Title: **Susceptibility to wireworm damage of different crops in semi-natural conditions**
Academic activity: Research Planning
Keywords: IPM, *Agriotes brevis, Agriotes litigiosus, Agriotes sordidus*
Level of access: Libera consultazione

1. INTRODUCTION

Recent development of legislative laws in response to the societal concerns on human and environmental health has affected the practices and products that can be utilized in the fields. In 2009, the European Union issued the Directive 2009/128/EC to make compulsory the implementation of a sustainable use of pesticides. Consequently, several chemical products which were prevalently used in pest control were also reduced or banned, including neonicotinoids which were used to control wireworms, because of their negative effects on the environment particularly the pollinators (Pisa et al. 2017).

Since the new legislation has made it mandatory to adopt IPM practices which emphasize more environmentally friendly techniques that can reduce the use of chemicals for controlling pests. Alternative methods such as crop rotation, mechanical control, and biological control are being explored to manage important pests in agriculture.

Among the serious pests are the wireworms. which are the larvae of click beetles (Coleoptera: Elateridae), rank among the major soil pests of a high number of annual crops in Europe and North America (Veres et al. 2020). The most harmful species in Europe are in the genus *Agriotes* Eschscholtz, 1829: *Agriotes brevis* Candèze, *A. lineatus* L., *A. litigiosus* Rossi*, A. obscurus* L., *A.s proximus* L.*, A. rufipalpis* Brullé*, A. sordidus* Illiger*, A. sputator* L.*,* and *A. ustulatus* Schäller (Elateridae: Elaterinae: Agriotini Champion, 1894) (Furlan et al. 2007). *A. obscurus*, *A. lineatus* and *A. sputator* are major threats to central northern Europe while *A. litigiosus* is the most serious threat to southeastern Europe (Furlan et al., 2001). In Italy, Po valley is mainly affected by four species: *A. brevis, A. litigiosus, A. sordidus*, and *A. ustulatus* (Furlan et al., 2000).

In Canada and Alaska, only 30 species are of economic importance with *Limonius* spp. cited as the most devastating in the Pacific Northwest (Nikoukar and Rashed, 2022). In Virginia, USA, the primary genera are *Melanotus* Ohira, *Conoderus* Eschscholtz, and *Aeolus* Eschscholtz (Kuhar and Alvarez, 2007). In the regions of Europe, North Africa, the Middle East, and North Asia, about 100 species of wireworms are economically important (Nikoukar and Rashed, 2022).

Life cycle

1.1 Life cycle of *Agriotes*

Wireworm species can be divided into two main groups (Furlan 2005): .

A) species with adults which do not overwinter, live a few days and lay eggs a few days after swarming: *Agriotes ustulatus* Schäller, *Agriotes litigiosus* Rossi, *Synaptus filiformis* F.

B) species with adults which overwinter and live for months. These lay eggs for a long period after adult hardening: *Agriotes sordidus* Illiger, *Agriotes brevis* Candeze, *Agriotes lineatus* L., *Agriotes sputator* L., *Agriotes obscurus* L., *Agriotes rufipalpis* Brullè, *Agriotes proximus* Schwarz.

Reliable information concerning the biology of the different species can be obtained by studying concurrently the phases of their life cycle under laboratory conditions (rearing chambers at constant temperatures), in rearing cages close to natural conditions and in open fields (Furlan 1996; Furlan, 1998, Furlan, 2004). When biological information obtained with the different methods are in agreement, then the overall understanding of the behavior of the species has been achieved.

Currently, good biological information is available for the following species:

Agriotes ustulatus (Furlan, 1994; 1996; Furlan 1998; Hinkin, 1983), *Agriotes sordidus* (Furlan, 2004; Furlan et al. 2004), *Agriotes brevis* (the study conducted in Italy has been completed and is ready to be published; some information has already been made available by Masler, 1982; Rusek, 1972b) *Agriotes litigiosus* (the study has been completed and ready to be published, some information for the variety *tauricus* has already been made available by Kosmacevsky, 1955).

Crop rotation and availability of food resources through the season, climatic-agronomic conditions (mainly organic matter content) and soil characteristics are the main factors influencing the composition of species communities and larval population density. For the species studied in Italy, the most important factor appears to be crop rotation (Furlan and Talon, 1997; Furlan et al., 2000; Furlan et al., 2002); this is the situation in other regions as well (e.g., Szarukàn, 1977). The presence of meadows and double cropping within the rotation cycle results in a population increase of species belonging to group B (overwintering as adults).

In southern Europe conditions the lifecycle ranged from 24 to 36 months, Furlan, 1998, 2004). Based on the temperature sum needed to complete the cycle, this may be prolonged up to 4 or more years also depending on other factors such as food availability and soil moisture. All species have prolonged period in the soil as larvae before pupation. Wireworms' extended life cycle lets them infest the soil for several years, despite not feeding for some time during their instar. In species overwintering as adults, such as *A. brevis* and *A. sordidus*, they lay eggs during May and early June (Furlan, 1996; Sufyan, 2012). In species non-overwintering as adults, such as *A. litigiosus* and *A. ustulatus*, they start lying once the adults have developed, during summer. The eggs are typically oval or ovoid in shape, though soil resistance against ovipositor may cause irregularities in shape and size. Eggs are typically laid in moist soil and can be found individually or grouped together in clusters containing anywhere from 2 to 39 eggs (Sufyan, 2012). The larvae vary in length between 13 to 37 mm and possess a yellow to yellow-brown exoskeleton (Nordin, 2017). They have an elongated cylindrical body shape and segmented body with biting jaws, and 3 pairs of short legs behind the head. The larvae undergo several stages of development called instars where their bodies transform and grow, each instar is separated by a molting process where the larvae shed their skin and stop feeding before, during and after the process (Sufyan, 2012). Furlan (1998) divided the process in-between two consecutive molting into three phases: (1) darkening and hardening of the mandible after molting, (2) feeding and (3) pre-molting. In the first and third phases, the larvae do not feed meanwhile the second one is the most destructive phase to several crops where the larvae continuously feed with little to no interruption. The length of the instars varies depending on the species and several factors, including temperature and food availability. In general, it takes several months for wireworms to reach maturity, up to several years in certain species. In species overwintering as adults, in late summer, larvae mature and prepare to pupate. They burrow deeper into the soil profile depending on the moisture and transform into pupae, appearing milky white in color (Furlan, 1998). This process can take several days depending on the species and temperature (Furlan, 1998; Sufyan, 2012). Adult click beetles go through a quick development process. Within a two-day span, they become darker in color. Within two weeks, the adults are fully developed with hard and colored skin (Sufyan, 2012). They feed on leaves of cultivated lands, but their damage is considered insignificant and therefore considered as not pests (Furlan 2004). Oviposition periods greatly vary according to the species (from April-May to mid-summer (Furlan 1996, 2004; Sufyan, 2012). To monitor click beetle population, synthetic sex pheromone lures are used. These lures imitate the natural pheromones emitted by female beetles, enticing males, and facilitating population surveillance (Furlan et al. 2001). Additionally, pheromone lures can contribute to the creation of targeted pest management approaches such as trapping and targeted application of insecticides in a strategy known as attract-and-kill (Furlan et al., 2020).

Feeding behavior and damage

Wireworms are extremely polyphagous in nature affecting crops such as vegetables including onion, leeks, garlic; sweet potato; ornamentals; beet; pulse crops such as chickpea, field pea, and lentils; and other wild plants species including weeds (Poggi, et. al, 2021; Knodel and Shrestha, 2018). Among the crops affected are cereals such as maize, winter wheat, solanaceous crops such as tobacco, tomato, potato, different kinds of vegetables such as lettuce, onions, leek, garlic, sugar beet, tomatoes, ground-resting fruits such as strawberries, melons, and wild plant species, including weeds (Edde, 2022; Garcia-del-Pino et al., 2018; Kabaluk, 2023; Poggi et al., 2021; Rashed et al., 2017; Tymon et al., 2021; Vernon et al., 2009; Vernon et al, 2000). Despite a long range of affected crops, some crops such as flax and buckwheat are not typically attacked while others tend to have higher tolerance towards wireworm damage such as pulses and soybean (Alberta Government, 2014).

Wireworm damage on plants is concentrated on feeding the neck and below ground parts. Feeding damage is caused by larval tunnelling through germinating seeds or seedlings, stems, roots, tubers, and wilted dying plants causing scars or holes (Barsics et al., 2013;). These injuries affect seedling mortality, plant growth, yield, and quality, and facilitate infection through secondary plant pathogens (Keiser et al., 2012).

Wireworm damage may cause yield reduction and quality loss of affected crops from seeds to seedling stage and deterioration of quality of root crops such as potatoes (Furlan, 2014; Kuhar and Alvarez, 2008) when economic population are exceeded.

Wireworms are a major problem in potato production as they can negatively impact the yield and quality of potato tubers. Unlike damage to the tubers, wireworms feeding on the seed potatoes rarely affect the growth of the plant itself (Kuhar et al., 2007). While finding wireworms feeding on seed tubers shortly after planting is possible, it does not necessarily indicate the extent of damage that will be done to the daughter tubers (Parker and Howard, 2002). Bigger potato tubers are also more likely to have wireworm damage and the percentage of damage increased with the time the tubers are left in the ground (Kuhar et al., 2007).

In the US, the standard for potato tubers is set at 6% external defects by the USDA (1997). However, Jannsson and Lecrone (1991) have observed that up to 45% of the total potato production can be affected by wireworm damage causing downgrade in quality and rejection causing substantial financial losses. The quality standard of potatoes is set to decline to accommodate the severity of the damage. In Austria, wireworms are responsible for approximately 10% of the total loss of table potatoes, amounting to around 30,000 tons and resulting in losses worth several million euros (EIP-AGRI, 2022).

Different potato cultivars exhibit varying degrees of susceptibility to wireworm damage. In Sweden, Olsson, and Jonasson (1995) found that wireworm damage (*A. obscurus*) on 10 to 13 potato genotypes was inversely related to the concentration of glycoalkaloids and directly correlated with the concentration of reducing sugars in the outer 2 mm of the tubers. Langdon and Abney (2017) observed that while the number of holes and percent injured tubers did not vary, the volume of potato tissue consumed was significantly affected by the cultivars, suggesting that wireworms tend to feed more on some specific cultivars.

Studies have also shown that crop damage is affected by the variability of species within a genus (Furlan, 1998; Furlan, 2004). *A. brevis* and *A. sordidus* can severely damage maize field while no damage occurs with *A. ustulatus* even with high density in the field (Furlan, 1998; Furlan, 2004). In long-term research in wireworms in maize, thresholds of three different species were established, specifically, no yield reduction when there are less than 1 larvae per trap for *A. brevis*, 2 larvae per trap for *A. sordidus*, and 5 larvae per trap for *A. ustulatus* (Furlan, 1998; Furlan, 2014).

Objectives of this research

Therefore, key factor to implement IPM is to complete the list of wireworm density thresholds for all the main crops (for any of the combination crop/harmful organism) based on the susceptibility to wireworm attacks of different crops and varieties.

Thus, the specific objectives of the research were:

1. To assess the severity of damage of different cereal and legume annual crops in terms of mortality, growth, and scars/holes due to three *Agriotes* species;
2. To determine the susceptibility of different varieties of potatoes; Our standard of comparison for wireworm impact is the damage on the first maize instars, profusely studied in the last decades (Furlan, 2014; Furlan, 2016).

In this study, we used three species of *Agriotes*, particularly *A. brevis, A. litigiosus*, and *A. sordidus*. Both *A. brevis* and *A. sordidus* were found to be the most harmful in terms of crop damage in Northeast Italy (Furlan, 2017). *A. sordidus* is also considered as a serious pest in Germany and France (Cocquempot et al., 1999; Lehmhus and Niepold, 2013). *A. litigiosus* is an important species spread throughout several regions of Italy especially in southern-eastern regions (Furlan, 2001).

2. MATERIALS AND METHODS

Two main trials were carried out inside a glass greenhouse in the Experimental farm of the University of Padova, Lucio Toniolo in Viale dell' Università 4, Legnaro, Padova 35020 (coordinates 45.35934546086371, 11.943106988402056) with the below cited goals:

1) Assess the susceptibility of major herbaceous crops to wireworm attacks;
2)Assess the susceptibility of potato varieties, being potato crop a major issue for wireworm damage

The trials were conducted using uniform preparation, materials, and location to maintain consistent methodologies with the materials used for the two trials listed below:

Common Materials

Containers: plastic pots with upper diameter 14 cm and volume 1,1 l with holes in the bottom closed with cotton tissue to prevent larvae from getting out, at the same time allowing water in excess to drop out.
Soil: mixture of 30% sand and 70% loam obtained from Toniolo farm. The sandy loam soil kept at maximum water capacity.
Wireworms: Wireworms were identified and selected for the feeding development stage to make sure that most of larvae were prone to feed on offered seeds and plants. . The selected wireworms were mixed up before introduction in the pots. the different wireworms of same species before introducing to the studies.
Distribution pattern: once prepared, pots were divided into randomized blocks and placed in a shadowy area.
Temperature. Temperature was controlled and recorded with analogical thermometer located inside the greenhouse during the trial period. Minimum and maximum temperature were registered once per day.

Figure 2.1. Preparation of the A. litigiosus larvae.

Figure 2.2. Pot set up in the greenhouse at Toniolo Farm.

2.1 Susceptibility of annual crops to wireworm attack at early stages of development

Maize seeds were the standard to refer the damage observed on the other nine crops since reliable wireworm damage thresholds for maize are available (Furlan et al. 2017, a and b).

Specific Methods

Preliminary evaluation of seeds suitability

Germination % test on seeds: before the trial, at least 10 seeds were put in pots filled with moistened soil to assess the percentage of germinable seeds. Suitable germination should be > 80%.

Biological test on seeds: in 3 vials, 2 untreated seeds were randomly put together 5 larvae in feeding phase per vial, got sure that larvae fed, and waited 7 days for evaluating the larval mortality.

Distribution pattern: once prepared, pots were divided into randomized blocks and placed in a shadowy area.

Irrigation: from the 3rd day onwards 2-3 mm per day per pot.

Temperature. Temperature was controlled and recorded by analogical thermometer located inside the greenhouse during the trial period. Minimum and maximum temperature were registered once per day.

Seeding: immediately before pot preparation, seeds/seedlings per pot planted with seeds interspaced evenly, for granting a constant level. assuring a constant depth according to recommended sowing depth;

Inspections and surveys :

a) Counting emerged plants and conditions assessment every two days until values were stable in 3 consecutive times.

b) After 3 consecutive times of stable values, seed and seedlings removal from pots in order to evaluate wireworm erosions and vegetative parameters. Pots content was then reversed on a towel to chip away at the ground by hand in order to identify the larvae, dividing them into three groups:
   - alive and moving larvae (left on the cloth go away quickly);
   - dying larvae (on the towel in a minute cannot take a specific direction) or not very mobile alive;
   - dead larvae;

   The larvae not found were calculated by difference.

c) For every plant, various parameters were collected, among which:
   - number of days required for emergence.
   - number of healthy plants
   - total number of damaged plants
   - number of damaged plants (alive)
   - number of damaged plants (dead)
   - number of damaged seeds
   - number of erosions + holes on the seeds
   - number of erosions + holes on the seedlings
   - aerial part height
   - roots length
   - fresh weight of roots once washed and dried from water in excess
   - dry weight of the whole plant

d) In order to make the evaluation more expeditious three "Synthetic evaluation indices" were set: "Seed damage index", "Plant condition index", and "Root ramification index" (synthetic comparative way).

Seed damage index	
1	Not attacked seed
2	Partially damaged seed (asportation < 20 %)
3	Damaged seed (asportation between 20-50 %) – germinated
4	Seriously damaged seed (more than 50 % has been removed/broken) - bad germination, weak
5	Seed condition going from badly damaged to destroyed - not germinated

Plant condition index	
1	Healthy plant
2	Alive damaged plant
3	Dead plant of average size
4	Dead damaged seed

Root ramification index	
1	Low ramification (see picture)
2	Average ramification (intermediate cases)
3	Good ramification (see picture)
0	Not developed

Figure 2.1.1. Root ramification index.

<u>Materials</u>

Ten annual crops were selected for the trial to evaluate the susceptibility of annual crops to wireworms. The varieties, number of seeds per pot, and sowing depth are shown in Table 2.1.1. The seeds were planted equally spaced in linear across the pot.

Table 2.1.1. Crops selected for the trial.

No.	Crop	Variety	Seeds per pot	Sowing depth (cm)
1	Maize*	Flour-like = farinoso	2	2.5
2	Maize flint	Nostrano Peroni	2	2.5
3	Bean	Borlotto Etna	2	2.5
4	Hemp	Futura 75	3	1
5	Linum Flax	Sideral	10	0.5
6	Oats	Flavia	6	1
7	Proteic pea	Astronaute	3	1.5
8	Sorghum	PR88Y91	3	1
9	Soybean	Parvati	3	1 or 2.5
10	Winter wheat	N/A	8	1

**Standard of comparison: maize (50 % damage with 6 larvae/ pot).*

Number of larvae: A total of **8 larvae** of *A. litigiosus* per pot immediately after seeding.
Number of repetitions: **4**.

Seeding, larvae placing, and survey were strictly conducted at the same time inside any block as shown in Table 2.1.2.

Table 2.1.2. Activities and dates for the trial.

Activity	Date
Pot preparation	10/29/2021
Planting	10/29/2021
Larvae placing	10/29/2021
Removal of pots	12/06/2021
Removal of larvae	12/06/2021

Temperature. Green vertical lines indicate pot preparation and end of trial.

2.2 Thresholds evaluation for potato varieties to wireworm attack

Fifteen potato varieties were evaluated for their resistance to wireworm damage as shown in the next table.

Number of repetitions: **6**.

Table 2.2.1. Description of potato varieties used.

Thesis	Cod. Tag	Cod. Tag	Variety	Origin	Resistance rate
1	MON	Monalisa	Monalisa	Furlan	Standard
2	MON+L	Monalisa+L	Monalisa	Furlan	Standard
3	BEL+L	Belami+L	Belami	France	Possibly tolerant
4	SEN+L	Sensation+L	Sensation	France	Possibly tolerant
5	JB007+L	JB 007+L	JB 007	France	Possibly tolerant
6	181/10-3+L	181/10-3+L	181/10-3	CREA	Tolerant
7	181/10-4+L	181/10-4+L	181/10-4	CREA	Tolerant
8	201/10-1+L	201/10-1+L	201/10-1	CREA	Tolerant
9	207/11-2+L	207/11-2+L	207/11-2	CREA	Tolerant

10	Q115-6+L	Q 115-6+L	Q 115-6	CREA	Tolerant
11	CHAC+L	*Solanum chacoense*+L	*Solanum chacoense*	CREA	Tolerant
12	AVA+L	Avanti+L	Avanti	Cologna Veneta*	Commercial
13	AGA+L	Agata+L	Agata	Cologna Veneta*	Commercial
14	COL+L	Colomba+L	Colomba	Cologna Veneta*	Commercial
15	AMB+L	Ambra+L	Ambra	Cologna Veneta*	Commercial
16	VIV+L	Vivaldi+L	Vivaldi	Cologna Veneta*	Commercial

*Denotes most used varieties.

Inspections and surveys of potato:

a) Assessment of tubers every week, replacing rotten tubers with a new tuber when appropriate.

b) After 4 weeks of survey, tubers removal from pots for final evaluation of wireworm erosions. Pots content was then reversed on a towel to chip away at the ground by hand in order to identify the larvae, dividing them into three groups:

- -alive and moving larvae (left on the cloth go away quickly);
- dying larvae (on the towel in a minute cannot take a specific direction) or not very mobile alive;
- dead larvae;

Larvae not found were calculated by difference.

c) For every potato tuber, parameters were collected, among which:

- Number of superficial holes/erosions
- Number of deep holes/erosions
- Categorized each erosions/holes based on the following:

Table 2.2.2. Types of potato erosions.

Erosion degree	Type of erosions	Diameter (mm)	Attacked part	Characteristics	Depreciation
Superficial (scars)	**Small**	1 - 2	Peel	Open wound	Not severe
	Ordinary	2 - 5	Peel	Open wound	Not severe
	Large	> 5	Peel	Open wound	Severe
	Old	any	Peel (healed)	Healed scar	Not severe
Deep (holes)	**Small**	1 - 2	Pulp	Open wound	Not severe
	Ordinary	2 - 5	Pulp	Open wound	Severe
	Large	> 5	Pulp	Open wound	Severe
	Old	any	Pulp (healed)	Healed scar	Not severe

Selection of potato tuber:

Every potato tuber is carefully selected to have the most similar shape and size as the rest of the selections for each variety.

Number of larvae: A total of **6 larvae** per pot immediately after planting.

Table 2.2.2. Number of larvae per replication.

Replication	Larvae introduced
1	6 *A. litigiosus*
2	6 *A. litigiosus*
3	6 *A. litigiosus*
4	6 *A. sordidus*
5	6 *A. sordidus*
6	6 *A. sordidus*

Table 2.2.3. Activities and dates for the trial.

Activity	**Date**
Pot preparation	03/31/2022
Planting	03/31/2022
Larvae placing	03/31/2022
Removal of pots	05/05/2022
Removal of larvae	05/05/2022

Temperature. Green vertical lines indicate pot preparation and end of trial.

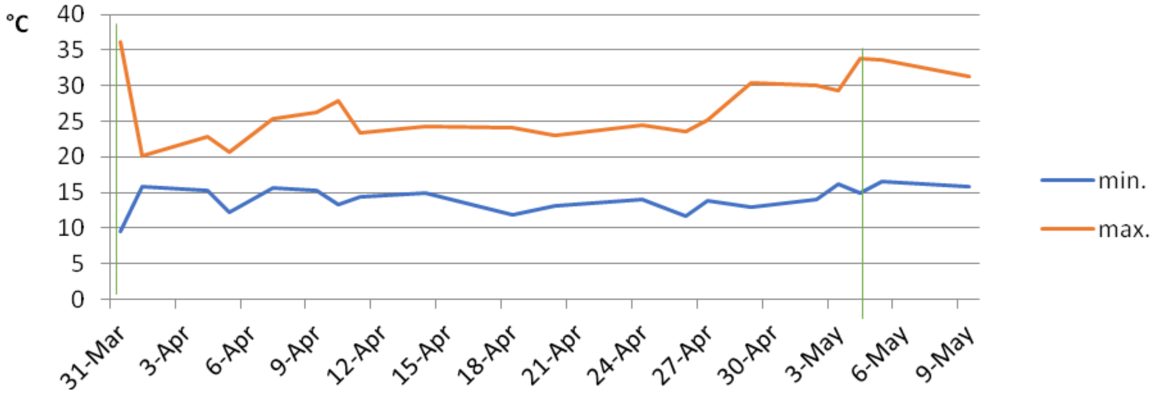

Figure 2.2.1. Photos of some of the potato varieties used.

2.3 Statistical analyses

For Trial 1 on herbaceous crops, for missing plants or plant parts (i.e., dead plants/missing seeds/only roots developed on the seeds), the values for their corresponding parameters are assumed to be zero. The data was transformed into vertical format then all the data were analyzed using ANOVA test and the means were separated using Tukey's honestly significant difference (HSD) at 95.0 percent. Treatments with and without larvae showed homogeneous groups based on 95.0 percent Tukey HSD.

For trial 2 on the evaluation of potato varieties, statistical analysis of data was carried out using ANOVA with the Tukey and Duncan test. Analysis was performed using one-way ANOVA by using R open-source software and R-commander as interface, after performing the Levene test for homogeneity of variance.

3. RESULTS

3.1 Susceptibility of annual crops to wireworm attack at early stages of development

Percent seed emergence

For preliminary evaluation of the seeds of the selected herbaceous crops, a germination test was conducted by planting 10 seeds of each crop and recording the number of germinated seeds. All the crops showed at least 90% germination rate which follows the standard suitable germination of at least 80%.

Table 3.1 Germination rate of selected crops.

No.	Crop	Variety	Germination rate
1	Maize	Flour-like = farinoso	90
2	Maize flint	Nostrano Peroni	100
3	Bean	Borlotto Etna	100
4	Hemp	Futura 75	100
5	Flax	Sideral	90
6	Oats	Flavia	100
7	Proteic pea	Astronaute	100
8	Sorghum	PR88Y91	100
9	Soybean	Parvati	100
10	Winter wheat	N/A	100

Based on Tukey HSD at 95.0 percent, there is a significant difference on the percent seed emergence of crops with and without wireworms as shown in Table 3.1.1. The emergence of crops was significantly decreased due to wireworms.

Figure 3.1.1 shows the interaction and 95.0 percent Tukey HSD intervals. Since any two intervals which do not overlap correspond to a pair of means that have a statistically significant difference, this figure shows that the percent seed emergence is significantly different between pots with larvae and with larvae for many crops.

While hemp showed no significant difference with or without wireworms, the percent seed emergence of all cereals crops particularly maize, maize flint, oats, sorghum, and winter wheat is significantly lower with wireworms. The percent seed emergence decreased by 28.5, 37.5, 17.6, 25.0, and 10.7 percent, respectively, with maize flint having the highest and winter wheat having the lowest decrease among cereal crops. Other crops, particularly beans and flax also decreased by 14.2 and 46.8%, respectively, with flax having the highest percent decrease across all crops. Other legumes, specifically proteic pea and soybeans did not show any decrease in percent seed germination, instead these crops showed higher germination despite the presence of wireworms.

Table 3.1.1. Multiple comparison of pair of means of the percent seed emergence by treatments using Tukey's honestly significant difference (HSD) at 95.0 percent.

Contrast	**Sig.**
0 – L	*

*Denotes a statistically significant difference.

Figures 3.1.1.a and 3.1.1.b show the crops with and without the larvae. The overview of the growth of the plants and the density of the emerged plants shows some differences due to the effects of wireworms on the plants.

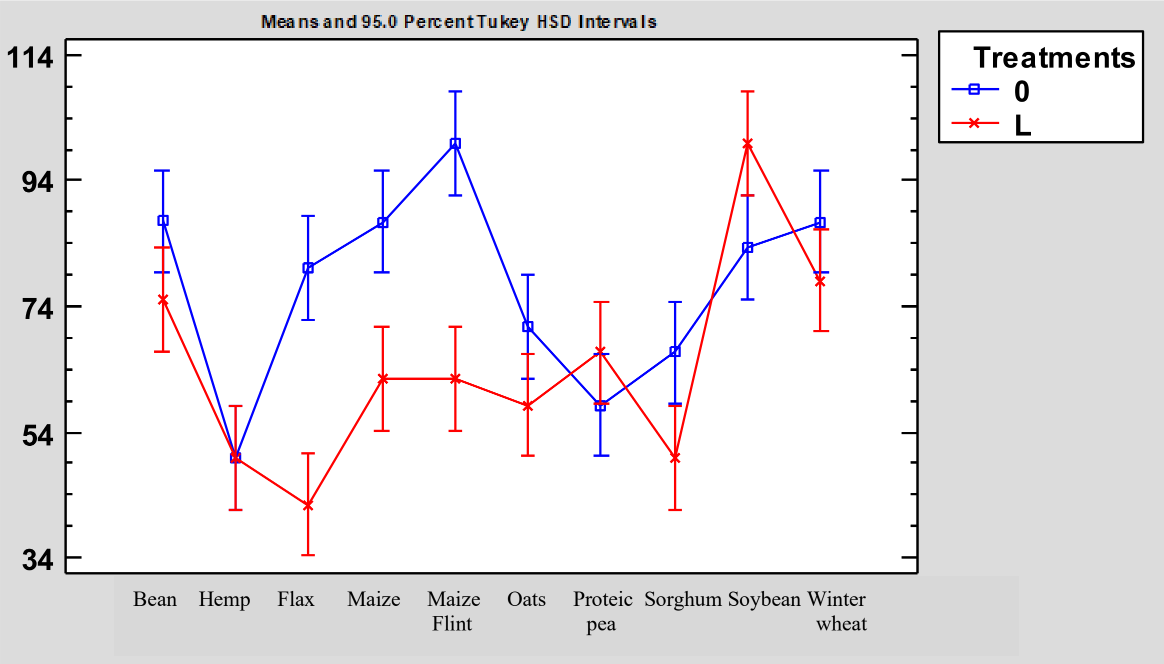

Figure 3.1.1. Percent seed emergence of crops with and without wireworms at 95.0 percent Tukey HSD Intervals.

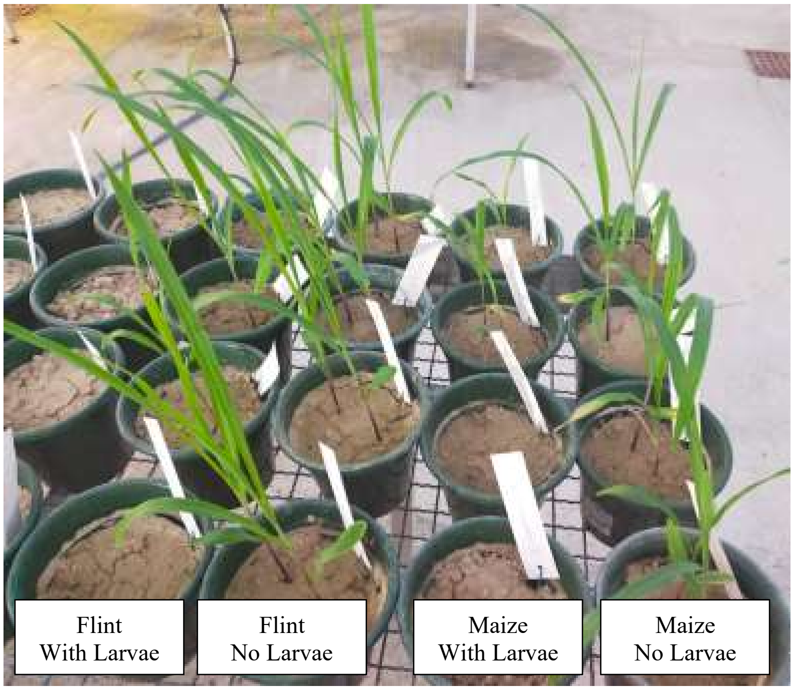

Figure 3.1.1.a. Maize and Maize flint with and without larvae.

Figure 3.1.1.b. Different crops with and without larvae.

Root ramification index

Root ramification index is a rating system that shows the overall growth of the roots based on the observations. The rating is from 1 to 3 with 3 being the value for best root growth and 0 for undeveloped roots. Table 3.1.2 shows that there is a significant difference on the root ramification index between with and without larvae with an implication that root growth is affected by the presence of wireworms.

Figure 3.1.2 shows the interaction and 95.0 percent Tukey HSD intervals of the root ramification index of crops and treatments. It shows that the means of each crop that do not overlap are statistically different from each other.

Based on Figure 3.1.2, almost all crops showed significantly higher root ramification index meaning better root growth without the presence of the larvae except the legumes proteic pea and soybean. The root system of the two crops did not seem to be affected regardless of the presence of wireworms. Hemp's root system is the most affected with 78% decrease in the index while other crops decreased by 20 to 56.2%.

Table 3.1.2. Multiple comparison of pair of means of the root ramification index by treatments using Tukey's honestly significant difference (HSD) at 95.0 percent.

Contrast	**Sig.**
0 – L	*

*Denotes a statistically significant difference.

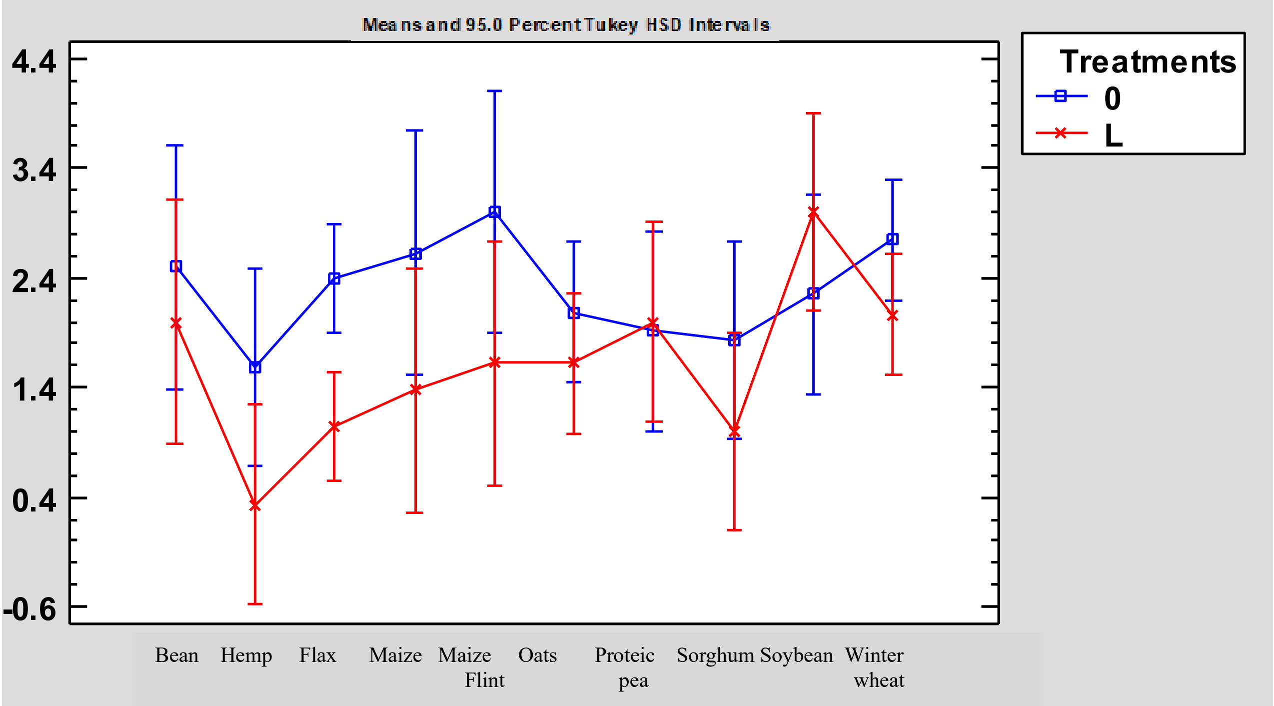

Figure 3.1.2. Root ramification index of crops with and without wireworms at 95.0 percent Tukey HSD Intervals.

Plant condition index

Plant condition index is a rating system that shows the observed overall growth of the crops usually in comparison with the untreated crops. The rating is from 1 to 4 with 1 being the healthy plant and 4 being an undeveloped plant because it could be a dead damaged seed. Table 3.1.3 shows that there is a significant difference between the plant condition index with and without the wireworms.

Plant condition index shows similar but negatively correlated trend to the root ramification index because of the inverse relationship between the rating values of the two indices. Most of the crops except proteic pea and soybean shown in Figure 3.1.3 showed significantly higher plant condition index without wireworms. This implies that the observed plant growth for all selected crops except proteic pea and soybean is not optimal when wireworms are present more likely because of the retarded growth and damage observed on the plants.

Table 3.1.3. Multiple comparison of pair of means of the root ramification index by treatments using Tukey's honestly significant difference (HSD) at 95.0 percent.

Contrast	**Sig.**
0 – L	*

*Denotes a statistically significant difference.

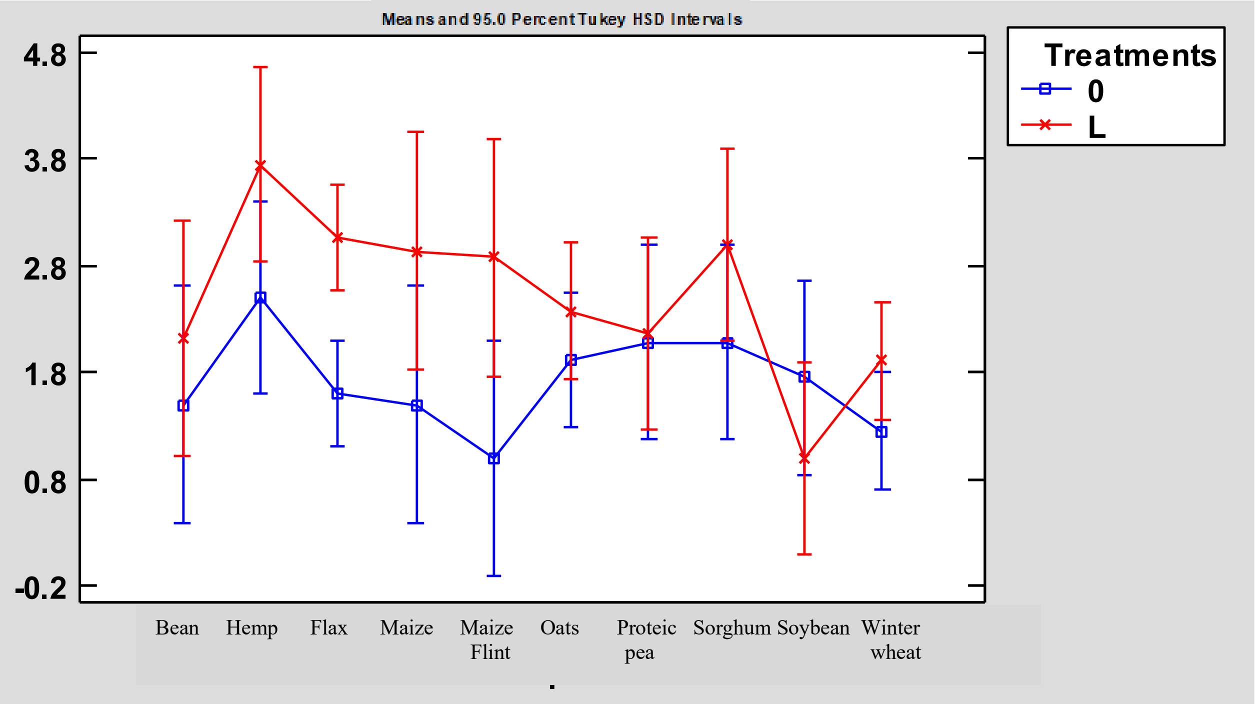

Figure 3.1.3. Plant condition index of crops with and without wireworms at 95.0 percent Tukey HSD Intervals.

Seed damage index

The seed damage index is a rating from 1 to 5 with 1 as undamaged seed and 5 as ungerminated seed due to severe wireworm damage. Based on ANOVA shown in Appendix 3.1.4, there is significant difference between the seed damage index across the selected crops.

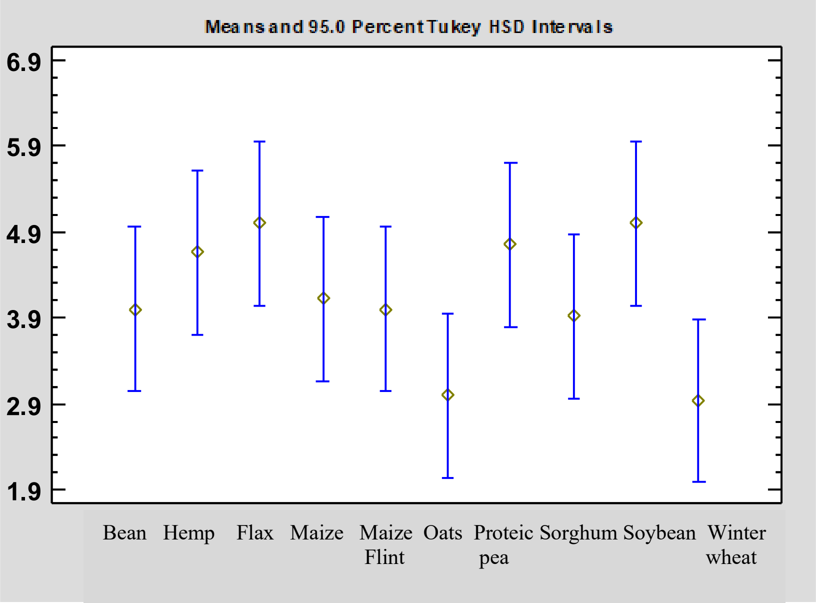

Figure 3.1.4. Mean seed damage index for each level of crop.

As shown in Figure 3.1.4, soybean and flax have the highest mean value of seed damage index with a value of 5 while winter wheat and oats have the lowest with 2.94 and 3.0, respectively. Other legumes such as bean and proteic pea have mean values of 4 and 4.75. Maize and maize flint have similar mean values of 4.13 and 4.0 while sorghum has 3.9. Hemp has a seed damage index of 4.67. With many of the crops' mean values of seed damage index closer to 3, damaged seeds were observed with asportation between 20-50% and as the mean values increasing, so does the damage on the seed. Despite the damage on the seed, it can still germinate as shown in Figure 3.1.4.a. where the seeds of maize flint showed being eaten but one was able to germinate into a stunted plant while the other was only able to grow roots by the time of termination of the trial.

In some cases, seeds were unable to germinate possibly because of the severity of the damage of the wireworms. In Figure 3.1.8.a, while both maize seeds with and without larvae did not germinate, the seed with larvae showed several portions of the seed eaten by the larvae.

After the trial, plants were carefully removed from the pots to determine aerial and root fresh weight and length and observe wireworm damage on each plant and seeds. Figure 3.1.4.c shows the crop sorghum prepared to be measured after retrieval from the pots. The soil in the pots were also filtered to find plant parts such as roots.

Figure 3.1.4.a. Maize flint plant and seeds exposed to wireworms.

Figure 3.1.4.c. Sorghum retrieved after the trial.

Root fresh weight (g)

There is a significant difference between the root fresh weight of crops with and without wireworms as shown in Table 3.1.1. Maize and maize flint roots have the highest decrease of root fresh weight due to the wireworms with around 70% reduction of weight as. Other crops showed slight reduction, but it is notable that both proteic pea and soybean showed no decrease in their root fresh weight as shown in Figure 3.1.5.

Table 3.1.5. Multiple comparison of pair of means of the root fresh weight by treatments using Tukey's honestly significant difference (HSD) at 95.0 percent.

Contrast	Sig.
0 – L	*

*Denotes a statistically significant difference.

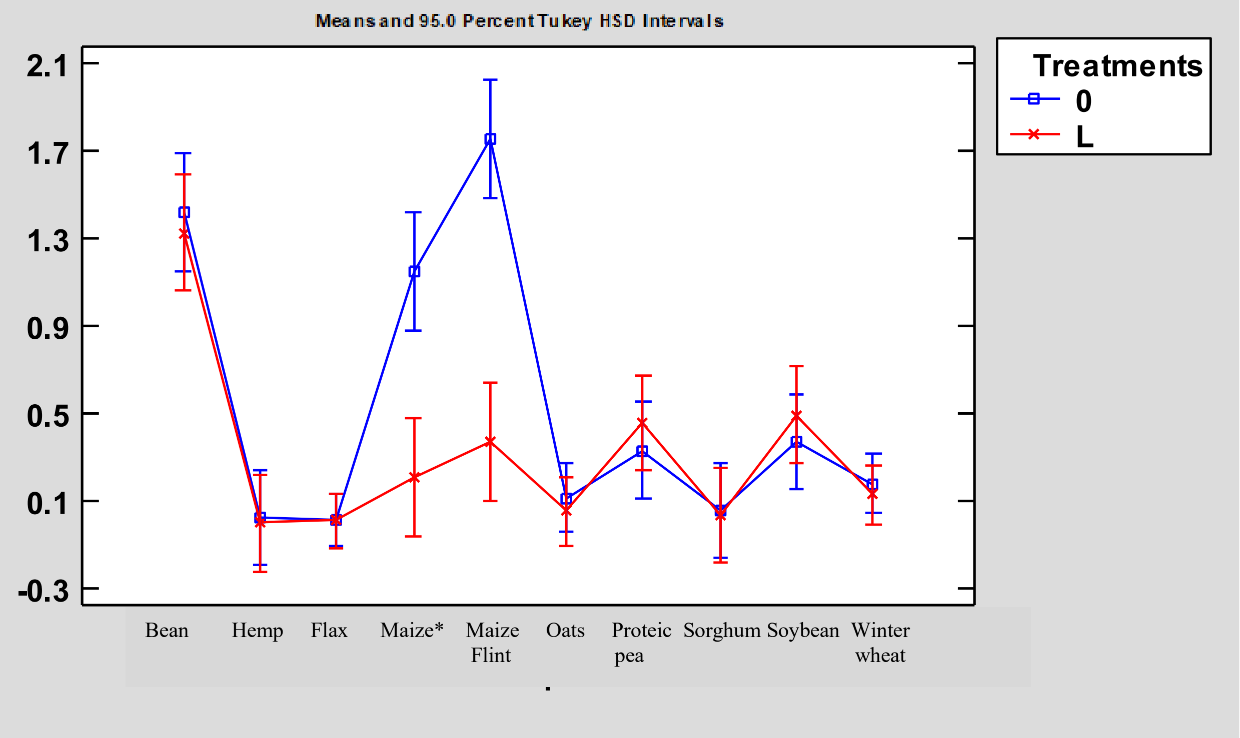

Figure 3.1.5. Root fresh weight interaction plot between crops and treatments.

Root length (cm)

Table 3.1.6 shows that there is a significant difference between the root length of crops with and without wireworms. All crops except soybean showed reduction in the root length. The majority of the crops showed reduced root length by 60 to 78% particularly hemp, flax, maize, maize flint, oats, and sorghum when comparing the length with and without larvae.

Table 3.1.6. Multiple comparison of pair of means of the root fresh weight by treatments using Tukey's honestly significant difference (HSD) at 95.0 percent.

Contrast	**Sig.**
0 – L	*

*Denotes a statistically significant difference.

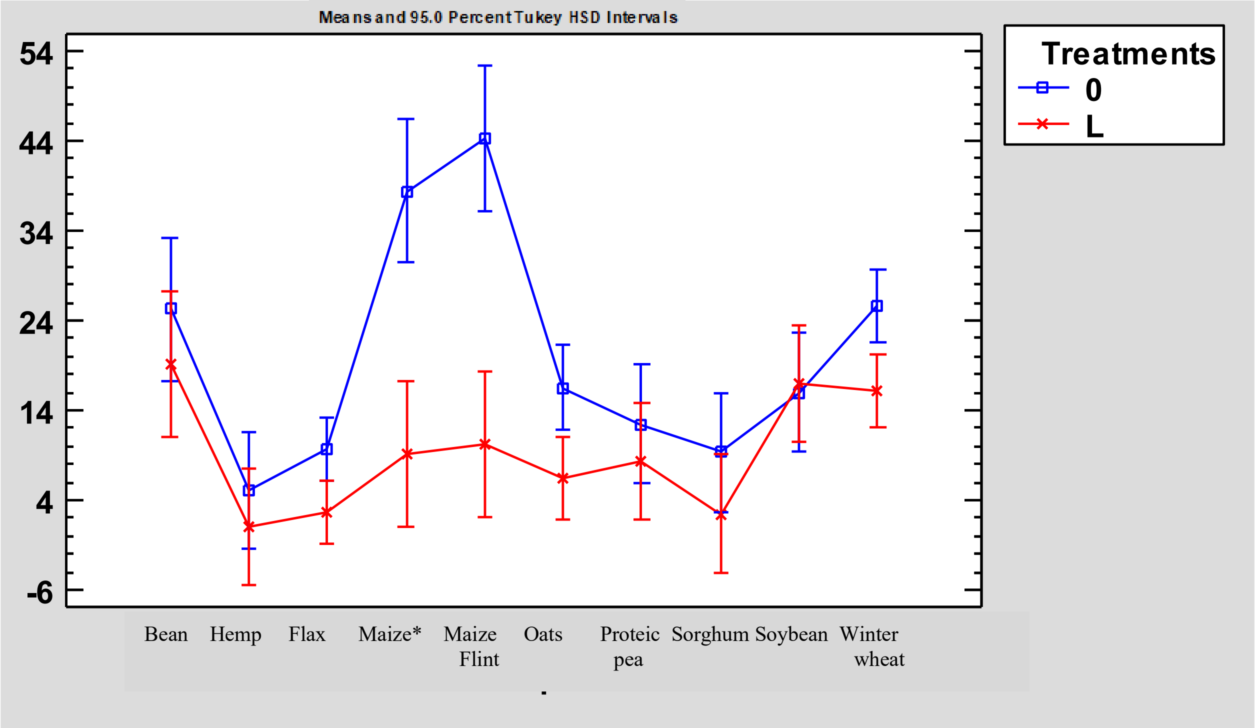

Figure 3.1.6. Root length interaction plot between crops and treatments.

Aerial part fresh weight (g)

Table 3.1.7 shows that the aerial part fresh weight of crops with and without wireworms has shown significant differences between the means. As shown in Figure 3.1.7, all the crops except proteic pea and soybeans have decreased aerial fresh weight when exposed to larvae. Maize, maize, and hemp have the highest reduction of weight when with and without wireworms are compared with about 78 to 84% reduction in weight.

Table 3.1.7. Multiple comparison of pair of means of aerial part fresh weight by treatments using Tukey's honestly significant difference (HSD) at 95.0 percent.

Contrast	**Sig.**
0 – L	*

*Denotes a statistically significant difference.

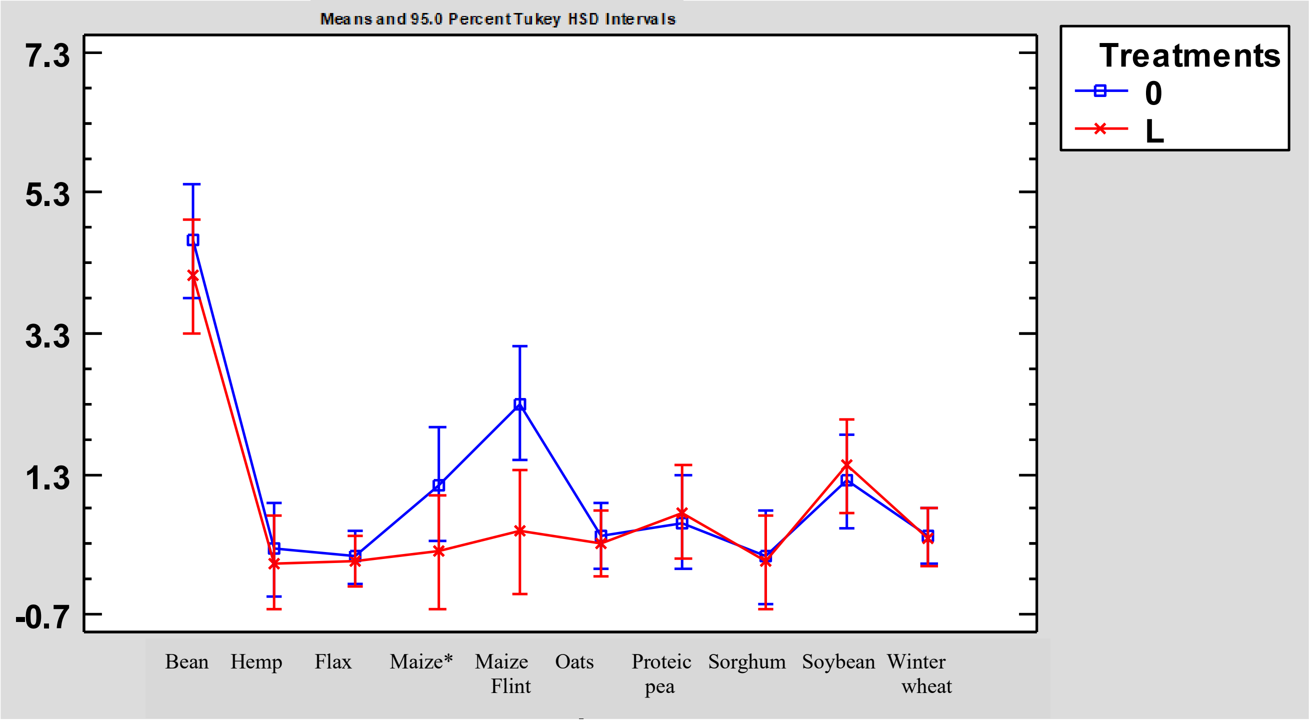

Figure 3.1.7. Aerial fresh weight interaction plot between crops and treatments.

Aerial part height (cm)

Table 3.1.8 shows that there is a significant difference on the aerial part height between with and without larvae. All the crops except proteic pea and soybeans showed a decrease in the aerial height of the plant. Three crops hemp, maize, and maize flint showed reduced height of around 67 to 83% showing reduced growth or stunting among affected plants.

Table 3.1.8. Multiple comparison of pair of means of aerial part height by treatments using Tukey's honestly significant difference (HSD) at 95.0 percent.

Contrast	**Sig.**
0 – L	*

*Denotes a statistically significant difference.

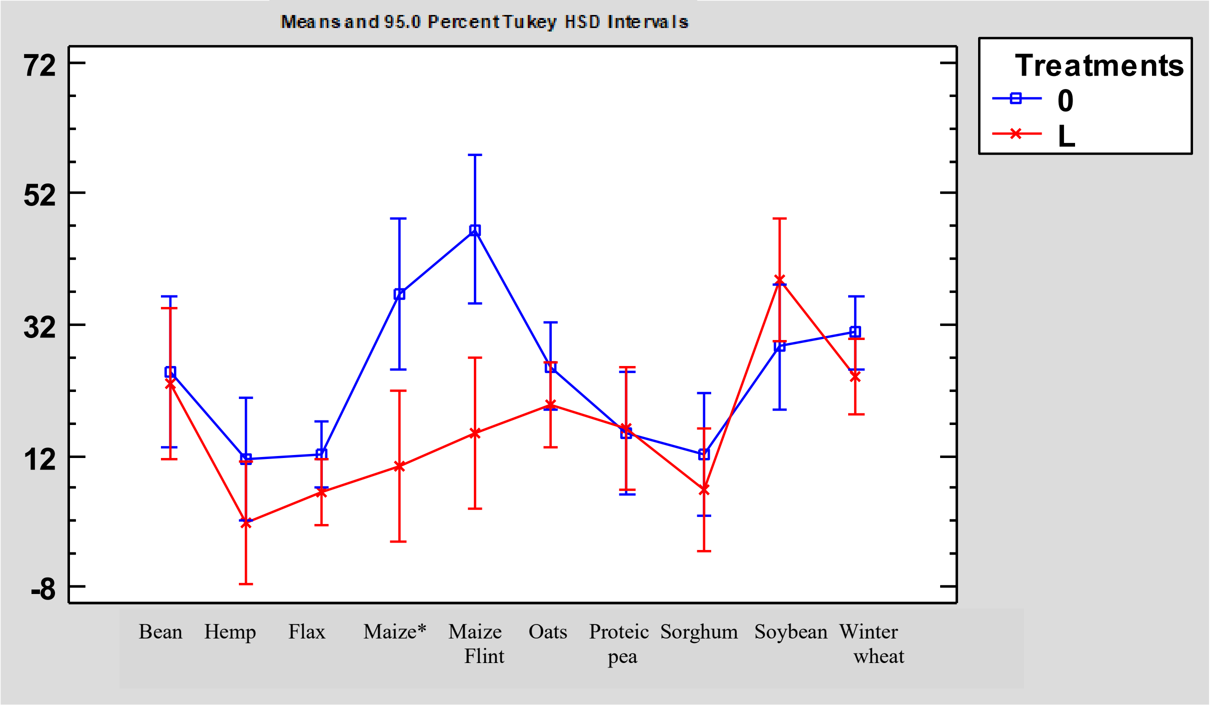

Figure 3.1.7. Aerial part height interaction plot between crops and treatments.

Seed, collar, roots, and total erosions

Scars and holes due to wireworm feeding were observed and counted collectively as number of erosions in specific plant parts. Based on the ANOVA in Appendix 3.1.9 to 3.1.12, there is a significant difference between the means of seed, collar, roots, and total erosion across the crops. Maize and maize flint have the highest number of seed erosions as shown in Figure 3.1.8 with a mean of 3.75 and 4.75 erosions, respectively. Eaten portions particularly on the embryo part of the maize seeds due to larvae consumption can also be observed in Figure 3.1.8.a in contrast to a seed without larvae.

As shown in Figure 2.1.8, erosions to the collar were more observed with legume crops particularly beans and soybean with mean erosions of 2.13 and 2.58, respectively, while the rest of the crops have mean erosions below 1. Figure 3.1.8.c shows some of the erosions on the collar area of the soybean. Some erosions can also be observed in winter wheat as shown in Figure 3.1.8c. Soybean also has the higher mean of erosions on the roots of 2.75 as shown in Figure 3.1.8 while the rest of the crops have 1 or less erosions.

Overall, soybeans have the highest number of total erosions of 9.41. Maize and maize flint have mean values of 4.13 and 6.25 mostly associated from the erosions on the seeds. Bean also has on average 4 total erosions while the least mean erosions is with winter wheat with only 0.22.

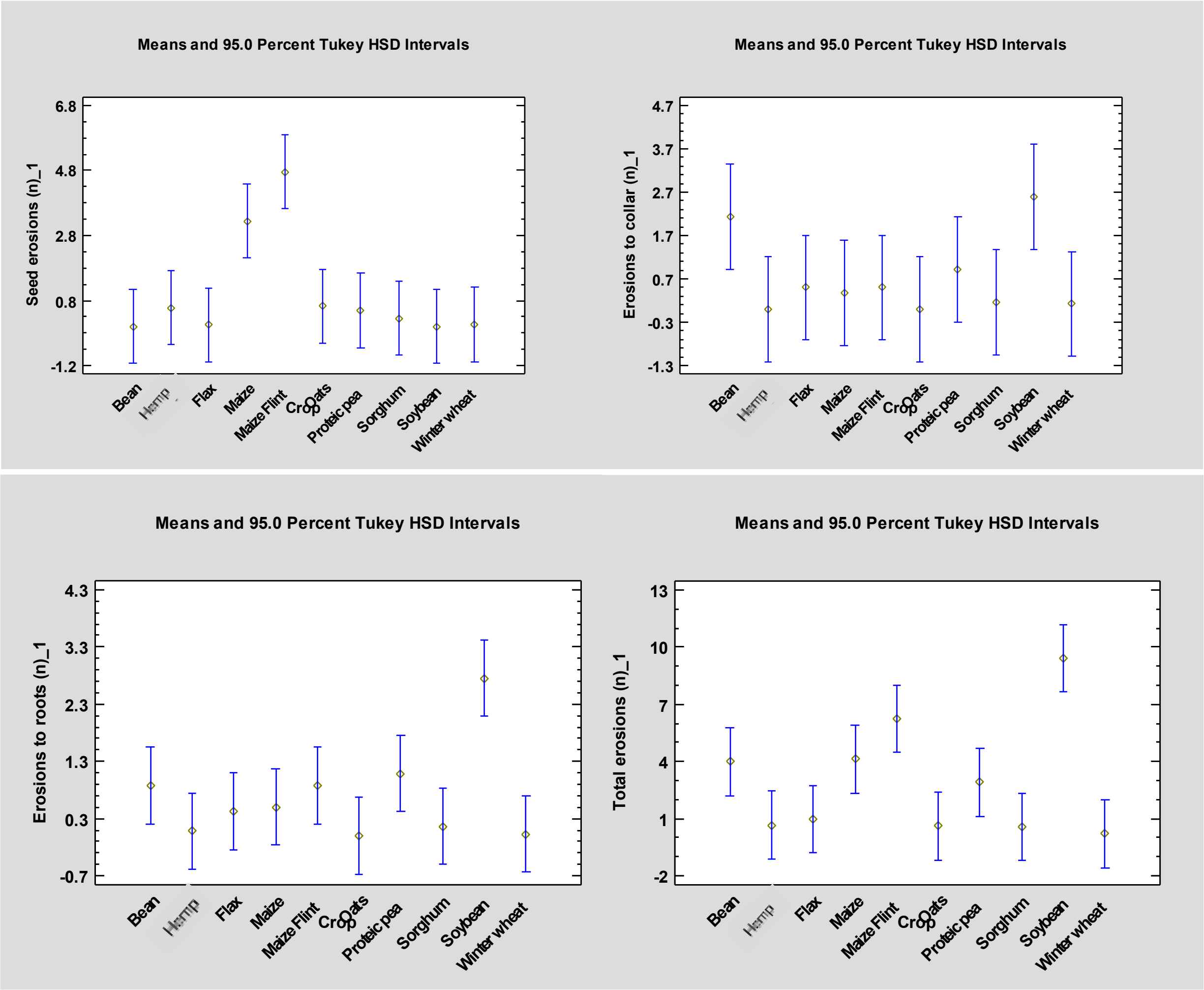

Figure 3.1.8. Means of seed, collar, roots, and total erosions.

Figure 3.1.8.a. Ungerminated maize seeds with and without larvae.

Figure 3.1.8.b. Winter wheat plants with and without larvae.

Figure 3.1.8.c. Soybean plants with and without larvae.

3.2 Thresholds evaluation for potato varieties to wireworm attack

As shown in Table 3.2.1, there is no significant difference on the small, ordinary, and large scars among the selected potato varieties. Although the mean values for large scars do not show significant differences, a majority of the varieties exhibit no large scars, with only five varieties reporting a range of 0.17 to 0.33 mean of large scars. The total number of scars also showed no significant differences between the means.

There is no significant difference between the means of small and large holes but there is a highly significant difference between the mean values of ordinary holes among the selected potato varieties. Colomba, which is a commercial variety, has the highest mean of ordinary holes of 5.83 while *Solanum chacoense* from CREA has the lowest mean of 1. There is also a highly significant difference between the means of sum of ordinary + large holes, and total number of holes in which Colomba is consistently the variety with the highest mean value with means 6.67 and 7.5, respectively. Three varieties from CREA 181/10-3, Q115-6, and *S. chacoense* have the lowest mean values of sum of ordinary + large holes with mean of 1.67, 1.67, and 1.17, respectively. Comparing the means of the total holes, *S. chacoense* showed the lowest mean of 1.17 followed by the varieties 181/10-3, Q115-6, and 207/11-2 with the mean of 1.83, 2.17, and 2.5, respectively.

Total wireworm erosions showed highly significant difference among the means with Colomba having the highest mean of erosions of 12.8 while followed closely by Vivaldi and Ambra with means 12.5 and 11.7, respectively. Overall, the variety 181/10-3+L showed the lowest mean of total erosions of 3.83 followed by *S. chacoense* with the mean 4.33. Figure 3.2.1 shows the total of scars and holes observed in different varieties of potatoes.

Table 3.2.2 shows that there is no significant difference between the means of retrieved alive, dying, and dead larvae, and missing larvae.

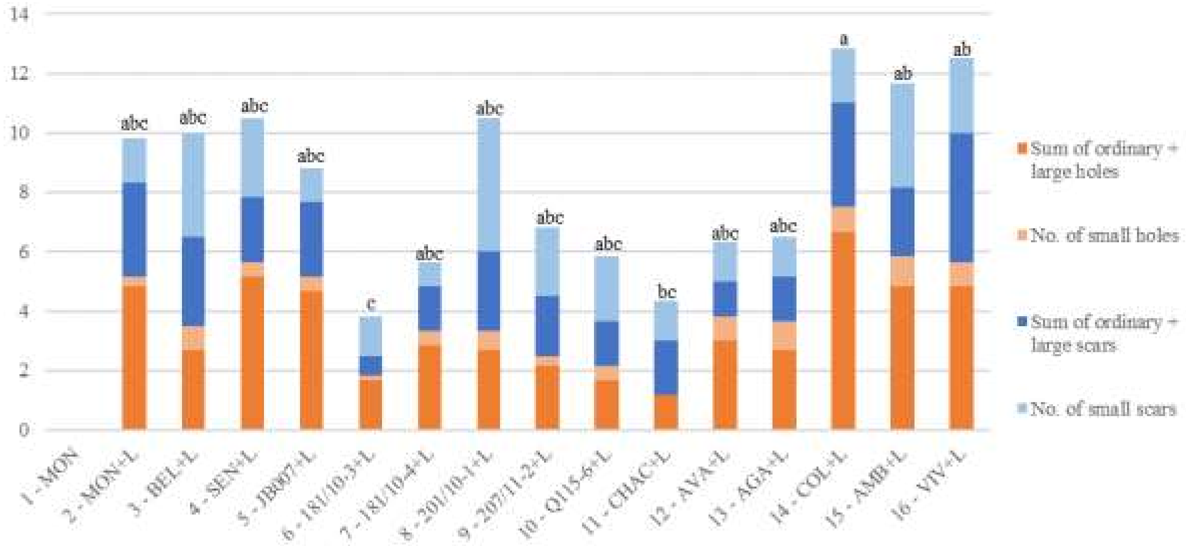

Figure 3.2.1. Erosions across selected potato varieties. (Means with the same letter are not significantly different for Tukey test at p=0.05.)

Figure 3.2.2 shows different types of erosion on different potato varieties in the first week of survey. The tuber of Avanti clearly shows an example of a large hole while Belami shows ordinary scars on the surface of the tuber. It has been observed several times during the surveys that the wireworm larvae burrow deep into the tubers leaving holes of different sizes and sometimes another whole that is interconnected to another hole as an entrance and exit of the larvae such as in the Avanti tuber. In some cases, the tissues around the ordinary or large holes depicted in the tuber of Colomba exhibit softening of tissues more likely due to the consumption of the flesh around that area of the tuber.

Figure 3.2.3 shows some of the potato varieties evaluated during the second week of survey. The tubers have different sizes of scars and holes with some holes closely clustered on some of the portions of the tubers such as in the tubers of Monalisa and Vivaldi or some holes are scattered on the surface such as in the tuber of JK 007 and 181/10-4.

Table 3.2.1. Table of means for erosions on different potato varieties.

Treatment	No. of small scars		No. of ordinary scars		No. of large scars		Sum of ordinary + large scars		Total of scars		No. of small holes		No. ordinary holes		No. large holes		Sum of ordinary + large holes		Total of holes		Tot. wireworm erosions	
1 - MON	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2 - MON+L	1.5	*a*	3.17	*ab*	0	*a*	3.17	*a*	4.67	*a*	0.33	*a*	4.33	*ab*	0.5	*a*	4.83	*ab*	5.17	*abc*	9.83	*abc*
3 - BEL+L	3.5	*a*	2.83	*ab*	0.17	*a*	3	*a*	6.5	*a*	0.83	*a*	2	*ab*	0.67	*a*	2.67	*ab*	3.5	*abc*	10	*abc*
4 - SEN+L	2.67	*a*	2	*ab*	0.17	*a*	2.17	*a*	4.83	*a*	0.5	*a*	4.67	*ab*	0.5	*a*	5.17	*ab*	5.67	*abc*	10.5	*abc*
5 - JB007+L	1.17	*a*	2.33	*ab*	0.17	*a*	2.5	*a*	3.67	*a*	0.5	*a*	3.83	*ab*	0.83	*a*	4.67	*ab*	5.17	*abc*	8.83	*abc*
6 - 181/10-3+L	1.33	*a*	0.67	*b*	0	*a*	0.67	*a*	2	*a*	0.17	*a*	1.67	*ab*	0	*a*	1.67	*b*	1.83	*bc*	3.83	*c*
7 - 181/10-4+L	0.83	*a*	1.33	*ab*	0.17	*a*	1.5	*a*	2.33	*a*	0.5	*a*	2.83	*ab*	0	*a*	2.83	*ab*	3.33	*abc*	5.67	*abc*
8 - 201/10-1+L	4.5	*a*	2.67	*ab*	0	*a*	2.67	*a*	7.17	*a*	0.67	*a*	2.5	*ab*	0.17	*a*	2.67	*ab*	3.33	*abc*	10.5	*abc*
9 - 207/11-2+L	2.33	*a*	2	*ab*	0	*a*	2	*a*	4.33	*a*	0.33	*a*	1.83	*ab*	0.33	*a*	2.17	*ab*	2.5	*bc*	6.83	*abc*
10 - Q115-6+L	2.17	*a*	1.5	*ab*	0	*a*	1.5	*a*	3.67	*a*	0.5	*a*	1.67	*ab*	0	*a*	1.67	*b*	2.17	*bc*	5.83	*abc*
11 - CHAC+L	1.33	*a*	1.83	*ab*	0	*a*	1.83	*a*	3.17	*a*	0	*a*	1	*b*	0.17	*a*	1.17	*b*	1.17	*c*	4.33	*bc*
12 - AVA+L	1.33	*a*	0.83	*b*	0.33	*a*	1.17	*a*	2.5	*a*	0.83	*a*	2.67	*ab*	0.33	*a*	3	*ab*	3.83	*abc*	6.33	*abc*
13 - AGA+L	1.33	*a*	1.5	*ab*	0	*a*	1.5	*a*	2.83	*a*	1	*a*	2.33	*ab*	0.33	*a*	2.67	*ab*	3.67	*abc*	6.5	*abc*
14 - COL+L	1.83	*a*	3.5	*ab*	0	*a*	3.5	*a*	5.33	*a*	0.83	*a*	5.83	*a*	0.83	*a*	6.67	*a*	7.5	*a*	12.8	*a*
15 - AMB+L	3.5	*a*	2.33	*ab*	0	*a*	2.33	*a*	5.83	*a*	1	*a*	4.5	*ab*	0.33	*a*	4.83	*ab*	5.83	*ab*	11.7	*ab*
16 - VIV+L	2.5	*a*	4.33	*a*	0	*a*	4.33	*a*	6.83	*a*	0.83	*a*	3.5	*ab*	1.33	*a*	4.83	*ab*	5.67	*ab*	12.5	*ab*
Sign.	.		.		ns		ns		*		ns		**		ns		***		***		***	
P	0.077		0.0709		0.734		0.121		0.0411		0.853		0.00182		0.285		0.0008		0.00027		0.0006	
F	1.684		1.712		0.734		1.531		1.889		0.605		2.844		1.212		3.101		3.42		3.177	
GdL	89		89		89		89		89		89		89		89		89		89		89	

Means with the same letter are not significantly different for Tukey/Duncan test at p=0.05.

Tukey

Duncan

Figure 3.2.2. Some photos of different potato varieties (Survey 1).

Figure 3.2.3. Some photos of different potato varieties (Survey 2).

Table 3.2.2. Table of means of larvae retrieved from the trial.

Treatment	**% alive larvae**		**% dying larvae**		**% dead larvae**		**% not found larvae**	
1 - MON	-	-	-	-	-	-	-	-
2 - MON+L	70.8	*a*	0.0	*a*	4.2	*a*	25	*a*
3 - BEL+L	87.5	*a*	0.0	*a*	0.0	*a*	12.5	*a*
4 - SEN+L	75.0	*a*	0.0	*a*	0.0	*a*	25	*a*
5 - JB007+L	87.5	*a*	0.0	*a*	0.0	*a*	12.5	*a*
6 - 181/10-3+L	91.7	*a*	0.0	*a*	0.0	*a*	8.3	*a*
7 - 181/10-4+L	79.2	*a*	0.0	*a*	0.0	*a*	20.8	*a*
8 - 201/10-1+L	70.8	*a*	0.0	*a*	8.3	*a*	20.8	*a*
9 - 207/11-2+L	70.8	*a*	0.0	*a*	0.0	*a*	29.2	*a*
10 - Q115-6+L	83.3	*a*	0.0	*a*	0.0	*a*	16.7	*a*
11 - CHAC+L	91.7	*a*	0.0	*a*	0.0	*a*	8.3	*a*
12 - AVA+L	62.5	*a*	0.0	*a*	0.0	*a*	37.5	*a*
13 - AGA+L	70.8	*a*	0.0	*a*	4.2	*a*	25.0	*a*
14 - COL+L	79.2	*a*	0.0	*a*	0.0	*a*	20.8	*a*
15 - AMB+L	91.7	*a*	0.0	*a*	0.0	*a*	8.3	*a*
16 - VIV+L	87.5	*a*	0.0	*a*	4.2	*a*	8.3	*a*
Sign.	ns		ns		ns		ns	
P	0.754		0.462		0.297		0.904	
F	0.714		1		1.195		0.536	
GdL	89		89		89		89	

Means with the same letter are not significantly different for Tukey test at p=0.05

4. DISCUSSION

4.1 Susceptibility of annual crops to wireworm attack at early stages of development

This trial showed different effects of the wireworm on several annual crops in terms of percentage of emerged plants, and plant growth. In terms of growth, cereal crops, particularly maize and maize flint showed more susceptibility to wireworm damage based on the reduction in average of root and aerial weights and lengths. Meanwhile, legumes, specifically proteic pea and soybeans showed more tolerance to the larvae as observed with their plant and root growth unaffected especially despite the soybean having the highest total erosions to the plant. The same trend of susceptibility of cereals and tolerance of two legumes was also observed in both the root ramification index and the plant condition index.

In terms of seed emergence, cereals are more affected by wireworms with all selected cereal crops exhibiting decrease in emergence. Maize and maize flint showed the highest reduction from 28.5 to 37.5% decrease due to larvae while other cereal crops showed 10.7 to 25% reduction compared to those without larvae. Differently, legume crops such proteic pea and soybean, with the exception of bean even showed an increase in the emergence with larvae further showing their high tolerance to wireworms even during the early seeding phase. Flax showed a low susceptibility as well.

The reduction of emergence of seeds for maize and maize flint can be associated with the relatively higher number of seed erosions of the two crops. However, the seed dame index did not reflect the same trend as the seed erosions or the seed emergence. This is probably because this index is based on maize and can be difficult to apply to other crops. Further evaluation of the seed damage index can be made in order to adapt to other crops, not only to standard maize.

In general, this trial shows that cereals tend to be more susceptible to wireworm damage while some legumes such as soybean and proteic pea are more tolerant as observed by other studies (Vernon, 2010; Alberta Government, 2014; Radcliffe and Lagnaoui, 2007). However, wireworms can still damage young legume crops such as bean and flax (Vernon, 2010; Glogoza, 2001).

4.2 Susceptibility of potato varieties to wireworm attack

In this trial, it was observed that different varieties of potato showed varying degrees of susceptibility to wireworm attack as elaborated by previous studies (Olsson and Jonasson, 1995; Kwon et al., 1999; Abney, 2017). Commercial varieties particularly Monalisa, Colomba, Vivaldi, and Ambra showed the highest susceptibility among the varieties evaluated. Colomba also showed the highest number of holes of different sizes from small to large holes. The susceptibility of common commercial varieties suggests that potato farmers need to impose more control measures to manage wireworms in the field.

As expected from the tolerant potato varieties from CREA, most of the varieties showed significant decrease in scars and holes due to wireworms except variety 201/10-1 which incurred the highest total scars. Variety 181/10-3 and wild potato *Solanum chacoense* showed the lowest damage while varieties 207/11-2 and Q1156 showed significant decrease in the number holes in the tuber. This shows a huge potential for CREA varieties to lessen the impact of wireworms on potato productiony and also the potential of *Solanum chacoense* as a source of breeding material to create more tolerant commercial varieties.

Olsson and Jonasson (1994) cited that glycoalkaloids, which is a natural toxic compound found in Solanaceae family, play a crucial role in potato tuber resistance. Wireworms were also observed to feed on sites with high sugar content and low glycoalkaloids.

5. CONCLUSION

Wireworms are polyphagous pests that can damage a wide range of crops, particularly annual crops. It is important to establish the susceptibility of different crops to be able to set reliable thresholds for IPM implementation. This research allowed us to find conspicuous differences between species making it possible to pinpoint the fields where a wireworm control is needed, and which crops may be planted without the risk of an economic damage. Some crops can be considered susceptible to wireworm attacks due to the significant plant reduction. In some cases, this reduction may result in an economic loss particularly in maize (Furlan 2014; Furlan et al. 2017a, 2020), for other crops, such as winter wheat, a 10% plant reduction is likely not to cause a yield loss.

The lower susceptibility to wireworm attacks of some potato varieties opens the same possibilities for potato production as well is recommended to allow farmers to have options for appropriate potato varieties especially in wireworm infested fields.

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Appendix 3.1.1. Analysis of Variance for Perc seed emerg - Type III Sums of Squares

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Block	9642.86	3	3214.29	1.65	0.1773
B:Crop	47930.1	9	5325.56	2.74	0.0043
C:Treatments	9852.09	1	9852.09	5.06	0.0251
INTERACTIONS					
BC	23787.2	9	2643.02	1.36	0.2062
RESIDUAL	608878.	313	1945.3		
TOTAL (CORRECTED)	710357.	335			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of perc emerged plant per line into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since 2 P-values are less than 0.05, these factors have a statistically significant effect on perc emerged plant per line at the 95.0% confidence level.

Appendix 3.1.2. Analysis of Variance for Root ramification index - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	3.1756	3	1.05853	0.68	0.5618
B:Crop	62.7464	9	6.97183	4.51	0.0000
C:Treatments	29.2765	1	29.2765	18.94	0.0000
INTERACTIONS					
BC	30.3012	9	3.3668	2.18	0.0233
RESIDUAL	483.699	313	1.54537		
TOTAL (CORRECTED)	627.926	335			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Root ramification index into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since 3 P-values are less than 0.05, these factors have a statistically significant effect on Root ramification index at the 95.0% confidence level.

Appendix 3.1.3. Analysis of Variance for Plant condition index - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	2.0558	3	0.685268	0.45	0.7200
B:Crop	66.5388	9	7.3932	4.82	0.0000
C:Treatments	39.9591	1	39.9591	26.03	0.0000
INTERACTIONS					
BC	35.8972	9	3.98857	2.60	0.0067
RESIDUAL	480.465	313	1.53503		
TOTAL (CORRECTED)	643.708	335			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Plant condition index into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since 3 P-values are less than 0.05, these factors have a statistically significant effect on Plant condition index at the 95.0% confidence level.

Appendix 3.1.4. Analysis of Variance for Seed damage index - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	1.32378	3	0.441262	0.72	0.5504
B:Crop	19.8543	9	2.20604	3.58	0.0048
RESIDUAL	16.6155	27	0.615387		
TOTAL (CORRECTED)	37.7936	39			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Seed damage index into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since one P-value is less than 0.05, this factor has a statistically significant effect on Seed damage index at the 95.0% confidence level.

Appendix 3.1.5. Analysis of Variance for Root fresh weight (g) - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	0.439934	3	0.146645	1.62	0.1839
B:Crop	43.7008	9	4.85565	53.75	0.0000
C:Treatments	3.3456	1	3.3456	37.04	0.0000
INTERACTIONS					
BC	10.3126	9	1.14584	12.68	0.0000
RESIDUAL	28.2745	313	0.0903338		
TOTAL (CORRECTED)	83.9117	335			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Root fresh weight (g) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since 3 P-values are less than 0.05, these factors have a statistically significant effect on Root fresh weight (g) at the 95.0% confidence level.

Appendix 3.1.6. Analysis of Variance for Root length (cm) - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	679.502	3	226.501	2.79	0.0407
B:Crop	18183.7	9	2020.41	24.88	0.0000
C:Treatments	7512.69	1	7512.69	92.51	0.0000
INTERACTIONS					
BC	5200.31	9	577.813	7.11	0.0000
RESIDUAL	25419.9	313	81.2138		
TOTAL (CORRECTED)	56610.7	335			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Root length (cm) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since 4 P-values are less than 0.05, these factors have a statistically significant effect on Root length (cm) at the 95.0% confidence level.

Appendix 3.1.7. Analysis of Variance for Aerial fresh weight (g) - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	1.80418	3	0.601393	0.72	0.5387
B:Crop	285.743	9	31.7492	38.18	0.0000
C:Treatments	7.17346	1	7.17346	8.63	0.0036
INTERACTIONS					
BC	15.3093	9	1.70103	2.05	0.0342
RESIDUAL	259.424	312	0.831486		
TOTAL (CORRECTED)	566.574	334			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Aerial fresh weight (g) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since 3 P-values are less than 0.05, these factors have a statistically significant effect on Aerial fresh weight (g) at the 95.0% confidence level.

Appendix 3.1.8. Analysis of Variance for Aerial part height (cm) - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	166.792	3	55.5972	0.34	0.7980
B:Crop	26813.3	9	2979.26	18.10	0.0000
C:Treatments	4164.94	1	4164.94	25.30	0.0000
INTERACTIONS					
BC	6164.19	9	684.91	4.16	0.0000
RESIDUAL	51517.5	313	164.593		
TOTAL (CORRECTED)	88355.2	335			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Aerial part height (cm) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since 3 P-values are less than 0.05, these factors have a statistically significant effect on Aerial part height (cm) at the 95.0% confidence level.

Appendix 3.1.9. Analysis of Variance for Seed erosions (n) - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	0.256229	3	0.0854097	0.10	0.9608
B:Crop	96.1306	9	10.6812	12.17	0.0000
RESIDUAL	23.6991	27	0.877745		
TOTAL (CORRECTED)	120.086	39			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Seed erosions (n) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since one P-value is less than 0.05, this factor has a statistically significant effect on Seed erosions (n) at the 95.0% confidence level.

Appendix 3.1.10. Analysis of Variance for Erosions to collar (n) - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	2.31469	3	0.771565	0.78	0.5154
B:Crop	29.5868	9	3.28742	3.32	0.0074
RESIDUAL	26.7072	27	0.989157		
TOTAL (CORRECTED)	58.6088	39			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Erosions to collar (n) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since one P-value is less than 0.05, this factor has a statistically significant effect on Erosions to collar (n) at the 95.0% confidence level.

Appendix 3.1.11. Analysis of Variance for Erosions to roots (n) - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	0.132186	3	0.0440619	0.15	0.9309
B:Crop	24.4954	9	2.72171	9.06	0.0000
RESIDUAL	8.10981	27	0.300363		
TOTAL (CORRECTED)	32.7374	39			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Erosions to roots (n) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since one P-value is less than 0.05, this factor has a statistically significant effect on Erosions to roots (n) at the 95.0% confidence level.

Appendix 3.1.12. Analysis of Variance for Total erosions (n) - Type III Sums of Squares

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
MAIN EFFECTS					
A:Block	1.97346	3	0.657821	0.31	0.8194
B:Crop	331.06	9	36.7845	17.22	0.0000
RESIDUAL	57.6855	27	2.1365		
TOTAL (CORRECTED)	390.719	39			

All F-ratios are based on the residual mean square error.

The StatAdvisor

The ANOVA table decomposes the variability of Total erosions (n) into contributions due to various factors. Since Type III sums of squares (the default) have been chosen, the contribution of each factor is measured having removed the effects of all other factors. The P-values test the statistical significance of each of the factors. Since one P-value is less than 0.05, this factor has a statistically significant effect on Total erosions (n) at the 95.0% confidence level.

Appendix 3.2.1. Analysis of Variance for large scars

	Df	Sum	Sq Mean	Sq	F value	Pr(>F)
Thesis_factor	14	0.2096	0.01497	0.734	0.734	
Residuals	75	1.5298	0.02040			

Appendix 3.2.2. Analysis of Variance for ordinary scars

	Df	Sum	Sq Mean	Sq	F value	Pr(>F)
Thesis_factor	14	7.647	0.5462	1.712	0.0709	
Residuals	75	23.930	0.3191			

Appendix 3.2.3. Analysis of Variance for small scars

	Df	Sum	Sq Mean	Sq	F value	Pr(>F)
Thesis_factor	14	1.321	0.09438	0.605	0.853	
Residuals	75	11.697	0.15596			

Appendix 3.2.4. Analysis of Variance for large holes

	Df	Sum	Sq Mean	Sq	F value	Pr(>F)
Thesis_factor	14	1.944	0.1389	1.212	0.285	
Residuals	75	8.593	0.1146			

Appendix 3.2.5. Analysis of Variance for ordinary holes

	Df	Sum	Sq Mean	Sq	F value	Pr(>F)
Thesis_factor	14	11.16	0.7969	2.844	0.00182	**
Residuals	75	21.01	0.2802			

Appendix 3.2.6. Analysis of Variance for small holes

	Df	Sum	Sq Mean	Sq	F value	Pr(>F)
Thesis_factor	14	1.321	0.09438	0.605	0.853	
Residuals	75	11.697	0.15596			