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Impact of fagopyrum esculentum on Agriotes obscurus (Coleoptera: Elateridae) development and orientation

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Abstract
Wireworms (Coleoptera: Elateridae), larvae of click beetles, form a complex of significant subterranean pests damaging important crops such as potatoes and corn, with *Agriotes obscurus* being prevalent in Switzerland. Buckwheat acts as a biofumigant and affect wireworms, reducing their feeding and their juvenile growth. This study aimed to evaluate the effects of common buckwheat (*Fagopyrum esculentum*) on the development of *A. obscurus* larvae, comparing four buckwheat varieties (Grauer Heiden, Val Pusteria, Kitawasesoba, Drushina) against a barley control. Larvae were subjected to no-choice feeding tests under controlled conditions, with measurements of weight, length, and head capsule width taken over 12 weeks. Behavioral responses to different buckwheat varieties were assessed via double-choice olfactometry to examine attraction and preference. Results indicated no significant differences in weight or head capsule width between treatments, though barley-fed larvae showed a slight growth advantage. However, larval length exhibited significant varietal differences, with certain buckwheat varieties inhibiting growth more markedly. Mortality rates were unaffected, likely due to the advanced larval stage tested. Olfactometry revealed no clear preference towards any buckwheat variety, suggesting volatile profiles do not strongly influence larval attraction. These findings suggest that while buckwheat can impair wireworm development, especially larval length, variation among buckwheat varieties offers potential for optimizing integrated pest management strategies. The observed lack of behavioural attraction differences may suggest an incorporation of buckwheat as a cover crop, may disrupt wireworm life cycles and suppress damage sustainably.

Keywords Performance · Wireworms behaviour · Choice · Varietal preference

Introduction

Wireworms (Coleoptera: Elateridae) are the larval stage of a click-beetles. The subterranean larvae are polyphagous, and they feed mainly on various plant tissues beneath the soil surface. Only a minority of species pose a problem in agriculture (Vernon and van Herk 2022). The damage caused by the larvae affects several economically important crops, including potatoes (*Solanum tuberosum* L.) (Parker and Howard 2001) and corn (*Zea mays* L.) (Furlan 2014). Depending on the type of crop and specific conditions, these larvae can reduce the quality and/or quantity of harvested products, resulting in significant economic losses for producers (Ritter and Richter 2013; Vernon et al. 2013). The three species most widespread in Switzerland belong to the genus *Agriotes* (Jossi et al. 2008). The larvae of this genus are recognized as particularly harmful to crops internationally (Furlan and Tóth 2007; Kabaluk et al. 2024). Various approaches, such as specific crop rotation or the use of attract-and-kill device, have been developed to control this pest and integrated pest management is becoming increasingly common and involves combining several techniques to limit damage to crops (Poggi et al. 2021). The use of plant materials with biocidal properties deserves further study (Pacifico et al. 2021; Batistič et al. 2025), as this strategy could not only offer a practical solution for farmers, but also improve scientific knowledge of the ecology and biology of wireworms.

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Buckwheat (*Fagopyrum esculentum* Moench) is recognized for its significant role in integrated pest management systems. Its rapid growth and dense canopy suppress weeds primarily through allelopathic root exudates, which have been shown to inhibit the growth of multiple weed species (Falquet et al. 2015; Gfeller et al. 2013). Buckwheat's abundant flowers attract beneficial insects, such as parasitoids and predatory insects, thereby supporting biological pest control in cropping systems and enhancing pest suppression (Pfiffner, 2014; Thurman and Furlong, 2024). Additionally, the incorporation of buckwheat as a cover crop can help disrupt pest life cycles and manage soil-borne pathogens, reinforcing its value in sustainable agroecosystems (Abbasi et al. 2019; Magdoff and van Es 2000). Wireworms' development and survival can be adversely affected when buckwheat is present in the rotation or used as a cover crop (Noronha et al. 2011). Feeding on buckwheat tissue has been associated with larval deformities, delayed molting, and increased mortality over time, indicating that certain secondary metabolites or nutritional imbalances may disrupt the pest's lifecycle (Noronha et al. 2023). These effects support the integration of buckwheat in pest management programs, particularly for reducing wireworm damage in sensitive crop rotations. Noronha (2011) reported that wireworms exhibited a preference for buckwheat over clover, and that it is also attractive to adult females (Brunner, 2025). Our study has three main objectives: (1) to evaluate the effect of common buckwheat nutrition on the development performance of advanced larval stages of *Agriotes obscurus*, a key wireworm species in Switzerland, hypothesizing that larvae feeding on buckwheat exhibit reduced growth compared to high-quality food; (2) to assess performance differences among four genetically distant varieties of common buckwheat, based on the hypothesis that varietal differences produce variable deleterious effects on wireworm larvae, measured through weight, head capsule width, length, and mortality; and (3) to determine whether the attractiveness of *A. obscurus* to buckwheat varies by variety, testing the hypothesis that genetically distinct varieties have sufficiently different volatile organic compound (VOC) profiles influencing larval orientation and preference.

Overall, this work intends to advance on wireworm control through strategic varietal selection of buckwheat.

Materials and methods

Wireworm rearing

The larvae of *A. obscurus* used in all experiments originated from a maintenance rearing established with specimens collected during the potato harvest in northern Vaud canton (46.83998417576745, 6.574372326864155) in October 2024. Larvae were manually removed from harvested tubers, without using any additional bait. Morphological identification following Furlan et al. (2021) was performed to retain only *A. obscurus* individuals. From harvest until experimental use, larvae were kept alive at 7 °C for three months in groups of about 40 per plastic box (20 × 8.5 × 10 cm), filled with 1.5–3 cm of soil substrate, and provided with fresh carrot or potato pieces as foodLarvae kept on feeding during the maintaining rearing during the three months period. The maintenance and performance test substrate had a pH (water) of 7.0 and conductivity of 1.6 mS/cm, per manufacturer. By volume, it consisted of coco-peat (35%), bark compost (30%), wood-fiber-based peat substitute (25%), topsoil (5%), and perlite (5%). Basal fertilization was included by the manufacturer.

Buckwheat varieties

Four varieties of *F. esculentum* were tested: "Grauer Heiden" (GRH, Austria), "Val Pusteria" (VAP, Italy), "Kitawasesoba" (KIT, Japan), and "Drushina" (DRU, Russia). These varieties were selected to maximize their genetic distances, based on genetic mapping from a previous study (Hess, unpublished). The GRH and VAP seeds came from ProSpecieRara, KIT from ETH Zürich, and DRU from Sativa. Spring barley (*Hordeum vulgare* var. Atrika) was included as a control, known to be a suitable wireworm host (Noronha et al. 2023). During plant cultivation for performance and olfactometry tests, substrates were kept moist through regular watering. Plants used for olfactometry tests grew in a substrate of 80% sand (0–4 mm) and 20% from the fertilized mix.

Behavioural assay: no-choice test (performance)

Plants were grown individually in pots (8 × 8 × 9.5 cm) for 21 days before use. Both plant culture and experiments occurred in a phytotron at 21 °C (day), 17 °C (night), 75% humidity, 16 h light (400 µmol/m^2·s), and 8 h dark. For the performance test, a slow-release fertilizer (15–3.9–10 + 1.2 Mg + trace elements) was added at 2.9 g/L. Prior to tests, larvae were acclimated to 20 °C for at least 72 h, with the temperature raised gradually through steps at 10 °C and 16 °C. Larvae were selected according to their locomotor activity (only active individuals were used), developmental instar, and molt status (pre-, mid-, or post-molt). As larval stage cannot be precisely determined morphologically (Sufyan et al. 2011), individuals for the performance test were selected by weight (30–45 mg). A random sample of 100 larvae (mean 36.69 mg, SD = 3.9) was distributed equally among treatments (20 replicates per treatment).

The treatments included the four buckwheat varieties and the barley control. Each pot contained one plant and one *A. obscurus* larva. To prevent escapes, filters at the pot base and aluminum collars were added. If a larva managed to escape and joined another one, they were both removed. In order to maintain plants of an appropriate size, individuals were transferred to new pots with a new 21-day-old plant every three weeks.

Fresh weight, body length, and head capsule width were measured at the start (S0), after 6 weeks (S6), and after 12 weeks (S12). Weight was measured to 0.1 mg precision (Mettler A30 balance). Length and head capsule width were determined to 0.01 mm accuracy using a digital microscope (Keyence VHX-7000, 10 × zoom) with larvae measured while moving to ensure full extension. Variation from extension affected all groups equally (Fig. 1a).

Behavioural assay: double choice

The olfactometry experiment was conducted at room temperature (~21 °C) in the darkness to prevent light-induced behavioral changes in larvae. Three Y-tube olfactometers (each with a main tube of 100 mm and arms of 100 mm at a 30° angle, internal diameter 20 mm, external diameter 22 mm) were used simultaneously and randomly arranged. Filters placed at the arm ends prevented physical contact between larvae and plants. The devices were set horizontally and covered with dark cloth to maximize shade during testing. Olfactometers were filled with 40 mL of tap water–moistened vermiculite, homogenized to avoid compaction and ensure larval mobility. The entire root system and substrate of a buckwheat plant were sealed within a polyamide bag with glass fittings, through which a Clean Air Supply System (CASS6, VAS, NY, USA) supplied filtered air at ~ 1.75 L/min. Outgoing air was channeled to each arm of the olfactometer (Fig. 1b).

Two different buckwheat varieties were tested against each other per olfactometer. Before each experiment, systems were left for one hour to stabilize volatile diffusion. A single wireworm larva was released at the Y-junction in each olfactometer and monitored regularly. The test ended when the larva fully left the neutral zone (main tube), or after 20 min if not. Non-responding larvae—those remaining in the neutral zone—were recorded as such.

For preliminary validation, the KIT variety was tested against plant-free substrate until 15 responses were recorded (21 replicates), with plants at phenological stages 13–14. In order to evaluate the potential of the varieties more quickly, the main olfactometry tests then compared KIT with each of the other varieties (DRU, VAP, GRH) at matched phenological stages, using new plants each time. Larvae for each comparison were weighed to ensure similar mean weights (KIT-DRU: 36.70 mg, KIT-GRH: 39.97 mg, KIT-VAP: 38.19 mg). Each test used new plants when a larva made a choice, and non-responsive larvae were replaced as needed. A minimum of 20 responses per comparison was obtained.

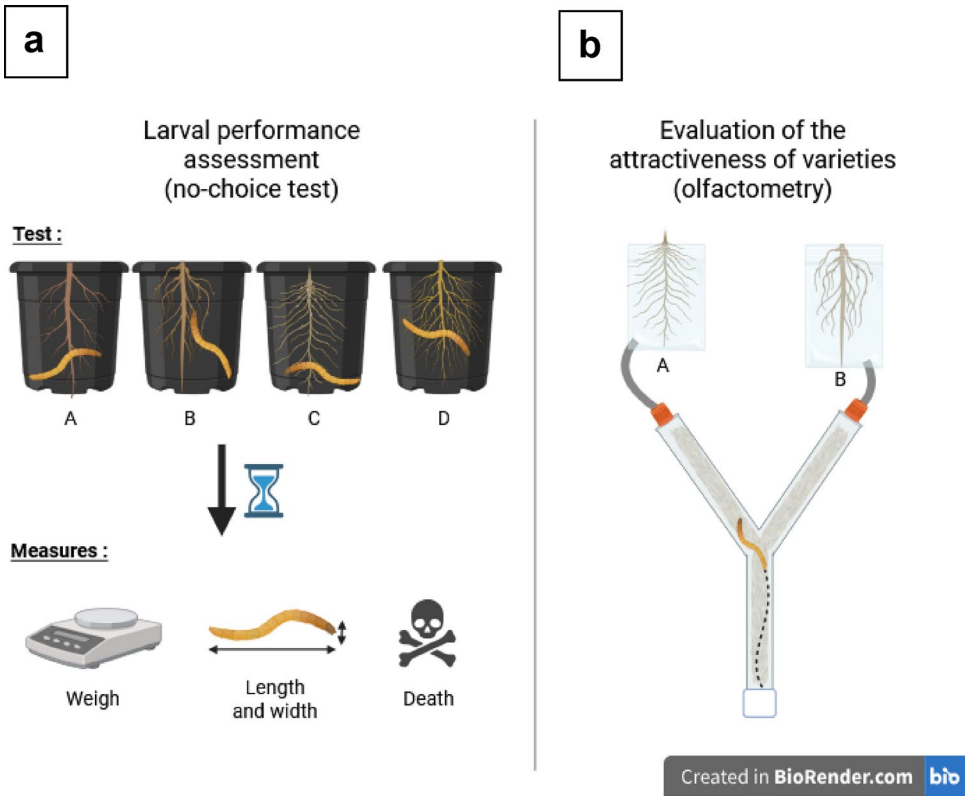

Fig. 1 Schematic representation of the behavioral assays: a) no choice test (performance) and b) double-choice olfactometer. The different buckwheat varieties are represented by the capital letters A, B, C, D

Varietal positions (left/right) were randomized for each replicate. Larvae were starved for at least 72 h before testing and not re-used in multiple experiments.

Olfactometers were cleaned with acetone and pentane, then baked at 200 °C for two hours before use.

Statistical analysis

For the performance test, one-way ANOVA was applied to evaluate changes in larval biomass, length, and head capsule width between the start, 6 weeks (S6), and 12 weeks (S12). Tukey's test was used for post-hoc mean comparisons. Mean weight and head capsule width at S6 and S12 were also analyzed by ANOVA; mean lengths by ANCOVA to adjust for initial differences at S0. Mortality, disappearance and survival rates among treatments were compared using Fisher's Exact Test. All performance test analyses were performed using Minitab (v22.2.2).

For olfactometry, observed varietal choice frequencies were compared to the theoretical expectation under the null hypothesis (50:50 split for two varieties) via binomial tests. Analyses were performed in R (v4.4.3), and all statistical assumptions were verified for each test.

Results

Behavioural assay: no-choice test

Buckwheat effect on biometric parameters

Analysis of data across all buckwheat varieties tested (DRU, GRH, KIT, and VAP) compared with barley (ORG) revealed an average weight gain between the start of the experiment (S0) and six weeks (S6) of + 2.8 mg for ORG and + 1.8 mg for the buckwheat varieties. Between S6 and 12 weeks (S12), mean weight differences were -0.3 mg for ORG and -1.5 mg for the buckwheat varieties. Overall, from the beginning to the end of the experiment, mean weight gain was + 2.5 mg for ORG and only + 0.3 mg for buckwheat varieties (Fig. 2). None of these differences reached statistical significance ($p > 0.05$).

In terms of the average width of the cephalic capsule, the measured values indicate a continuous trend for larvae exposed to buckwheat varieties. The average trend for barley is positive between S0 and S6 and negative from S6 to S12 (Fig. 3). The differences are not significant ($p > 0.05$).

The average change in length is virtually identical between treatments from S0 to S6. It is then -0.6 mm for ORG and -0.1 for buckwheat varieties in the second part of the experiment (Fig. 4). However, no significant difference is observed ($p > 0.05$; Table 1).

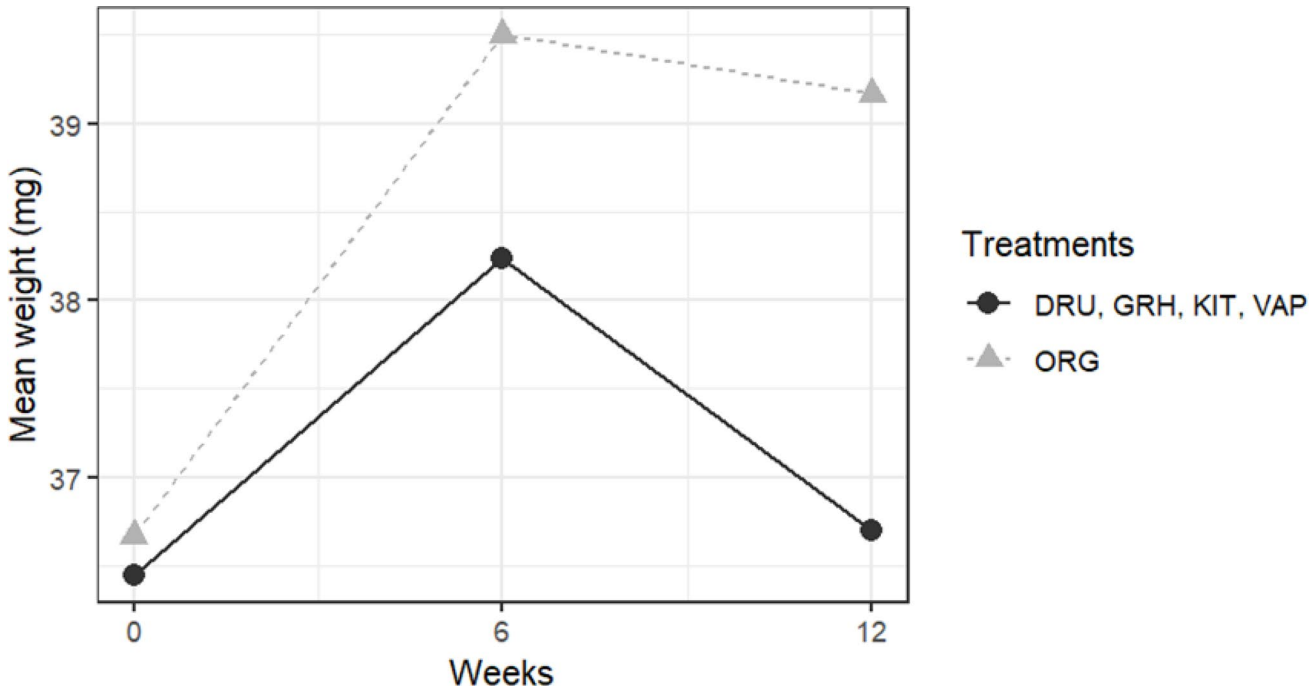

Fig. 2 Change in average weight of larvae that consumed barley (ORG) or buckwheat (DRU, GRH, KIT, VAP). n = 55

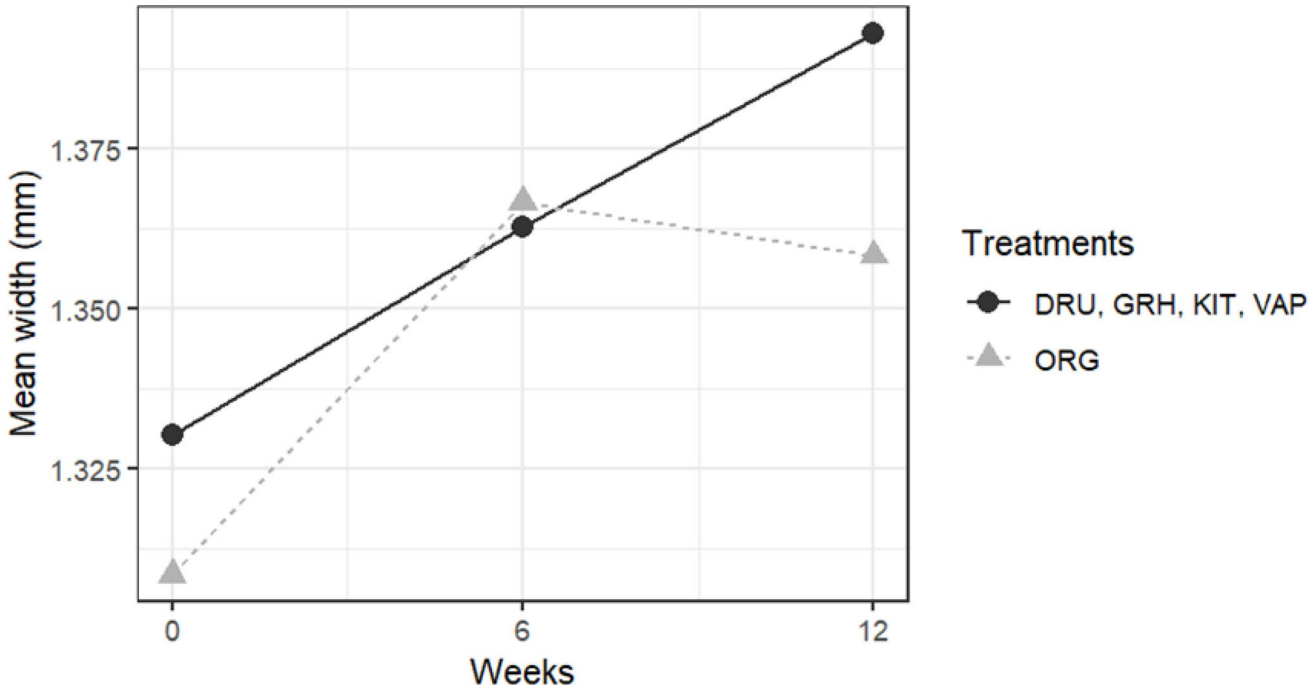

Fig. 3 Change in the average width of the cephalic capsule of larvae that consumed barley (ORG) or buckwheat (DRU, GRH, KIT, VAP). n = 55

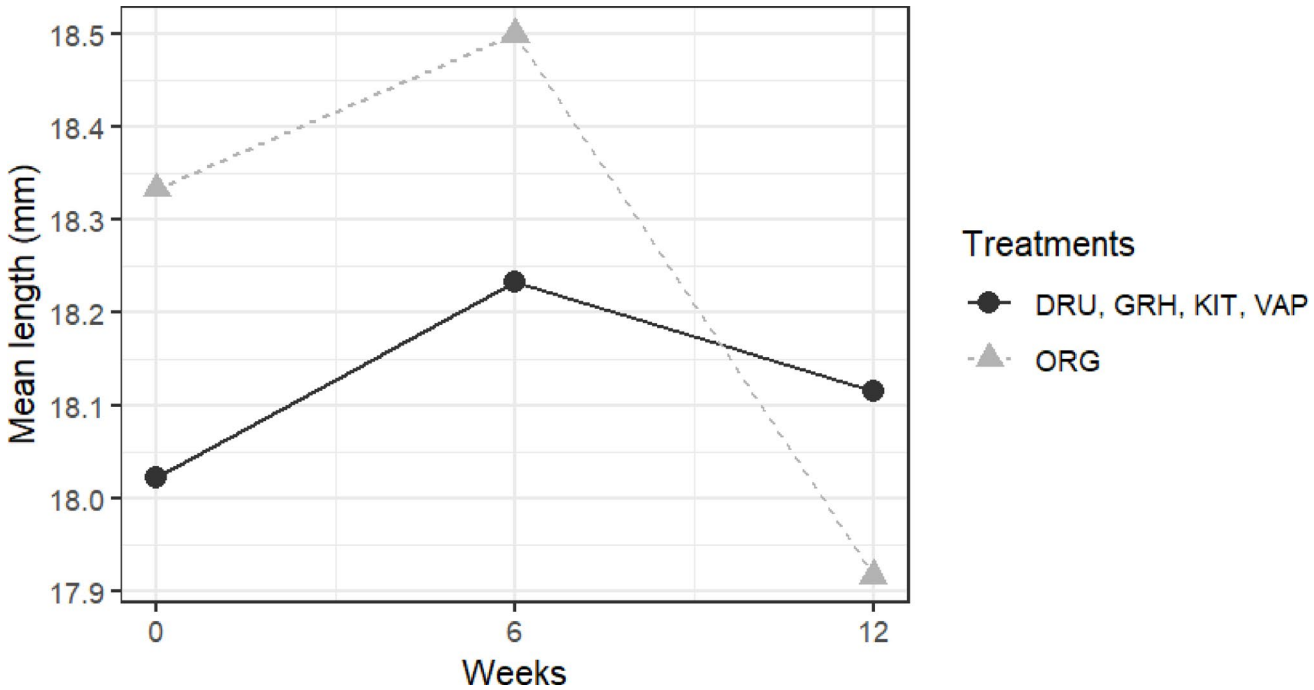

Fig. 4 Change in the average length of larvae that consumed barley (ORG) or buckwheat (DRU, GRH, KIT, VAP). n = 55

Table 1 P-values from the analysis of variance (ANOVA) testing the effect of buckwheat (DRU, GRH, KIT, VAP) vs. barley (ORG) on the evolution of three biometric parameters over time. n = 55

	0–6 weeks	6–12 weeks	0–12 weeks
Weight	0,350	0,468	0,133
Width of the cephalic capsule	0,208	0,134	0,622
Larvae length	0,902	0,291	0,267

Varietal effect on biometric parameters

Evolution

Observing the five treatments, the data obtained indicate

that the average weight change of the individuals tested was always positive between S0 and S6 (Fig. 5). This change becomes negative in all treatments between S6 and S12. With the exception of the average weight of individuals assigned to DRU, the average weight of the larvae in each treatment increased between the start and end of the experiment. With an average weight gain of 3.9 mg from S0 to S6 and a loss of 3.2 mg from S6 to S12, VAP is the treatment for which the differences were greatest between the three measurements. Also, it was the only treatment with a bigger weight gain than ORG between S0 and S6. Over the whole period, ORG was the treatment with the highest weight gain. However, the differences in average weight change are not significant between treatments at any recorded period ($p > 0.05$).

Descriptively, the average width of the cephalic capsule of the larvae changed positively in all treatments between the start and end of the experiment (Fig. 6). ORG is the only treatment for which the average width of the cephalic capsule decreased between S6 and S12. The average width of VAP stagnated over the same period and all others increased. Statistically, the data revealed no significant difference between treatments in terms of the average change in cephalic capsule width ($p > 0.05$).

With regard to length, the data obtained indicate different trajectories for each treatment (Fig. 7). The KIT and GRH varieties are the only ones for which the average length increased between the start and end of the experiment. The average length for DRU decreased between S0 and S6 and remained stable between S6 and S12. For ORG and VAP, the values increased up to S6, then decreased from S6 to S12. The largest differences between two measurement times were observed with the VAP treatment, which showed an average change of + 0.9 mm and -1.2 mm between S0-S6 and S6-S12, respectively.

The average change in length is significantly different between certain treatments (Table 2). Firstly, in the period from S0 to S6 ($p = 0.001$), the average change of DRU is at least 0.57 mm and 0.01 mm lower than the CI for VAP and GRH, respectively, according to the estimates and their 95% confidence intervals (CI) (Fig. 8).

For the period from S6 to S12, the average change in length is also significantly different between several treatments ($p = 0.010$). Based on the estimates and their 95% CIs, we can consider that the average change in larval length for VAP is at least 0.08 mm less than that for KIT. This difference reaches at least 0.19 mm between VAP and GRH (Fig. 9).

When analysing the average changes in length for the entire experiment, we see that the difference between treatments is, once again, significant ($p = 0.012$). Here, the DRU and GRH treatments stand out. The estimates and their 95% CIs indicate that their respective average changes differ by at least 0.13 mm (Fig. 10).

Intermediate and final states

The initial average weights show a maximum difference of 3.34 mg (Fig. 55). At S6, this difference is only 1.61 mg and reaches 3.84 mg at S12. However, none of these differences

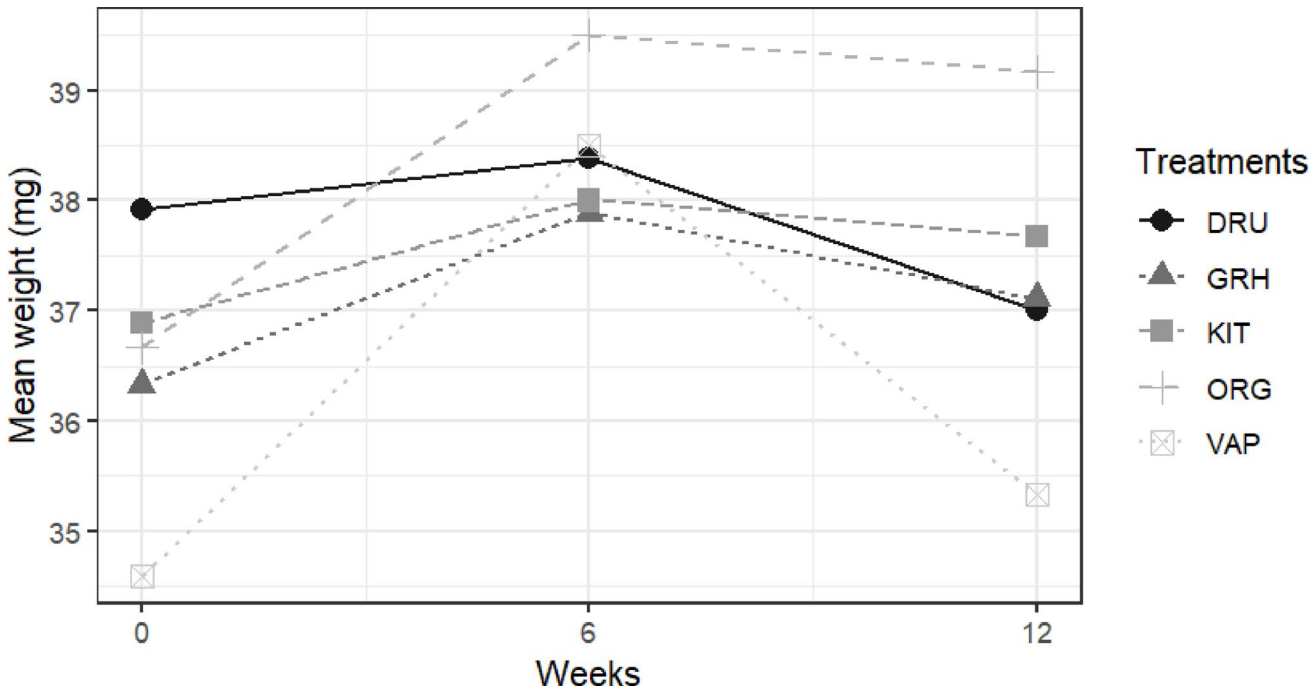

Fig. 5 Change in average larval weight for each treatment. n = 55

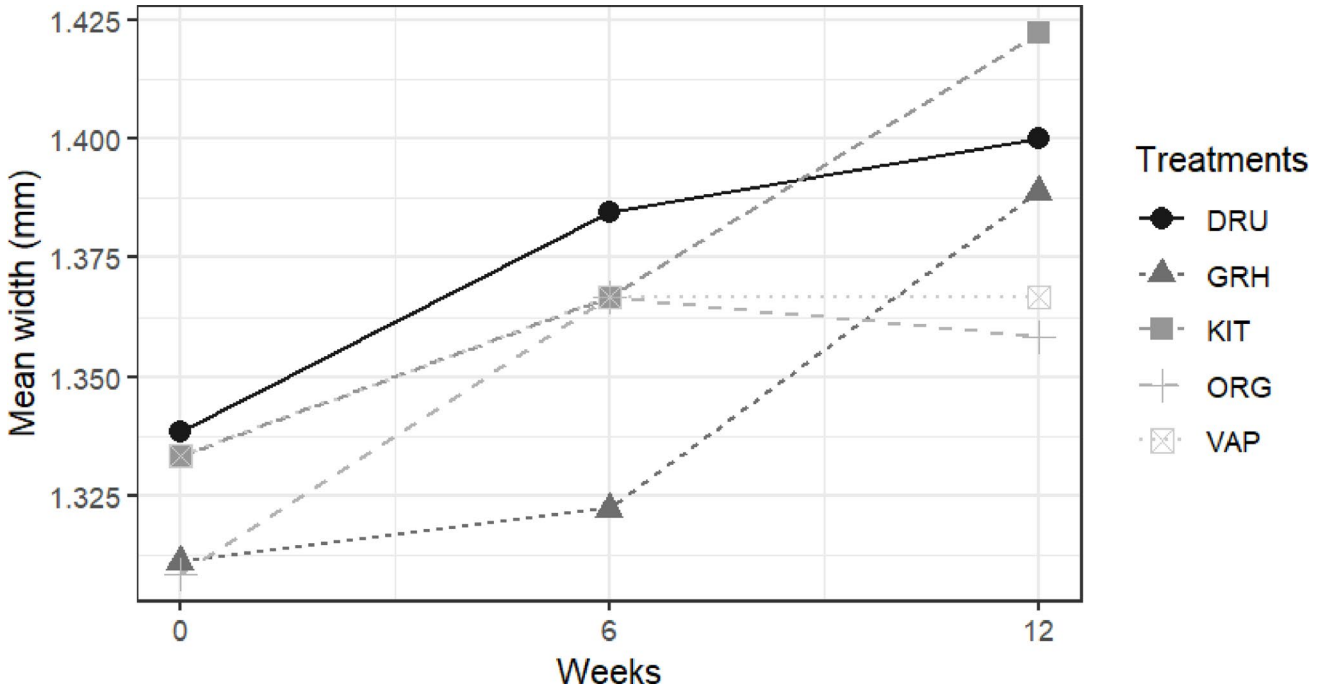

Fig. 6 Change in the average width of the cephalic capsule of larvae for each treatment. n = 55

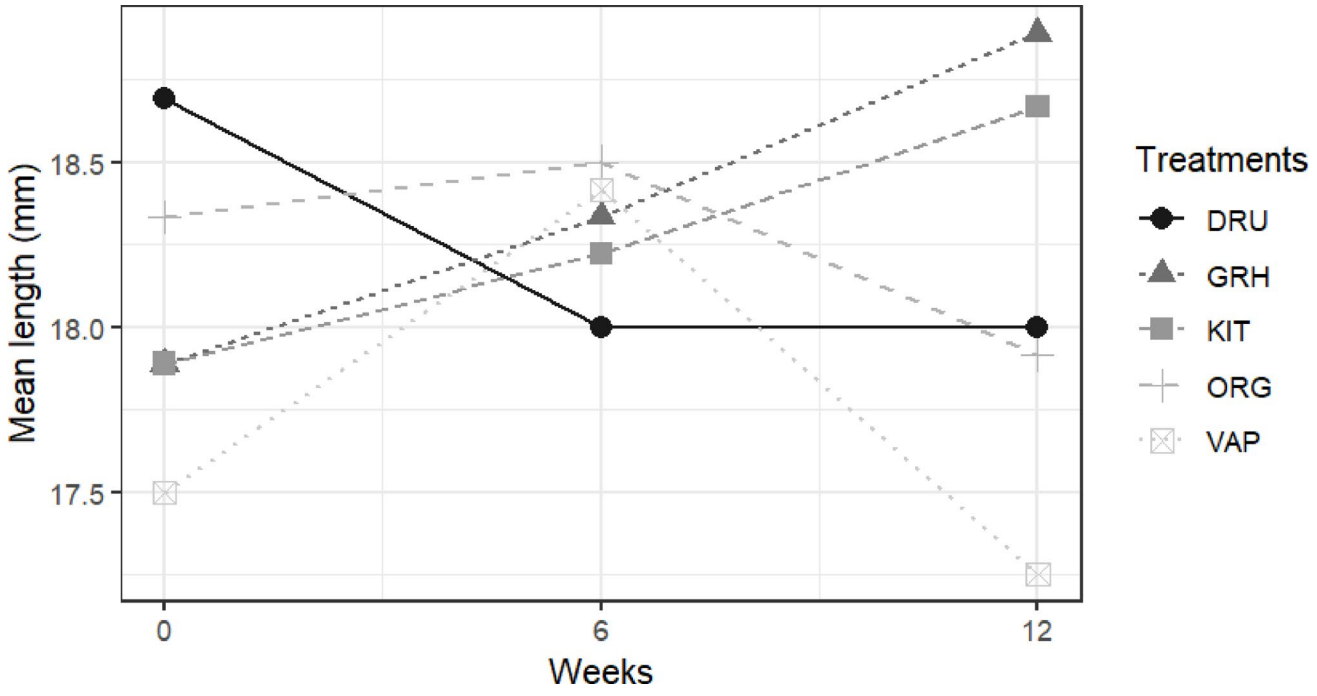

Fig. 7 Change in average length for each treatment. n = 55

are statistically significant (Table 3). The average widths are within a range of 0.03 mm at S0 and 0.06 mm at S6 and S12. These differences are not statistically significant (Table 3).

The initial average lengths show a difference of 1.19 mm between the two extremes. This difference is statistically significant at the 5% threshold ($p = 0.016$), which justified the adjustment of the statistical tests for S6 and S12. At week 6, the average lengths show a maximum difference of 0.50 mm. This difference is not significant ($p > 0.05$) (Table 3). The maximum difference in average lengths is 1.64 mm at S12. The difference between treatments is significant at the 1% threshold ($p = 0.005$). Based on the estimates of means and

Table 2 P-values from the analysis of variance (An. = ANOVA) and analysis of covariance (Anc. = ANCOVA) testing the effect of the five treatments on the evolution of three biometric parameters over time. n = 55

	0–6 weeks	6–12 weeks	0–12 weeks
Weight	0,083 An	0,652An	0,489 An
Width of the cephalic capsule	0,524 An	0,113An	0,527 An
Larvae length	0,001** An	0,010* Anc	0,012*Anc

*(p < 5%), **(p < 1%)

their 95% CIs, it appears that the average length for VAP is at least 0.11 mm shorter than that for KIT and at least 0.33 mm shorter than that for GRH (Fig. 11).

Mortality

Fifty-five per cent of the individuals tested remained in the pots and alive from the beginning to the end of the experiment (Fig. 12). A total of 29 larvae left their pots up to S6. Migration then ceased. Throughout the experiment, seven

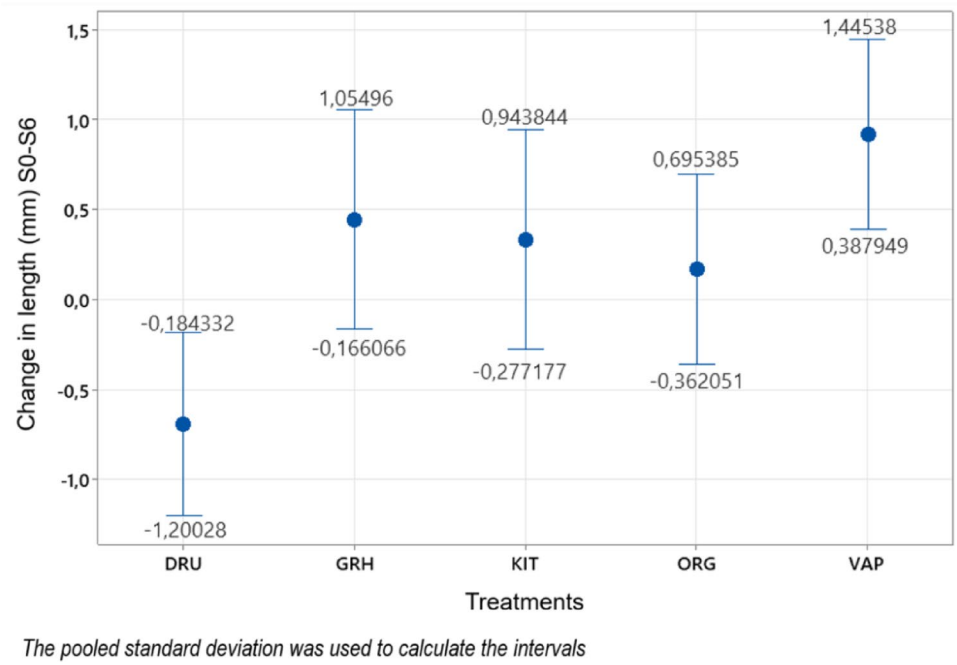

Fig. 8 Tukey's 95% confidence intervals for the mean change in length between S0 and S6. n = 55

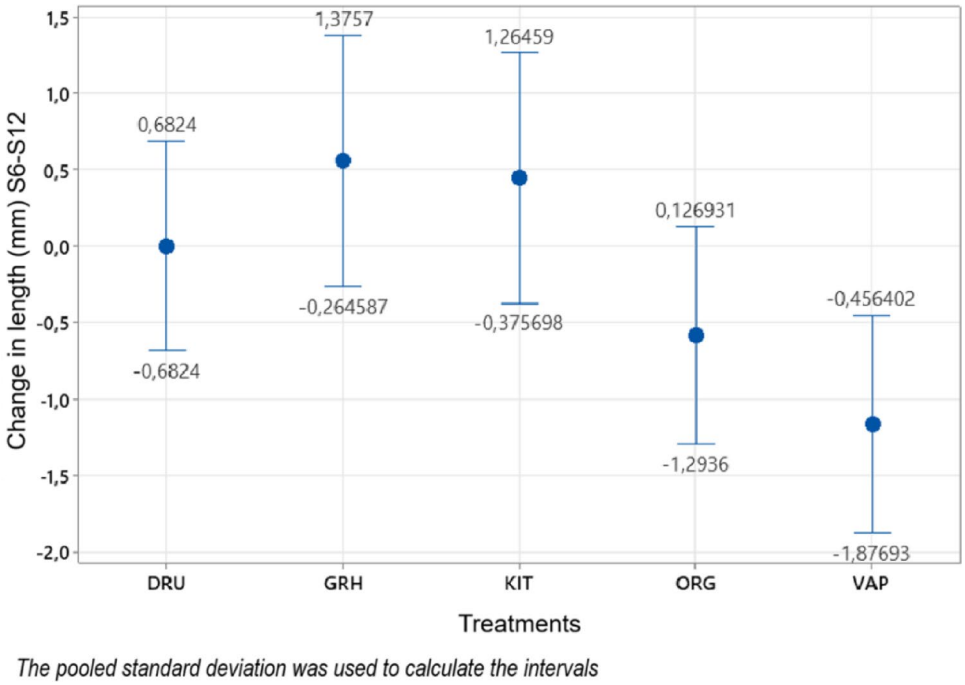

Fig. 9 Tukey's 95% confidence intervals for the mean change in length between S6 and S12. n = 55

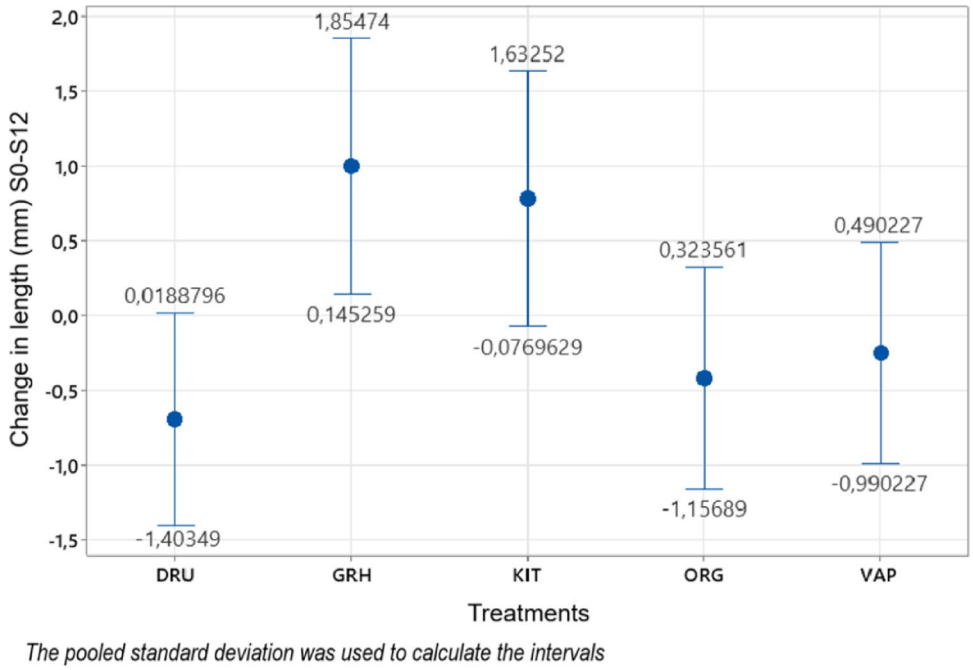

Fig. 10 Tukey's 95% confidence intervals for the mean change in length between S0 and S12. n = 55

Table 3 P-values from analysis of variance (ANOVA) and analysis of covariance (ANCOVA) testing the effect of the five treatments on three biometric parameters after different periods of nutrition. n = 55

	Week 0	Week 6	Week 12
Weight	0,267 an	0,946 an	0,532 an
Width of the cephalic capsule	0,783 an	0,233 an	0,228 an
Larvae length	0,016* an	0,077 anc	0,005** anc

*(p < 5%) and **(p < 1%). Seven values are derived from ANOVA (an.) and two values are derived from ANCOVA (anc.)

other individuals died and nine were not found. No statistically significant difference was observed between the proportions of individuals found alive, lost or dead in each treatment (p > 0.05). This was also not the case for the cumulative proportion of lost and dead larvae compared between treatments (p > 0,05).

Behavioural assay: double choice olfactometers

Wireworms did not significantly orient toward KIT buckwheat (p = 0.7963, $x^2 = 0.066667$; 71% of individuals made a choice).

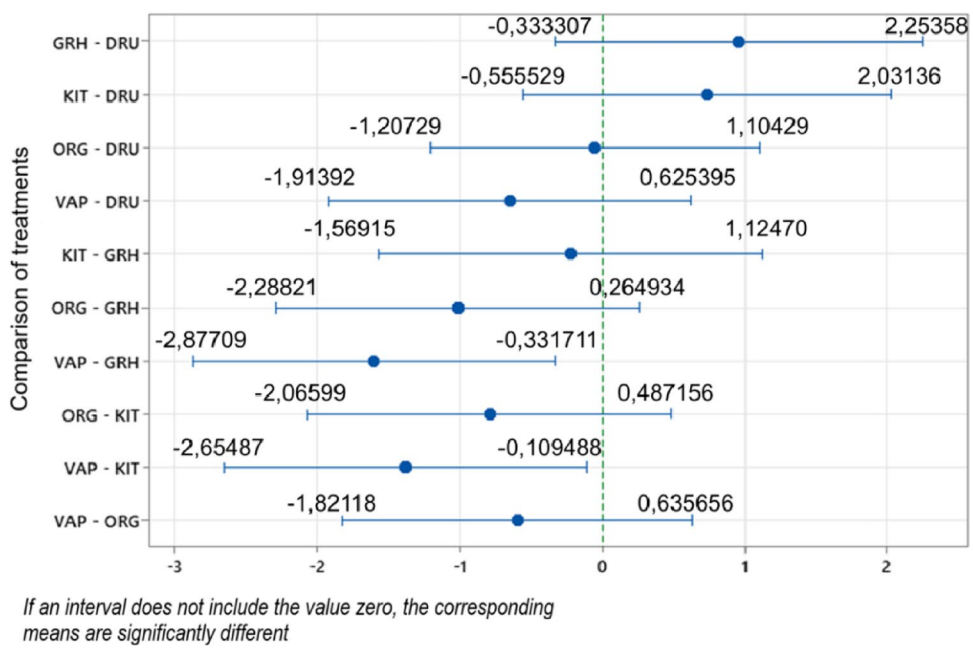

Fig. 11 Comparison graph of Tukey's 95% confidence intervals for the average length of larvae after 12 weeks. n = 55

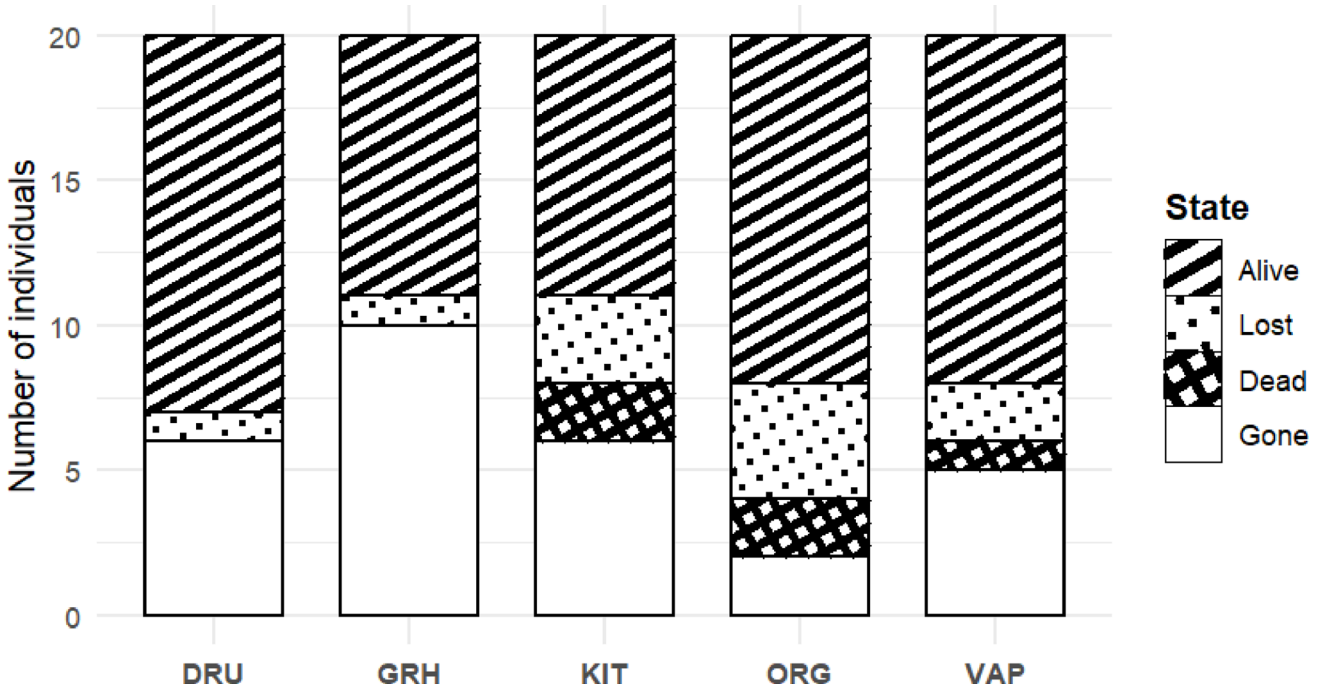

Fig. 12 Distribution of individuals by state at the end of the experiment. n = 100

To check that the side assigned to the treatment in the olfactometer (left or right) was not related to the larvae's choice of variety, Fisher's test was performed for each comparison with a $p < 0.05$ for KIT-VAP comparison.

Wireworms did not significantly orient toward a variety in the KIT-DRU comparison ($p = 0.3711$, $x^2 = 0.8$; 67% of individuals made a choice). The same negative results was highlighted for the KIT-GRH comparison ($p = 0.3938$, $x^2 = 0.72727$; 65% of individuals made a choice), and the KIT-VAP comparison ($p = 0.8273$, $x^2 = 0.047619$, 78% of individuals making a choice) (Fig. 13).

Discussion

Weight and head capsule

No significant differences were observed between treatments (ORG vs. buckwheat) in fresh weight, head capsule width, or their evolution over time. However, some visual trends emerged: mean weight was consistently at least 1.3 mg higher for ORG from S6 onward, and overall mean growth was greater for ORG (Fig. 2). The average head capsule width evolved similarly between treatments, with the gap remaining stable between S0 and S12 (Fig. 3).

Comparing ORG with the individual buckwheat varieties (DRU, GRH, KIT, VAP), no significant differences were found either. Still, weight gain trends diverged: VAP showed at least 1.1 mg higher mean increases until S6 and a decrease of at least 1.8 mg lower than all other treatments between S6 and S12 (Fig. 5). For head capsule width, DRU, GRH, and KIT exhibited more marked growth than ORG and VAP, whose widths remained stable or decreased after S6 (Fig. 6). Wireworm progress through distinct instars separated by molts, during which the rigid head capsule is shed and replaced by a larger one. Studies across different insect species showed that head capsule width remains essentially constant within each instar and increases in a stepwise, roughly geometric pattern at each molt, consistent with Dyar's rule (Shaheen et al. 2024; Mohammadi, 2010; Panzavolta, 2014). In *Agriotes* larvae, head capsule width increases stepwise with each molt but is constant within an instar, especially the final one (Sufyan et al. 2014). In our experiments, larvae (especially in ORG and VAP) were already in the final instar at or before S6 (Fig. 6). We observed a more marked growth in head capsule width for DRU, GRH and KIT, which suggests a higher proportion of larvae still molting to higher instars, which would produce detectable head width increases alongside weight gain. Consequently, head capsule width would be expected to remain stable, even while weight continues to increase and later decline with changing feeding conditions. In contrast, soft tissues can grow continuously, so larval weight and length may change substantially between molts without any change in head width (Hoshizaki, 2020). In addition, final-instar larvae are generally distinguished by minimal additional head growth and by reaching species-specific size limits, rather than continued head enlargement, and

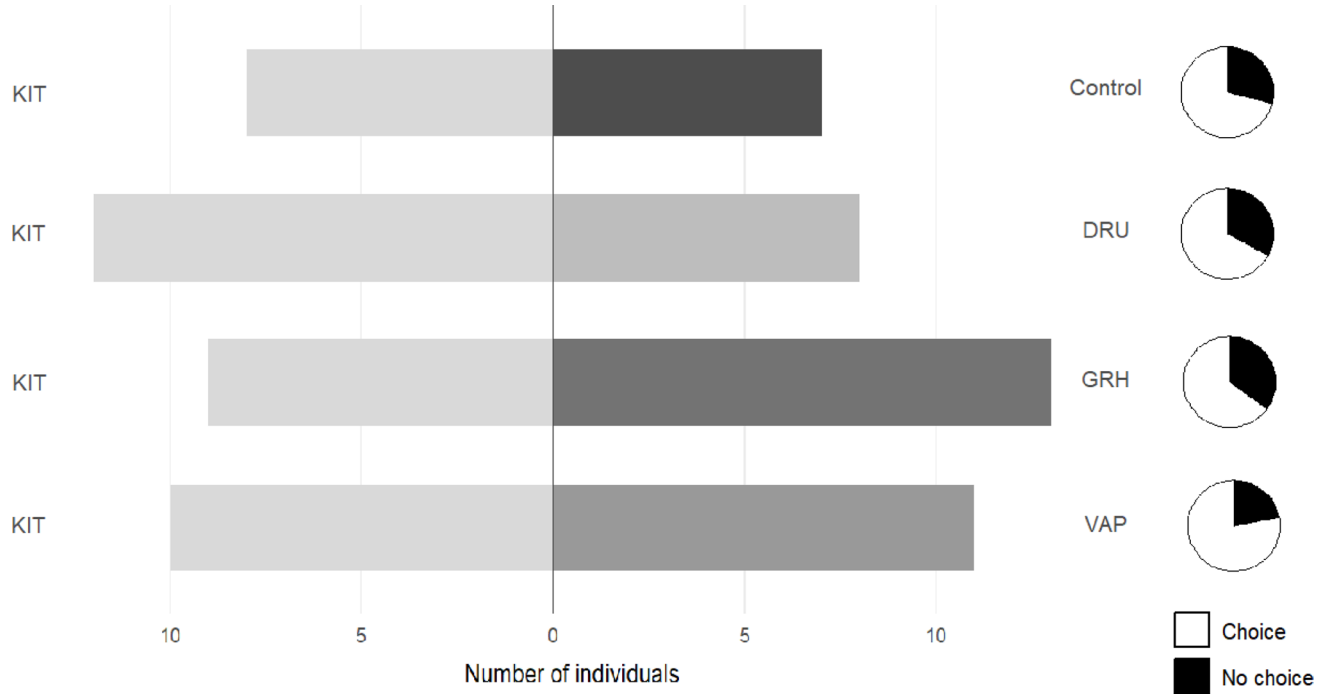

Fig. 13 Results of the two-choice olfactometry test between the varieties *Fagopyrum esculentum* KIT and a) DRU b) GRH c) VAP. All p-values from the adjusted chi-square test are greater than 5%

may explain why weight/length may change without corresponding head-width change (Furlan et al. 2021).

The lack of significant differences may be explained by two main factors if varietal or species effects do exist. First, larval stage should be considered, as weight gain requires more time in advanced stages and relative gain is smaller (Reinbacher et al. 2023). In this study, only ORG larvae increased weight by over 1 mg over the experiment, representing less than 3% change in all other treatments, lower than values reported by Noronha et al. (2023) and Bohorquez Ruiz et al. (2019) with younger larvae. Mean head capsule width increases (0.03–0.09 mm, 2–7%) were also smaller than those by Noronha et al. (2023). These authors suggest positive carryover effects from previously ingested food may temporarily mask disadvantages from unfavorable food. Ideally, larval development tests should begin at hatching to better control growth conditions, requiring a breeding colony that can take years due to the long and variable life cycle of wireworms.

Secondly, non-automated control of substrate moisture may have limited larval growth. Substrate suction force, if too high or low, significantly reduces larval feeding and weight gain (Evans 1944). The low water-buffering capacity and limited substrate volume per plant caused cyclic dry and overly wet periods, unfavourable for normal growth. More pronounced development might occur under optimal moisture conditions.

Additionally, fresh weight measurements do not fully reflect the metabolic use of food for *Agriotes* development. Evans (1944) showed fresh weight/dry weight ratios vary by food type. For example, mustard consumption produces fresh weight gains similar to wheat but insignificant dry weight gains. Thus, increased fresh weight may not indicate true structural growth.

Length

Significant differences in larval length and its evolution were found between buckwheat varieties but not between ORG and all buckwheat varieties combined, despite a larger average length decrease for ORG (-0.6 mm) compared to buckwheat (-0.1 mm) between S6 and S12 (Fig. 4).

These results indicate diet influences larval length growth, consistent with literature (López-Gámez et al. 2024). Moreover, results for DRU (S0-S6) and VAP (S6-S12) also suggest that length may decrease depending on food consumed (Figs. 7, 8); a phenomenon not yet formally documented for wireworms. Published wireworm performance tests commonly measure weight or head capsule width but rarely length, though length is useful for approximating larval stage (Furlan 1998; Sufyan et al. 2011).

These distinct changes may have nutritional or toxic origins. Buckwheat varieties vary in dry matter content and phytochemical compounds (Kalinova et al, 2007), which, even in subtle variation, can influence insect development

(Lehrman et al. 2012; Simmonds 2001). Notably, rutin levels vary significantly among buckwheat roots (Kalinova et al, 2007). Excessive consumption of this flavonoid can reduce larval weight through pre-ingestion deterrence and reduced food conversion efficiency (Hoffmann-Campo et al. 2006; Isman and Duffey 1982). High dry matter content may also reduce larval feeding and growth (Schmidt and Reese 1988).

Given the results, it appears that under suboptimal feeding conditions, *A. obscurus* larvae prioritize weight gain and head capsule width increase over length. Since head capsule width increase is considered indicative of larval stage progression, larvae may favor transitioning to pupation—even in poorer condition—over stagnation in an intermediate larval stage.

Mortality

Over 12 weeks, species and variety had no significant impact on larval mortality. The larvae that disappeared during the trial might have died and decomposed in the substrate. However, even when they were included in the count of dead larvae, no significant difference was observed. Noronha et al. (2023) noted that *A. sputator* larvae initially weighing 4–10 mg required at least six additional weeks beyond freshly hatched larvae to exceed 80% mortality. This study tested larvae initially weighing 30–45 mg, representing more advanced stages. Thus, deleterious effects likely take longer to manifest at advanced stages. Three main causes could explain this delay: first, as above, nutritional benefits from prior food may mask current effects; second, relative weight gain is lower at advanced stages, potentially diluting negative impacts; third, older larvae undergo longer fasting phases (Evans and Gough 1942; Furlan 1998), reducing continuous exposure to phytochemicals. Also, none of the buckwheat varieties contained highly toxic compounds—such effects would have been observable within the study period (Grove et al. 2000; Hall 2003). Some authors recognize that buckwheat slows growth or increases mortality of early instar larvae, at least for *A. sputator*. However, results here indicate these effects are not observed for advanced instars of *A. obscurus*, corroborating Bohorquez Ruiz et al. (2019), though absence of effect may be due to short observation periods in both studies. Mortality rates also seem unaffected by variety, possibly due to the advanced stage of larvae in this study, consistent with Noronha et al. (2023).

Behavioral response

These behavioral tests were conducted to highlight varietal preference of wireworms. Based on larval behavior, it was possible to show that wireworms make a choice when confronted with olfactory stimuli. Although no trend emerged toward preferring one odor source over another, individuals responded positively to olfactometry tests with an average response rate of 70%. Another important aspect is that the plants used in the tests were healthy and theoretically did not produce herbivore-induced plant volatiles (HIPVs). The presence of HIPVs can indeed modify attractiveness for wireworms (la Forgia et al. 2023). Literature shows that varieties within the same plant species can have different effects on damage caused by wireworms, attributable to their attractiveness or palatability (Johnson et al. 2008; Furlan et al. 2024). Wireworm orientation notably depends on volatile organic compounds (VOCs) emitted by plants (Barsics et al. 2012; Gfeller et al. 2013). Johnson and Gregory (2006) describe three stages leading to food source choice for subterranean insects: first, guidance by CO_2 gradients; second, distant perception of plant-specific semiochemicals directing movement; finally, at physical contact, plant semiochemicals must be suitable to the insect. In this experiment, no physical contact occurred, the wireworms being constrained inside the olfactometer by a filter. Only olfactory stimuli reached the insects, the plants being separated by the filter and connection tube length. Beyond physiological effects, buckwheat's influence on wireworm orientation behaviors was also tested, revealing no significant differences in attractiveness among varieties based on constitutive VOC profiles. Thus, no specific buckwheat variety seems suitable for "push–pull" or "attract-and-kill" strategies. Similar results were found by la Forgia et al. (2020) comparing maize varieties differing in VOC profiles. The authors concluded that CO^2 probably remains the main cue for orientation when significative differences between varieties are lacking. Tests here did not capture the effects of HIPVs inherent to natural settings.

Larval stage

Larval stage may influence results; olfactometry tests typically use early or mid-larval stages (Bohorquez Ruiz et al. 2019; Noronha et al. 2023; la Forgia and Verheggen 2017). In this test, larvae were mostly late instars. Older larvae are more resilient to fresh plant material deprivation (Furlan 1998) and possibly lower quality plants (Noronha et al. 2023). Thus, advanced-stage larvae may be less selective when seeking food, a hypothesis warranting tests comparing activities across larval stages. This study highlights the possibility that larval development is influenced by varietal choice. Results indicate larval length is the first parameter affected by this choice, preceding weight and head capsule width where no significant differences emerged.

To conclude, this study highlights the possibility that larval development is influenced by varietal choice. Results

indicate larval length is the first parameter affected by this choice, preceding weight and head capsule width where no significant differences emerged. While diet effects on insect larval length are known (López-Gámez et al. 2024), a reduction in length has not yet been formally documented. Further testing is needed to confirm the impact of developmental delay on wireworm population dynamics. Varietal choice appears relevant for selecting green manures or main crops to detriment wireworms.

Varietal differences in buckwheat phytochemistry

Although wireworms were not repelled by *F. esculentum* and feed on it, this food source causes deformities and difficulties in moulting. Secondary metabolites may be involved on the wireworm's performance and vary between varieties of the same species (Kalinova, 2008). This suggests that phytochemicals may interfere with development, or that buckwheat is not a sufficiently nutritious food source (Noronha et al. 2023; Brunner, 2025). Bohorquez Ruiz et al. (2019) highlighted that the time required for symptoms to appear is longer in older larvae, which could potentially be explained by the beneficial effect of previously ingested food or because older larvae eat less.

Common buckwheat cultivars showed indeed marked genotypic variation in their phytochemical profiles, which may be relevant when interpreting potential effects on wireworms. Comparative studies demonstrate significant differences among cultivars in protein, individual phenolic acids, rutin and other flavonoids, total phenolics and mineral composition, both within common buckwheat and between common and tartary buckwheat (Bystrická et al. 2011; Podolska et al. 2021; Luthar et al. 2020). For instance, ferulic and p-coumaric acids dominate in some common buckwheat cultivars, whereas vanillic and syringic acids prevail in others, highlighting clear cultivar-specific mineral patterns (Podolska et al. 2021). Buckwheat phytochemistry varies strongly with the geographic origin of the variety: rutin, quercetin, kaempferol, and vitexin levels differ markedly among cultivars in leaves, flowers, and grain (Rauf et al. 2020). These studies support the interpretation that the buckwheat varieties used in our experiment likely differed in the qualitative mixture of flavonoids and phenolic acids, which could contribute to treatment-specific effects on larval growth and survival. In addition to flavonoids, palmitic acid and gallic acid may also harm wireworms (Noronha 2011), just as they inhibit weed growth (Kalinova et al. 2007).

In our study, we did not investigate the chemical differences among the buckwheat varieties used. Nevertheless, such variation is likely to influence larval performance and warrants further investigation. Future research should specifically address how differences in secondary metabolite profiles among buckwheat varieties affect larval growth and survival, as this would provide a more comprehensive understanding of root–wireworm interactions.

Conclusion and future perspectives

Wireworms represent a significant economic threat to many crops worldwide. Damage can be both qualitative and quantitative depending on the crop and pest pressure. Despite this undeniable importance, effective, practical, and regulation-compliant control measures are currently lacking (la Forgia and Verheggen 2019).

In light of the limited agronomic options, scientific research must propose new integrated protection strategies that are economically and practically viable. Their relevance will also depend on their synergy with existing control measures.

The use of biocidal plant materials also presents a promising avenue. Integration of common buckwheat *F. esculentum* in rotations is notably effective at reducing wireworm damage on potatoes. Buckwheat can be marketed or used as a green manure without requiring incorporation to express its effects.

Detrimental effects of buckwheat likely stem from its low nutritional value or toxicity of certain compounds. Although buckwheat varieties exhibit variable biochemical profiles, varietal impact remained to be demonstrated.

Future studies could investigate varietal effects on early larval stage development to maximize likelihood of detecting treatment differences. Further behavioral understanding could arise from testing attractiveness of varieties previously exposed to root herbivory. Analyzing secondary metabolites released by roots would be particularly important for both developmental and behavioral tests, potentially identifying compounds responsible for wireworm biological and behavioral responses and facilitating selection of varieties optimized for this purpose.

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Declarations

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Ethical approval The manuscript presents research on animals that do not require ethical approval for their study.

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