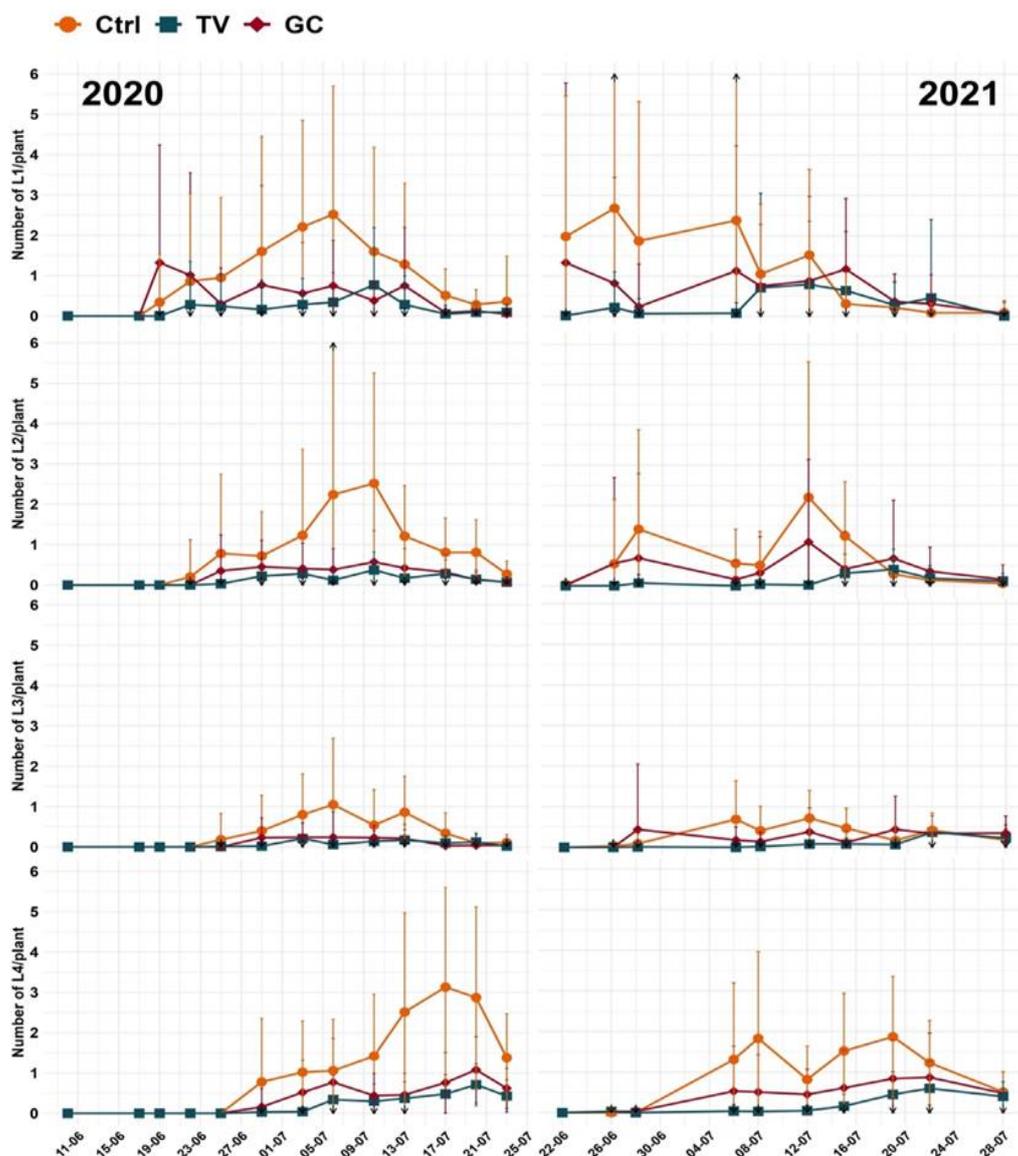


Figure 5. Average number of *Leptinotarsa decemlineata* larvae per plant (\pm standard error, SE) in 2020 and 2021 across plots without mulch (M-), with grass-clover (GC), and triticale-vetch (TV) mulch. Data are shown separately for larval stages L1–L4. Each plot included 30 sampled plants and four replicates. Black arrows indicate SE values that exceeded the plotted range. Significant differences are reported in **Figure 4**. Note: heavy rainfall in 2021 reduced the number of sampling occasions.

Table 3. Number of parental adults, eggs and larvae of *Leptinotarsa decemlineata* (Colorado potato beetle) per plant at potato flowering in plots with no mulch application (M-), grass clover mulch (GC) and triticale-vetch mulch (TV).

Year	Mulch	Adults	Σ Offspring	SD	Eggs	% Offspring	SD	Larvae	% Offspring	SD
2020	M—	0.2	4.4	0.6	1.0	22.0	4.7	3.5	78.0	8.4
	GC	0.2	2.6	0.5	0.9	36.9	4.9	1.6	63.1	5.4
	TV	0.3	2.8	0.6	2.4	84.8	7.4	0.4	15.2	1.8
2021	M—	0.0	4.5	0.1	1.0	21.5	5.6	3.5	78.5	5.2

	GC	0.1	3.8	0.3	1.4	38.3	6.5	2.3	61.7	5.0
	TV	0.1	2.8	0.3	1.6	57.4	7.9	1.2	42.6	3.4
2022	M—	0.1	4.3	0.4	3.2	75.1	10.5	1.1	24.9	2.6
	GC	0.1	2.8	0.3	1.5	55.4	6.8	1.2	44.6	2.7
	TV	0.2	9.0	0.5	6.8	75.7	22.7	2.2	24.3	2.7

Note: Sampling took place during the potato flowering stage on 29 June 2020 (3rd of 10 assessments), 15 July 2021 (7th of 10 assessments), and 8 July 2022 (2nd of 3 assessments). The highest mean value in each dataset is highlighted in bold.

Across all three years, despite considerable variation in weather and resulting microclimatic conditions, mulching consistently reduced *Leptinotarsa decemlineata* (CPB) infestation. Meanwhile, potato agronomic performance—including yield and stems per plant—remained largely unaffected, with nitrogen content differing significantly only once. Egg and larval development were slowed or inhibited in mulched plots compared to unmulched controls, leading to delayed and reduced emergence of adult beetles. Over the years, as pest pressure increased—partly because experiments were conducted in adjacent plots in successive seasons—the effect of mulch on egg numbers became more apparent, although high variability prevented these differences from reaching statistical significance. In 2022, similar mulch effects were observed later in the season when a second beetle generation emerged.

It was not possible in this study to definitively determine whether initial adult beetle infestation was higher in unmulched plots. Early-season observations in 2021 and 2022, showing more eggs in unmulched plots, suggest this could be the case, and the twice-weekly sampling regime makes it unlikely that early egg-laying was missed. However, larval counts in unmulched plots remained higher over time even when egg numbers were similar, indicating that mulch may directly influence egg and/or larval development. The combination of higher early egg counts (2021 and 2022) and consistently higher larval numbers in unmulched plots suggests that unmulched potato plants are more attractive to incoming CPB adults when given a choice, supporting observations by Junge *et al.* (2022) [2]. Release-recapture experiments by Szendrei *et al.* (2009) and Weiler *et al.* (in press) similarly demonstrated lower CPB immigration into mulched plots compared to unmulched ones [8, 22]. This preference for unmulched plants likely explains the higher initial egg deposition and aligns with the elevated larval and second-generation adult numbers observed later in the season. Possible reasons for this preference include changes in olfactory or visual cues due to ground cover, higher nutritional value of unmulched plants for beetles, or the mechanical barrier effect of mulch materials [8, 12, 23, 24]. Targeted experiments under choice and no-choice conditions are needed to clarify these mechanisms.

While the elevated larval numbers in 2020 cannot be fully attributed to more egg masses, advanced larval stages emerged earlier in unmulched plots, with stage-four larvae appearing in significantly higher numbers in 2020 and 2021. Since third- and fourth-instar larvae consume roughly ten times the leaf mass of first- and second-instar larvae during their development, large numbers of stage-four larvae also increase the likelihood of a substantial second-generation adult population [1, 15].

These patterns could not be clearly observed in 2022 due to a reduced number of sampling events, which likely led to missing key developmental stages. By the final assessment in 2022, fourth-instar larvae in unmulched plots may have already burrowed into the soil for pupation, leaving triticale-vetch mulch plots with the highest larval counts at that time (**Table 3**). This is further supported by the observation that unmulched plots already contained an average of 2.2 second-generation adult beetles per plant, whereas mulched plots had only about one-tenth of this number (**Figure 3**). The delayed egg hatching and later appearance of advanced larval instars in mulched plots indicate a prolonged CPB life cycle, corroborating findings by Winkler *et al.* (2024) [15]. Consequently, in 2022, mulch effectively postponed the development of the second generation of CPB, which likely contributes to the roughly tenfold higher number of second-generation adults observed in unmulched plots.

Another factor potentially contributing to the elevated second-generation adult numbers in 2022—and the overall delayed CPB emergence in 2021—may be the lower soil temperatures under mulch (**Figure 1**), which can slow larval development in the soil. Soil moisture and temperature are key abiotic factors influencing emergence following hibernation and could similarly affect second-generation adult emergence [25, 26]. In addition to pest-related effects, cooler soil and ridge temperatures during hot periods likely reduced climate stress on the potato plants, contributing to improved tuber quality. Therefore, mulching can play a dual role in mitigating climate stress and, in years with foliar pathogens such as late blight, has been shown to reduce disease incidence [27–29].

Since unmulched potatoes in 2022 retained sufficient leaf mass for CPB feeding, adult beetle migration between plots was likely minimal. However, such migration was observed in 2018, when a second CPB generation emerged and unmulched potatoes—but not mulched ones—had already been defoliated by the first generation [2].

It has been proposed that the observed developmental delays may result from differences in leaf nutritional quality or plant microbiome composition, which could influence larval growth [12, 30]. A simpler explanation is the modification of the microclimate by mulch. Liao *et al.* (2022) reported that exposing eggs for 4 hours to 35°C or 39°C reduced hatching rates by 31 percent and 43 percent, respectively, compared to the optimal 27°C, while female egg-laying declined by 58 percent and 84 percent under the same conditions [18]. Logan *et al.* (1985) found that baseline egg mortality is around 10% and rises progressively with exposure to 35°C, reaching 15% after four hours and 70 percent after 24 hours [17]. Furthermore, CPB larvae in the prepupation stage (ceasing feeding prior to pupation) were unable to pupate when temperatures exceeded 33°C during the fourth larval stage. During our study, canopy temperatures in mulched plots, particularly the temperature peaks, frequently exceeded 35°C more often than in unmulched plots (**Figure 1**). Many of these peaks occurred in June, coinciding with the period of highest egg abundance, suggesting that elevated egg mortality may have contributed to the lower larval numbers observed. Some of the later temperature peaks likely overlapped with the pre-pupation stage, which could have reduced the size of the second-generation population in mulched plots in 2022. The observation that unmulched plots had higher early-season egg numbers, whereas mulched plots showed relatively higher egg numbers later in 2021 and 2022, further supports this interpretation (**Figure 2**).

Although both grass-clover and triticale-vetch mulch effectively reduced CPB infestation, triticale-vetch had a stronger impact. Grass-clover mulch generally decomposed more rapidly, potentially diminishing its barrier effect on CPB migration sooner than triticale-vetch. Additionally, triticale-vetch retained moisture longer, which may have amplified canopy temperature peaks compared to grass-clover plots. It should be noted, however, that microclimatic conditions were not directly measured in the grass-clover plots. Further detailed studies are necessary to evaluate whether a 5–6 cm mulch layer acts as a significant physical barrier to CPB movement and how mulch structure influences this effect.

Conclusion

Both grass-clover and triticale-vetch mulch consistently reduced *L. decemlineata* infestation in potatoes, regardless of initial pressure from overwintering adults or prevailing weather conditions. Our findings indicate that slower or inhibited egg and larval development is a key mechanism driving the overall reduction in infestation over time. This also included a notable delay and suppression of the second CPB generation when it occurred. For the first time, our results suggest that mulch-induced changes in CPB infestation may result not only from delayed egg laying but also from prolonged developmental times and increased egg mortality. These effects may be partially explained by the albedo properties of the mulch, which, together with its hygroscopic characteristics reducing relative humidity, created extended periods of critically high temperatures affecting egg viability and pre-pupation stages.

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