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Late to the Party—Transferred Mulch from Green Manures Delays Colorado Potato Beetle Infestation in Regenerative Potato Cropping Systems

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Abstract: The Colorado potato beetle (CPB) is an exceptionally challenging potato pest. Some regenerative farmers have reported that the use of transferred green manure mulch can considerably reduce CBP damage. Previous studies confirm this observation, but mainly with straw mulch, which is rarely used in Central Europe, and not embedded in the new regenerative cropping approach. For this, six trials conducted between 2014 and 2019 were evaluated, comparing CPB infestation in potatoes with and without transferred mulch as well as under a plough as a minimum till regime. In three out of six experiments, compost application was an additional factor. (I) Over all experiments, mulch significantly reduced initial infestation (−24%), egg masses (−27%) and larvae (−75%). Compost and reduced tillage added to these effects; (II) Mulch mainly resulted in delayed CPB infestation; (III) In a particularly warm season, when a second generation of CPB managed to emerge, regulatory effects of the mulch were not sufficient; (IV) Combination of transferred nutrient rich green manure mulch with reduced tillage, compost and other regenerative or agro-ecological techniques is recommended to achieve maximum regulation of CPB.

Keywords: agroecology; compost; organic farming; organic mulch; reduced tillage; regenerative agriculture; regenerative plant protection

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1. Introduction

Colorado potato beetle (*Leptinotarsa decemlineata Say*) (CPB) is a challenging insect pest because it integrates diapause, dispersal, feeding, and reproduction into an ecological "bet-hedging" strategy, distributing their offspring both spatially (within and between host habitats) and temporally, within and between seasons [1]. Potatoes are initially infested by overwintering adult beetles emerging from the soil of the previous year's potato fields; subsequently, they mate and deposit their eggs. The emerging larvae cause the main damage on the potatoes. Their feeding activity depends on the initial population and temperature [2] with the potential of a 2nd generation developing in warm years. Total loss of foliage and potentially yield may occur if infestation occurs early in the season and/or no control measures are applied. On the one hand, synthetic insecticides for the control of the potato beetle are more and more restricted in conventional agriculture; only Neem based insecticides are available to organic farmers. For effectiveness, these have to be timed precisely during the larval stages.

In addition to problems with CPB, potato production poses high erosion risks due to a relatively long phase of low soil cover combined with regular soil disturbance through hilling, usually leading to a reduction in soil humus contents in the wake of potato crops [3]. In view of these ecologically critical problems, potato cropping systems are ideally suited for a systemic approach as intended by regenerative agriculture to alleviate soil and other environmental problems.

The principle of regenerative agriculture (RA) is rooted in a farming systems approach that combines various concepts of conservation agriculture such as reduced tillage, cover crops and crop rotation [4], compost application, social and economic aspects [5], as well as other elements of the organic agriculture and permaculture movement [6], and is widely spread via social media [7]. Although manifold RA definitions exist [8], all interpretations have in common that an improved soil environment forms the base upon which sustainable agricultural management is built, as pointed out by Schreefel et al. [5].

Since 2014, we have experimented with mulch materials with a low C/N ratio (12–25) in combination with reduced tillage and compost application to develop regenerative potato growing systems that aim at building soil and improving the soil structure [9]. Ploughing is replaced by rototilling to 5–7 cm depth, using specially formed knives to avoid sealing the soil, combined with gently loosening with a chisel plough at 12–15 cm depth before planting. Subsequent hilling operations are then avoided by applying transferred low C/N ratio mulch shortly before crop emergence. Besides leading to considerably reduced soil erosion and soil improvements and adequate weed suppression [9], we documented reductions in foliar pathogens, especially potato late blight, caused by *Phytophthora infestans* [10]. In addition, we have observed strong effects of the system on CPB infestation. In part, these effects are already known: occasionally, soil conservation [11–13] and compost application [14,15] have been reported to reduce CPB damage but overall have been researched poorly and they have not found their way into practice as a plant protection method against CPB so far.

Some research has been conducted in the last 30 years on the effects of straw and transferred mulch from green manures that are also part of the methods applied in regenerative potato production and their effects on CPB (Table 1). Depending on which developmental stages had been assessed, results were variable. Thus, reductions of immigrating adults by mulch were reported in five out of twelve cases. In two out of nine cases where eggs were assessed, the number of eggs were reduced while in one study, where textile mulch was used, the number of eggs were increased. In seven out of ten studies where the number of larvae were reported, their numbers were reduced in mulched plots compared to unmulched plots with some cases reporting an increased development time of larvae [16,17]. A reduction of leaf herbivory was found in all six studies that reported on this trait (Table 1).

Table 1. Summary of published results of mulch applications on potato beetle life stages. Arrows indicate increases (↑) or decreases (↓). In the columns, x indicates the CPB stages investigated in the publications.

Mulch (Quantity)	Mulch Effects	Mechanisms Suggested by Authors	Adults	Egg Masses	Larvae	Predators	Defoliation	Yield	Reference
Wheat straw (6–10 cm)	↓ Adults, egg masses ↑ Development time larvae ↑ Yield	Effects on plant volatile compounds ↓ Water stress Physical obstruction	x	x	x			x	[16]
Rye straw (10 cm) **leaf Mulch** (0–5 cm)	↓ Defoliation by 50% ↑ Yield	↑ Predators ↓ Ability of larva to climb back after falling mulch type or depth affects the effect	x	x	x			x	[17]
Wheat straw (8–10 cm)	↓ Larvae ↑ 2nd Gen. Adults and Larvae ↑ Predators on Plant ↓ Defoliation	↑ Predators	x	x	x	x	x		[18]
Wheat straw (2.4 t ha)	↓ Larvae (1st, 2nd and 4th instar) ↑ Soil predators ↓ Defoliation	↑ Predators	x	x	x	x	x	x	[19]
Straw (15–30 cm)	↓ Defoliation	Difficulty in finding plants due to mulch Potato variety and senesces process of the foliage	x				x		[20]
Straw mulch [1]	↓ Adults ↓ Larvae ↓ Defoliation	↑ Predators ↓ Attractiveness of potato plants infected by *Verticillium dahliae and Pratylenchus penetrans*	x	x	x		x	x	[21]
Wheat straw 1–1.3 t ha^{-1}	↑ initial Adults ↓ Adults in later Season ↑ Soil Predators	↑ Soil Predators Temporal influences on CPB population	x	x	x			x	[22]
Wheat straw 1.5–5 t ha^{-1}	↓ CPB infestation (ns.) Dose effects	↑ Soil Predators	x	x	x		x	x	[23]
Rye 5cm, **vetch** (Residues) 10 cm	Interfere field colonization	visual or chemical deterrence and/or physical barrier	x						[24]
polypropylene-textile Mulch **Chopped grass** (2.5 cm)	↑ eggs in textile mulch ↓ Larvae ↑ Yield	↑ Soil Temperature	x	x	x			x	[25,26]
Winter **wheat** or **rye straw** 18–22 t ha^{-1}	↓Larvae in 3/4 Experiments ↑ Predators ↑ Yield	↑ Number of predators in pan and pit traps	x		x	x		x	[27]
Triticale mulch 133 t ha^{-1}(fresh matter)	↓ eggs ↓ Larvae ↓ Defoliation ↑ Yield	balanced nutrition by mulch makes potato plants less susceptible to potato beetle	x	x	x		x	x	[10,28]

Little is known about the mechanisms leading to CPB reductions in mulch-based potato cropping systems. Four studies reported an increase in predation, while three additional studies assumed increased predation despite the lack of data provided in these papers (Table 1). Furthermore, altered olfactory cues and thus reduced host recognition, as well as barrier effects for mobile stages, were discussed and, in the case of plastic mulch, unfavorable temperature regimes were also mentioned as possible reasons for reduced infestation levels (Table 1).

The most commonly used mulch material in the studies summarized in Table 1 was straw, which has no or a very low fertilizing effect, due to a wide C/N ratio [29]. Some of the more recent studies including our work made use of low C/N ratio fresh green mulch materials that also serve as fertilizers, increasing yields in most cases [9,10,24,30].

The aim of this study was to determine the effects of mulch materials used for plant nutrition on the development of the CPB. Between 2014 and 2019, we conducted a total of six experiments using green manure mulch of different qualities and quantities. Experiments were conducted under ploughed as well as reduced tillage conditions and with and without compost applications. In all years, CPB infestation dynamics by overwintering adults were recorded early in the season in regular intervals as well as the ensuing egg depositions into clutches, hereafter referred to as egg masses, and larval densities. In 2016, 2018, and 2019, the total number of eggs was also recorded. When possible and not disturbed by late blight, developmental stages were assessed more than once per season. In addition, in 2018, when no late blight occurred, leaf area losses were assessed. The current analysis addresses the following questions: (I) What are the effects of transferred mulch on the different life stages of CPB? (II) What are the effects of the differing C/N ratios of the mulch materials used? (III) Finally, in what way do mulch effects interact with reduced tillage and compost application?

This study presents data for investigating the effectiveness of nutrient rich mulches on Colorado potato beetle stages over several years under different climatic conditions. In addition, their combination with regenerative cropping measures such as reduced tillage and compost application is investigated.

2. Materials and Methods

All **experiments** were conducted under central European conditions in Neu-Eichenberg (51°22′51′′ N, 9°54′44′′ E,) near Kassel, Germany. The experimental site is 223 m above sea level. The annual mean temperature of the years 1991–2020 was 9.3 °C, the mean annual precipitation 663 mm. The organically managed experimental field (since 1988) has a slope of 3% with a fertile Haplic Luvisol soil with 3.3% sand, 83.4% silt, and 13.3% clay (USDA classification Zc). The soil warms up slowly, has good water holding capacity and tends to silt up after rains.

Experimental factors and details are summarized in Table 2. The experiments in 2014, 2015 and 2018, 2019 were integrated into two parallel long term experiments (LTE), shifted in time by 1 year and that had been started in 2010 (Experiment 2014 and 2018) and 2011 (Experiment 2015 and 2019). The LTEs compare plough tillage with reduced tillage (RT) with and without the application of compost. In 2014 and 2015, potatoes in RT but not in the plough treatments received mulch. In 2018/19 both RT and plough treatments received mulch or not. The experiments are described in detail elsewhere [31]. All other experiments were conducted in fields that are regularly ploughed. Conventional tillage (CT) treatments were generally ploughed 20–25 cm deep. Reduced tillage (RT) was performed 5–15 cm deep by chisel ploughing in 2014 and 2015. From 2016 onwards, RT was performed by surface composting of cover crops before potatoes through 5–7 cm deep rototilling followed by chisel ploughing 12–15 cm deep. Where compost (5 t DM ha^{-1} year^{-1} on average) was applied, it was broadcast before tillage. Planting density was always three plants m^{-1} in 75 cm dams (44,000 plants ha^{-1}). The mulched plots were hilled once before mulch application, and unmulched plots 2–3 times as needed for weed control. Mulch was applied just before the potatoes emerged. The *Bacillus thuringiensis* toxin (Novodor® FC) was sprayed in 2019 to regulate CPB when it went out of hand.

Weather conditions in 2014–2019 were highly variable (Figure 1). In 2016 and 2018, May was warmer than usual with the year 2018 being an extremely hot and dry year from April onwards. Therefore, no late blight occurred and all foliar damage was due to CPB feeding in that year. In all other years, CPB and late blight together resulted in leaf area loss, making it impossible to clearly assign foliar damage due to the CPB.

Temperature

	Apr	May	Jun	Jul	Aug	Sep
2014	8.1	11.9	15.2	18.7	19.2	12.5
2015	10.9	11.8	15.0	18.6	15.7	14.7
2016	8.0	13.8	17.0	18.6	18.0	17.5
2018	12.8	15.6	17.6	20.6	20.2	14.9
2019	9.3	11.0	19.3	18.0	19.2	14.0
1991-2020	8.9	12.9	15.9	18.1	17.8	13.8

Color Variance: ≤−2.0 °C; −1.0 °C; 0.0 °C; +1.0 °C; ≥+2.0 °C

Precipitation

	Apr	May	Jun	Jul	Aug	Sep
2014	29	96	37	125	79	37
2015	36	25	28	95	160	51
2016	47	42	99	65	24	21
2018	29	33	15	15	31	37
2019	38	109	69	37	47	38
1991-2020	38	61	65	71	70	52

Color Variance: ≤−30 mm; −15 mm; 0 mm; +15 mm; ≥+30 mm

Figure 1. Mean monthly and overall mean temperature (°C) and deviation from mean total monthly pre-cipitation (mm) of the experimental years, compared with long-term (1990–2020) mean temperature and mean total monthly precipitation.

Since plant development and CPB colonization vary depending on climate conditions, plots were regularly scouted and **assessments** started when the first beetles were seen. For the initial immigrating adult CPBs this occurred +/− 10 days of potato budding (BBCH 51). Assessments were conducted either in all plots or in selected neighboring plot pairs with the different treatments to reduce spatial effects due to the colonization behavior of the CPB. Depending on the experiment, 15–50 plants were examined for immigrating adults (B), egg masses (M), eggs (E) and larvae (L) (Table 2). In order to better understand the dynamics of the changes over time, in the two experiments conducted in 2016, assessments were conducted twice. The last assessment in 2016 represented the last date when beetles could be assessed before loss of foliage due to late blight. In 2019, CPB infestation was extreme and had to be stopped by twice spraying *Bacillus thuringiensis,* this also stopped assessments after three weeks (Table 2). As no late blight occurred in 2018, weekly assessments could be conducted for seven weeks in 2018 and all foliar damage could be attributed to CPB. Leaf area losses were assessed with the help of aerial photos via Leaf Area Index estimation using ImageJ 1.52a software [32].

Table 2. Experimental factors and CPB and other relevant parameters assessed in the six experiments. All experiments were conducted with four replications.

Year	>Tillage [1]	>Other Factors	Mulch [2]				>Plot Size (m)	Number of Assessed		>CPB-Assessment	>BBCH [3]	Assessments					Diseases [5]
			>Type	>t FM ha^{-1}	>t DM ha^{-1}	>C/N-ratio		>Plots	>Plants			>Adults	>Egg Masses	>Eggs	>Larvae	>Defoliation [4]	
2014 (LTE)	CT, RT	2 precrops, +/− compost	RP	49, 6	25	28	6 × 15	64	50	17.6.	51	x	x		x		*P. infestans*
2015 (LTE)	CT, RT	2 precrops, +/− compost	TV	88, 3	30	23	6 × 15	64	30	3.7.	54	x	x		x		*P. infestans, Alternaria*
2016a	CT		GC, TV	147, 129	35, 33	39, 41	4.5 × 17	12	30	16.6.; 6.7.	50	x	x	x	x		*P. infestans*
2016b	CT		T	133, 0	37	52	4.5 × 15	8	30	20.6.; 25.7.	45	x	x	x	x		*P. infestans*
2018 (LTE)	CT, RT	+/− compost	TV	63	33	19	6 × 15	16/64; 64/64 defoliation	30	4., 13, 20, 27.6.; 4., 9., 16.7.	31	x	x	x	x	x [4]	-
2019 [6] (LTE)	CT, RT		TV	47	23	24	6 × 15	16/64	15	18., 25.6., 10.7.	52	x	x	x	x		-

[1] CT = conventional plough tillage, RT = reduced non-inversion tillage, LTE = integrated in a long-term experiment. [2] GC = grass-clover, RP = rye-pea, T = triticale, TV = triticale-vetch, S = straw; in parentheses under dry matter (DM): %Nmin in DM. [3] BBCH for the first assessment date is given. [4] Defoliation was assessed with aerial photographs. [5] Leaf reducing pathogens: Early blight (*Alternaria solani*) and Late blight (*Phytophthora infestans*). [6] Application of Novodor® FC (*Bacillus thuringiensis*) 28.06.2019, 17.07.2019.

The **data analyses** of imagines, egg masses, eggs and larvae at the individual dates were carried out with the help of a permutational multivariate analysis of variance (PERMANOVA) using the Adonis function from the R package vegan [33]. The design was included in each analysis using the strata parameter. To determine the effect of the mulch, univariate Permanova was used on the raw data. The univariate tests were run using a Euclidean distance matrix with 999 permutations. The advantage of this method is that it allows the inclusion of the split-plot design and at the same time does not assume normal distribution of errors [34]. Adonis (value~mulch/WDH, strata = $WDH, data = DF). Data of the trial in 2016b were analyzed using a paired Wilcoxon test. The total numbers of imagines, egg masses, eggs and larvae at all time points were analyzed with generalized mixed models to account for the different levels of experiment and years. The models were fitted using the lme4 package in R [35]. For this purpose, different models were applied due to the different data structures. The model validation was performed using the R Package DHARAMa [36]. The data of the imagines and the egg masses were converted into binomial data for analysis purposes and analyzed with the function glmer and the Binomial family. Larval count data were also analyzed using a generalized linear mixed model. Here, due to the overdispersion of the data, the negative binomial distribution of the data was applied. The egg count data were converted into percentages of the respective trial infestation due to their very divergent distribution at plot level in the different years, in order to reduce the large differences between years. A mixed linear model was then applied to the square root transformed data. Leaf area losses were transformed via a Box–Cox transformation ($\lambda = 0.303$) to ensure normality of the residuals. After model simplification due to non-significant factors and because of lower values of the Akaike information criterion (AIC), a mixed linear model was applied.

3. Results

In the vast majority of experiments, transferred mulch from green manures reduced the **initial infestation** by between 23 and 80% (Figure 2A), but this was not significant, despite high standard deviations. Over all the experiments, the initial infestation was significantly reduced by 24% ($p < 0.001$). The resulting egg masses (Figure 2B) and the number of eggs (Figure 2C) were also reduced in many cases. In 2014 and 2019, where immigrating adults were increased (+27% and +6%), the number of egg masses in 2014 and the number of eggs in 2019 were nevertheless significantly reduced by 49% and 52%, respectively (Figure 2A–C). Overall, while the reductions in immigrating adults, egg masses and eggs in mulched plots were not always statistically significant (Figure 2A–C), in all experiments the number of larvae were reduced significantly (Figure 2D).

In experiment 2016b, no larvae were found on 20 June (Figure 2D). However, five days later the same significant mulch effect was evident (Figure 3C). Across all mulch types and experiments, the number of larvae was significantly reduced by 75% ($p < 0.0001$) compared with the unmulched treatments.

In 2016, 2018, and 2019, additional **assessments across the growing period** were carried out before the destruction of the foliage by *P. infestans*. While the adult immigrating beetles were usually reduced in mulched plots at the first assessment time, later, more beetles were present in the mulched plots in 2016 and 2019 (Figure 3A,D). In 2016 and 2019, no 2nd generation beetles had emerged by the time of the latest assessments and the adults apparently had migrated from the unmulched plots to the mulched plots (Figure 3A). Parallel to the reductions in adult immigrants, the number of eggs was also reduced in the first assessments.

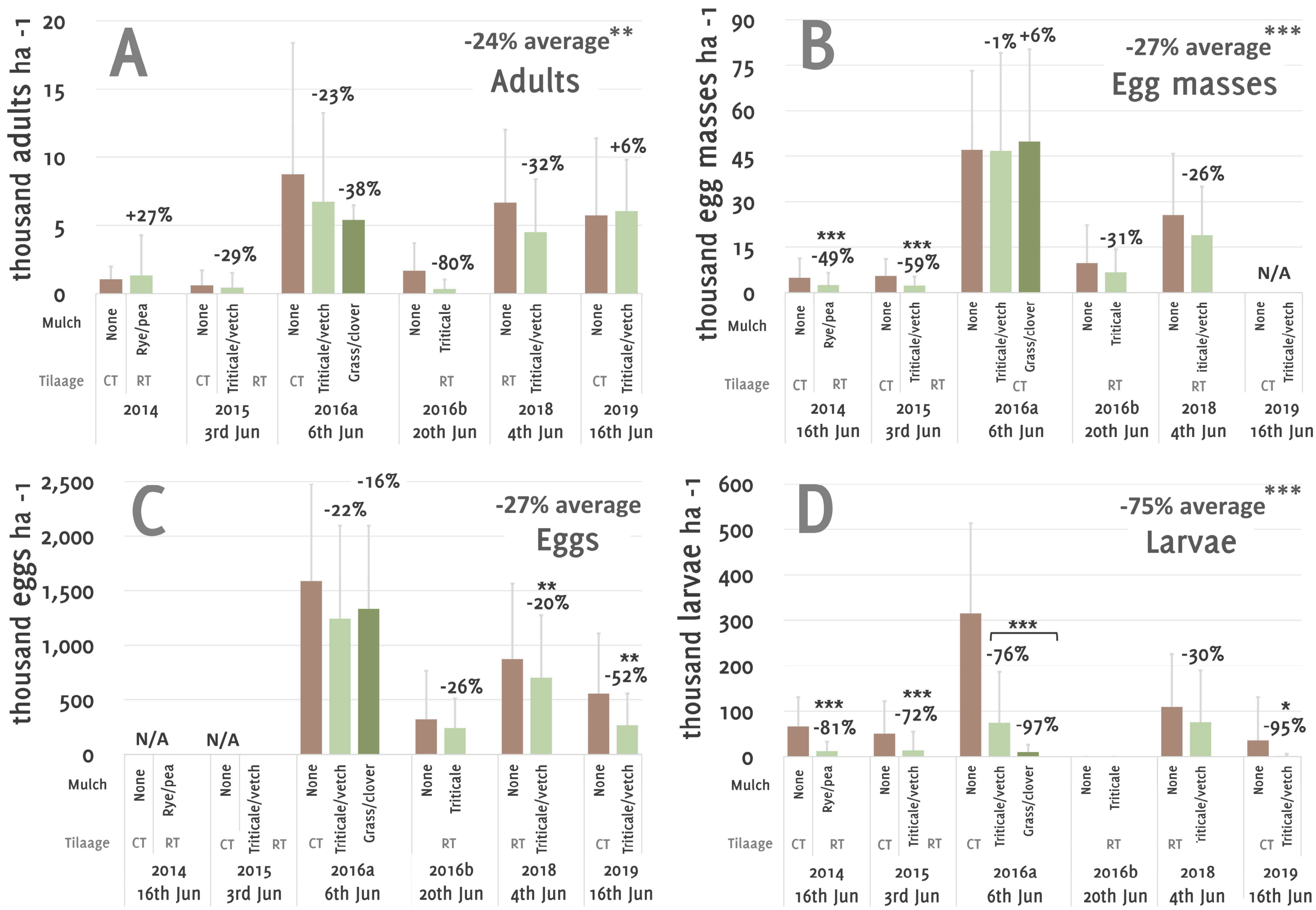

Figure 2. Effect of various mulch materials on different developmental stages (**A**–**D**) of CPB during initial infestation in the different experiments in mulched and unmulched variants under conventional (CT) and reduced (RT) tillage. Relative numbers (%) show the differences between the mulched and unmulched control. Lines above the bars indicate the positive standard deviation. Statistical differences are indicated by * ($p < 0.05$), ** ($p < 0.001$) and *** ($p < 0.0001$).

Later, however, the number of eggs was higher and the number of larvae lower in the mulched plots, indicating that development from egg to larvae in the mulched plots was delayed (Figure 3B,C).

In 2018, the initial infestation occurred about two weeks earlier than in 2016 and 2019. Additionally, beetle development was not halted by late blight as the drought suppressed the disease. Due to the high temperatures, development was fast and by mid-July a second generation of adults had emerged leading to an order of magnitude higher numbers of adults by mid-July compared to 2016 and 2019 (Figure 3D versus A, observe the different *y*-axis scales!). As in 2016 and 2019, early in the season (4 June 2018) immigrating beetles were reduced by 32% in the mulched plots and over the next three to four weeks beetle abundance in the mulched plots increased considerably over the unmulched plots—up to about three times higher (+193%) by 27 June (Figure 3D). Again, the reduced or delayed egg laying in early June had resulted in reductions and the delay of the number of larvae for the following two weeks. Only after 3 weeks was the number of larvae in mulched and unmulched plots the same (Figure 3F). However, by 9 July 2018, larval feeding had decimated the leaf area in many of the unmulched plots to the point that the beetles had to migrate to the mulched plots (Figures 3F and 4). Thus, while the increase of beetles between 4 and 9 July was from 5300 to 122,800 adults ha^{-1} in the unmulched plots and the increase in the mulched plots was only from 7700 to 73,300, the ratios switched by 16 July: adults increased to 221,000 in the unmulched plots but many migrated and subsequently they increased to 317,000 in the mulched plots (Figure 3D). The migration is also manifested by the fact that, despite higher numbers of adults on 9 July in the unmulched plots, the number of eggs was higher in the mulched plots at that time already, with the same pattern for the larvae (Figure 3E,F).

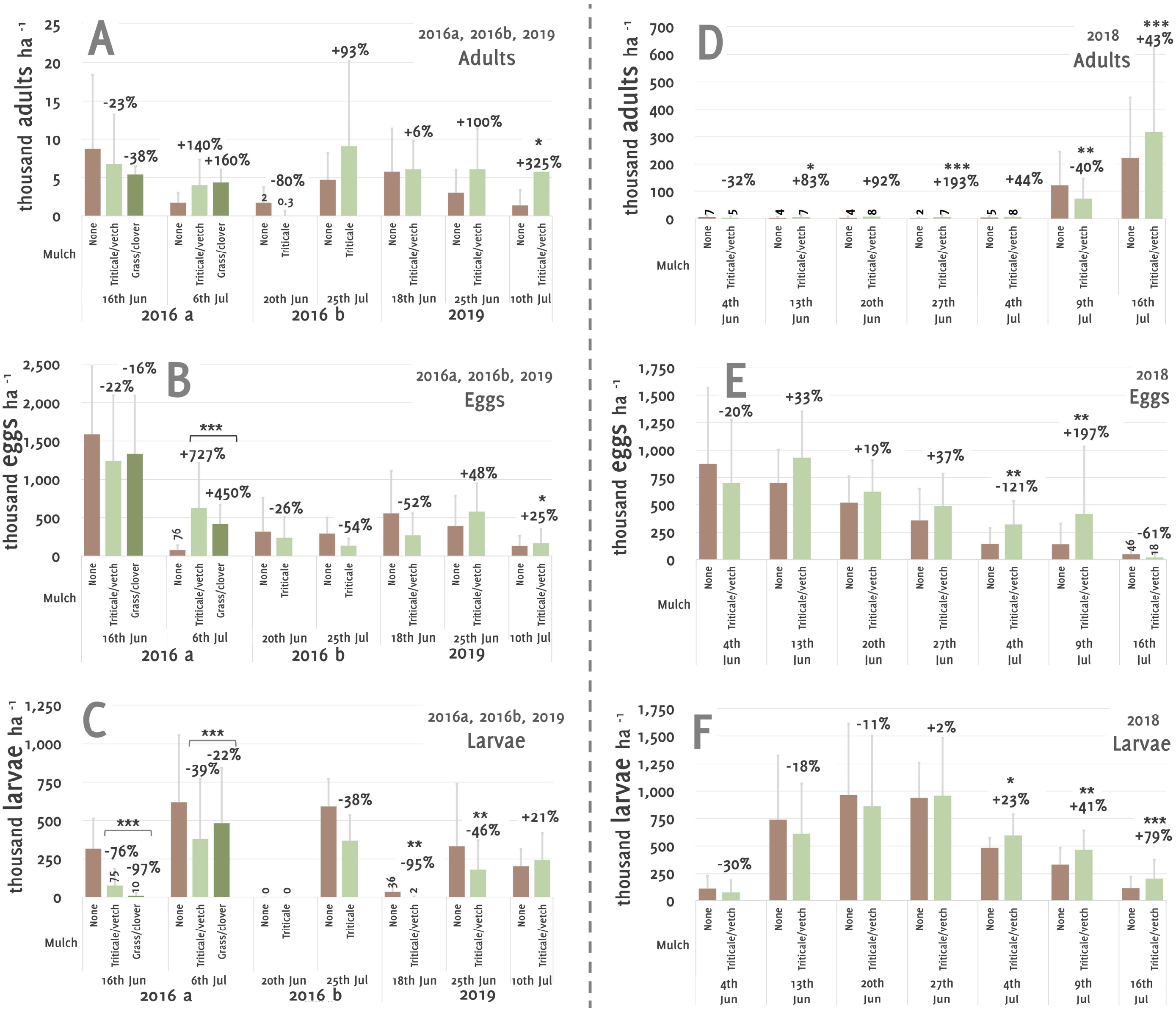

Figure 3. Effect of various mulch materials on different developmental stages (**A**–**C** for 2016a, 2016b, 2019 and **D**–**F** for 2018) of CPB in the different experiment over the vegetation period. Relative numbers (%) show the differences between the mulched and unmulched control. Lines above the bars indicate the standard deviation in the positive direction. Statistical differences are indicated by * ($p < 0.05$), ** ($p < 0.001$) and *** ($p < 0.0001$). Observe that the y-axes are scaled differently for 2018 compared to the other years.

Figure 4. Comparison of unmulched and triticale-vetch mulched potatoes on 9 July 2018. Left: Skeletonized leaf damage in unmulched potatoes before flowering. Right: Initial infestation started in the south-west exposed plots resulting in a distinct gradient from the edge of the field (Figure modified according to [9]).

Despite the strong spatial pattern in **foliar damage** in 2018 that was due to the migration of the beetles from the south-west to the eastern side of the field (Figure 4), mulch effects were evident when averaging across treatments (Figure 5).

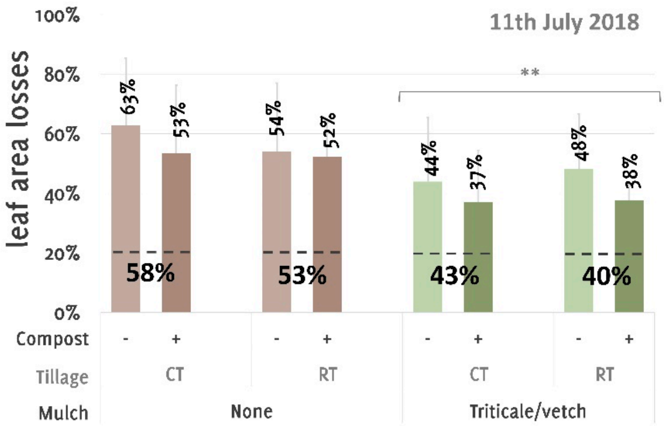

Figure 5. Leaf area losses of the 2018 trial on 9 July in the treatments with (+) and without (−) compost under conventional (CT) and reduced (RT) tillage as well as unmulched (none) and mulched (triticale/vegetation). Relative numbers below the dashed lines indicate mean values of the marked variants. Lines above the bars indicate the standard deviation in positive direction. Statistical differences (LME) are marked with ** ($p < 0.001$).

Regardless of the tillage treatment, mulch reduced leaf damage significantly by about 25%. Where compost was applied, tillage, compost and mulch appeared to have a cumulative effect on leaf area loss. Plough without mulch and without compost had the highest leaf area loss of 63%, while in reduced tillage with mulch and compost, a leaf area reduction was 37%.

4. Discussion

Across all years and experiments, transferred mulch from green manure consistently slowed down initial colonization with Colorado potato beetles (CPBs), leading to later egg laying and later emergence of larvae. In years when no second beetle generation occurred, this led to an overall reduction of larvae that are responsible for the main feeding damage over time. When a second generation occurred, apparently, the beetles moved to the less damaged plants leading to increased numbers of larvae in the mulched plots at the end of the season. Nevertheless, even in this scenario, overall damage was delayed in mulched plots due to the effects in the first generation.

All mulch materials, **regardless of C/N ratio** (from 19 to 52) and **application rate** (23 to 37 t DM ha^{-1}) reduced the initial infestation with adult beetles and confirmed that besides straw that had been shown to reduce CPB infestation in the older literature, fertilizing mulch with a narrow C/N ratio can also reliably regulate CPB. The strongest **effect in the different life stages** was on the number of larvae and the time of their occurrence, the most important stage in relation to leaf area loss. They occur in much higher numbers than the adult stages, up to 377 individuals per female adult and consumption of 0.5–12 cm^2 leaf larva^{-1} day^{-1} have been reported [2]. The repeated samplings over time (Figure 3) showed that the reduction of Colorado potato beetles and the damage caused, as found in the literature, is due to a delay in colonization by the adults as over time the numbers become more similar or the trend might revert if defoliation is strong and a second beetle generation emerges as observed in 2018. The inconsistent reductions of adult stages recorded were due to the timing of the first assessment with respect to the first beetles that were detected during weekly controls. The same applies to egg and larval stages. Leaf area losses in 2018 indicate slight **interactions between tillage, compost and mulch**. Leaf damage was somewhat reduced by compost and reduced tillage in addition to the mulch effect. The effects of high value compost in reducing CPB infestation and damage have been reported previously by Hofmeester [14] and, in food choice experiments, Schaerffenberg [15] found that 48 h after release, 82% of the adults chose potato plants without compost fertilization instead of compost fertilized plants. While on average, in the LTE, only 5 t DM ha^{-1} year^{-1} were applied, right before potatoes, 10 t DM ha^{-1} were applied for two years. Our data suggest that even these low amounts of compost have an effect that is additive with the mulch effect under reduced tillage. From 2014 to 2019, the RT compost variants increased the microbial Carbon in the top 15 cm by 58%. The CT treatments without compost remained at a constant level [37]. The increase of soil carbon was accompanied by increased soil suppressiveness against fungal pathogens of peas. This confirms other studies that showed positive effects of compost application on soil quality [38], plant nutrition [39], and plant health [40].

Colonization from the field border field nearest to the previous year's potato fields resulted in high standard deviations. Thus, in addition to the treatment effect, there was also a location effect on the CPB population in the respective plots, which is a general problem in the study of pests in field experiments [41]. As reported by Johnson et al. [22] and Zehnder and Linduska [13], adult beetles migrated from the mulched plots with skeletonized leaf damage to the neighboring, less damaged mulched plots as we also observed in 2018. This migration complicates interpretation and explains the inconsistencies in the reported reductions of CPB stages in the previous studies. Additional complications arose as beetle development was terminated or interfered with by the destruction of the foliage through late blight in 2014, 2015 and 2016. Both early blight (*Alternaria solani*) [42] and late blight [10] can be delayed by transferred mulch. This leads to longer green leaf area duration in mulched compared to unmulched plots and, as a consequence, to the migration of adult CPBs to the mulched plots. In 2019, the extremely high CBP infestation had to be terminated by spraying *Bacillus thuringensis* to save the experiment.

There are several possible explanations for the delay in infestation: (i) During colonization, the CPB first orientates itself visually and only in the proximity of host plants olfactorily [43]. Thus, visual irritation as assumed by Alyokhin et al. [44] could occur. (ii) Additionally, at least temporarily, olfactorial masking [45] and irritation might play a role. (iii) Mulch represents a physical barrier, as shown by Lashomb and Ng [46]. They found that the time needed for CPB to cross a wheat field was thrice that of bare soil, which was not only related to terrain but also to temperature reduction in the wheat field.

Temperatures near the ground in freshly mulched plots were likely cooler than in unmulched bare soil plots. Szendrei et al. [24], using marked adult beetles, showed that their locomotion and colonization were hindered by field residues. (iv) The mentioned lowered soil temperature due to the mulch layer [47] can delay the development of the mulched potato plants, which might also have contributed to delayed colonization. (v) Since mulch represents a massive organic fertilization, there could also be a nutritional effect similar to that of compost. Alyokhin et al. [44] and Phelan [48] have shown that organic fertilization differs drastically from synthetic fertilization in terms of nutrients in the leaves of potato and maize plants, respectively. According to Phelan [48], this type of fertilization should increase the buffer capacity in plants and thus lead to a mineral balance in the plant. The result was reduced larval vitality and thus larval infestation by the European corn borer (*Ostrinia nubilalis*). Feeding studies using differentially fertilizes potatoes are required to determine if CPB reacts with developmental alterations. (vi) Finally, as pointed out above, various studies have documented significant increases of soil predators [22] as well as predators in the phyllosphere [16], feeding primarily on larval but also adult stages (see also Table 1).

Similar to what Brust [19] had pointed out, **CPB reduction efficacy** by transferred mulch as a single component approach was not sufficient, particularly in the very warm season of 2018, when a second larval generation developed. Instead of combining the agronomic advantages of mulching with insecticides as suggested by Zehnder and Hough-Goldstein [16], synergies in suppressing CBC damage with regenerative, agroecological management approaches could also be implemented: crop rotation [49] and where possible targeted potato crop spacing in time with more than 1.5 km distance to previous year's potato fields [50] and adapted plant nutrition management [51] could be added to the system in addition to the mentioned compost applications and reduced tillage. Besides its effects on CPBs, transferred mulch in potatoes is recommended because it also irritates aphids, reducing infestation and thus protecting against aphid transmitted viruses [52], consistently reducing infestation by *Phytophthora infestans* [10,53] *Alternaria solani* [42], helping to suppress weeds [27], and contributing to plant nutrition [9].

5. Conclusions

The initial infestation of CPB and its subsequent stages can be reduced by using transferred green manure mulch. However, the available data cannot explain the reason for the delay in infestation nor is it possible to unequivocally show if the developmental time from egg to larva to adult is changed. This will require detailed controlled feeding experiments. A monocausal explanation for the delay or even suppression of the different CPB stages is unlikely. Research approaches to separate physiological effects on CPB development from agroecological interactions need to be explored to provide insights into the mechanics of the interacting effects. In addition to the yield impact of the delaying effect, further research needs to examine whether mulch causes (i) visual and (ii) olfactory irritation, in addition to (iii) a physical barrier effect for CPB. Is (iv) delayed plant development due to mulch the cause of delayed CPB infestation? Also to be examined is (v) whether the way plants are fertilized by mulch affects the CPB population. In addition, predators should also be identified for Central Europe and their mutual population dynamics determined. Finally, (vi) potato beetle predators for Central Europe should be identified and their mutual population dynamics investigated.

Just as regenerative agriculture has the soil as its base, regenerative plant protection should be thought of as from the soil. We recommend embedding transferred mulch into complementary regenerative, soil fertility management and other agro-ecological practices, to increase effectiveness. However, spreading the mulch is an operational challenge and therefore especially interesting for small direct-marketing farms. Nevertheless, the described systemic approach can on the one hand elegantly reduce CPB abundance and overcome the need for direct intervention with insecticides, while at the same time providing nutrients and additional plant protection with respect to late blight and weeds.

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