Wireworm
Biology and Nonchemical Management in Potatoes in the Pacific Northwest

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This bulletin is one of a series on organic potato production developed by OSPUD, a collaboration among Oregon State University personnel and 11 farmers operating diversified organic vegetable farms. The purpose of OSPUD is to improve potato quality and profitability through a participatory learning process and on-farm, farmer-directed research. The first 2 years of OSPUD were supported by Western SARE Grant SW05-091. For more information on OSPUD, visit ospud.org.

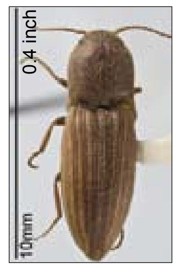
Wireworm is the common name for the larvae of click beetles (Coleoptera: Family Elateridae). The adults do little or no damage, although there are some anecdotal reports that they can damage certain crops (e.g., grapes and stone fruits) by feeding on flowers. However, larval wireworms are among the most destructive of soil insect pests. They are important pests of potatoes and other crops, including corn, cereals, and carrots. Less frequently attacked are melons, beet roots, and strawberry fruits. Wireworms can also damage germinating seeds, but transplants are generally less susceptible. Their importance as crop pests seems to be increasing (Parker and Howard, 2001).

This publication reviews the wireworm literature and provides information on wireworm biology, monitoring, risk assessment, and nonchemical control options that can be integrated into a variety of production systems.

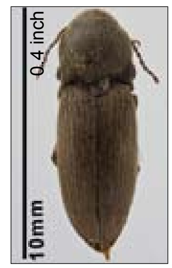
Background

Description

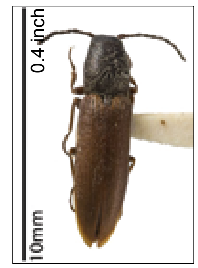
Adult click beetles are slender, hard-shelled beetles. They range from tan to dark brown and from about 8–20 mm long (⅓–¾ inch), depending on species (Figure 1). Click beetles get their name from their ability to snap a spine on their thorax, thus producing a sudden clicking sound and allowing them to jump in the air. All beetles in this family have this ability, which they use to avoid predation or to get back on their feet after falling on their back.



Agriotes lineatus

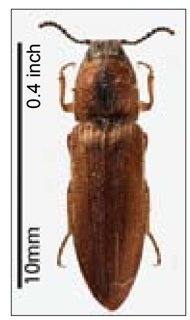


Agriotes obscurus



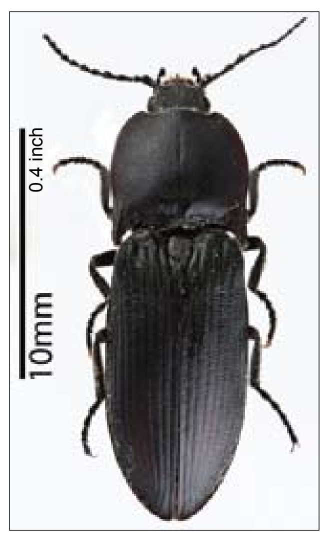
Limonius subauratus

Limonius californicus



Limonius canus

Limonius infuscatus



Ctenicera pruinina

Figure 1. Click beetle adults of the Pacific Northwest. (Photos by Christopher J. Marshall, Oregon State Arthropod Collection—2008, Department of Zoology, Oregon State University, Corvallis, OR. http://osac.science.oregonstate.edu. Images taken using Visionary Digital Imaging System)

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After mating, each female lays an average of about 80 eggs in the soil, either singly or in small clusters. Eggs of most wireworms are white, spherical, and about 0.5 mm in diameter.

Immediately after egg hatch, wireworm larvae are white; with age they darken to tan or reddish brown. Unlike the immature stages of most insects, wireworms have a hardened, shiny shell (exoskeleton) and very few hairs (Figure 2). They have three body regions: a fairly distinct head, a thorax with three pairs of legs, and a segmented abdomen with processes or prongs at the tail end. Depending on species, wireworm larvae range from about 2 mm long after hatching to 4 cm long or more at maturity (1/16–1½ inches).

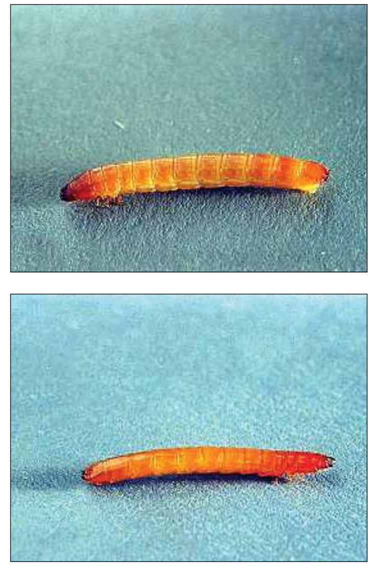

Figure 2. Wireworm larvae: *L. californicus* (top) and *L. canus* (bottom). (Photos by Ken Gray, Oregon State University)

Life cycle

An understanding of the wireworm life cycle allows one to more effectively manage populations on the farm by taking advantage of the insect's more vulnerable stages. In the Pacific Northwest, wireworms overwinter in the soil as larvae or adults. Overwintering adults mate the following spring from mid-April to early June. Mating occurs in or on the soil, sometimes after short flights. Although adults can fly, they usually prefer to remain where they developed as larvae.

Females lay eggs a few days after mating. They tend to prefer laying eggs in grassy areas. A female may lay from 50 to more than 350 eggs, singly or in small clusters, 2.5–15 cm (1–6 inches) deep in moist soil. After laying most of their eggs, some females emerge from the soil and make short flights to nearby fields, where they continue egg laying in newly colonized areas.

Eggs usually hatch in 3–4 weeks under favorable conditions. Larvae can live 2–5 years in the soil, depending on species, feeding on seeds and belowground plant parts. Wireworms from the same clutch of eggs may develop to the beetle stage at different rates. Some larvae may spend up to several years in the soil and be found as deep as 0.3–1.5 m (1–5 feet) or down to the hard pan.

Mature larvae pupate in the soil from spring through midsummer. The pupal stage lasts about 3 weeks. Adults emerge from late spring through summer. Figure 3 shows the phenology of indigenous wireworm species.

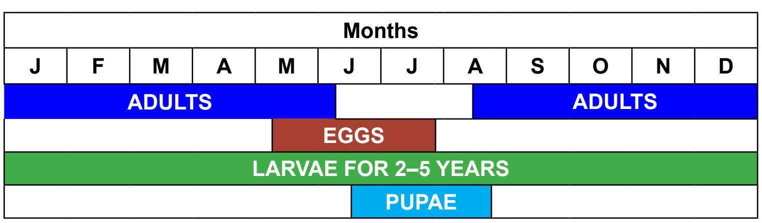

Figure 3. Wireworm life cycle. (Adapted from Berry, 1998)

Prepared by Nick Andrews, Extension faculty, small farms, North Willamette Research and Extension Center; Mario Ambrosino, faculty research associate, Integrated Plant Protection Center; Glenn Fisher, Extension entomologist; and Silvia I. Rondon, entomologist, Hermiston Agricultural Research and Extension Center; all of Oregon State University.

Crop damage

In addition to feeding on and destroying planted seeds, wireworms bore into roots and crown tissue and even tunnel up the stems of plants (Figure 4), depending on the crop attacked. Injury is most severe to seeds and seedlings and can result in stand loss. Root feeding causes wilting, stunting, and distortion of seedlings that usually kills the plant. Wireworms are usually most damaging in poorly drained areas on upland soils.

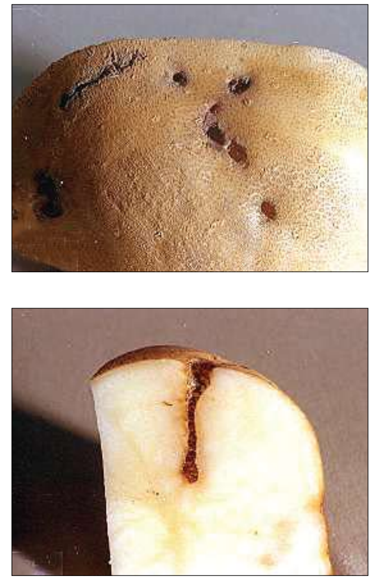

Figure 4. Wireworm damage to potato tubers. (Photos by Ken Gray, Oregon State University)

Pest wireworm incidence in the Pacific Northwest

As many as 39 species of wireworms from 21 genera have been reported to attack potatoes (Jansson and Seal, 1994). More than one species are often present in a field at a time. In eastern Oregon, species composition differs in irrigated and dryland crops.

On irrigated land, the most common species are the Pacific Coast wireworm (*Limonius canus*), the sugar beet wireworm (*L. californicus*), the western field wireworm (*L. infuscatus*), and the Columbia Basin wireworm (*L. subauratus*). Of these, the Pacific Coast and sugar beet wireworms are the most common. In recent years, reports of damage to irrigated crops in the Pacific Northwest are more common. Almost all of the potatoes in the region are irrigated.

In areas with annual rainfall not exceeding 15 inches, the most common species is the Great Basin wireworm (*Ctenicera pruinina*). In the Columbia Basin, various species of *Limonius* can be found, although damage varies from year to year.

Invasive European species

In recent years, invasive European species have become established in the Pacific Northwest. Three European wireworm species were introduced into British Columbia beginning in the 19th century: the exotic click beetle (*Agriotes sputator*), the dusky wireworm (*A. obscurus*), and the lined click beetle (*A. lineatus*). They are thought to have been introduced in soil used for ship ballast and possibly in plant material.

The latter two species have been present in various locations in British Columbia, Canada since 1950 and were found near the northern border of Washington as early as 1997 (Vernon and Päts, 1997). Surveys of these exotic wireworm pests by the Washington State Department of Agriculture in 2000, 2004, and 2005 found increasing numbers of these two species in several locations in western Washington. The pests reached southwest Washington in 2005 (LaGasa et al., 2006).

In Europe, these two species have been major economic pests in many crops for a long time, and in Canada they are causing increasingly greater damage to potatoes, corn, and small fruits (especially strawberries). Organic vegetable production is especially susceptible to damage from these two species, and organic growers in Canada have been experiencing heavy economic damage in various row crops (LaGasa et al., 2006).

In 2004–2006, researchers from the Oregon Department of Agriculture and Oregon State University found low levels of both species in port, nursery, and potato field sites in Multnomah and Clackamas counties near Portland. None were found in any of the other 17 counties sampled (ODA, 2006). Trap catches at ports and nurseries could indicate recent transport into Oregon, but pest presence in potato fields indicates that these species may already be established in those areas. Their distribution and pest status in Oregon is expected to increase over time. Because no exotic wireworm surveys were conducted in Oregon in 2007, and because earlier surveys were not extensive, the identity of wireworms in infested crop fields in Oregon should be checked to determine whether these exotic species are present.

Monitoring and risk assessment

Risk assessment is important for predicting the potential for wireworm damage. It can also support decisions to implement nonchemical management strategies, treat fields, or plant alternative crops.

Larval monitoring

Unfortunately, current larval monitoring methods are time-consuming and laborious and often do not reflect field populations or damage potential. This is largely because of the aggregated and patchy distribution of these pests in fields (Salt and Hollick, 1946; Blackshaw and Vernon, 2006), their ability to injure some crops at very low population levels, and their vertical mobility within the soil profile. However, thorough and consistent scouting can help indicate whether a field is at low or high risk.

Soil samples

Historically, wireworms have been monitored by extracting and sifting through soil cores to locate larvae. Treatment thresholds based on numbers of larvae per sample have been developed (Robinson, 1976). Since the distribution of wireworms in a field tends to be patchy and unpredictable, large numbers of samples are required. The process is time-consuming and often not sensitive enough to detect problems.

Bait traps

Baits have largely replaced random soil sampling since they are less labor-intensive and may detect low wireworm populations that soil samples can miss (Figure 5). Wireworms are attracted to carbon dioxide (CO_2), and several baits that take advantage of this behavior have been tried. All attract about the same numbers of wireworms under the same conditions. Baits are most effective when other crops or decaying crop residues are not present to release CO_2. We recommend the following procedure.

- Set bait traps in the spring when soil temperature exceeds 6–10°C (43–50°F) in the top 2 inches of soil. Generally the best sampling times are mid-April through May, when wireworms are feeding near the surface in response to adequate moisture and temperature.
- We recommend trapping in a bare field whenever possible, as the effectiveness of bait traps is reduced when alternative food and CO_2 sources are plentiful; for example, in standing or recently incorporated pastures or cover crops.

Figure 5. Bait traps. (Photos by H. Meberg)

- Make traps by presoaking cereal seeds overnight and burying them 15–20 cm (6–8 inches) deep in the ground. About 3 tablespoons (or a film canister) each of spring wheat and corn or barley works well. Seeds can be placed directly in the soil, in a 9–10 cm (3½–4 inches) planting pot filled with vermiculite (with drainage holes or drilled holes), or in a porous bag.
- Cover the baited soil with black or clear plastic to warm the surrounding soil.
- Place at least 25 bait stations for 30 acres. More traps allow a better chance of detecting damaging populations. Fields of less than 30 acres should have at least 4 traps.
- Place traps randomly around the field. If part of a field has been in grass, sample it separately, since wireworms may be present in only those areas.
- Flag bait stations in the field and leave them undisturbed for 10–14 days to allow wireworms to approach. Collect the bait and soil immediately around the bait (about 4–6 inches diameter) for sorting. Wireworms can be extracted from soil by hand sorting, by floating them off in a bucket of water, or by using Berlese funnels. The latter two methods generally are used only in laboratories.
- Move the traps when resetting them in the same field (Ward and Keaster, 1977).

Brunner et al. (2007) compared different baiting methods and found that baits in pots were the most effective. Seventy-five percent of wireworms were found in baited pots rather than in the surrounding soil, compared to 63 percent with plates and 53 percent with mesh bags. The sampling of surrounding soil is time-consuming and may not be necessary when using pots.

Adult monitoring

Males are attracted to sex pheromones released by female click beetles. Pheromone traps (Figure 6) are available for the invasive species *Agriotes lineatus* and *A. obscurus* (Toth et al., 2003; Vernon, 2004), but not for species indigenous to the Pacific Northwest. Where *Agriotes* spp. are established, pheromone trap counts can be used with larval monitoring to assess risk. Elsewhere, they are used mainly to monitor the presence and spread of populations. Traps are available commercially (see Vernon Beetle Trap in “References and Resources”).

Figure 6. Pheromone trap. (Photo by Nick Andrews)

Thresholds and damage potential

Economic thresholds vary depending on crop susceptibility, the cost of control measures, market tolerance of pest damage, and other factors. Trap counts vary depending on the time of year, soil temperature (at least 15–17ºC at 31 cm; 59–63°F at 12 inches) and moisture, and the presence of nontrap attractants and food sources in the field (i.e., decomposing or actively growing plant material) (Horton and Landolt, 2002; Horton, 2006). As a general guide, Table 1 (page 6) shows thresholds developed for bait traps in Idaho potatoes to prevent more than 3 percent tuber damage.

Table 1. *L. californicus* and *L. canus* thresholds using corn and wheat seed, chopped carrot, potato, oatmeal, or wheat flour baits. At least 25 traps were recommended for every 30 acres. (Adapted from Bechinski et al., 1994)

Average number of wireworms per bait station	Risk of economic damage (3% tuber damage)	IPM recommendation
0	Low (<10% risk)	Control not needed; continue sampling if greater confidence is desired
Up to 0.5	Moderate (30% risk)	
0.5–1.0	<50% risk	Continue sampling
1.0–2.0	Probable (>50% risk)	
2.0–4.0	High (75–90% risk)	Apply insecticide at planting
More than 4.0	Extreme	Do not plant potatoes

Horton (2006) modeled the relationship between bait trap counts (using rolled oats) and crop damage by *L. canus* in Wapato, Washington. Table 2 provides a damage forecast based on bait counts before and after planting potatoes. It is difficult to predict crop damage from trap counts, so these values should be used for guidance only.

Table 2. Predicted *L. canus* damage incidence to potatoes at various population densities measured with trap counts using rolled oat baits. (Horton, 2006)

Average number of wireworms per bait trap	Preplanting		Postplanting				
	Predicted percentage of tubers suffering any damage						
	4/20	4/26	5/3	5/10	5/17	5/24	6/22
0	5	2	6	7	8	7	7
0.25	14	24	15	16	16	20	50
0.5	22	40	23	24	23	32	69
1.0	37	62	36	38	35	49	83
1.5	49	74	47	49	45	61	86
2.0	59	81	56	57	52	70	86
2.5	68	85	63	63	59	75	87
3.0	75	88	68	68	65	80	87
4.0	85	90	76	75	72	84	87
5.0	93	90	81	79	77	87	86
10.0	>100	91	91	85	84	89	86
15.0	>100	91	92	85	85	89	86

A wireworm risk assessment formula was created by R.S. Vernon (Syrovy and Meberg, in press) to assess the likelihood of damage occurring to a potato crop in regions where *A. lineatus* and *A. obscurus* are established. The formula provides a rough risk estimate based on the number of wireworm larvae collected in bait traps and the number of adult click beetles collected in pheromone traps. The risk rating formula and interpretation are:

r = w*a; where "r" is risk, "w" is the total number of wireworm larvae collected, and "a" is the total number of adult beetles collected

Low risk = 0–10

Moderate risk = 10–25

High risk = 25–60

Very high risk = 60++

Field history

A history of damage in a field is a strong indicator of possibly damaging wireworm populations. Since wireworms are vertically mobile in the soil, large portions of a population may survive control efforts in any given year. Research from the 1930s on *Limonius* spp. in many crops (Jones and Shirck, 1942) found that throughout much of the growing season more than half of the population was 15–45 cm (6–18 inches) or more below the soil surface. The greatest numbers were found near the surface from April through June.

A long history of grass pasture or seed production is often correlated with large wireworm populations (Anon., 1944). In Nova Scotia, Fox (1961) found much higher wireworm populations in fields under grass for 10 or more years than in fields under grass for less than 10 years.

A survey of *Agriotes* spp. conducted in 62 fields in the United Kingdom over 3 years (Parker and Seeney, 1997) found few to no wireworms in grass fields up to 4 years old. However, fields in grass for more than 10 years were usually infested. These researchers found larger *Agriotes* populations in lower bulk density (lighter) soils.

Nonchemical management methods

Larvae live 3–5 years, and the oldest wireworms are the most damaging. Therefore, long-term management plans are needed to reduce populations throughout the wireworm life cycle rather than just during the production of susceptible crops. When wireworms are present at damaging levels, management strategies that integrate more than one mortality factor are more effective.

The methods described below include preventive techniques that usually are carried out preceding a potato crop (i.e., crop rotation, soil drying, flooding, and cultivation), as well as curative techniques generally used during the potato season (i.e., resistant varieties, trap crops, soil amendments, and biological control).

Crop rotation

Wireworms have a wide range of hosts, and the effect of crop rotation on populations is complex and poorly understood. As discussed above, fields in long-term grass are known to be at risk for high wireworm populations. Fields planted after small grains, grass pasture, or grass hay often exhibit the greatest potential for wireworm problems. When a field is rotated out of long-term grass production, Dirlbek et al. (1973) reported more than a 90 percent reduction in click beetle density after 5 years of cultivation.

Many other crops, including potato, wheat, barley, sweet and red clover, corn, onions, lettuce, melons, carrots, beets, beans, and peas, as well as weedy fields, have been reported as hosts that can be damaged by wireworms.

In the 1930s and 1940s, near Prosser, Washington, Gibson et al. (1958) found that 2- to 4-year alfalfa rotations consistently reduced wireworm populations dominated by *L. canus* and *L. californicus*, the species most commonly found in irrigated ground. Nearly half of the larvae matured to adults in potatoes; approximately one-fourth emerged from wheat, corn, sweet clover, and sugar beet; and only 3–18 percent matured in alfalfa. Due to the long life of larvae in the soil, it takes 3–5 years for populations to drop below damaging levels. *L. canus* was noted to lay eggs in bare soil (i.e., cultivated crops), while *L. californicus* laid eggs under vegetation.

In small-plot studies (0.068 ha, 0.17 acre) in Parma, Idaho, Shirck (1945) found that alfalfa inconsistently reduced wireworm populations. When plot size was increased to at least 0.5 ha (1.25 acres), he found that alfalfa significantly reduced wireworms when initial populations were high (6–10 wireworms/sq ft). He reported dramatic population increases under red clover and continuous vegetable rotations. Shirck and Gibson both concluded that rotations consisting of 3–4 years of alfalfa followed by 3 years of row crops were prudent when managing wireworms.

In the Willamette Valley, Oregon, however, G. Fisher (personal observation) reports high wireworm populations in rotations that include alfalfa and clover. In this region, temperatures are milder and soils are heavier than those in the Washington and Idaho studies.

Masler (1975) found higher wireworm populations after alfalfa and lower populations after continual corn in Czechoslovakia. He attributed these differences to cultivation. In Germany, Schepl and Paffrath (2005) reported reduced wireworm damage in a rotation that included only one winter cereal when compared to a rotation with two winter cereals and a year of grass/clover mix. Earlier information from the UK recommended flax, peas, beans, and vetch as tolerant crops in heavily infested fields (Anon., 1944).

Soil drying

The response of wireworms to soil moisture varies somewhat with species. The Great Basin wireworm (*C. pruinina*) favors dry soil and usually disappears as a pest when dryland fields are converted to continual irrigation. Conversely, *L. californicus* and *L. canus* do not survive well in dry soil. Campbell (1936) found that *L. californicus* preferred soil with 8–16 percent moisture and noted that saturated soil sometimes killed wireworms. Shirck (1945) reported that soil drying reduced wireworm populations in his rotation experiments.

If the top 40 cm (15 inches) of soil can dry out thoroughly for several weeks in midsummer, most *L. californicus* and *L. canus* larvae (especially the young larvae) and eggs will die. This is sometimes achieved by withholding irrigation from alfalfa or cereals just before harvest. This method is most effective in lighter sandy to silt loam soils (Landis and Onsager, 1966).

Flooding

Early research into flooding for wireworm control was inconclusive, and damaging populations were often reported in soils that flood in the winter. Lane and Jones (1936) discovered a relationship between soil moisture and temperature. All *L. canus* and *L. californicus* larvae submerged under soil and water were killed in 4 days at 30ºC (86ºF). As the temperature dropped, larvae survived longer, until at 10 and 15ºC (50 and 59ºF) only 26 percent mortality was reported after 21 days. Wireworms survived much longer when submerged in water alone. In field trials in Walla Walla, Washington, mortality was 82–99.9 percent when soil was flooded for 2–23 days in July. Mean air and soil temperatures were approximately 24ºC (75ºF) at the time.

Hall and Cherry (1993) published a simple model to represent the relationship between duration of flooding, soil temperature, and percent mortality of *Melanotus communis* in Florida:

$$Y = -94.4 + 7.12(X1) + 4.31(X2)$$

Where Y = expected percent mortality of wireworms, X1 = number of weeks of continuous flooding, and X2 = flooding temperature in degrees Celsius.

Predicted mortality rates from the Hall and Cherry model are only about 23 percent of the observed mortality rates in the Lane and Jones study. It should be noted, however, that the species and locations of the studies are different.

Alternating periods of soil flooding and drying have also been effective. In Florida, Genung (1970) found that a 4-2-4 weekly alternating cycle of flooding and drying consistently gave complete control of *M. communis* and *Conoderus falli*, and he concluded that a 3-2-3 weekly pattern would normally provide sufficient control. These trials were conducted in midsummer, when mean soil temperatures were approximately 26ºC (80ºF).

More recently, van Herk and Vernon (2006) reported that at 5 and 10ºC (41 and 50ºF) it took 55 days of flooding to kill 90 percent of wireworm larvae (LT90) in Agassiz soil. The LT90 fell to 16.5 days at 20ºC (68ºF). In Delta soil, however, they found an LT90 of 62.4 days at 5ºC, and 8.6 days at 10 and 20ºC. The Delta soil had 5–20 times the concentration of various mineral nutrients as the Agassiz soil, so the researchers suggested that increased salt concentrations may have contributed to quicker mortality when the Delta soil was flooded. This also explains Lane and Jones's 1936 observations of extended wireworm survival in water with no soil.

Cultivation

Pupae are susceptible to mechanical damage from cultivation, but larvae and adults usually survive cultivation. Rotary cultivation may be more effective than plowing (W.E. Parker, personal communication).

Cultivation can kill a large percentage of wireworm pupae and reduce wireworm populations in a field. However, crop damage is not reduced immediately since the subsequent adults would have caused no damage, and larvae cause very little damage before they are 1–2 years old. Larger larvae survive in cultivated soil and continue to damage susceptible crops.

In the Pacific Northwest, pupae are present in the soil during July and early August, so cultivation must occur at this time to be effective. Pupae are generally formed 7–38 cm (3–15 inches) below the surface, with an average depth of 15 cm (6 inches). Plowing to 23 cm (9 inches) was shown to kill up to 90 percent of pupae. Subsequent harrowing or plowing a second time was shown to increase pupal survival by burying surviving larvae, thus protecting them from desiccation and predation.

Plowing was most effective when plowed soils produced clods. Best results were obtained with heavy soils that were dry to somewhat moist (7–18 percent moisture). Plowing was generally less effective on sandy soils than on clay or loam soils. Mortality dropped to 36–68 percent in soils that were very dry or that did not form clods. Pupae may be formed at greater depths when soil is very hot and dry, resulting in reduced mortality from cultivation (Shirck, 1936).

Seal et al. (1992) found that plowing three times during the summer reduced wireworms collected at bait traps from 1.75 per bait trap to 0.2 per bait trap, compared to no change in unplowed control plots. This reduction was attributed to exposure to predators, heat, low moisture, and other stresses. Long-term cultivation has been reported to control wireworms in Czechoslovakia, central Bohemia, and Florida (Masler, 1975; Dirlbek et al., 1973; Jansson and Lecrone, 1991).

Resistant varieties

Plant resistance to wireworms can be an important component of integrated control. In New York, Rawlins (1943) was surprised to find reduced incidence and severity of wireworm damage in the potato varieties 'Warba' (34 percent damaged tubers), 'Heavyweight' (37 percent), and 'Rural Russet' (41 percent), compared to damage in 'Burbank Russet' (57 percent), 'Irish Cobbler' (56 percent), and 'Bliss Triumph' (52 percent).

Parker and Howard (2000) found slight differences in seven cultivars commonly grown in the UK. The cultivars 'Maris Piper' (25.6 percent damaged tubers) and 'Pentland Dell' (27.5 percent) were damaged less than half as severely as 'Cara' (55 percent), the most susceptible variety in the trial, but these differences were not statistically significant.

Kwon et al. (1999) tested 50 potato cultivars for resistance to several wireworm species, including *Selatosomus puncticollis* and other species not believed to be important in the Pacific Northwest. Injury rates varied between 80 and 96 percent in susceptible cultivars, and several varieties were found to be highly resistant. Reported injury rates in highly resistant cultivars are shown in Table 3.

Novy et al. (2006) tested somatic hybrid varieties and found levels of resistance equivalent to or better than insecticidal control. They found regional differences in the resistance of these hybrids, which they attributed to different responses by wireworm species to the glycoalkaloids in the resistant potatoes.

Laboratory and field trials in Scotland (Johnson et al., 2008) found statistically significant differences in the incidence and severity of wireworm damage, as well as in weight gain of wireworms in no-choice tests. In choice tests, wireworms preferred the susceptible varieties. These results were largely confirmed by field trials, except that one moderately susceptible variety in the laboratory ('Mayan Gold') was the most resistant variety in the field. The percentage of damaged tubers (out of 20) is shown in Table 4.

A comparison of 15 varieties by researchers in Oregon found that the percentage of tubers damaged by wireworms ranged from 1 to 30 percent. Results are shown in Table 5.

Table 3. Injury rates in highly resistant potato cultivars. (Kwon et al., 1999)

Early potatoes	
'Anco'	12%
'Irish Cobbler'	16%
'Maritta'	22%
'Superior'	22%
'Jopung'	24%
Midseason potatoes	
'Alamo'	1%
'Shinyseo'	15%
Late-season potatoes	
'Whitu'	3%
'Sieglinde'	4%
'Spunta'	6%
'Some Miore'	6%
'Ojiro'	10%
'Corine'	11%
'Rosa'	11%
'Norin #2'	15%

Table 4. Percentage of damaged tubers in choice tests. (Johnson et al., 2008)

'Maris Piper'	10%
'King Edward'	15%
'Harmony'	20%
'Nadine'	25%
'Estima'	30%
'Cabaret'	35%
'Saxon'	35%
'Orla'	45%
'Mayan Gold'	50%
'Rooster'	60%
'Marfona'	65%
'Maris Peer'	65%

Table 5. Percentage of infected tubers for various potato varieties.

'AC9521'	1%
'VC1009'	1%
'Cherry Red'	3%
'Ozette'	13%
'Yukon Gold'	15%
'Colorado Rose'	16%
'Austrian Crescent'	17%
'Red LaSoda'	17%
'Satina'	20%
'Mountain Rose'	20%
'Nicola'	24%
'POR01PG22'	24%
'Sangre'	27%
'Huckleberry'	28%
'Jacqueline Lee'	30%

The mechanisms of host plant resistance have not yet been fully determined. Thorpe et al. (1946) demonstrated that wireworms prefer the taste of several compounds, including all sugars, polyhydric alcohol (also important in the human sense of sweetness), triolein (the only pure fat preferred), and animal proteins. (Intact plant proteins did not confer resistance, but partially broken-down plant proteins may do so.)

Olsson and Jonasson (1995) reported that wireworm damage was negatively correlated with the concentration of glycoalkaloids and positively correlated with the concentration of reducing sugars near the potato skin. Resistance to *S. punticollis* in South Korea was correlated with total nitrogen and total sugar content (Kwon et al., 2000). They found the role of glycoalkaloids to be statistically insignificant. Johnson et al. (2008) found only a weak relationship between glycoalkaloid content and resistance to wireworms. It should be noted that high concentrations of glycoalkaloids can be toxic to humans.

Soil amendments

A 2004 insecticide trial at the Hermiston Agricultural Research and Extension Center (eastern Oregon) included compost as a treatment after reduced damage was observed in compost-treated watermelons. Compost was banded over the row before planting at 24 ton/acre and incorporated at planting. Damage in compost-treated plots was significantly less than in control plots and equivalent to that in plots treated with 1,3-dichloropropene, metam sodium, ethoprophos, and fipronil (G. Clough, unpublished research data). The control mechanism is not well understood, but may be due to CO_2 production by the compost. Or, the compost may have provided an alternative food source.

Brassicas used in rotation or as soil amendments may have lethal or sublethal effects on wireworms, but research results are inconclusive. Allyl isocyanate, a breakdown product of glucosinolates (mustard oil) produced some mortality in *L. californicus* larvae and displayed antifeedant properties lasting up to 137 days (Williams et al., 1993).

In laboratory trials, Elberson et al. (1996) determined the LC90 of rapeseed meal to be 533 g/kg soil at 7 days and 486 g/kg at 21 days. Since this represents approximately a 50-percent concentration in soil, they concluded that this method of control would be impractical unless *Brassica* species with higher glucosinolate concentrations are developed.

More recently, Italian researchers working with *Agriotes* species (Furlan et al., 2004) found high larval mortality in pots placed in the field after incorporating freeze-dried whole mustard plants (*Brassica juncea*) at the equivalent of 18 ton/ha (16 ton/acre) and various Brassicaceae seed meals at 3–6 ton/ha (2.7–5.3 ton/acre). However, the lethal effects disappeared within 72 hours. Glucosinolate concentrations in mustard seed meals were only slightly higher in the Furlan study than in the Elberson study (approximately 180 µmol/g and 123 µmol/g respectively).

In potted plant studies, Furlan (2007) recently reported that *Brassica carinata* defatted seed meal killed most larvae and protected tubers from scarring. While imidacloprid also seemed to protect the tubers, the seed meal was more lethal to larvae. However, it is not yet registered by EPA for this purpose. Researchers in the UK continue to study these materials in the field, and preliminary results appear less promising than those from the potted plant studies (W.E. Parker, personal communication).

Other plant extracts have been found to reduce wireworm (*M. communis*) damage to potatoes. Villani and Gould (1985) screened extracts from 78 plant species for their ability to deter wireworms and reduce tuber damage. Some members of the Araliacea, Asclepiadaceae, Compositae, and Labiatae families were active. Plants with the highest extract ratings are shown in Table 6.

Table 6. Extract ratings for various plant species. (Villani and Gould, 1985)

Asclepias tuberosa (butterfly milkweed)	21
Hedera helix (English ivy)	19
Santolina virens (santolina)	19
Thymus vulgaris (thyme)	15
Artemisia dracunculus (tarragon)	15
Rhododendron sp.	14

Extract ratings based on the following formula:

ER = (B1 – B2) + (A1 – A2)

Where ER = extract rating, B1 = number of control baits damaged, B2 = number of treated baits damaged, A1 = number of wireworms found in half of chamber containing control baits, A2 = number of wireworms found in half of chamber containing treated baits.

The agronomic crops tested were not very active, and no extracts from active species are commercially available at this time.

In order to be distributed with any claims that it can control wireworm, a product must be registered by EPA or must qualify for exemption from registration. If a grower, homeowner, or other person applies a product as a pesticide on crops, and that product is not registered by EPA or exempt from registration, the application may not be legal. In some situations, such applications may be allowed on the applicator's own crops or sites, as long as there is no distribution of the product with claims made to its pesticidal activity. A homeowner using salt or beer to control slugs is an example. No distribution of such a product may be made with claims (implied or expressed, verbal or written) that it controls a pest.

EPA must establish a tolerance level for any pesticide active ingredient applied to a food or feed crop unless the material is specifically exempted from the requirement for a tolerance. Some biopesticides and alternative pest control substances are exempt from this requirement. Check with your state department of agriculture or with EPA if you have a concern about crop tolerances or legal pesticide applications.

Early harvest

Wireworm damage increases as the season progresses. Two recent studies in Germany have shown that early harvest may reduce the risk of tuber damage. Schepl and Paffrath (2005) found less tuber damage when tubers were harvested in late July or early August (8–50 percent) compared to early to mid-September harvests (72–77 percent). Neuhoff et al. (2007) also found increasing damage from early August to late September. While the trend was fairly consistent, it was statistically significant only at some sites.

Depending on the variety, early harvest may impact tuber yield or skin set. When tubers have reached an acceptable size, destruction of the foliage about 4 weeks before harvest can help to ensure good skin set.

Trap crops

Soil insects rely on chemical and physical cues to locate food. Wireworms are attracted to increasing CO_2 concentrations at a distance of up to 12–16 cm (5–6 inches) (Doane et al., 1975). At closer distances, more specific plant compounds may be involved in wireworm food preferences (Horton, 2007). Since the CO_2 responsible for long-range orientation is emitted by all plant and animal material, selective attraction is most likely due to more specific compounds that attract wireworms over a short distance (olfactory) or stimulate biting (taste). These chemicals could contribute to both host plant resistance and wireworm feeding preference (see "Resistant varieties"). For a trap crop to be effective it must be more attractive than the cash crop.

Vernon et al. (2000) demonstrated that trap crops of wheat planted 8 days before interplanted strawberries reduced damage to transplants. The effect was increased with insecticide-treated seed. A rate of 2.4 treated seeds/cm (about 1 seed/inch) in rows spaced 0.5 m (about 20 inches) apart provided optimum attraction and mortality (Vernon, 2005). The insecticides used in these trials have since been withdrawn from registration in Canada. Research in Georgia (Seal et al., 1992) found that wheat–corn bait traps set in sweet potato hills reduced tuber damage from wireworm.

Biological control

There is little information on the biological control of wireworms. Birds and predatory ground beetles prey on wireworm larvae, entomopathogenic nematodes have been isolated from wireworm larvae, and entomopathogenic fungi (*Beauveria* and *Metarhizium* sp.) can attack wireworms. Indigenous natural enemies have not reduced populations below damaging levels when infestations are present, however.

Researchers in British Columbia are evaluating the efficacy of two biological control materials—*Metarhizium anisopliae* and spinosad—and their potential synergistic effects when used against *A. lineatus* and *A. obscurus* (Kabaluk et al., 2005; Ericsson et al., 2007; Kabaluk and Ericsson, 2007). *M. anisopliae* is an entomopathogenic fungi; spinosad is a fermentation product derived from a soil actinomycete and is a nerve toxin.

In laboratory bioassays, Ericsson et al. (2007) reported that a combination of spinosad and *M. anisopliae* killed more wireworms than would be explained by their additive effects. Subsequent field trials using *M. anisopliae* strain F52 and spinosad as seed treatments to control wireworms on corn found that the fungus was effective. Spinosad did not increase crop stands or yield on its own or in combination with *M. anisopliae*. The research team continues to investigate these materials and other promising methods, but economic analyses and practical applications are pending.

In The Netherlands, Ester and Huiting (2007) reported significant reductions in wireworm populations after treatment with *Beauveria bassiana*. Results were equivalent to those obtained with use of ethoprophos granules, but not to results with chlorpyrifos.

To date, entomopathogenic nematodes have shown very limited control. Toba et al. (1983) documented some *L. californicus* mortality in *Steinernema feltiae* bioassays and caged field trials, but concluded that the lethal dose was cost prohibitive. Ester and Huiting (2007) found *S. feltiae* to be ineffective. Integration of resistant sweet potato cultivars with *S. carpocapsae* provided 25 percent control of soil insects, including wireworm, except during a very wet year when nematodes were leached from the rhizosphere (Schalk et al., 1993).

Nonchemical management summary

This review identifies wireworm management strategies that could be integrated into a variety of production systems. The potential risk of damage from wireworms in a field should be assessed before planting potatoes or other susceptible crops. Wireworm monitoring with bait stations is recommended, and established thresholds or a history of damage can be used as guides.

When wireworm populations are sufficient to damage crops, a combination of preventive and responsive methods can be used to limit damage to the current crop and to reduce populations over time. When populations are high enough to cause severe damage to potatoes, more tolerant crops can be grown while a longer term plan to reduce the population is implemented.

Promising nonchemical management methods include the following.

- Crop rotations that include alfalfa and high-glucosinolate Brassicas may help to reduce wireworm populations over time.
- If soil can be thoroughly dried out during the summer, *Limonius* populations may be reduced.
- If soil can be flooded or thoroughly saturated for at least 2 weeks when soil temperatures are above 20ºC (68ºF), wireworm populations should drop significantly. Alternating periods of flooding and drying can increase wireworm mortality.
- Intensive plowing, three or more times during the late spring and early summer, can reduce wireworm populations.
- Several resistant potato varieties are worth testing in the Pacific Northwest.
- Soil amendments and some organic residues show some promise as a management tool. High rates of compost may reduce wireworm damage, but more research is needed.
- Where possible, harvesting in late July or early August may reduce the risk of wireworm damage when compared to September harvests. This method from Germany may need adaptation to the Pacific Northwest.
- Trap crops such as wheat may provide an alternative food source for wireworms and reduce damage to the cash crop.
- Entomopathogenic fungi and other biological control agents may provide some control in the future, but application methods need further research and commercialization.

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