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An ecological study of certain wireworms with consideration of their control.

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C O N T E N T S

INTRODUCTION

Various species of the coleopterous family Elateridae are economically important because of their ravages on crops essential to man and animals. Larvae of the Elateridae, because of their hardy and wiry appearance, are known as wireworms. The adults are called "click" beetles or "snapping jacks" because of their habit of snapping into the air when placed on their backs. The term wireworm as used in this paper refers to the larval stage of the beetle.

Damage to the roots of crops, seedling plants, tubers, and stems is caused by the boring of the larvae. Affected plants may appear normal for a few days after coming up but soon may become wilted and die. Upon examination such plants may show the superficial boring of the wireworm on some part of the root or stem. After plants have become established, external indications of wireworm damage are not very evident because the plant usually overcomes such damage if it is not too heavy. In severe cases of wireworm attack, stunting of plant growth may result. The underground work of the larvae may cause older plants to die, as in the case of corn, or the roots or tubers may be badly scarred, as in carrots or potatoes.

Wireworms hibernate in the soil and are partially starved when they migrate upward in the soil in the spring. Crops planted at this time are readily attacked. For this reason much of the early control work was done with a view of protecting the seed from wireworm attack. In the 1890s and thereafter, numerous compounds were recommended for this type of control. Results were variable and what one worker claimed to be a highly successful treatment was branded a failure by another investigator. Some of these compounds are discussed under the heading of "Seed Treatment".

During the same period the usual recommendation for wireworm control was fall plowing. This was supposed to have killed the larvae, pupae and adults by exposing them to adverse weather conditions. This recommendation seems to have been made without very definite knowledge as to the effects of such treatment upon the various stages supposedly affected. It is now generally felt that the value of fall plowing is practically nil. Unless they are injured, larvae that are turned up on the soil surface can readily bore down into the soil. Many larvae may be below the plow line and is also true of both the pupae and adults. Fall plowing and other cultural methods of control are discussed in another section of this paper.

The complete life cycle of elaterids commonly found in the fields of this locality is considered to last about three years. The eggs are small, 1/40 to 1/50 inch long and pearly white in color. Mating of adults and egg-laying occurs in the latter part of May and early June. Young larvae appear in 2 to 4 weeks and overwinter in the soil at depths of 4" to 9" on the average. In the spring larvae migrate towards the soil surface and begin feeding on organic matter in the soil. The larva feeds throughout the summer and transforms into a whitish pupa in August-September. The pupal stage lasts from 2 to 4 weeks and the adult remains in the soil until the following spring when it emerges and begins its mating activities.

SCOPE OF THE PRESENT WORK

Research on the control of wireworms has been increasing steadily. Early research was concerned chiefly with the control of harmful species. During the past twenty years, control studies have continued to be numerous but other phases of wireworm investigation have not been neglected. Life history studies of many species have been undertaken, environmental and ecological studies are more numerous, the morphology and taxonomy of hitherto unknown species has been published.

Despite all this research and its effect upon the control of wireworms, there is still a need for an inexpensive but effective control of this subterranean type of field pest. The present study was undertaken to attempt to find a suitable control or controls and to examine the environmental factors surrounding the wireworms in the field.

Preliminary field scouting in 1938 and 1939 showed that many fields had been seriously infested with wireworms in previous years. One field in the "Meadows" section of Northampton had a history of wireworm infestation of about fifteen years. Nearly thirty acres along the west bank of the Connecticut River were found to be infested. Most of this land is given over to the raising of potatoes and truck crops and the rest of it is usually in sod.

ECOLOGICAL FACTORS AND THEIR INFLUENCE ON WIREWORM CONTROL

Various environmental factors affect the activity of wireworms in the soil. The type of soil may influence the amount of control possible with certain types of insecticides. For example, a loosely formed soil may be suitable for treatment with such a fumigant as chloropicrin. In compost soil, diffusion of this gas would be lessened to the point where it would be hardly effective. The pH of soils may be changed by insecticidal treatment and soils thus changed may affect the growth of plants. Dichloroethyl ether, in appropriate dosages, may not directly injure plant growth but subsequent changes in soil pH due to this material may injure plant growth. Soil moisture directly affects the activity of wireworms. It has been shown that the downward migration of many species in mid-summer is due to a combination of several factors, chief of which is the lack of soil moisture in the upper area. Controls tried at the time of such a migration might prove to be ineffective. Soil temperature is another ecological factor having an important bearing on control. Low soil temperatures of less than 50°F. may not be enough to stop the larvae from coming up to feed on the roots of newly germinated plants. The effectiveness of certain soil insecticides at these temperatures may be very low.

The abundance of food for wireworms may affect the degree of control obtained. One of the easiest ways to recognize the seriousness of a wirewom infestation is to witness the effect of wireworm feeding on newly germinated crops sown in the spring. Areas of infestation can readily be seen where plants have withered or failed to come up. In the use of bait crops, it is desirable to provide an abundance of food by proper spacing of plants or seeds.

REVIEW OF LITERATURE ON ECOLOGY OF WIREWORMS

The study of the ecology of wireworms has been a comparatively recent event in wireworm research. Early workers, concerned with finding a control for these pests, often overlooked factors which led to failure in their control operations. It soon became apparent that in order to bring about more effective control, a more adequate knowledge of all the ecological factors was necessary.

The relationship between wireworm abundance and environmental factors is not always evident. There are certain characteristics of the environment which limit the occurrence and abundance of a particular species in a certain type of environment. Some wireworms seem to prefer a loose soil while others are found in a compact type of clay soil. For some species moisture is a necessity along with a type of soil rich in humus. Other species like a dry inorganic soil type. These factors along with others, interact to form a suitable type of environment for wireworm activity and are now to be discussed in greater detail.

Wireworms in Relation to Soil and Soil Types

The larvae of Elateridae are found in various types of soil and a few species are found working in rotted or decaying wood. Among the various soil-inhabiting species preference is found for soils that are dry and inorganic in nature to wet soils rich in humus. The sand wireworm, *Horistonotus uhlerii* Horn, a pest of all cultivated plants in certain areas of the south Atlantic states, is limited in its range to a certain type of light sandy soil that is deficient in humus (Tenhet and Howe, 1939). Numerous species of the genus *Agriotes* seem to prefer a heavier type of soil, rich in humus and with considerable moisture. *Agriotes obscurus* L. has been observed by Miles (1939) to oviposit in the damp soil of grassland just below the surface. Miles (1921) found the greatest number of larvae of *Agriotes obscurus* L. and *Athous haemorrhoidalis* F. to be in sandy soils with a great abundance of root fibers. Subklew (1934b), in Germany, has observed *Agriotes obscurus* L. in light sandy, heavy clay, or moor soils while *A. lineatus* L. was found in soil rich in humus, especially moor, but not in clay soil. Pospelova (1939) has reported *Agriotes obscurus* L. as constituting 93.7% to 100% of all wireworms found in fallow land or in land in potatoes, crucifers, clover or peas, in the Tomsk region of Russia. *A. obscurus* L. was found in medium clay soils and in peaty arable land; *A. lineatus* L. in heavy clay soil, of Leningrad region, Russia (Merkul'eva, 1937).

Agriotes mancus Say, one of the economically important species of elaterids in eastern United States, was reported as early as 1916 by Hyslop as normally a grass feeder. This fact has been corraborated by the work of Rawlins (1934) who states that sod or grassland is thought to be the source of infestation by this species. Hawkins (1930) thinks that the absence of hatched larvae of *Agriotes* from cultivated land indicates that very few eggs are laid in cultivated soil.

Other species of elaterids seem to prefer a habitat similar to the grass or sodland type favored by *Agriotes mancus*. Hawkins (1936) mentions the habitat of *Cryptohypnus abbreviatus* Say as being very near that of the wheat wire-worm, *Agriotes mancus* Say, although larvae of the former are found in fairly dry soil also. *Aeolus dorsalis* Say, *Conoderes auritus* Herbst, *C. bellus* Say, and *C. lividus* De Geer, are found in Kentucky living in sodland and injuring crops following sod (Jewett, 1939).

Larvae of the genus *Ludius* show a preference for soil containing clay but are found elsewhere associated with larvae of *Agriotes mancus* Say. Larvae of *Ludius* sp., however, prefer a better drained soil than *A. mancus* (Hawkins, 1936). The same worker notes that a relatively dry, light soil is favorable to the maximum abundance of *Melanotus* sp. A certain amount of moisture is necessary for survival of the larvae of *Melanotus*.

Larvae of the spotted click beetles, *Monocrepidius vespertinus* Fab. occurring in some sections of the South, are found in any type of soil, from light sandy to a heavy silt soil. This particular species never goes more than 6" below the soil surface at any time in its life cycle.

Heteroderes laurentii Guer. prefers soft or cultivated soil for egg deposition. Agriotes lineatus L., A. sputator L., Corymbites (Selatosomus) latus F. and Melanotus brunnipes Germ. were observed by Safronova and Legatov (1931) to lay their eggs almost exclusively in hard compact soil. Takano (1935) reported Lacon musculus as one of the important pests of sugar-cane in Formosa. This wireworm is more common in the sandy soils, a fact corroborated by Takahashi (1938).

Corymbites sjaelandicus Mull., seldom reported as a pest in Russia years ago, is now found damaging vegetable plants in the vicinity of Moscow. Durnovo (1935) states that this is the predominant species in peat soil. It is just as numerous as Athous niger in clayey soil and practically absent from sandy soil, which is inhabited chiefly by Agriotes spp. Corymbites (Selatosomus) aeneus L. is reported by Merkul'eva (1937) to predominate in sandy plots of soil in the Leningrad region of Russia.

Reporting on a survey of wireworms in several fields of Tolland Co., Conn., Beard (1940) found no correlation between physical and chemical nature of the soil and wireworm injury.

Various groups of elaterids of the United States are listed as having preference for certain soil types. Lane

(1935) states Corymbites and Ludius spp. are mainly pests of dry land crops whereas Limonius spp. are found usually in moist soil; Melanotus spp. chiefly on soil grown to maize; and Agriotes spp. are plentiful on slightly acidic soils.

In Maine, larvae of the genus Limonius have been found mostly in the sandy soil of river valleys which is moderately well drained (Hawkins, 1936). These are probably not L. agonus Say which are comparatively rarely taken. Limonius californicus Mannh has been known as a pest of sugar beets, corn and alfalfa in California for many years. Graf (1914) states that a loose, damp soil is preferred by the adult for laying of eggs. Sandy unflooded land is more infested by this species than is land flooded occasionally and rich in heavy silt and humus.

Reaction of Wireworms to Hydrogen Ion Concentration of the Soil.

The numerous species of elaterid larvae differ in their reaction to varying degrees of soil acidity and alkalinity. The factors effective upon the acidity and alkalinity of the soil are numerous, such as soil moisture, type of cover crop, planting and cultural practices, etc. Wireworm reaction to the pH of the soil may be influenced by any one of these factors.

Generally speaking, some wireworms, especially Melanotus, Agriotes and Corymbites are abundant in low, acid, and poorly drained soils. Limonius larvae prefer a higher, drier, and more alkaline type of soil.

Thomas (1940) states that Agriotes in Europe and A. mancus in eastern United States prefer acid soils and are therefore more damaging. In the alkaline soils of the Pacific coast there are no economically important species of Agriotes. Ladell (1938) found no relationship between wireworm density and pH of soil.

Agriotes obscurus L. and A. lineatus L., the chief elaterid pests of cereals in Germany, were observed by Langenbuch (1932) to congregate at soil levels which had a pH of 4 to 5.2. Depth of larvae of Agriotes obscurus L. in Russia, according to Bobinskaya (1937) depends not only on soil moisture but also on soil acidity which in turn is dependent on the type of crop grown. This worker found the majority of A. obscurus larvae in soil levels where the pH was less than 6. The preference of Agriotes larvae for acid soils was reported by Blunck and Merkenschlager (1925) who found a common feature of Agriotes larvae in Germany to be their assembling where soil had lowest percentage of alkalies. A high degree of acidity did not repel the larvae. Agriotes obscurus L. and A. lineatus L. were noted by Subklew (1934) to inhabit soils with a wide range of pH as well as soil structure.

Printz (1935) found _Agriotes obscurus_ larvae, in laboratory tests, to concentrate at soil depths having a pH of 5. MacLeod (1933) asserted soil acidity had no effect on numbers of potatoes injured by larvae of the wheat wireworm _Agriotes mancus_. Gui, (1935) working with _Agriotes mancus_ larvae in potato fields of northeastern Ohio, states that pH had no definite relationship to wireworm population.

Limonius canus Lec. (_Pheletes canus_ Lec. of authors) is reported by Lane (1935) to withstand a wide range of pH. _Limonius_ spp. on the Pacific Coast in the United States and in Europe is usually found in alkaline soils. Mail (1932) found that _Limonius canus_ Lec., in laboratory tests, could tolerate a range of pH from 4.8 to 8.2. This is a wider range than that of the Minnesota soils inhabited by _Limonius canus_, where the pH varied from 6.1 to 7.7.

In Connecticut, _Pheletes ectypus_ (_Limonius agonus_), the eastern field wireworm, showed an apparent tendency to congregate at soil levels having a pH of 5.15 to 5.20. There was no correlation between soil reaction and larval population (Lacroix, 1935). This particular species is the chief pest of potatoes and truck crops in the "Meadows" field of Northampton.

Although Limonius sp. prefers a higher, drier, and more alkaline soil, Marlatt (1930) reported larvae as hatching in soils of pH 1.44 to 7.28 and continuing their development in these soils. However, larvae in acid soil seemed less active than larvae in more alkaline soil.

Pheletes (Limonius) californicus larvae were not visibly controlled by the use of Sulphur up to 1000 lbs. per acre even though there was a decided increase in soil acidity (Campbell and Stone, 1932).

Larvae of Lacon variabilis Cand. damaging sugar cane in the macKay district, Queensland, were observed by McDougall (1934b and 1935) to infest cultivated fields having a pH of 3.9 to 5.8. Usually, the parts of the field infested by this wireworm were more acid than the remainder of the field.

Soil Moisture

Moisture and temperature are the most important environmental factors, besides food, affecting the growth and development of insects. Elaterid larvae are definitely affected by the amount of soil moisture. Their activity in the soil as well as their growth is limited by the amount of moisture. Different species require varying amounts of moisture.

Hawkins (1936) found in experimental work that moisture in the soil visibly affected the growth of larvae of

Agriotes mancus Say. Larvae kept in containers with well moistened soil reached a length of twice that of larvae kept in soil where there was just enough moisture to support life.

Moisture in the soil is responsible for vertical migration of larvae and consequent damage to crops. Masaitis (1929) found moisture and temperature the chief factors responsible for vertical migration of several species of wireworms in Russia. Wireworms in general are very sensitive to drying of soil. As the upper layers of soil dry out, the larvae go deeper into the soil. This characteristic of wireworms has been utilized in control by keeping the soil dry. For example, MacLeod and Rawlins (1933) have observed the adults of *Agriotes mancus* Say not to oviposit in soil that is bare and dry. Consequently, potato fields should be kept free from dense cover during May and June when the beetles are most abundant. Growing unirrigated wheat has lessened soil moisture enough to result in a significant reduction in damage by the larvae of *Limonius californicus* Mann . (Shirck and Lanchester, 1936).

Excessive moisture has been used as a control measure. Flooding of fields to a sufficient d pth at a time when soil temperature is 70°F. or over has resulted in varying degrees of control.

Calvino (1922) advocated flooding of heavily infested land. Other workers doubted the value of flooding as a means of control. Lane (1935, 1937) reported high mortality of wireworms by flooding for one week when soil temperature was 78°F. or above. It is doubtful if flooding would be a successful means of controlling wireworms, especially under conditions of low soil temperature found in the "Meadows" fields during early spring infestations.

Flooding of some sections of the "Meadows" area may be responsible for small larval populations in low areas adjacent to the experimental fields. These low spots have been flooded during late April and May for a number of years. Drainage is poor in these spots and the soil is usually heavy and damp. These conditions may discourage adult beetles from laying eggs there and consequently result in low populations in these areas.

Numerous workers have reported the varying amounts of soil moisture tolerated by different species of wireworms. Agriotes larvae prefer low wet clayey soils. Limonius sp. are usually more abundant in well drained areas. Melanotus larvae prefer soil moisture conditions somewhat like those tolerated by Agriotes. Horistonotus uhlerii Horn has never been found in completely dry soils nor in low, heavy, wet soils. Its specific environment is a sandy well-drained soil with a noted absence of humus matter (Tenhet and Howe, 1939).

Agriotes mancus adults do not oviposit in soil that is bare and dry (MacLeod and Rawlins, 1933). They are most abundant in low, wet, clayey soils. Hawkins (1936) found *Agriotes mancus* Say to prefer a moist soil. In experimental tests, *A. mancus* larvae as well as those of *Melanotus* sp. showed a decided preference for moist soil over dry soil.

Hawkins used pots containing dry, moist, wet, and saturated soils. Wet soil is most favorable to larvae of *A. mancus* Say and *Melanotus*, but larvae of *A. mancus* can live longer in saturated soil than *Melanotus* sp. larvae. First instar larvae of *A. mancus* exposed to laboratory atmosphere in watch glasses were dead in eighteen hours. Eggs of *A. mancus* similarly exposed for an hour failed to hatch but 50% of newly laid eggs placed on moist soil in a sealed container hatched. Low moisture is probably not responsible for any degree of wireworm control in Maine because of the downward migration of larvae to escape drying. Under conditions of excessive moisture, larvae of *A. mancus* Say come up from soil and go into tomatoes, muskmelons and pumpkins lying on the ground.

In Europe, *Agriotes lineatus* L. and *A. obscurus* L., two of the most important injurious wireworm species, likewise prefer a low wet environment for their development. Subklew (1934c) noted that although the larvae occurred in soil having a wide range of pH, their distribution is closely connected with the water content of the soil. Langenbuch (1932) showed that the optimum soil moisture for _A. lineatus_ and _A. obscurus_ was between 60% and 90% of saturation. He maintained, however, that plants were not injured if soil humidity were sufficient. Eggs and young larvae require an atmosphere saturated with water vapor. Older larvae are less sensitive to drying. In tests with _A. obscurus_, moist soil rich in humus was more attractive than slices of potato placed in soil. Lack of moisture might be favorable for outbreaks of larvae in humus soils.

At its optimum temperature, 20°C., _Agriotes obscurus_ larvae were concentrated in soil depths where moisture content was 50 per cent or over (Printz and Bobinskaya, 1936). Feeding on green plants began when soil moisture was less than 25 per cent of saturation but not above. _A. obscurus_ L. was observed by Pospelova (1937) to prefer weedy plots overgrown with _Aropyrum repens_. Moisture conditions under such a cover crop would be more ideal for the larvae than cultivated or fallow fields. Pilyugina (1935) observed that no larvae of _Agriotes sputator_ or _Corymbites latus_ occurred in dusty soil or in very moist soil.

Masaitis (1929) stated that temperature and moisture were the chief factors regulating the vertical distribution of Agriotes obscurus L., A. lineatus L., A. sputator, Selatosomus latus F. and S. spretus Mann. in Siberia.

Elaterid larvae of the genus Limonius prefer lighter and drier soils. Morrill and Lacroix (1937) found Limonius ectypus Say (L. agonus Say of authors) more persistent in lighter soils. The latter worker (1935) stated that there was no correlation between abundance of this wireworm and soil moisture, temperature or pH reaction.

Lane (1925) found Limonius larvae in the West to prefer a moist soil resulting from an annual rainfall of 18". Larvae of Ludius sp. were found to prefer drier soils where rainfall was less than 18" a year. Ludius inflatus Say is the chief pest wireworm of Washington, Oregon, and Idaho in the arid transition zone having an annual rainfall of 18-20" a year; Ludius noxius Hyslop in areas having 10-18" of rain annually. Pheletes occidentalis Candeze was found mostly in swampy places and in irrigated land. Fluctuations of Limonius larval populations were affected more by moisture than by temperature. Strickland (1933) stated that larvae of Ludius aereipennis tinctus Lec. ceased to feed if soil contained less than 15 per cent of water holding capacity.

Hawkins (1936) found larvae of Limonius sp. in Maine chiefly in the sandy soils of river valleys and in soil moderately well drained. Limonius agonus larvae collected in the fields alongside the Connecticut River in Northampton were found in similar localities. Ludius larvae were found in Maine (Hawkins, 1936), associated with Agriotes mancus larvae in heavier types of soil but their preference is for a better drained soil than that inhabited by Agriotes mancus larvae. Melanotus larvae, however, prefer a light, relatively dry soil but a certain amount of moisture is, of course, necessary to their survival. Melanotus tamsuyensis Bates have been found in Formosa to go to a depth of 17" during the dry season (Miwa and Yanagihara, 1929).

Horistonatus uhlerii Horn is found in certain sections of the south only in sandy well drained soils. It has never been found in completely dry soils nor in low heavy, wet soils (Tenhet and Howe, 1939). They are very sensitive to extremes in soil moisture.

Lacon larvae in Queensland were observed by McDougall (1931) to inhabit the top two or three inches of moist soil from August to September. Depth of population depends on amount of soil moisture. Older larvae withstand lack of moisture better than do the younger ones. Excessive moisture (McDougall, 1933) is needed during December to February for the establishment of Lacon variabilis Cand. larvae.

Corymbites larvae are usually more injurious on higher ground (Semenov, 1930).

Campbell (1937) noticed *Limonius californicus* Mann. larvae to respond, in field observations, to variations in temperature and moisture. A moisture gradient consisting of six galvanized iron cylindrical sections fitted together was devised. Percentages of moisture in the different sections of the gradient varied from top to bottom from 3 to 24. Wireworms migrated from soil with 3-4 per cent moisture and the soil with 12-15 per cent moisture was found to be most favorable. In a check tube, where moisture was the same at all depths, the presence of food probably retarded the downward migration of the larvae. These experiments indicate dry soil has the greatest effect in driving wireworms downward.

Relation of Wireworms to Soil Temperature

Temperature is one of the more important environmental factors affecting the growth and activity of wireworms. All insects have an optimum temperature at which their activity is the greatest and a minimum temperature beyond which activity and growth are delayed. Elaterid larvae are no exception to this condition and their injurious activities become more pronounced when temperatures become optimum.

The fall of temperature with the approach of cold autumn months is no doubt the chief reason for the downward migration of larvae. This characteristic movement of the larvae to escape cold has been observed by many workers. The downward migration may not be as pronounced in sections where weather conditions vary but it exists, nevertheless. Horistonotus uhlerii Horn, the sand wireworm of the Carolinas, overwinters at a depth of 18" to 30" but it is said to be able to move sluggishly even at this depth. Hence it might be described as not having a true hibernation period (Tenhet and Howe, 1939). Other larvae, like those of Agriotes mancus Say, in Maine, overwinter just below the plow line and are capable of surviving in frozen earth. Hawkins (1936) thinks that very few wireworms are killed by cold temperatures in Maine. Snow may act as an insulator for the soil and thus keep larvae protected from extreme surface weather conditions. In Connecticut, larvae of Limonius agonus Say have been observed by the writer to survive weeks of remaining in the top six inches of frozen soil. Wireworms have been found at extreme depths, presumably going to such depths in order to escape adverse temperatures. Pospelova (1937 and 1939) found larvae of Agriotes obscurus L. at a depth of 40". King, Arnason, and Glen (1933), in Canada, observed that wireworms go down a few inches deeper in the fall with the approach of cold weather. Only a few go below the plow line and then only an inch or two. Some of the larger larvae may be found in the upper few inches of soil in the spring, apparently unharmed by the winter temperatures there.

Agriotes ustulatus L. larvae are found 1" to 4" below the soil surface in the Spring but hibernate at much greater depths (Rambousek, 1929b). Gueniat (1934) reported that wireworms did not go down in the soil in winter to escape the cold. The wireworms he observed were Agriotes obscurus L., A. sputator L., A. lineatus L., and Lacon murinus L. Hawkins (1936) thought wireworms might be caught in the soil frozen by sudden cold but most of them had migrated downward to escape the cold. Bobinskaya (1937) noted that autumn downward migration of Agriotes obscurus L. depended mainly on soil temperatures. These migrations began when the soil temperature at a depth of 2" was 9°C. When the temperature of the upper layers was 6°C. - 7°C. wireworms went down to 18" and at the end of November, when the soil was frozen to 10", they occurred at depths of 20" to 24". In the spring, injury to crops was first noticed when mean temperature of soil was 11°C.

Agriotes obscurus L. and A. lineatus L. resisted a temperature of 14°C. for several hours if sufficient moisture was present (Langenbuch, 1932).

Feeding by the larvae of Ludius aeripennis tinctus Lec. was noted by Strickland (1933) to be heaviest in soils with a temperature of about 26.7°C. Very little feeding was done when soil temperature was above 30°C. or below 21°C. In the summer time, when the soil gets warmer and its surface drier, wireworms might go down deeper into the more moist and cool layers of soil and feed very little.

Pheletes ectypus Say and Limonius plebejus Say were found at a depth of 6" to 9" during the growing season (Lacroix, 1933). Feeding by these larvae took place all summer. In October and November, the larvae moved upward and most of them were found at a depth of 3" to 6".

The optimum temperature for the activity of larvae of Limonius (Pheletes) canus Lec. and L. (P.) californicus Mann. in Washington was reported by Marlatt (1930) as being between 21.5°C. and 23°C. The limits of their activity were 16°C. and 38°C. In California 35% of the larvae of L. (P.) californicus were found at a depth of 1" to 8", some were found at 13" and a few at 22".

Mail (1930) reported that the larvae and adults of Melanotus communis Gyll. have a sufficiently low freezing point to withstand Minnesota winter temperatures if they hibernate below 4" in the ground. Snow is normally an adequate protection for insects below 4" where temperatures seldom go below 1°C. (Mail 1930). Rain or a rise in temperature inducing a thaw destroys the temperature gradient in the first 2 feet. If rain or thaw is followed by a decided drop in temperature, high mortality may result.

Larvae and adults of Melanotus communis can withstand temperatures in Minnesota to an undercooling point of -14.6°C. and a freezing point of -12.8°C. These temperatures were determined by the contact method and checked by microscopic examination for ice crystals.

Limonius sp., according to Lane (1935) are affected more by soil moisture than by soil temperature. The greatest injury by wireworms was observed in the spring when the soil was cool and moist. Higher summer temperatures drove the larvae downward where soil temperatures were more suitable.

Fulton (1928) noted that the usual habitat of adults of Melanotus communis Gyll. was near sod land. Adults cannot live long on the soil surface on hot days. Using a temperature gradient, he found that the preferred soil temperatures were lower than the maximum temperatures in open fields during summer. Larvae were more resistant to heat than adults.

Bryson (1934) observed that Melanotus larvae were active in the upper few inches of soil even before corn had germinated. They remained near the surface through the winter and became active when the soil temperature was slightly above the freezing point. Evidently the larvae can withstand freezing temperatures without injury. Melanotus andAeolus larvae moved vertically in response to surface conditions (Bryson, 1935). Specimens were found alive in frozen masses of soil. Temperatures above 27°C. and below 0.5°C. were unfavorable. The average depth of larvae was 6" to 10.7". Downward migration, either to pupate or to escape heat, occurred between late June and mid-July and the return upward in mid-September. Larvae descended below the 6" plow line in autumn.

The movements of larvae of Limonius californicus Mann. have been experimentally observed in a temperature gradient by Campbell (1935, 1937). Temperatures in the gradient varied from 1.5°C. to 42°C. Wireworms placed in the hot end quickly moved to cooler soil while those placed at 2.5 - 6°C. did not move at all. Campbell reports that temperature preferences change with the seasons--a low temperature is preferred in summer, rising gradually to a peak in early fall, and dropping again with the onset of winter. The chosen winter temperature where over 50 per cent of larvae occurred was 14 - 21°C. The chosen temperature in spring was 15 - 21°C. and for early fall, 18 - 22°C.

Relation of Wireworms to Food

Under this heading the importance of food to wireworms as well as injury to plants, the preferred food plants, and factors affecting food supply will be reviewed.

Elaterid larvae feed on both animal and plant material. Many of the plant feeders may temporarily become feeders on animal matter. Subklew (1934) noted that the larvae of Agriotes lineatus L. in Germany usually fed on living plants but sometimes became carnivorous. Lacon murinus L., usually regarded as a vegetable feeder, has been observed in the laboratory to feed on small earthworms and larvae of Melolontha. (Schaerffenberg, 1939). This ability to take in animal matter is evid ntly more characteristic of older larvae, especially in the case of plant feeding wireworms.

Plant feeding wireworms are usually lim ted by several factors. Moisture and temperature play an important part as limiting factors of wireworm abundance in certain crop areas. Shirk and Lancaster (1936) found that damage to wheat, one of the preferred foods of Limonius larvae, was reduced 50 per cent when wheat was grown on unirrigated areas. This would indicate a decided limitation of wireworm feeding by lack of moisture even though the food supply was abundant. A rise in soil temperature and the hunger of starved wireworms are no doubt the most important factors responsible for attacks on plants and seeds in the spring. Seeds may be attacked before the soil temperature becomes warm enough for their germination. In the summer, extreme rixes of temperature with consequent drying of soil, is responsible for the downward migration of larvae even though the food supply may be abundant at this time.

The type of food is, of course, one of the most important factors affecting the abundance of wireworms in certain crops. Damage by Agriotes larvae in this country and in Europe usually accompanies planting of crops in areas previously in sod. Many workers have reported on the preference of sod land by various _Agriotes_ species for egg laying and feeding. Zacher (1931) observed _Agriotes lineatus_ L. to lay eggs especially in grass land. Newly hatched larvae fed chiefly on humus and decomposing matter. Young larvae were able to live in soil containing a few pieces of humus for many months. Subklew (1934) reported that larvae of _A. lineatus_ L. were facultative feeders on humus for the first year and attacked living plants after the first year. _Agriotes mancus_ Say is considered as being normally a grass feeder where humus is abundant and soil humidity usually high. MacLeod and Rawlins (1933) stated that this species does not oviposit in soil that is bare and dry. (Hawk ns, 1930) reported that meadows and oatfields were the favorite breeding grounds in Maine. In northeastern Ohio, Gui (1933) found that dark Mahoming loam had a higher organic content than that of two other types of soil. This type also had the greatest population of _Agridtes mancus_ larvae. However, the exact relationship of wireworm abundance to organic content of soil is not known. Ohio muck soils, although high in organic content, are not infested with _A. mancus_ Say.

Yaroslavtzev (1930) found that fields grown to clover for three or more years were very favorable locations for infestation by *Agriotes lineatus* L., *A. obscurus* L., and *A. sputator* L. The soil humidity and food supply in such fields is evidently ideal for these species.

Langenbuch (1932) reporting on the feeding habits of *Agriotes lineatus* L. and *A. obscurus* L. stated that in sandy soils with no humus, wireworms ate less potato at lower moisture percentages than at moisture percentages of 65 and up. In humus soil with moisture percentages up to 50, the amount of potato eaten was as much as that recorded for 60 per cent. moisture in sand. At 60 per cent. moisture in humus soil feeding was materially less and at 75 to 90 per cent. moisture no feeding occurred. Therefore it would seem that wireworms prefer to feed in sufficiently moist soil rich in humus to potatoes and other plants. *A. obscurus* L. probably lives on organic substances for the most part but when the moisture or humus content decreases they attack living plants. In soils lacking in humus, living plants will be attacked.

Not all elaterid plant-feeding species favor a humus-bearing type of soil environment. *Lacon* sp., injuring sugar cane in Queensland prefers a dry sandy type of soil environment. *Horistonotus uhlerii* Horn prefers a light, sandy, porous type of soil deficient in humus. Tenhet and

Howe (1939) reported that they were unable to determine whether or not the sand wireworm utilizes organic matter in the soil. Larvae placed in soil rich in humus but with no other food, died in 60 days.

Limonius californicus Mann. and L. canus Lec. larval infestations may increase or decrease dependent on type of crop rotation practiced. Shirk and Lanchester (1936) found that growing of red clover favors the increase of these species whereas growing of unirrigated wheat resulted in a reduction of wireworm population.

Strickland (1939) reported on the food requirements of the northern grain wireworm, Ludius aeripennis destructor Brown. He found that young larvae can be fairly readily starved while the third and fourth instar larvae, in which most larvae pass their first winter, cannot be practically starved in the field. Recently emerged larvae, kept in damp soil, died after 8 days, perhaps from starvation. The young emerged larvae will feed on any roots offered them but this does not mean that they can survive on any type of diet. A monocotydedonous diet is suitable for young larvae although a small percentage can survive on dicotyledonous plants.

Bencomo (1915) described Agriotes (Elater) segetis as properly a pest of cereals and vegetables in Cuba. This species turned to feeding on tobacco when vegetables were no longer grown on the former infested areas.

Thomas (1931) noted a relationship between wireworm infestation and the occurrence of a grass crop at some time in the field, according to the data he had collected.

Types of Wireworm Injury to Plants

Wireworm injury to plants is often difficult to distinguish from injury by other insects. All parts of the plant may be attacked. Numerous investigators have reported on wireworm injury.

Agriotes mancus Say damage to potato tubers has been described by Hawkins (1936). Early in the season, feeding on the tubers causes pits and scars to appear and misshapen potatoes are formed. Feeding later in the season results in pits, holes, and tunnels. Rawlins (1932) reports similar damage by A. mancus to potatoes in New York. Damage to potatoes by Limonius agonis Say has been observed locally. Seed pieces may be tunneled so badly as to affect sprouting. Early injury, although it heals over, produces scarred and misshapen potatoes. Late feeding results in deep holes and tunnels, often lined with potato scab fungus.

Injury by larvae of Pheletes ectypus Say (Limonius agonus Say of authors) to tobacco in Connecticut has been reported by Lacroix (1935). Wireworms tunnel the roots of newly set plants causing them to wilt and die. It was formerly thought that larvae did not attack reset plants but recent investigations show that larvae may be present all summer feeding on the fine roots of tobacco plants.

In some severe cases of infestation, even the reset plants have been destroyed and a third planting may be nécessary. Numerous other plants are tunneled by wireworms and these are mentioned in the list of plants attacked by wireworms (Table I).

Seeds of plants are attacked by numerous species. Seeds of carrots, spinach, beets, and corn have been entered by wireworms causing failure of the seeds to germinate.

The greatest injury to graminaceous plants is done to the roots. In stands of wheat and grass wireworm feeding on the roots may not be particularly evident because of the density to which the plants are sown. In fields of corn, however, severe wireworm infestations are easily noticed by the number of poorly growing or dead plants, or missing hills in the field.

Langenbuch (1932) described the feeding of larvae of <u>Agriotes lineatus</u> L. and <u>A. obscurus</u> L. These two species feed on humus as well as on living plants. The larvae do not seem to take in plant cells, starch grains, etc. but filter them out with their mouth bristles and squeeze the juices out with their mandibles.

TABLE I

SOME OF THE MORE IMPORTANT ECONOMIC SPECIES OF WIREWORMS OF THE WORLD AND THEIR FOOD PLANTS

Species	Locality	References	Food Plants
Aeolus dorsalis	Kentucky	Jewett (1939)	Crops following sod
Aeolus mellilus	Ontario	Stirrett(1936)	Crops following sod but does not feed much on humus.
Agriotes aterrimus	Germany	Blunck(1925)	Forest seedlings
Agriotes gurgistanus	Russia	Gilyarov(1937)	Rubber plants of southern Ukraine
Agriotes lineatus	Europe Russia	Subklew(1934a) Langenbuch(1932) Masaitis(1929)	Facultative feeder on humus and living plants after first year. Cereals, truck crops, etc.
Agriotes mancus	U. S. A.	Petit (1910,'24) Hyslop (1916) Gui (1933) Hawkins (1936a) Rawlins (1940)	Wheat, truck crops, potatoes etc. in the eastern states.
Agriotes obscurus	Europe Russia	Miles (1939) Masaitis(1929) Subklew (1934a)	Similar to *Agriotes lineatus.*
Agriotes (*Elater*) *segetis*	Cuba	Bencomo(1915)	Properly on cereals and vegetables but feeds on tobacco grown where formerly truck crops grew.
Agriotes sericeus	Japan	Takahashi and Tsumagani(1938)	Tobacco
Alaus putridus	Formosa	Mitono(1932)	On *Pinus luchuensis*
Athous haemorrhoidalis	England Germany	Miles(1922) Blunck(1925)	On crops in sandy soil having an abundance of root fibers.

TABLE I
(continued)

Species	Locality	References	Food Plants
Athous subfuscus	Germany	Blunck (1925)	Forest seedlings
Brachylacon murinus	Poland	Chrzanowski (1931)	Young sugar beets
Conoderes auritus) Conoderes bellus) Conoderes lividus)	Kentucky	Jewett (1940)	Crops following sod
Corymbites aeripennis destructor	U.S.A.	Munro and Schifino (1938)	Potatoes
Corymbites (Diacanthus) latus	France	Regnier (1921)	Truck crops
Corymbites sjaelandicus	Germany Russia	Subklew (1934a) Durnovo (1935)	Cauliflower,cabbage,onions.
Corymbites tesselatus	Germany	Subklew (1934a)	Truck crops
Dolopius marginatus	Germany	Blunck (1925)	Forest seedlings
Drastia elegans	U.S.A.	Forbes (1892)	Corn
Hemicrepidius memnonius	New York	Rawlins (1934)	Potatoes
Heteroderes amplicallis	Cuba	Calvino (1922)	Tobacco
Heteroderes carinatus	Queensland	McDougall (1931)	Sugar cane
Heteroderes laurentii	New York	Comstock and Slingerland(1891) Cockerham and Dean (1936)	Potatoes,root crops, grains.
Horistonotus uhlerii	So.U.S.A.	Tenhet and Howe (1939)	Truck crops, grasses,etc.
Ischnodes sanguicollis	Germany	Subklew (1934a)	Potatoes

TABLE I
(continued)

Species	Locality	References	Food Plants
Lacon murinus	Germany	Blunck(1925)	Potatoes,ornamentals, forest seedlings.
Lacon musculus	Formosa	Takano(1925)	Sugar cane
Lacon stricticollis	Fiji	Veitch(1919)	Sugar cane
Lacon varisbilis	Queensland	McDougall(1934a)	Sugar cane shoots and seed pieces.
Limonius agonis	Eastern U.S.	Lacroix(1933) Bryson(1930) Hawkins(1933)	Truck crops, tobacco, root crops.
Limonius californicus	Western U.S.	Stone(1941)	Beets,beans,etc.
Limonius confusus	Illinois	Davis (1910)	Potatoes
Limonius (Pheletes) ectypus	Conn.,N.Y.	Lacroix(1933) Rawlins(1934)	Truck crops,tobacco, potatoes
Limonius (Pheletes) occidentalis	Wesrtern U.S.	Lane(1925)	Alfalfa, potato, etc. in Upper Sonoran zone.
Limonius aeruginosus	Poland	Chrzanowski(1931)	Young sugar beets
Ludius aeripennis destructor	No.U.S. Canada	Glen and King(1938) Strickland(1939)	Potatoes and monocotyledons
Ludius aeripennis tinctus	"	"	" " "
Ludius noxius	U.S.A.	Lane(1925,1931)	Wheat
Ludius inflatus	"	Lane(1925)	Wheat
Megapenthes opaculatus	Cuba	Calvino(1922)	Tobacco

TABLE I
(continued)

Species	Locality	References	Food Plants
Melanotus fissilis	Illinois	Forbes (1892)	Corn stalks above the root
Melanotus communis	Washington Florida	Scobey (1892) Ingram et al. (1939)	Wheat Sugar cane.
Melanotus cribulosus	Connecticut	Lacroix (1935)	Tobacco
Melanotus tamsuyensis	Formosa	Miwa and Yanagihara (1929)	Sugar cane
Monocrepidius (Conoderes) bifoveatus	Cuba	Calvino (1922)	Tobacco
Monocrepides pollipes	Fiji	Veitch (1919)	Sugar cane
Monocrepidius vespertinus	South Car.	Conradi and Eagerton (1914)	Seed corn
Selatosomus aeneus	Germany	Blunck (1925)	Cereals, root crops, forest seedlings, tobacco.
Selatocomus latus) Selatosomus spretus)	Siberia	Masaitis (1929)	Cereals
Simodactylus cinnamumeus	Fiji	Veitch (1919)	Sugar cane

Food of Adult Click Beetles

Damage to plants by the Elateridae is generally considered as being done in the larval stages. The adults feed, too, and on a variety of plant substances. Damage resulting from adult plant-feeding, however, can be considered slight.

Blunck (1925b) lists a number of adult feeding records observed in Germany. Corymbites purpureus, C. castaneus and C. tesselatus were all observed injuring the bark of young oaks by their feeding. C. tesselatus also injured the bark of young pine. Agriotes aterrimus and Lacon murinus were found injuring the young oak bark and L. murinus also attacked flower stems of rose.

Subklew (1934a) noted adults of Corymbites tesselatus, Agriotes lineatus, A. obscurus and Selatosomus aeneus feeding on grain seedlings in Germany. Agriotes ustulatus feeds on the pollen of umbelliferous and other plants according to Rambousek (1929b). Agriotes obscurus and A. lineatus were observed by Langenbuch (1932) to press the juices from the leaves of small barley plants with their mandibles. They also fed on the juice oozing out from freshly cut pieces of potato. Agriotes sp. in Switzerland were observed by Gueniat (1934) to emerge in March and feed on plant parts rich in food such as leaves of cereals and cereal seeds swollen by germination. These adults were never found feeding on animal matter.

Ludius aeripennis tinctus was reported by Strickland (1935) to feed on carrots but this worker doubted if these adults did much feeding in the field.

Adults are often found in flower blossoms of field or ornamental plants or fruit trees where they might do considerable damage. Monocrepidius vespertinus was reported as early as 1914 as damaging the buds of cotton as well as in the squares. Folsom (1936) found the adults of this species common on all parts of the cotton plant, especially in July. Damage is done by feeding in bud clusters and leaves of small plants. Thomas (1940) has noticed adults of Monocrepidius lividus DeG. on peach trees in spring and summer but does not think that they are injurious to the trees. Limonius pilosus Loske have been found to feed on apple trees and may cause serious damage to trees with few flowers (Van Poeteren, 1933). The flowers and fruit of citrus trees in Japan have been damaged by the adult-feeding of Corymbites notabilis Cand. Cockerham and Deen (1936) reported corn pollen as the chief source of food for adult Heteroderes laurentii Guen. Thomas (1940) noted Pheletes ectypus to be common on flower heads of rhubarb in May. Adults would also feed on cut surfaces of potato lying on the ground. In the laboratory, adults preferred cut slices of potato to apple but they did feed on apple. Limonius agonus were observed by the writer evidently feeding on dandelion flowers adjacent to a plowed field in late May.

The chief source of food in the field for <u>Lacon variabilis</u> Cand. is considered by McDougall (1934b, 1935) to be the soft underground portions of plants. Tenhet and Howe (1939) reported that <u>Horistonotus uhlerii</u> adults evidently feed by rasping the stem and blades of corn and grasses and sucking the juices. Lockwood (1933) has described the injury done by click beetles by feeding on stone fruits.

REVIEW OF LITERATURE ON CONTROL OF WIREWORMS

Seed Protection

Wireworms are particularly destructive to seeds and young stages of plants. The seed, or germinating seed, and the young plant have not the resistance necessary to overcome wireworm injury as do older plants. Much of the early work on wireworm control was based on the idea of protecting the seed against wireworm attack. Many compounds, both organic and inorganic, were used for this purpose. Thomas (1930a) notes several seed coating compounds such as arsenicals, flourine or copper compounds, mercury or sulphur compounds. Of the organic compounds, kerosine, tar, formalin, turpentine, strychnine and others are mentioned.

The results obtained in using these compounds in early wireworm control were variable. Later research indicated the inadvisability of using some of the seed-treating compounds. At the present time, seed-treatment as a wireworm repellent is not generally practiced. Wireworms are now known, according to Thomas (1940) to reject the first few mouthfuls of food. Such a habit would make seed treatment useless. King, Arnason and Glen (1933), among others, do not recommend the use of poisons for seed coating nor their use in poison baits. Woodworth (1938) notes several reasons for the rejection of arsenicals in poison baits by wireworms. His experiments evidently indicate the inability of Limonius canus larvae to ingest arsenicals. The larva of this species has a mechanical means of preventing undesirable substances from entering the digestive tract. Two sclerotic plates in the anterior part of the buccal cavity when relaxed, close off the digestive tract completely. Large particles are prevented from reaching the digestive tube by means of numerous bristle-like hairs distributed over the anterior edge of the ventral closing plate, on the hypopharynx, on the mandibles, maxillae and labial palpi. This apparatus is probably sufficient to keep undesirable materials--even soluble materials--from entering the digestive tract. Woodworth's experiments lead him to believe that poisons found in the blood stream enter the blood through the integument (contrary to Subklew (1934c), who states that salts may enter the body through the digestive tract).

One of the earlier and more extensive reports on wireworm control is the account given by Comstock and Slingerland in 1892. These authors state that up to 1895 there had been no extensive series of experiments on wireworm control. Their experiments were directed toward (1) protection of the seed, (2) destruction of larvae, (3) destruction of pupae and adults. In their experiments with materials to protect the seed, coating or soaking the seeds with various compounds was tried. Coating with Paris green and flour gave no protection against wireworms and possibly was of no harm to wireworms, for many fed on seeds thus treated. Coating with tar not only retarded germination but caused many kernels to die. Larvae attacked seeds thus coated. No control was obtained by soaking the seed in a salt solution or a copperas (sulphate of iron) solution. Wireworms ate seed soaked in a solution of lime and copperas. Seeds soaked in kerosine were not touched in the fall but were attacked in the spring. Soaking of seed in spirits of turpentine or in a strychnine solution did not repel wireworms.

Fernald (1889) recommended soaking of seed in water for a short time and then putting seed in a mixture of Paris green and flour, the flour to attract the wireworms. Forbes,(1892) said Paris green on corn was useless against wireworms and often toxic to germination.

Hood (1907) said results from use of tar, paris green or kerosine on seed was not very successful and did not recommend treatment of seed with these materials.

Fernald (1909) recommended coating of seed with tar and then coating it with a dust composed of paris green and fine road dust. No harmful effect on germination of seed was noticed after treatment with this method. Criticism that this method was ineffective was answered b Fernald (1911), who maintained that reported failures were probably due to use of incorrect type of tar and use of paris green alone, instead of in combination with road dust. Graf (1914) found paris green ineffective as a repellent against wireworm attack.

Other compounds that have been tried are calcium fluosilicate, lead fluorite, copper sulphate solution, copper nitrate and copper carbonate. Equally ineffective are mercuric chloride, mercurous chloride, sulphur, sodium sulphite dust, ferrous sulphate and potassium sulphide.

Recent workers have shown that most of these compounds, organic and inorganic, are inadequate for protecting the seed against wireworm attack. To date, no compound has been developed which will adequately protect the seed against wireworm attack and still enable it to germinate. Some compounds, such as copper carbonate used as a fungicide, may enable a stand to be more vigorous and thus indirectly assist it to overcome, in part, damage due to later wireworm attack (see Lane, 1931).

Thus it can be seen that coating of seeds with poisonous compounds, although it may be repellent to some wireworms, has no great value as a means of protecting the seed against wireworm attack. As a matter of record a brief history of some of the work on seed protection is given.

Contact Insecticides

The use of contact insecticides against wireworms has not been very extensive nor very successful. The type of soil in which the contact insecticide is used is the limiting factor affecting the efficiency of most insecticides of this type. The nature of the soil may be responsible for lack of penetration of the material used or it may leach out the essential killing properties of the insecticide. Furthermore, because of its use in the soil a greater amount of the insecticide may have to be used, consequently resulting in added expense of control. Further difficulties may be encountered in applying the material most efficiently to the areas to be treated. New apparatus may be necessary.

Other factors to consider in the use of contact insecticides is the effect of the materials used upon living plants and upon the soil itself. All these factors should be carefully investigated before any compoundis accepted for general use as a contact insecticide against wireworms. These factors also serve the same purpose in choosing a suitable stomach poison or fumigant against wireworms.

Kerosene was tried out as a contact insecticide by Comstock and Slingerland (1892). These workers found out that kerosene emulsion killed more larvae than did kerosene alone. To be effective in the field, however, both compounds would have to be applied in such quantities that it would be destructive to vegetation. Their results with crude petroleum, pure and as an emulsion, were not as good as those obtained by using kerosene.

Petroleum, paraffin, tar oils, and soap solutions have been recommended by various authors, Ormerod (1881), Curtis (1845, 1860), Bourcard (1913), Regnier (1921). These have not been very successful but are listed here as a matter of record.

Salt has no apparent effect on wireworm activity. Comstock and Slingerland (1891) used salt in their experiments with wireworms in cages at the rate of 1000 lbs. to the acre. No kill of wireworms was obtained at this rate. These investigators were of the opinion that in order to be effective, salt would have to be used at the rate of 8 tons to the acre. This heavy application would ruin vegetation. Hawkins, (1933) found salt, used at the rate of 1000 lbs. to the acre, had no effect on _Agriotes_ larvae. This amount did not affect crops.

Tobacco dust mixed with soil, had no apparent effect on _Pheletes_ (_Limonius_?) _agonis_ larvae in Thomas' (1930) experiments. MacLeod (1929) advised the use of a nicotine dust at time of sowing. Hawkins (1936a) found that ground tobacco stems applied to soil at the rate of 1000 lbs. per acre resulted in more vigorous and larger potato plants than those in check plots. This tobacco treatment did not result in an evident decrease in the wireworm population.

Pyrethrum applied to wireworms did not injure them, according to Forbes (1886). Thomas (1930) stated that a good grade of pyrethrum powder mixed with soil was toxic to wireworms. Headlee (1930a) reported on the use of pyrethrum specifically for wireworm control. In his experiments, "Pyrethrol", a proprietary substance containing 5 per cent.oleoresin of pyrethrum and 45 per cent. sodium oleate soap, diluted 1 to 15 and 1 to 25, was used. This solution was applied to the soil at the base of infested cabbage, sweet corn, horse radish, lima beans, and string beans without causing any injury to the plants. Mortality was proportional to the strength of the solution except where the strength became greater than the optimum. Depth of penetration and type of soil affected toxicity of the solution. In 1930b, Headlee stated that fresh "Pyrethrol" at the rate of 1 to 50 killed many wireworms at base of plants treated with this material. Burdette (1931, 1932) found that pyrethrum extracts were relatively inefficient against wireworms probably due to failure of penetration in soil. Lacroix (1932) found a solution of "pyrethrol", 1 to 25 and 1 to 50 poured into holes in which tobacco plants were set, affected neither the plants nor the wireworms at the 1 to 50 mixture but the 1 to 25 mixture severely injured the plants and only paralyzed the wireworms. Morrill and Lacroix (1938) reported that cube root powder, pyrethrum extract and pyrethrum oleoresinate were ineffective against Limonius agonis larvae attacking young tobacco plants in Connecticut.

Stomach Poisons

One of the newer ideas in wireworm control is the development of stomach poisons. These poisons, mixed with the soil, are harmful to larvae taking in soil. Japanese beetle grubs have been successfully controlled by mixing lead arsenate with the soil. This practice is good for soil-ingesting species but wireworms evidently are able to hold back any undesirable substances (Woodworth, 1938).

As a matter of record, some of the work done with stomach poisons for wireworm control is briefly reviewed. Lead arsenate may be used for treatment of golf greens at the rate of 5 lbs. per bu. of sand where wireworms are excessive (Pettit, 1932). Tenhet and Howe (1939) found lead arsenate at rate of 40 lbs. per acre ineffecive against Horistonotus uhlerii larvae. Zinc arsenite applied in water used at the time of transplanting tobacco plants was effective against Limonius agonis larvae in Connecticut (Morrill and Lacroix, 1938).

Mercury compounds have been tried as stomach poisons by a few workers. Watering of young tomato plants in greenhouses with a mercury bichloride solution checked wireworm damage, according to Staniland and Beaumont (1936). Mercurous chloride (calomel) has been tried in laboratory experiments by Hawkins (1936a) who found it somewhat toxic to wireworms. Thomas (1940) noted wireworms feeding unharmed on cabbage plants treated with mercuric chloride for control of cabbage midge.

Care should be used in employing stomach poisons in the soil. According to Bryson (1928, 1930), sodium compounds are harmful to the soil and arsenic compounds cause serious injury to plants. Furthermore, the effect of poisons on beneficial soil bacteria should be considered before extensive application of a compound is recommended.

Fumigants

One of the most desirable ways to control wireworms is by the use of fumigants in the soil. Diffusion of a gas through the soil has certain advantages over contact or stomach insecticide. Usually smaller amounts of material need be used which often results in more economical control. Less waste may be encountered in using a fumigant because of the method of application. Soil penetration may be better because of the gaseous nature of the fumigant. There are, however, numerous disadvantages in using fumigants for control of soil pests. The greatest disadvantage is that of injury to the soil or living plants. Often control of attacking wireworms is necessary when plants are on the soil and under such a condition some types of fumigants are out of the question.

Thomas (1930) lists several qualifications of a suitable soil fumigant, as outlined by Miles (1929) and Wardle (1929). In the first place it should be cheap. It should be easily obtained and applied without special machinery and without any injury to operator or to stock. It should be easily diffusible through the soil and should not be leached out of the soil by water. It should not affect the germination or growth of plants. It should be capable of storing without deterioration. McCollough and Hayes (1929) also note other factors to be considered in using fumigants. These chemicals may be changed or changee the chemical, physical and biological nature of the soil. They may destroy soil bacteria or protozoa or stimulate the growth of others and thus affect plant life directly or indirectly. Thus there are many factors to consider in choosing the correct fumigant. It is doubtful if any one fumigant possesses all the necessary qualifications of an excellent control of wireworms in the soil.

Carbon Disulphide

One of the earliest uses of soil insecticides was that of CS_2 against the grape phylloxera in France by Marion (1877). In the United States this material was first used against wireworms, experimentally, by Comstock and Slingerland (1891), who reported a good kill obtained by applying 3 to 5 cc of CS_2 to the soil of a breeding cage. Bourcart (1913) notes several European workers who obtained favorable results with this compound. Other workers in the early 1900's, Umnov (1913), Steinberg (1914), Bencomo (1915), reported less favorable results.

Melander (1917) placed CS_2 in saucers under canvas covering strawberry rows and obtained kill of root weevils as well as wireworms. In 1923, Melander found CS_2 permeated soil quickly, especially if it was damp. French (1916) was unsuccessful in getting control of wireworms attacking beets and beans in California by putting CS_2 in the furrow and then covering it up. Patti (1914) recommended injection of 40 cc of CS_2 per sq. meter to control Agriotes lineatus larvae in the Trappani district of Italy. Regnier (1921) advised soil fumigation at the rate of 1 oz. per sq. yd. for control of Corymbites latus larvae in vegetable gardens.

Headlee (1924, 1925) reported on extensive experiments with CS_2 in New Jersey. Good kill was obtained when the soil temperature was 16°C, or above and no plants in the ground. Planting may take place a week after this treatment. He concluded that CS_2 treatment was too expensive for use in field control work. Britton (1926) found that CS_2, 1 part to 360 parts water, applied at time of transplanting tobacco plants killed the plants. A solution of 1 part CS_2 to 720 parts water did not repel wireworms. Muir and Swezey (1926) found CS_2 unsatisfactory to use in Hawaian sugar cane fields while Miwa and Yanagihara (1929) recommended its use in sugar cane fields of Formosa. Krauss (1931) used CS_2 in combination with naphthalene and obtained a kill of 95 per cent. of Euxoa (Agrotis) segetum larvae. CS_2 alone resulted in a kill of 55 per cent.

Lane and Gibson (1932) reported CS_2 can be used in loose, damp soil. Good kill was obtained by placing doses of 1 fluid ounce in holes 4" deep and 18" apart. For best results, soil should first be prepared by plowing. Lane (1935) reported kills of 80 to 100 per cent. using CS_2. Marlatt (1933) reported CS_2 as a favorable control for wireworms in irrigated areas of Pacific Northwest. The rate of application should be 1 oz. of CS_2 to a depth of 4" at 18" intervals.

Lehman (1933) compared the toxicity of CS_2 with 13 other fumigants in the laboratory. Larvae were kept in wire baskets not in soil. Allyl isothiocyanate, ethylene chlorohydrin and chloropicrin were all more toxic than CS_2. In the soil, however, CS_2 was found to be more toxic than those compounds which killed more readily in the air.

Jones (1933) studied the effect of temperature on the toxicity of CS_2 to wireworms. Relation of temperature to toxicity was determined by a method in which median lethal concentrations were the basis of comparison--those concentrations which kill exactly 50 per cent. of test insects in a period of 5 hours. Toxicity of CS_2 at temperatures of 7°, 12°, 17°, 22°, and 32°C. were tested. Results showed that median lethal concentration of CS_2 increases with a decrease in temperature. For every 10 degrees drop in temperature the concentration necessary to kill 50 per cent. is approximately doubled. When temperature is lowered there is an increase in absorption and adsorption. At the same time there is a loss of water from the soil and the diffusion of the gas is decreased.

Lacroix (1934) used a CS_2 emulsion diluted 1 to 20 with water and applied in furrows 3" deep at rate of 1 qt. to 2 linear feet of furrow. Examination of furrows three days later showed a few living wireworms but no dead ones.

Pepper (1937) used CS_2 emulsified with sulfonated caster oil or "Aresklene", carrying naphthalene or PDB. Good results were obtained in controlling wireworms and onion thrips with this mixture.

Other workers who have tried CS_2 include Vershinskaya (1932), McDougall (1934b, 1935), Pettit (1932). Vershinskaya (193) tried CS_2 at the rate of 250-300 gms. per square meter. He found it completely ineffective after 5 days. McDougall (1934b, 1935) obtained less than 50 per cent. control with 350 lbs. per acre of CS_2 placed close to sugar cane sets. Pettit (1932) advised CS_2 emulsion to keep golf greens free of wireworms.

Cyanides

Potassium, sodium, and calcium cyanide have often been recommended for soil fumigation against wireworms. Calcium cyanide is now generally referred to when a recommendation for use of cyanide is made.

Probably the first reference to the use of a cyanide for wireworm control is that of Forbes (1892) who treated seed with a solution of KCN. Graf (1914) used dry KCN against larvae of Limonius californicus. He found that this material, drilled into the ground, did not give a very even distribution. Soaked into the ground in irrigated fields, KCN killed many wireworms as well as beets. Miwa and Yanagihara (1929) recommend soil fumigation with KCN for control of injurious wireworms in sugar cane fields of Formosa. Potassium cyanide is now seldom recommended as a soil fumigant.

Sodium cyanide has had a more extensive use as a soil insecticide. Hyslop (1914) found sodium cyanide efficient and safe to use. He suggested drilling the material into soil or applying it to soil at time of spring or fall plowing. Planting of the field should not take place until 40 days after treatment. The danger of killing soil bacteria with sodium cyanide is not great nor serious. French (1916) used sodium cyanide drilled into the ground after he had noticed its repellent effect on wireworms when placed in baits. DeOng (1917) recommended sodium cyanide for fumigating loose porous heaps of soil. Expense of such treatment would prohibit its use on a large scale. Peterson (1918) used sodium cyanide experimentally in the laboratory. He found that KCN applied to wireworms in flowerpots at the rate of 200 lbs. per acre, brought good kill after 7 days' exposure. Field application of this material would be too expensive for practical use.

Melander (1923) found sodium cyanide fairly effective in comparison to CS_2, PDB, and calcium cyanide. Muir and Swezey (1926) found sodium cyanide applied at the rate of 900 lbs. to the acre effective against soil insects but its use is not recommended because it leaves a residue of free alkali in the soil. Ladell (1938) used sodium cyanide mixed with anyhdrous magnesium sulphate. A 45 per cent. reduction in wireworms was said to have resulted from plowing this mixture under in furrow bottoms at rate of 840 lbs. to the acre. Miles (1938) mentions sodium cyanide as one method of control in England.

Sodium cyanide appears to be used more for control of wireworms than KCN. Both of these cyanides, however, have given way to the use of Calcium cyanide, whereever fumigation with cyanide is recommended.

Quayle (1923) early recognized the value of calcium cyanide as a soil fumigant. Control of the wooly apple aphis was obtained by an application of 2 oz. of calcium cyanide per square yard.

Horsfall (1924) published an account of how calcium cyanide resulted in control of wireworms in plots of cabbage. Poison bran bait and corrosive sublimate had failed to control the injurious wireworms. Six to eight grams of granular calcium cyanide per plant were placed 3" from the plants in the furrows made by cultivation and resulted in an average of 81 per cent. control. Horsfall and Thomas (1926) reported on four methods of applying calcium cyanide to the soil. Best results were obtained by drilling calcium cyanide into the soil after planting baits or trap crops. Cyanide placed in a plow furrow, by drill and then covered, resulted in a greater yield of potatoes. Headlee (1929) reported a kill of 85 per cent. of wireworms that could be found down to a depth of 2 ft. by treating the soil with granular calcium cyanide at the rate of 0.1 oz. per sq. ft. In 1926, 1927, and 1928, vegetable crops on treated areas were practically untouched whereas nearby untreated fields had a heavy infestation. Campbell (1924) tested calcium cyanide in the laboratory and in the field. Laboratory experiments indicated calcium cyanide did not kill wireworms below the level at which it was placed. In the field, results showed less kill at lower temperatures or in wet soil. Wet soil absorbs hydrocyanic gas. A very loose or very compact soil showed a poor kill with CaCN. Planting may be safe a week after treatment. In 1926, Campbell reported application of

200-300 lbs. calcium cyanide to the acre with a grain drill gave a high percentage of kill under certain conditions. Soil pl wed 7" deep and then covered with cyanide at the rate of 175 lbs. per acre or more, after which the plot was packed, showed a good kill, but it was expensive. Because of the expense of above methods, bait crops or rows were thought to be more practical.

Miles (1926) indicated that calcium cyanide, used with a system of prebaiting, is likely to prove an economical way of controlling wireworms.

Baiting, in conjunction with calcium cyanide, has been tried by numerous workers in the United States. Thomas (1930) notes several factors that he and other workers have had to consider in using baits with cyanide. (1) Crop remnants and weeds should be removed and field plowed and harrowed before baiting. (2) Use baits in spring when wireworms are becoming active. (3) Best baits to use are wheat, oats, corn, drilled in rows about 2.5 feet apart and about 2" deep. (4) Allow 2 weeks between baiting and treating with cyanide. (5) Apply cyanide when soil is easily worked but not when soil is wet. (6) Apply cyanide uniformly below bait. (7) Use 6 lbs. granular calcium cyanide per 1000 ft. of row. (8) Do not plant regular crop for 7-10 days after such treatment.

Varying results with the bait-cyanide method have been reported by different workers. Wakeland obtained poor results using this method in 1927. Miles and Petherbridge (1927) controlled wireworms using baits and cyanide between growing plants without harming the plants. Britton (1926) noticed injury to tobacco plants in using calcium cyanide. Jarvis (1927) used calcium cyanide with a bait crop of peas for control of wireworms on sugar cane.

Other references to the use of baits, or bait crops, and calcium cyanide include Parks (1930, Caesar (1931), Campbell (1931, 1932, 1933), Miles (1932), Britton (1933), Webster (1934), Michelbacker (1937), Glen and King (1938).

Calcium cyanide may be drilled into the soil at the base of infested plants. Although wireworms are usually killed by such treatment, plants may also be killed or injured. Lacroix (1934)used this method to control Pheletes ectypus larvae on young tobacco plants. Applied at the rate of 100 lbs. per acre, he obtained approximately 66 per cent. control after 4 days. Morrill and Lacroix found calcium cyanide drilled beside newly-set tobacco plants at the rate of 1/4 to 1/2 oz. by weight per plant killed both the wireworms and the plant.

Broadcasting of calcium cyanide has already been noted as an effective but expensive control of wireworms. Application of the material in this manner has certain advantages which baiting, drilling, and planting in furrows do not have. Less time is required to spread the material and it can be used in fields having an abundance of organic matter where wireworms may not be attracted to baits.

Chloropicrin

Chloropicrin (trichloronitromethane, $C\ Cl_3NO_2$) commonly called tear gas, has lately come into use as a possible wireworm control. This compound has been used for control of pests in grain and stored products. It is a colorless liquid, about 3-3/4 times heavier than water. It is practically non-inflammable and is only slightly soluble in water. On vaporizing it has a very strong odor and irritates the lungs and eyes, causing tears to flow.

Investigations in England by Matthews (1919) and Russell (1920) indicated chloropicrin was an effective compound to use in wireworm control. It was said to be harmless to plants and beneficial to soil bacteria. Hasson (1920) used a special applicator on a plow which sprayed the upturned earth of the preceding row, on the sod being turned up, or on all parts of the furrow. The apparatus used 1-3/4 pints of chloropicrin a minute. Chloropicrin was found to be 500 times more toxic to wireworms than is chloroform and 350 times more toxic than nitromethane (Tattersfield and Roberts, 1920).

Johnson and Godfrey, (1931) reported using chloropicrin for control of nematodes attacking pineapple.

Applied at the rate of 180 lbs. to the acre, chloropicrin resulted in an increase of 20 per cent. in plant size and 57 per cent. in yield. Cost of treatment was about $100.00 an acre. Stone and Campbell (1933) used chloropicrin as an emulsion with an equal amount of fish-oil soap plus water. This solution was effective in killing 100 per cent. of wireworms down to a depth of 4" but toxicity decreased with soil depth. Dilute solutions did not injure germinating seeds or young plants. Lehman (1933) found the median lethal dosage to be 0.69 mgm. per liter. Chloropicrin was observed to affect the nervous system of wireworms leaving them paralyzed for two months.

Lacroix (1934) applied chloropicrin at the rate of 1 fl. oz. in holes 3" deep and 18" apart. Kill of larvae was obtained within 7" of holes. Chloropicrin was emulsified with fish-oil soap and applied directly to soil at various dilutions. It was found to be extremely toxic to young plants. As regards use of this material for control of wireworms on tobacco, Morrill and Lacroix (1938) concluded it was unsafe and not good.

Savchenko and Palchik (1935) used chloropicrin against larvae of <u>Limonius</u> <u>aeruginosus</u> Ol. and <u>Corymbites</u> <u>latus</u> F. injuring tobacco seedlings in Russia. Chloropicrin, used at the rate of 2 oz. per sq. ft., distributed 4-10" deep destroyed wireworms within 5 days. Planting in fumigated areas should be avoided until two weeks or more have elapsed. Tobacco plants were killed if planted within 20-25 cm. of treated plots less than 14 days after treatment. The effect of chloropicrin on soil is said to be a temporary decrease of nitrates in the soil, becoming normal in 6 weeks. Other Russian workers who have reported using chloropicrin include Kuzetov (1935) and Korab, Savchenko and Yarmolenko (1937).

In Queensland, McDougall (1934b, 1935) found chloropicrin unsatisfactory for controlling Lacon variabilis larvae in sugar cane fields. Abraham (1940) gives a popular account of how to treat small garden plots, greenhouses and compost piles. He warns that soil temperature should not be under 16°C. at the time of application.

Because of the danger to living plants, chloropicrin cannot be generally recommended as a control for wireworms attacking living plants. For soil sterilization, chloropicrin may be satisfactory if the following procedure is used: (1) Plow the soil and get it in a loose, friable condition, (2)apply at desired depths when temperature is at least 8°C., (3) water surface to retain gas, (4) cover with wet burlap bags for a few days, (5) allow sufficient time for all gas to leave soil before planting.

Naphthalene

One of the early references to wireworm control by naphthalene is that of Bencomo (1915) who found that a solution of naphthalene in water did not control larvae of *Agriotes* (*Elater*) *segetis* injuring tobacco in Cuba. It should be noted that naphthalene is not soluble in water. Gray and Wheldon (1919) found naphthalene up to 500 lbs. per acre did not appreciably reduce the number of wireworms.

Zappe (1922) noted the repellent effect of naphthalene placed near newly-set plants. Targioni-Tozzetti (Bourcart p. 345) noted the effect of naphthalene against wireworms. Headlee (1927) has obtained, experimentally, a good kill of wireworms by naphthalene as did Thomas (1930).

Tattersfield (1928) found that an even mixing of soil and naphthalene resulted in a fairly toxic action on wireworms. Toxicity was observed to disappear rapidly in rich organic soil and persisted longer in sterile sand and soils than in unsterilized soils. Toxicity persisted longer in dry soils than in wet soils. The number of soil bacteria was at first decreased by adding naphthalene but as decomposition of naphthalene is accelerated, the growth of soil bacteria seems to be stimulated. Evidence indicates loss of naphthalene in soil is due to soil bacteria. Miles (1929)reviewed the use of naphthalene as a soil insecticide and noted much the same results as those reported by Tattersfield (1928).

Other workers reported little success with naphthalene. Rambousek (1929a) found it ineffective as a wireworm repellent even if the wireworms were starving. McDougall (1934b, 1935) found naphthalene and slaked lime ineffective in controlling larvae of Lacon variabilis Cand. injuring sugar cane eyes and shoots. Miles (1938) and Miles and Cohen (1938) describe experiments where naphthalene, applied at the rate of 300 lbs. to the acre, before land was ridged up, had no effect on potatoes but it did not appreciably lessen wireworm damage.

Naphthalene, despite reported failures, has decided merit as a control for wireworms. Its success as a fumigant depends upon its proper use. Naphthalene should be thoroughly mixed with the soil. Soil temperature at the time of application should be 21°C. or over. Soil should not be very wet or else toxicity will be lessened. Naphthalene is cheaper than most soil fumigants, it is insoluble in water, and has no lasting toxicity to plants.

Krauss (1931) reported that CS_2 emulsion containing naphthalene killed 95 per cent. of larvae of Euxoa segetum at depth of 1-1/4" to 1-1/2". Toxicity was reduced to 50 per cent. when naphthalene was omitted from the emulsion. Headlee (1930) obtained favorable experimental results with naphthalene mixed with soil. He found a blanket of mixed soil and naphthalene applied over wireworms in clean soil in tins was not a good control. Marlatt (1933) reported a kill of 85-95 per cent. in first 10" of soil when naphthalene was applied at the rate of 800 lbs. to the acre. Hawkins (1936a) obtained a reduction of 11 per cent. in the number of wireworms in plots treated with naphthalene at the rate of 272 lbs. to 600 lbs. per acre. He concluded the extra cost of materials and labor would not justify using naphthalene in the field.

Lacroix (1932, 1935) noted repellent effect of dry naphthalene placed around newly set tobacco plants. Most wireworms attacking the plants were repelled, a few were paralyzed. Injury to plants from naphthalene was noticed. Naphthalene was mixed with "Kayso"and applied to plants but burning of the plants resulted, the amount of burning dependent on the amount of naphthalene used. Morrill and Lacroix (1938) tried plowing naphthalene into soil at the rate of 800 lbs. per acre and then immediately setting tobacco plants in treated plots. Plants showed signs of burning at first but soon recovered. In 1940 this treatment gave an average reduction of 47 per cent. of wireworms in treated plots.

Other workers have recommended the plowing in of naphthalene for wireworm control. Lane (1935, 1937) stated that if naphthalene is thoroughly mixed with the top soil when the soil temperature is 27°C. or above, as high as 85 to 95 per cent. of total wireworm population could be killed. Glen, King and Arnason (1936) recommended soil fumigation with naphthalene where the added expense was justified. Strong (1936) reported a kill of 95 to 99 per cent. of Limonius canus and L. californicus larvae in irrigated land with naphthalene applied at the rate of 800 lbs. per acre when ground was being plowed and when soil temperature was 21°C. or above. Ladell (1938) obtained a reduction in wireworm population of 59.8 per cent. when he used crude naphthalene, 1120 lbs. to the acre, scattered in the furrow and covered by the plow.

Paradichlorobenzene (PDB)

Paradichlorobenzene is reviewed as an insect fumigant by Duckett (1915). It was used at this time chiefly for control of stored product insects, household and museum pests. Later on it was used in the control of the peach tree borer (Blakeslee, 1919). Eissig (1926) tried PDB against wireworms injuring dahlias. He recommended a dosage of 1 teaspoonful PDB placed about 2" above the tuber.

Early reports concerning PDB were not very favorable. Hawkins (1928, 1936a) found 100 to 200 lbs. per acre not very effective and too expensive for field use. Muir and Swezey (1926) found it unsatisfactory when it was applied broadcast and plowed under. Bryson (1930b) reported that PDB reduced the yield of plants where it was used. McDougall (1934b and 1935) found it unsuccessful against larvae of Lacon variabilis applied at the rate of 650 lb to the acre. Nor was it more effective when it was m with CS_2 or slaked lime. Used at the rate of 2000 lbs. per acre, it was ineffective against Horistonotus uhlerii larvae (Tenhet and Howe, 1939). Safronova and Legatov (1930) found that dosages of 18 grams per sq. meter did not harm millet plants nor did it repel wireworms

More successful controls have been reported by other workers. Lacroix (1933) noted some wireworm control when one teaspoonful of PDB was placed on the soil near the newly set tobacco plants. A teaspoonful of PDB placed in the hole where plant was set injured the young plant. Headlee (1934) reports control of wireworms attacking cabbage and beet by applying 1-2 gms. of PDB to soil surface around the plant. No injury to plant was noticed. Pepper (1937) used PDB in combination with naphthalene and CS_2 emulsion. He obtained better kill in loose or sandy soils than in compact or clayey soils.

Dichloroethyl Ether

Dichloroethyl ether (bis (beta-chloroethyl) ether) $C_4H_8Cl_2O$, is a colorless liquid with a chloroform-like odor. It has a boiling point of 178.5°C. and a specific gravity of 1.22 at 20°/20°C. It is soluble in practically all oils and organic solvents and in water to the extent of 1% at 20°C. Use of an emulsifier such as "Ultrawet" or "Aresklene" increases the solubility in water to about 30 per cent. For use in soils, emulsification with "ultrawet" or "Aresklene" is generally recommended. "Aresklene" is the proprietary name for a sodium salt of sulphonated diphenyl compounds. "Tergitol" penetrant, a synthetic aliphatic compound, is frequently recommended as a wetting agent and aid in penetration.

One of the earliest uses of dichloroethyl ether as a soil insecticide was against sod webworms in blue grass lawns of Los Angeles Co., California (Campbell and Stone, 1937). Snapp (1939) has used it for controlling the larvae and pupae of the plum curculio (Conotrachellus nenuphar Hbst.) in the soil under peach trees. Dichloreethyl ether with "Tergitol" penetrant 7 has given satisfactory control of Japanese beetle grubs when the grubs were near the soil surface. Wireworm control with dichloroethyl ether was tried by Campbell and Stone (1937) against the larvae of Limonius californicus. In preliminary tests in sandy loam, these workers reported kills as high as 100 per cent. Pepper (1940) summarized four seasons' work with dichloroethyl ether stating that 1.5 cc applied in 0.33 pints of water per plant (cabbage and cauliflower) resulted in practically 100 per cent. kill of attacking wireworms.

MacLeod and Rawlins (1937) assert dichloroethyl ether to be one of the most toxic insecticides tested against the larvae of Limonius agonis Say. Morrill and Lacroix (1938) tried dichloroethyl ether in the water used in setting young tobacco plants as a control against Limonius agonis larvae. The kill of wireworms was good but plants were burned when the material was applied in warm weather.

Wilcoxon and Hartzell (1938) tested dichloroethyl ether as a greenhouse fumigant. The material was left in shallow pans to evaporate into the air. It has been shown to control Aphis rumicis, red spider, gladiolus thrips, and the adult white fly.

As a soil fumigant, dichloroethyl ether has been reported as a successful control for numerous pests. Chandler (1939) notes it has been used successfully in peach tree borer control. Control is fairly good even under conditions of low soil temperature. The control of plum curculio in the soil has been tried by Snapp (1939). In tests under caged trees in the orchard, he found one gallon of water containing 1 fl. oz. of dichloroethyl ether caused complete mortality of pupae. At the rate of 1/3 fl. oz. per gallon of water applied to one sq. yd., only 0.9 per cent. of larvae emerged. In addition to previously mentioned references, dichloroethyl ether has also been used for woolly apple aphis control (Underhill and Cox, 1940), as a soil fumigant for the Juniper midge (Parker and Wenger, 1940), for the rose midge (Blauvelt, 1940) and for the pear thrips (Jones, 1940).

Dichloroethyl ether was one of the compounds used for wireworm control by the writer. Results of control tes will be discussed later on in the paper.

Miscellaneous Fumigants

Numerous other compounds have been suggested and tried as soil fumigants for control of wireworms. A few of them are listed in this section.

Benzene was reported as satisfactory to use with a trap crop according to Jarvis, (1927).

Toluene was not effective (Russell, 1920).

Cresylic acid reported as having some insecticidal value according to Russell (1920).

Tetrachloroethane was tried by Parker (1928) who found it unsatisfactory.

Formaldehyde is ineffective as a wireworm control (Hyslop, 1915a).

Ammonia is harmful to wireworms (Russell, 1919). Delpont (1926) obtained some control of wireworms by using 1400 lbs. of crude ammonia to the acre, 3-4 months before planting. Speyer (1929) used powdered ammonia carbonate at the rate of 4 oz. per sq. yd. and watered in. Tomato plants set in plots 4 days after treatment were not injured. No plants in these plots were injured by *Agriotes* larvae.

Of 13 fumigants tested against *Limonius californicus* larvae, Lehman (1933b) found allyl isothiocyanate to be the most toxic. Its median lethal dosage was 0.16 mgm. per liter while that of CS_2 was 31.5 mgm. per liter.

Fertilizer as a Control Measure

Fertilizers have been recommended by numerous workers as a means of controlling wireworms. Many users of fertilizers attribute success to the action of the fertilizer as a contact insecticide or as a fumigant. It is doubtful if control of wireworms is due to such a simple action of the fertilizer. Numerous other factors, environmental and cultural, enter into the success or failure of a fertilizer as a wireworm control. Perhaps the best thing to be said for fertilizers is that properly used, they tend to stimulate plant growth and make plants more capable of overcoming wireworm injury. Ormerod (1881) stressed the stimulating effect of manures on plants.

Thomas (1930) states that kainit was used as early as 1850 in England against wireworms. It was recommended by Smith (1891, 1892, 1906) in the United States. Comstock and Slingerland (1891) used kainit experimentally and decided that dosages required for wireworm control were too expensive for practical use. Fernald (1899) believed 1000 lbs. of kainit per acre helpful in controlling wireworms. Chittenden (1912), Orton and Chittenden (1917) recommended its use, while Webster (1899) and Herrick (1925) doubted its insecticidal value.

Hawkins (1936a) summarized three years of field trials in the use of kainit for wireworm control. He states that it cannot be used for wireworm control with any degree of certainty due to its variable chemical condition and other factors. Furthermore, the added expense and labor involved did not seem justifiable in the light of results obtained.

In Europe, considerable work with kainit as a wireworm control has been done by Langenbuch and Subklew. These workers concluded (1934) that different wireworm species from the same locality, or the same wireworm species from different localities, are differently affected by Kainit. Subklew (1936) stated that kainit seems useful against wireworms in the loam sand soils of central, western and southeastern Germany. Applied at the rate of 1000 lbs. per acre and watered in, some degree of control resulted. No control was noted on moorland soil.

Manure has often been recommended for the control of wireworms, not as an insecticide but as a plant stimulant. Manure, guano, etc., may indirectly be a stimulant for an increase of wireworm population. The additional organic matter introduced by use of manures may be favorable for certain species of wireworms while other species may avoid manured areas. The larval population of <u>Horistonotus uhlerii</u> Horn. in South Carolina can be reduced by increasing the organic content of the soil (Nettles, 1936). The same procedure was recommended by Jarvis (1930) against wireworms on rattan cane. <u>Limonius</u> larvae in western United States tend to increase in areas planted to potatoes and manured year after year (Marlatt, 1932). MacLeod (1933) found injury by Agriotes mancus larvae to increase with use of manure. According to Morris (1927) wireworm populations were encouraged by the use of stable manures. Hay manure, guano, have been listed as having value in wireworm control (Thomas, 1876).

Other fertilizers that have been tried or recommended include Muriate of Potash (KCl) (Smith, 1891; Comstock and Slingerland, 1891; Washburn, 1892), Nitrate of Soda ($NaNo_3$) (Ormerod, 1881; Fernald, 1899; Chittenden, 1912), Ammonia Sulphate (Patti, 1914; Schaffnit, 1919), Superphosphate (Miles, 1922; Umnov, 1913; Strickland, 1933; Glen and King, 1939; Petherbridge, 1938; Ladell, 1938), Lime (Thomas, 1876; Ormerod, 1881; Bourcart, 1913; Pettit, 1924; Hawkins, 1936a).

Baits and Repellents

Baits used for wireworm control are of two types, poisoned and unpoisoned. The unpoisoned type of bait may consist of any plant material, or any other substance attractive to the larvae. Such baits are of particular use in small gardens where they can be periodically examined and the wireworms on them destroyed. Slices of potato, apples, carrots, beets, turnips, etc., have been put in the soil before planting, or between rows of planted material. Several workers have reported on this method including Ormerod (1881), Washburn (1892), French

(1916), Mesnil (1930), Langenbuch (1932), Wolcott (1933, Glen and King (1938). Other workers have tried seeds, brans and flowers as larval baits.

Treherne (1919), Jarvis (1925), and King (1928) used wheat or rice shorts, rice bran, cornmeal, etc. Hawkins (1930) said molasses added to graham flour made it second to wheat in attractiveness to larvae of <u>Agriotes</u> <u>mancus</u>.

Spuler (1925) stated that germinating seeds of vegetables are more effective as a bait than is flour. Metcalf and Flint (1928) mention germinating peas, beans and corn, and graham and rice flour made into a dough as wireworm baits. Hawkins (1930) found sprouting wheat most effective bait for <u>Agriotes</u> <u>mancus</u> larvae.

The unpoisoned type of bait requires a considerable amount of time, labor and material. In order to provide a more efficient type of bait, numerous workers added poison to the bait material. Chittenden (1901) tried poisoning sections of various vegetables with lead arsenate, arsenic, paris green, etc. Jarvis (1927) found some value in the addition of nitrobenzene to poisoned bran baits. Poisoned bran, maize, cornmeal dough, or flour baits, have been advocated by some workers (Smith (1906),Chittenden (1912), Chrzanowski (1927), Masaitis (1927). Other workers have found addition of poisons, especially arsenicals, to baits was repellent to larvae and did not result in satisfactory control even if the baits were eaten. In this connection, Woodworth's (1938) work on the reaction of wireworms to arsenicals may be mentioned. He found that larvae of Limonius canus Lec. were able to reject undesirable substances. Thus any arsenicals found in the body evidently entered through the body wall.

Another method of baiting for wireworms is to grow trap crops to attract the larvae either before the regular planting season or along with the regular crop between the rows or hills, etc. The trap crop can be disposed of when it is attacked either by digging it up or by treating it with calcium cyanide, CS_2, or some other suitable fumigant. Trap crops and calcium cyanide have already been discussed under calcium cyanide on pages 53 to 58.

It can be readily seen that the use of plant baits and poisoned baits is an expensive and time-consuming method of control of wireworms. Such a control would be impractical on a field basis for some crops, but might be advisable in the small garden. Trap crops with the use of cyanide is a better method of wireworm control on a field scale. In the case of a crop like tobacco, a trap crop with cyanide is a good method to use.

Baits for Adults

The use of baits for controlling adult Elateridae has been frequently recommended. Effective control, however, has not always been obtained. As early as 1888, Comstock reported that large numbers of adults were attracted to baits that were intended as larval attractants. The baits included sliced potato, clover, and corn meal dough. Most of the beetles taken were <u>Agriotes</u> mancus with <u>Drasterius</u> (<u>Aeolus</u>) <u>dorsalis</u> next in number. This method of baiting for adults has also been suggested by Lintner (1896) and Theobald (1928). It should be noted that clover baits seem to attract only <u>Agriotes</u> sp. (Thomas, 1940).

Poisoning of baits used for adults has been advocated by Lintner (1896), Lovett (1913), and Howard (1925). Other workers have found poison baits repellent to adults. Graf (1914) found <u>Limonius</u> <u>californicus</u> adults unattracted by baits made of bran, alfalfa meal, clover poisoned with paris green, etc. Fulton (1928) obtained only a small amount of kill of <u>Melanotus</u> adults by using baits of oat hulls, honey and paris green.

Adults have been attracted to grass or clover piles left on the ground. Some workers have taken advantage of this habit to destroy the adults either by burning or poisoning the piles. French (1916) reported piles of bean straw and other straw placed about the field to have some value against *Limonius californicus* adults. Jarvis (1930) recommended a bait of chopped grass dipped in a solution of Sodium arsenite and molasses. Marlatt (1932) reported on *Limonius* adults trapped beneath piles of Malwa in Califonnia. Campbell and Stone (1939) used piles of malwa to trap adult *Pheletes* (*Limonius*) *californicus* but obtained no apparent reduction in wireworm population. Miles and Cohen (1938) used grass traps for adults of *Agriotes obscurus* in sodland and in ploughed fields. They reported one and one-half as many beetles in grassland as in plowed land, probably due to lesser temperature changes in grassland. Pospelova (1939) reported seven species of click beetles attracted to grass traps of *Agropyrum repens* but mostly all beetles were *Agriotes obscurus*.

Other workers have noted the attractiveness of various materials to click beetles. Bryson (1928) found that adults are attracted to sweet materials, such as syrups, honey, sap, honeydew, etc. Champlain and Knull (1932) noted that a mixture of molasses and water, 1 to 10, remained attractive to adults up to the time the mixture became putrified. Lehman (1932) reported extensively on the use of bait materials. He tested over 150 essential oils and compounds in an olfactometer on adults of *Limonius canus* and *L. californicus*. The fourteen most attractive materials were tested in the field but all gave unsatisfactory results.

Adult Elateridae have often been noted in Japanese beetle traps. Metzger and Sim (1936) reported 400 specimens of *Melanotus* sp. caught in Japanese beetle traps in New Jersey. Thomas (1940) reported only a few *Limonius ectypus* adults captured in similar traps in Pennsylvania. Sheppard (1935) reported some specimens of *Aelus* sp., *Elater* sp., and *Melanotus* sp. caught in Japanese beetle traps in Ontario.

Farm and Cultural Practices

Farm Practices

In addition to the insecticidal and bait methods of controlling wireworms, there are two general methods of attack which growers frequently use. By planting practices such as depth and time of planting, amount of seed used, forcing plant growth or thinning, and replanting, many attacks of wireworms may be considerable lessened. Cultural practices, such as harrowing, plowing, fallowing, etc., may do mugh to diminish wireworm populations and thereby reduce damage to growing crops.

Time of planting may be an important factor in wireworm injury. Early planting may permit plants to get a foothold before wireworm damage can become severe. Late planting may be favorable to some plant species and weather conditions at such a time may be unfavorable to wireworms. If possible, planting should take place when wireworm activity is at a minimum.

Graf (1914) found early planting of beets a good protection against larvae of <u>Limonius califonnicus</u> Mann. Thomas (1930a, 1940) found the same true regarding beets in Pennsylvania attacked by <u>Pheletes agonus</u>. Strong (1935) recommended early planting in South Carolina to overcome damage by <u>Horistonotus uhlerii</u>. Others who have advised early planting include Vereschlagin (1936), Wakeland (1936) and Nettles (1938).

Early planting has been found to be inadvisable according to some workers. Lockwood (1929) found that field tomatoes planted early were damaged severely while those set later were not nearly so damaged. Bryson (1930a, 1934) noted that corn planted early in April and May was damaged more than corn planted after mid-May. Rawlins (1939) reported that potatoes in western New York should be planted as late as economically feasible. <u>Limonius ectypus</u> damaged early planted potatoes more severely than late planted potatoes. Ingram, Jaynes, and Lobdell (1939) recommended delayed planting to overcome damage to sugarcane by <u>Melanotus communis</u> Gyll.

The amount of seed used in planting is sometimes important in overcoming wireworm damage. An abundance of seed gives wireworms the opportunity to have a wider range of food plants and consequently damage is not so evident. The same number of wireworms on a lesser amount of seed might result in pronounced damage. Lane (1931) advised sowing 5 lbs. extra of wheat to allow for damage by _Ludius_ sp. in the northwest. Masaitis (1927, 1929) reported that the percentage of wheat destroyed by wireworms was equal at densities of 50, 80, and 110 lbs. of seed to the acre. Consequently the denser sowing would result in a more normal crop. Bryson (1930) noted that the further apart that corn was grown, the greater the amount of wireworm injury, which was probably due to the greater number of wireworms per plant in sparsely planted rows. Cockerham and Deen (1936) reported practically the same for corn attacked by _Heteroderes laurentii_ in Alabama.

Depth of planting may also be an important factor to consider in avoiding wireworm damage. Strickland (1927, 1933), Mail (1928), Glen and King (1939) found that shallow seeding resulted in much less wireworm damage than seeding several inches deep. Dry soil near the surface may repel wireworms somewhat and result in more favorable seed germination.

Cultural Practices

Plowing, cultivating and fallowing, crop rotations, draining and flooding, and other similar items come under the heading of cultural practices.

Such methods of cultivation as plowing, harrowing, and discing have been recommended as controls for wireworms in the field. The object behind these recommendations is that any one of these methods used at the right time might result in destruction of egg, larval, pupal, or adult stages of the injurious elaterid. However, a knowledge of the wireworms in question is necessary before any specific recommendation can be made. Many workers have been concerned with this aspect of wireworm control and some of their experiments and recommendations are noted. Comstock and Slingerland (1891) state that fall plowing is supposedly beneficial but they doubt Gillette's (1889) reason for this, namely, fall plowing controls larvae by starvation. Comstock and Slingerland suggest fall plowing at the time when pupae and adults are in the soil. Summer and fall plowing has been recommended by Lintner (1896), Hyslop (1915), Strickland (1927), and Hawkins (1928). Other workers recommending fall plowing include Miwa and Yanagihara (1929), Watson (1931), and Boyd and Donaldson (1933). Bryson (1929) showed that the average depth of elaterid pupal cells in Kansas was 9". In order to reach these, deep fall plowing would have to be practiced. Other workers have doubted the value of fall plowing and recommend summer plowing. However, this cannot be always recommended for most growers have crops growing at this time. Early spring and summer plowing before the crops are sown has been recommended by Conradi and Eagerton (1914), Treherne (1923), Jarvis (1930), King and Glen (1933), Strickland (1933), MacLeod (1936). Hawkins (1936a) stated that a 3 or 4 year period of clean cultivation is enough to reduce the population of Agriotes mancus larvae to harmless proportions.

Discing, harrowing, and cultivation may help to destroy some larvae, pupae, and adults by mechanical action but these practices are not sure methods of control.

Summer fallow and clean cultivation have often been suggested for wireworm control. Leaving the land free of vegetation and keeping well tilled is supposed to do away with the wireworms' food supply, especially for the younger larvae. Many larvae, however, are able to live months without food. In the laboratory, four specimens of Limonius sp. larvae were kept without food in tin salve boxes. One of the larvae survived a year in this environment. Thomas (1940) reported Limonius larvae kept for 8 months in loam soil without roots. Zacher (1921) found Agriotes larvae could live many months in soil containing only a few particles of humus. Graf (1914) recorded several specimens of Limonius californicus larvae kept alive without food for over a year. Thus it can be seen that it would be difficult to starve larvae under field conditions.

Lane (1927a) recommended clean summer fallow every year against dry land wireworms, Ludius sp., in the northwest. First year larvae were said to be unable to survive this treatment. In 1931 and 1935 he recommended the summer fallow against Ludius noxius.

Wireworms may cause much damage to crops following summer fallow. Lane (1927a) thought the reason for this might be that summer fallow fields were not kept clean enough. Masaitis (1929) stated that fallow land attracts Agriotes beetles, especially if it is weedy and grassy. Hawkins (1936a) found fallowing not more efficient in reducing Agriotes mancus population than raising a cultivated crop.

Rotation of crops is a frequently recommended cultural practice. By a system of changing the crops, using immune crops, and leaving the land fallow, conditions unsuitable to wireworm activity were supposed to result, that is, lack of suitable food or adverse environmental conditions. These practices are not, however, a complete solution of the wireworm problem. McCollough and Hayes (1922, 1929) warn that "rotation cannot be practiced successfully unless a thorough study is made of soil conditions and suitable crops". It should be borne in mind that all soil areas are not the same--what grows well in one section may fail in another section having the same soil conditions. A crop supposedly immune to wireworms may be a good source of food supply for other pests. All these factors are to be considered in recommending crop rotation for control of wireworms.

Crop rotations were early recommended by Forbes (1892), Webster (1892), Hood (1907), and Hudson (1922). Crop rotations for control of particular species of wireworms have been suggested as follows:

Species	Suggested by
Horistonotus uhlerii	Nettles (1936), Conradi and Eagerton (1914b), Conradi (1910), Tenhet and Howe (1939), Pierce (1917).
Monocrepidius vespertinus	Conradi and Eagerton (1914), Conradi (1910), Pierce (1917).
Agriotes mancus	Hawkins (1931, 1936a, 1937) MacLeod and Rawlins (1935), MacLeod (1934, 1935), Rawlins (1934, 1936, 1940).
Melanotus sp.	Hawkins (1931, 1936a)

Immunity

As an adjunct to control of wireworms by crop rotations, the sowing of more or less resistant crops is sometimes recommended. Certain plants are less readily attacked than are others. Some plants may actually be avoided and are therefore termed immune to wireworm attack. The question of immunity of some plants seems to be debatable. Many early workers suggested white mustard (Brassica alba L.) as an immune crop. Ormerod (1881), Lintner (1896), and Theobald (1928) have claimed the use of mustard in an infested field will soon clear it of wireworms. Comstock and Slingerland (1891) stated they found a crop of mustard would not clear the field of wireworms. Use of mustard is not generally recommended now.

It is doubtful if any crop is truly immune to attack by wireworms. Some plants may be more resistant to larval feeding either because they are unattractive to wireworms or because of certain physiological and morphological characteristics. So-called plant immunity may not be due to the plant itself but to environmental factors operating to the disadvantage of wireworms.

Biological Control

Parasites

There are numerous records of parasitic and predatory attacks on various species of Elateridae. The frequency of bacterial or fungus diseases attacking wireworms, however, is not as great.

Thomas (1929) reviewing the literature on the parasites of wireworms, states that elaterids are comparatively free of parasites and that attacking parasites are usually quite local. Only in a few cases could parasites be considered as important in controlling wireworms. One of the most frequently quoted records in this connection is that of Zolk (1924) who stated that 25 per cent. of the larvae of

Agriotes obscurus collected in Esthonia were parasitized by a hymenopterous parasite, *Paracodrus apterogynus*.

Parasites of wireworms are usually either Hymenoptera or Diptera. Hymenopterous parasites are either of the family Serphidae or Bethylidae. Klippart (1860) stated that *Proctotrupes viator* was a common parasite of wireworms in the United States. Hyslop (1915) found a *Melanotus* larval skin attached to what resembled an empty hymenopterous pupal case, probably belonging to a *Tiphia* cocoon. In 1916 Hyslop recorded *Pristocera armifera* as parasitic on larvae of *Limonius agonus*. Thomas (1924) found a cocoon of *P. armifera* attached to a skin of a *Melanotus* larva at Riverton, New Jersey. Hayes (1927) noted a dead larva of *Aeolus dorsalis* with *P. armifera* parasitic upon it.

Blunck (1925) has reared the parasitic serphid *Paracodrus apterogynus* from *A. sputator* larvae in Germany. Subklew (1934b) has recorded *P. apterogynus* on *Agriotes sputator*. Other Serphidae recorded as parasitic are *Phaenoserphus fuscipes* on *Athous haemorrhaidalis* larvae (Rymer-Roberts, 1919) and *P. pallipes* on *Agriotes obscurus* larvae in France (Regnier, 1928). Miles and Cohen (1940) state that in England *Paracodrus apterogynus* is occasionally found parasitic on *Agriotes obscurus* larvae.

Several workers have reported no instances of parasitism in any of the thousands of wireworms examined by them (See Conradi and Eagerton, 1914; Gibson, 1916; Graf, 1914; Strickland, 1927; Tenhet and Howe, 1939).

There are few cases of parasitism of wireworms by Diptera. Forbes (1892) noted an undetermined dipteron bred from a Melanotus fissilis larva in Illinois. A dexiid fly, Ateloglossa cinerea, was reared from a larva of a Melanotus sp. (Packard, 1929).

Nematodes and other worms are known to parasitize adult and larval elaterids. Conradi and Eagerton (1914) found a Horistonotus uhlerii larva attacked by an enchytraeid worm. Tenhet and Howe (1939) found 8.5 per cent. of H. uhlerii larvae collected in the field were parasitized by a nematode, Diplogaster, a form not known to be parasitic heretofore. These workers noted that laboratory reared wireworms in 1934 were infested with a parasitic nematode Cephalobus persegnis Bastian.

Hawkins (1936a) found adults of Agriotes mancus parasitized by nematodes, Hexameris sp., which were 45 mm. long. Adult beetles died after the emergence of the parasites. Hawkins also found one adult click beetle infested with a species of Rhabdites. Miles and Cohen (1940) found 3 cases of nematodes parasitizing adult click beetles, noting that the worms left the beetles' bodies through the mouth after the beetles' death.

Predators

The predatory enemies of olaterids are of more value in the natural control of these pests than are the parasites. Thomas (1940) states that predators have undoubtedly destroyed large numbers of wireworms and click beetles. Rawlins (1940) maintains that reduction of 10 to 70 per cent. in wireworm populations of experimental plots is too great to explain as due to sampling error, and such reductions are due for the most part to mortality from natural causes including parasites and predators.

Many workers have noticed the presence of mites on wireworms. It is generally agreed, however, that probably most of these were not feeding, but were the non-feeding hypopi or migratory nymphs of tyroglyphid mites (See Thomas, 1940; Hyslop, 1915; Masaitis, 1929; Hawkins, 1936; and Stone, 1941).

Spiders have been noticed by a few workers to feed on adult elaterids. Eagerton (1914) reported a small field spider _Pencetia viridans_ Htz. as an important enemy of _Monocrepidius vespertinus_ and occasionally of _Horistonotus uhlerii_. Hawkins (1936) noticed the spider _Xysticus ferox_ feeding on adult _Agriotes mancus_ beetles. Frequently adult click beetles are found enmeshed in a spider's web but this is usually accidental and does not mean the insect was hunted.

Insect predators of wireworms have been frequently noticed. The most abundant predators belong to the

Hemiptera, Coleoptera, and Diptera.. Conradi and Eagerton (1914) and Eagerton (1914) found a reduviid Apiomeris crassipes catching adults of Monocrepidius vespertinus and possibly H. uhlerii adults. Tenhet and Howe (1939) noted three hemipterous predators feeding on adults of H. uhlerii. These were Apiomerus crassipes, Oncocephalus geniculatus (Stal), and Zelus cervicalis Stal.

The most important group of coleopterous predators attacking wireworms are the Carabidae or ground beetles. Numerous workers have reported carabids feeding on unidentified wireworms (See Curtis, 1845; Ford, 1917; Masaitis, 1929). Thomas (1940) quotes correspondence from Headlee of New Jersey in which the latter worker tells of a heavy infestation of wireworms apparently eradicated by larvae of undetermined carabids. Hawkins (1936) noted the carabid Poecilus lucublandus Say eating larvae of A. mancus. Staphylinus badipes Lec. was observed feeding on P. lucublandus Say. Stone (1941) found Calasoma concellatum Esch. feeding on click beetles, particularly under traps.

Dipterous predators of elaterids include some members of the families Asilidae and Therevidae. Conradi and Eagerton (1914) noted a robber fly Proctacanthus brevipennis Wied. catching adult males of Horistonotus uhlerii in South Carolina while Eagerton (1914) found the same species of asilid catching adults of Monocrepidius vespertinus. In the family Therevidae, Hyslop (1910) reported that the larvae of Thereva egressa feed on wireworms. Conradi and Eagerton (1914) reported a larva, possibly Psilocephala (Epomyia) pictipennis Wied. eating a Horistonotus uhlerii larva. Larvae of Psilocephala rufiventris Loew are known to feed on the sand wireworm to a minor extent (Tenhet and Howe, 1939). Stone (1941) states that larvae of Psilocephala frontalis feed on Limonius californicus larvae. Ten of the fly larvae ate 33 wireworms in two weeks.

The most important groups of vertebrates known to feed on adult elaterids are the frogs and birds. Thomas (1940) lists several species of Bufo and the elaterid contents of a given number of stomachs. In the stomachs of 533 toads (Bufo americanus Lec.) there were found 185 adult click beetles and only 12 wireworms. Melanotus and Monocrepidius species were the most frequently represented. Toads are omnivorous feeders and these records do not indicate any preference for elaterids as a group. Sweetman (1936) notes that the toads frequently take in various elaterids.

Frogs are known to feed on click beetles to some extent. Rana pipiens, Hyla versicolor, R. palustris, R. sylvatica, R. clamitans were found to have adult elaterids in their food by Surface(1913). Cockerham and Deen (1936) report that the chief natural enemies of Heteroderes laurentii in Alabama are the toads Bufo quercus and B. terrestris.

Birds are probably the most important natural enemies of elaterids. Thomas (1940) states that the records of the United States Biological Survey show that the remains of elaterids have been found in the stomachs of over 225 species of birds. Elaterid remains were most frequently found in the stomachs of crows,(Corvus brachynchus), starlings (Sturnus vulgaris), nighthawks (Chordeiles virginianus), robins (Planesticus migratonius), red-eyed virio (Vireosylva olivacea), and meadowlarks (Sturnella magna). Hyslop (1915) lists 95 species of birds known to have fed on elaterids, chiefly on adults. Stone (1941) found the California shrike, Lanius ludovicianus gambeli to be the most important bird feeding on Limonius californicus adults. Hawkins (1936a) has noticed the vesper sparrow and the bronze grackle to follow the plow and eat upturned larvae.

Bacterial Diseases

Diseases of the Elateridae, especially of their larvae, are widespread according to Thomas (1940). He believes, however, that very few diseased wireworms are found in the field because of the rapid disintergration of the larvae. Under laboratory conditions bacterial diseases spread rapidly and wipe out entire cultures of larvae.

Graf(1914) reported a red bacterium invading cultures of Limonius californicus larvae, causing considerable loss among the younger wireworms. Masaitis (1929) thought that some relation existed between a bacterial disease and tyroglyphid mites. The disease was much more widespread when the mites were abundant. Agriotes larvae not infested with mites remained immune to the disease.

Fungus Diseases

Several workers have reported the prevalence of fungus diseases in wireworms especially under artificial rearing conditions. In the field these diseases are not very abundant and are not usually considered effective controls of wireworms. Thomas (1940) describes the green muscardine fungus Metarrhizum anisopliae as the wireworm disease most frequently mentioned in literature. This disease causes the larva to become somewhat rigid though it can still move its legs. Mycelium appears at the leg joints and other places where the membrane is thin. The entire body may soon be covered with mycelial growth. Wolcott (1933) found several species of wireworms attacked by this fungus especially in wet soils but its incidence was very uncertain. Hyslop (1915) tried to introduce it into a field in Pennsylvania that was infested with Melanotus larvae but met with no success. Hawkins (1936a) found the disease prevalent in soil cages.

Entomophthora carpentieri Gir. was found to attack adults of Agriotes and Elater sp. in France by Picard (1914).

Tenhet and Howe (1939) reported this fungus attacking Horistonotus uhlerii in South Carolina. Entomophthora sphaerosperma is noted by Durnovo (1935b) to infect 80 per cent. of the adults of Agrictes sputator and A. obscurus in the grassy headlands of Russia.

Control of elaterids by natural means has generally been local in nature. The prospects of developing any of the natural enemies as an effective control of adult or larval elaterids does not seem very bright. Clausen (1940) states that the hymenopterous family Serphidae, regarded as the most important parasitizing wireworms is not significant enoggh either in numbers or in damage done to be considered as an effective parasite. None of the predators are specific feeders on wireworms. Bacterial and fungus diseases, although they do affect wireworms under certain conditions, are not always effective.

Tenhet and Howe (1939) conclude that the natural enemies of the sand wireworm are not very effective. Lane (1941) states that the natural enemies of wireworms in irrigated soils are comparatively few and cannot be depended upon for control.

Summary of Control Methods

A review of the literature on the control of wireworms shows that there is a multitude of control methods. Many of the recommended controls are unsatisfactory. Seed protection is usually unsuccessful in repelling wireworm attacks. Contact insecticides have not been successful because of the difficulty in reaching the larva in the soil. Stomach poisons are not feasible to use because of the ability of wireworms to reject distasteful substances.

Satisfactory control under certain conditions can be obtained with soil fumigants. Naphthalene and paradichlorobenzene can be used effectively if soil temperatures are high enough (21°C. or higher) to permit rapid diffusion of the gas through the soil. Cyanides have been used alone or in conjunction with a trap crop. The attendant expense prohibits the economic use of cyanide on a field scale but it can be used satisfactorily on choice plots. The same is true of chloropicrin.

Cultural practices can be used to great advantage in wireworm control. The proper use of a field for various crops in rotation plus a system of clean summer fallow brings about ecological conditions unfavorable for wireworm development. The success of plowing, discing or harrowing depends on the depth of the larvae or pupae at the time these methods are practiced. Fall or spring plowing, however, does not always affect the majority of the wireworms or pupae because they may be below the soil level disturbed by these practices.

Biological control of elaterids would be a satisfactory method of attack. Unfortunately, control by natural enemies is not very widespread and the possibility of its increase is not very bright.

PROCEDURE

Location of Plots

Field work on the problem of controlling wireworms in the soil started with preliminary investigations during the summer of 1939. Numerous fields in Amherst, Sunderland, Northampton, and other nearby towns were examined for the purpose of finding a heavy infestation of wireworms. Most of the fields did not show enough wireworm damage or a sufficiently high wireworm population to warrant using them as experimental plots in ecological and control studies. Other fields reported to have heavy wireworm infestations had larvae other than elaterids, or else had been infested but were now relatively free of infestation.

Late in the summer of 1939, a heavy wireworm infestation was located in a potato field on the western bank of the Connecticut River in the "Meadows" section of Northampton. The field is owned by J. W. Parsons of Northampton, and its location can best be determined by reference to the map (Fig. I). Other fields in this vicinity were infested with wireworms but to a lesser extent than the Parsons field.

The Parsons field is approximately 35 acres in area, rectangular in shape, running south and north. It is divided into two parts, equal in area, by a road cutting through the field west from Riverbank Road towards the Connecticut River. These two parts of the field are designated in this paper as the North and South parts because of their position in regard to the road passing through the field. This road is called the Middle Road. The northeastern corner of the plot is 100 ft. and the southeastern corner about 1000 ft. from the west bank of the Connecticut River. The eastern edge of the field rises on a terrace six feet above the land extending to the river. This terrace has a windbreak of deciduous trees for nearly three-quarters the length of the field. Land east of the Parsons field to the river is sodland for the most part.

The western part of the field is bordered by sodland which rises up a gentle 5 ft. terrace along the top of which runs Riverbank Road. North and south the field is bound by sodland which is on the same level as the potato field.

The Parsons field is located on the inside of a huge bend in the Connecticut River (See Fig. I). During periods of flooding, this field is in the main current of the flood waters and its topography and soil structure have been materially altered thereby. This will be discussed later in the section "Physical Environment".

History of Plots

The greater part of the acreage in this seBtion of the "Meadows" is devoted to potato growing and truck

FIGURE I

MAP OF THE MEADOWS SECTION OF NORTHAMPTON, MASS. SHOWING THE LOCATION OF THE PARSONS FIELD.

crops; field corn and hay occupy a lesser part. Usually the poorer sections of the land, especially those areas likely to be flooded at the time of spring planting, are in a rotation of corn and grass. One or two years of corn may be followed by several of grass, depending on the stand of grass. Potatoes and truck crops are usually grown on the same area without being rotated with any other crop. The Parsons field has a land use typical of many of the other fields in this part of the "Meadows".

During the early 1920's the eastern half of the Parsons field was used for growing onions. This crop, however, did not prove to be successful probably because of low yield and some insect damage. Potatoes were tried in the latter part of the 1920's on a small scale. In 1930 about 15 acres on the east side of the field were in potatoes. The western part of the field up to this time was in a corn-grass rotation. Usually a section of 3 to 4 acres was in corn one year and the rest of the western area in grass. The following year, corn would be followed by grass and a fresh section of grass land planted to corn. Potato acreage was gradually extended to 18 acres in 1938 and by 1941, 20 acres were in potatoes. In 1939, 3 acres on the eastern side of the North plot were used for vegetable crops and 2 acres on the western side of the North plot were turned over from sod to potato raising. In 1940, 2 acres of the South plot, northeastern corner, were used for vegetable crops and about 1 acre on the western side was turned over from sod to potatoes. The truck crop area in the North plot in 1940 and 1941 was the same as in 1939. In 1941, another acre was added to the truck crop area of the South plot and more than an acre was added to the potato area from sodland on the western border of the North plot.

In 1938, 2 acres on the western side of the South plot near Riverbank Road, were used for field corn. In 1939 and 1940, all the land in the North and South plots west of the potato area was in grass. In 1941, corn was planted on about 3 acres turned over from sod on the western side of the North plot. This was the first year that all of the acreage of the North plot was in cultivated crops. Crop records for the past several years are shown in Figures II to V.

Various types of fertilizers have been added to different sections of the Parsons field during the past ten years. In addition to the commercial fertilizers used at the time of planting, manure had been applied to the eastern part of the South and North plots until 1937. From that time to the end of 1941 growing season, no manure had been added to the field. Fertilizers have been applied, as a rule, in the planting row at the time of seeding. It has been a practice for a number of years to plant rye to the field after all crops have been harvested. The rye is turned under the following spring

FIGURE II

MAP OF PARSONS FIELD SHOWING LOCATION OF CROPS IN 1938

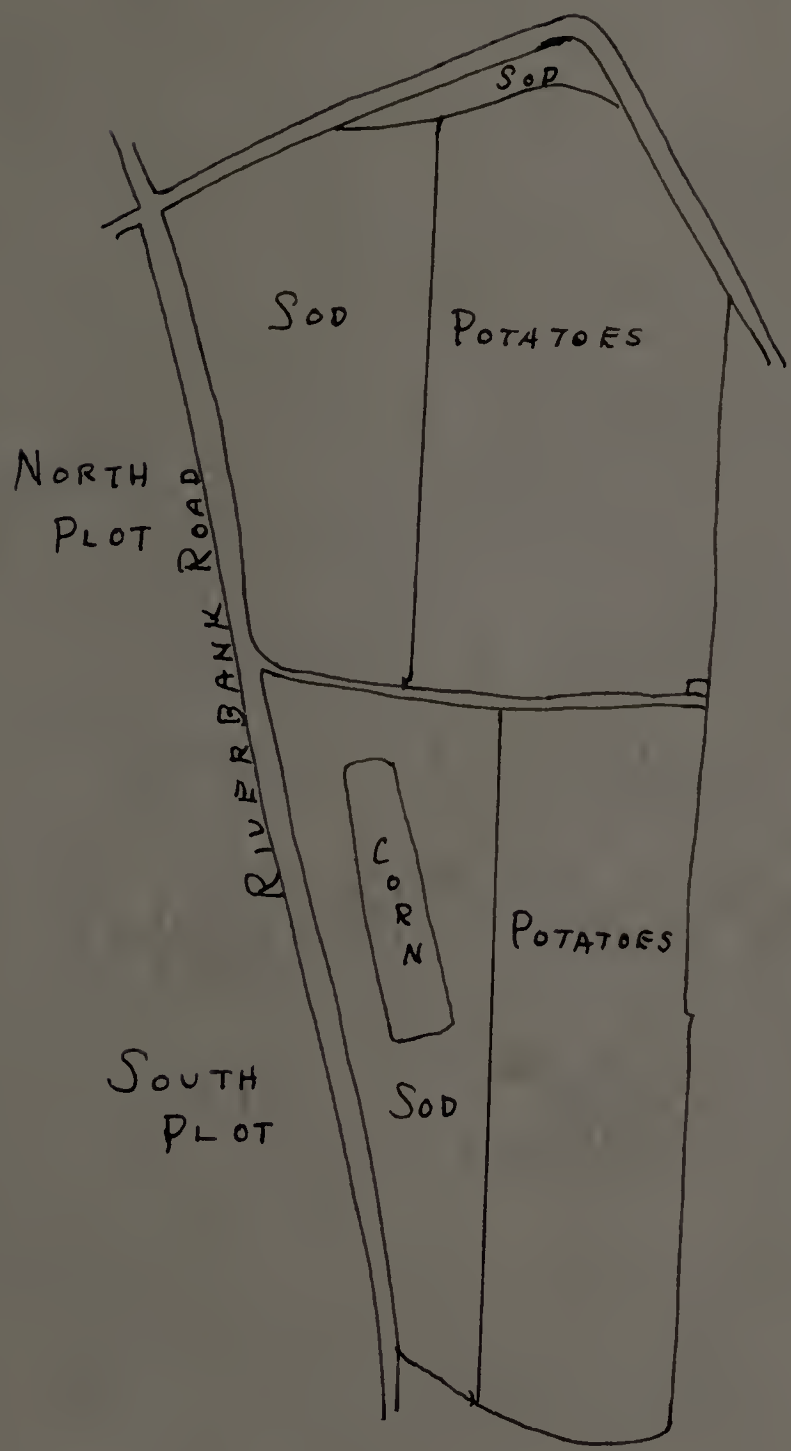


FIGURE III

MAP OF PARSONS FIELD SHOWING LOCATION OF CROPS IN 1939

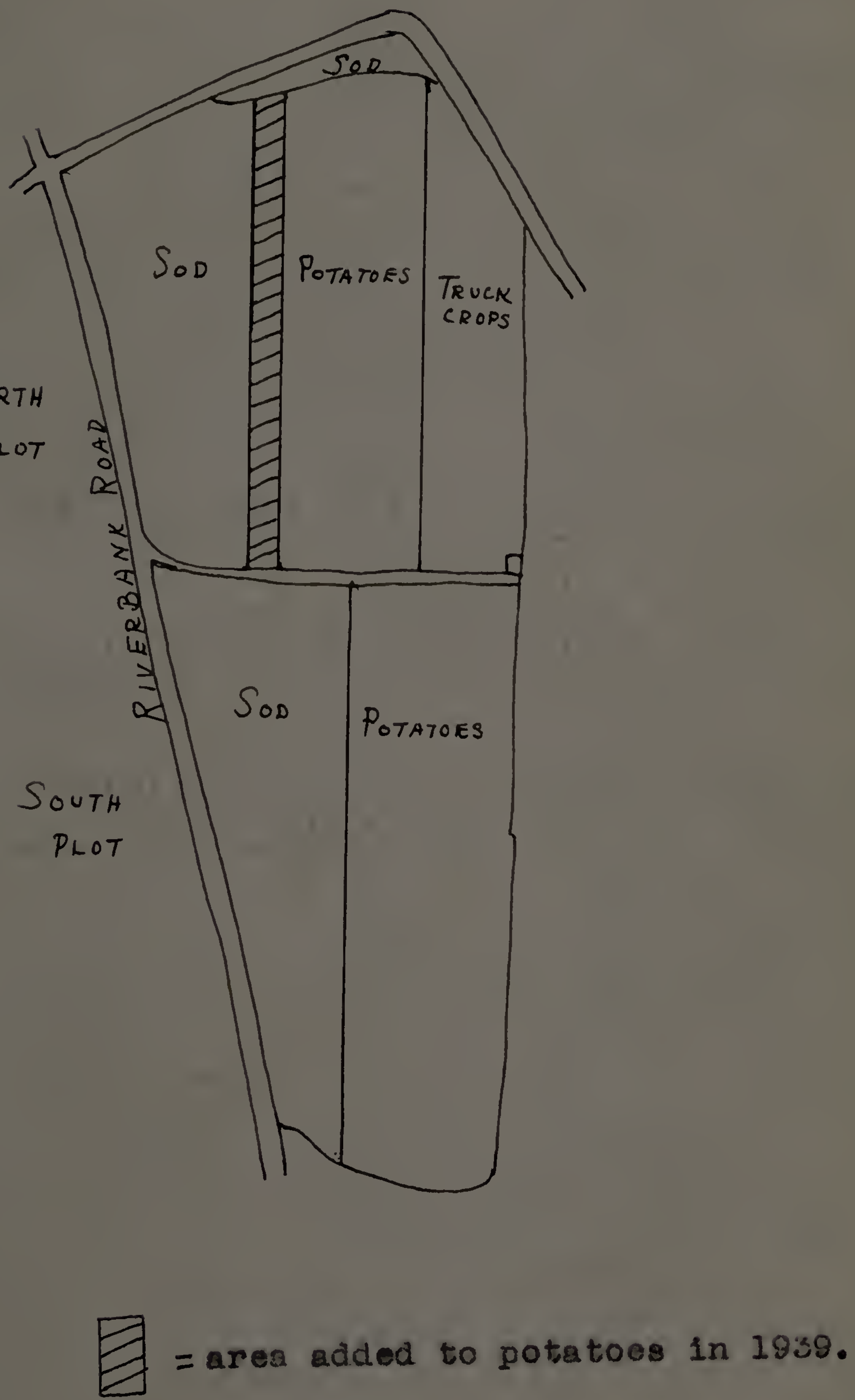
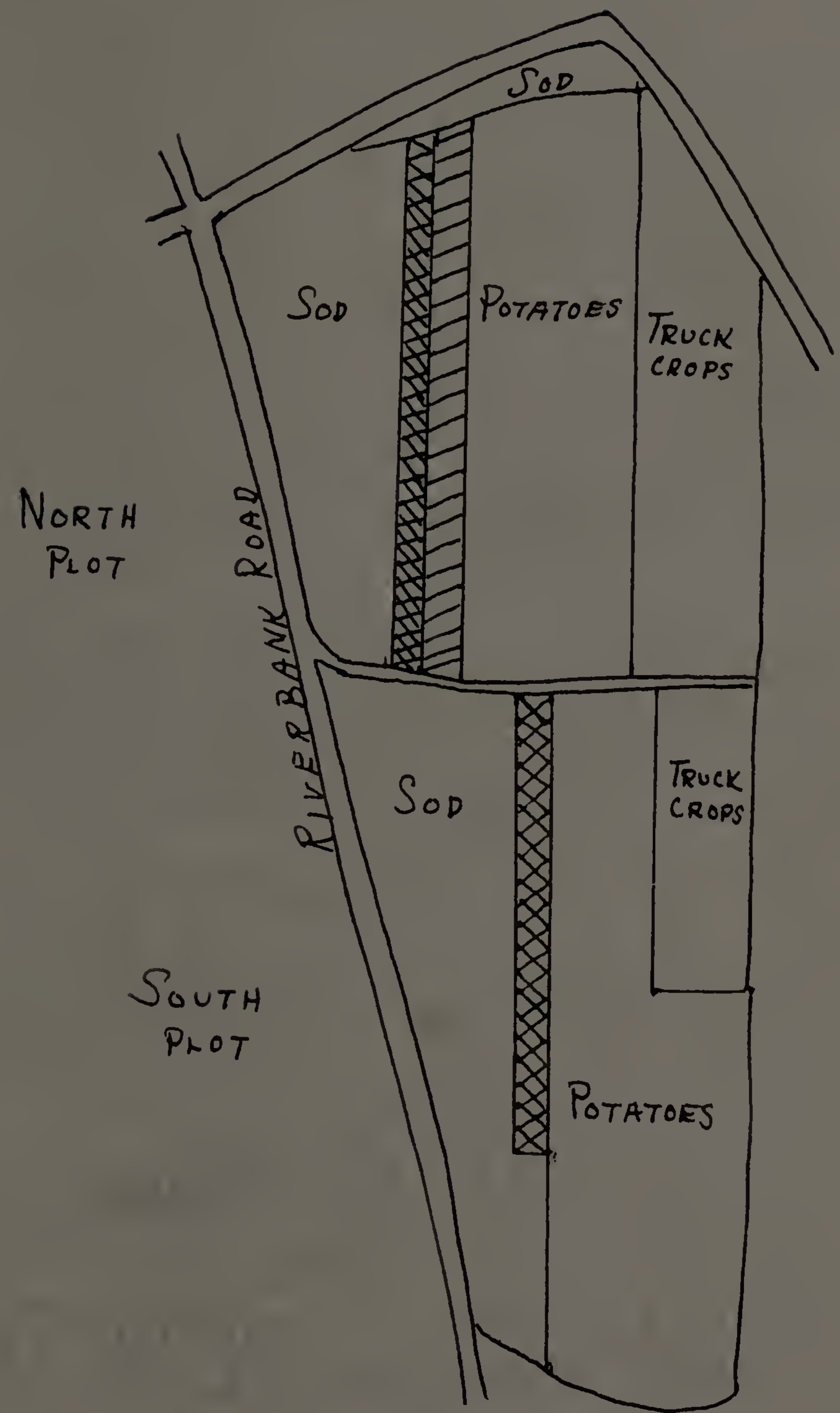


FIGURE IV

MAP OF PARSONS FIELD SHOWING LOCATION OF CROPS IN 1940

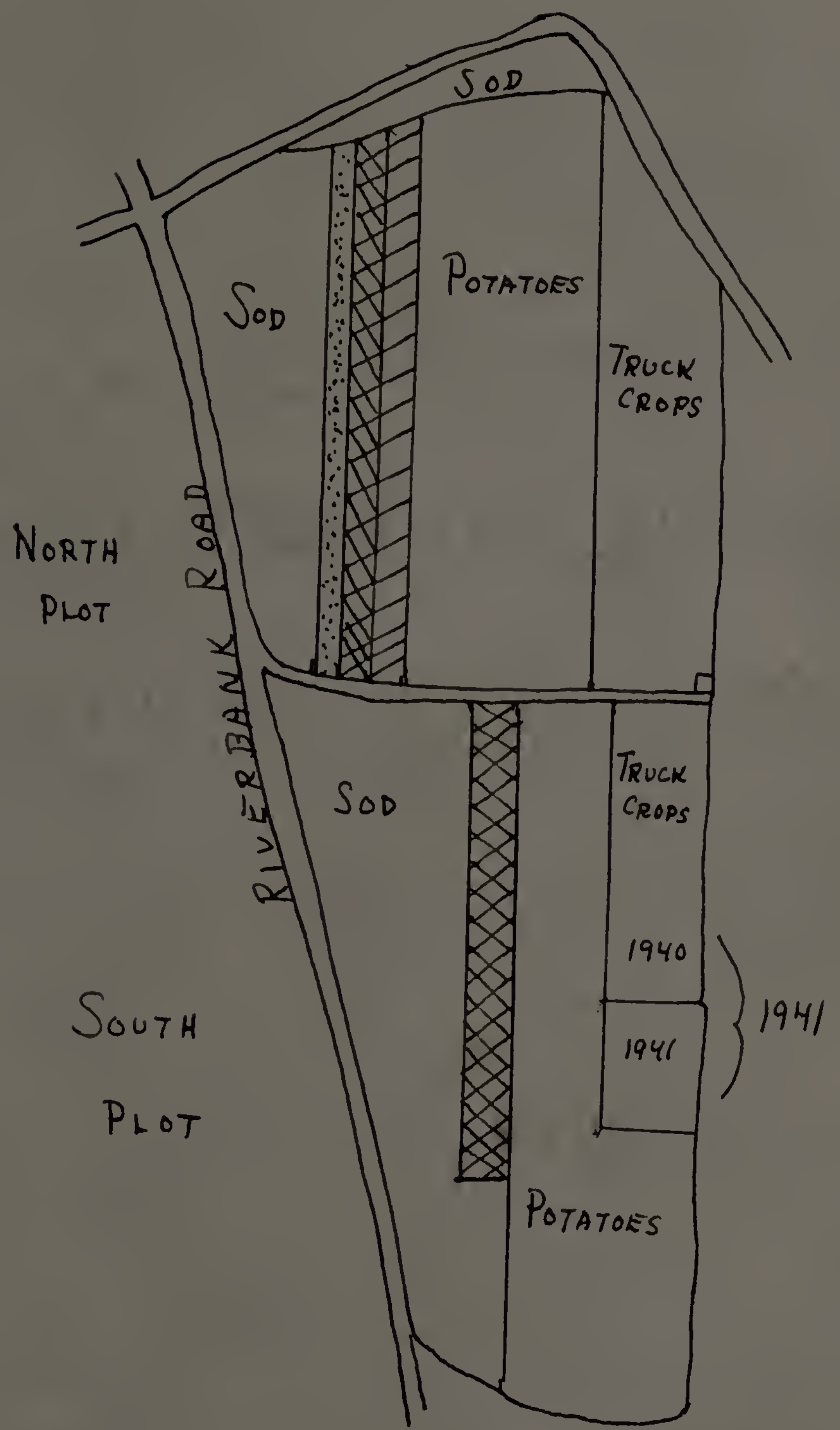


= area added to potatoes in 1939.

= area added to potatoes in 1940.

FIGURE V

MAP OF PARSONS FIELD SHOWING LOCATION OF CROPS IN 1941



=area added to potatoes in 1939.

=area added to potatoes in 1940.

=area added to potatoes in 1941.

as a green manure. It also serves the purpose of holding down the soil in case of severe wind or flood.

The 1939 crop of potatoes in the field showed a considerable amount of scab and wireworm injury in the central longitudinal section of the North and South plots. In an attempt to correct this injury, the grower had these areas treated in May, 1940, with sulphur at the rate of 400-600 lbs. per acre. The 1940 harvest of potatoes did not show any appreciable decline of scab or wireworm injury in the sulphur treated areas. In 1941, these areas of severe infestation were again treated by the grower, this time with tobacco stems at the rate of 200-300 lbs. per acre. The tobacco stems were harrowed into the soil before the spring planting of potatoes. Both of these treatments are located on maps in Figures VI and VII.

In the spring of 1936, all the "Meadows" land was flooded with about 10 ft. of water. Much silt, sand and debris was left by the flood, particularly on the Parsons field. At the time of high flood, the main current of the water is longitudinally across the Parsons field. Consequently, severe flooding of the "Meadows" usually leaves this field in a poor condition for growing crops. The hurricane and heavy rain of September, 1938, resulted in heavy flooding of Parsons field. After the 1936 and 1938 floods it was necessary to scrape the sand, silt and debris from certain sections of the field before any

FIGURE VI

MAP OF PARSONS FIELD SHOWING DOTTED AREA TREATED WITH SULPHUR
MAY, 1940

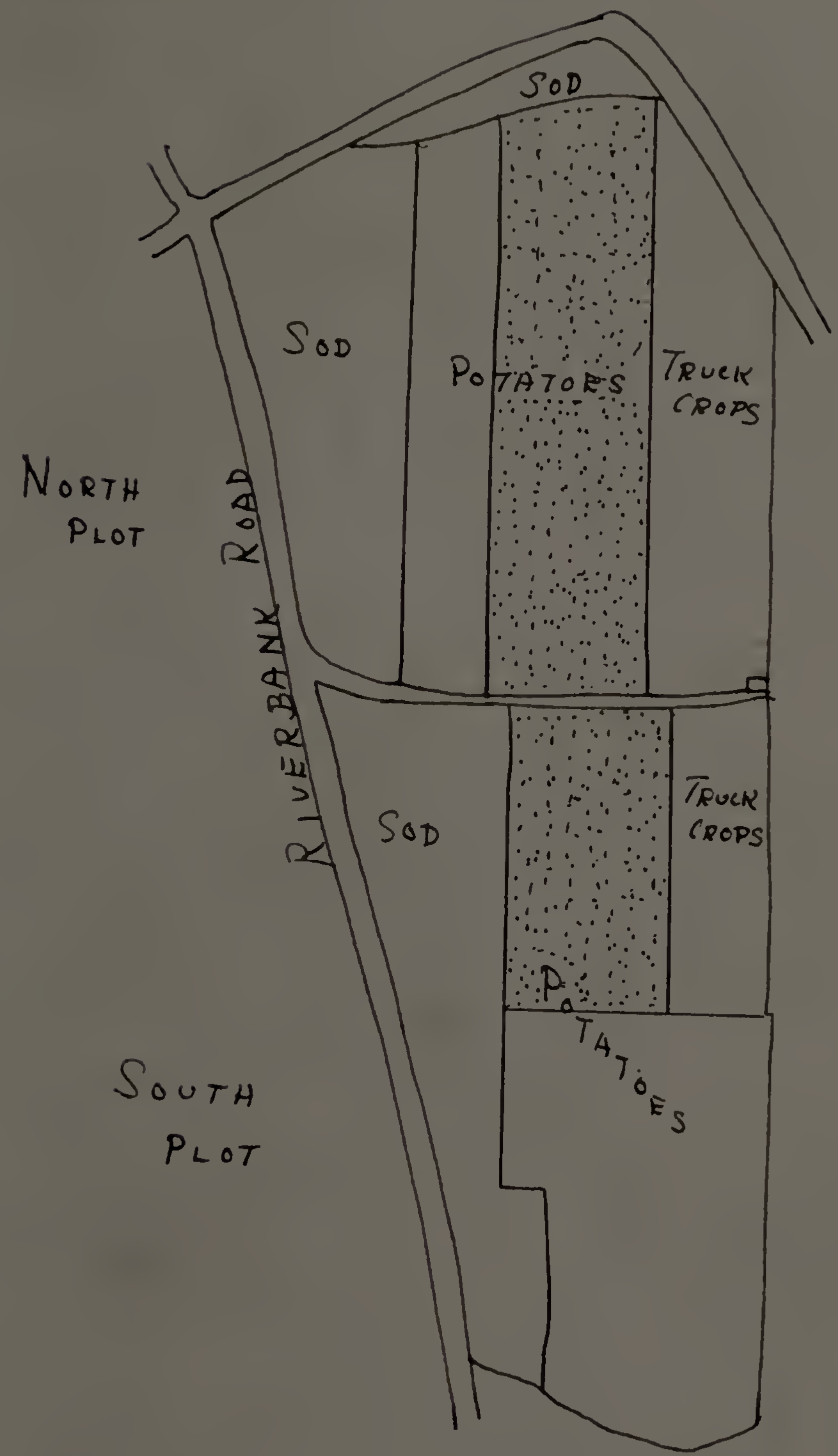
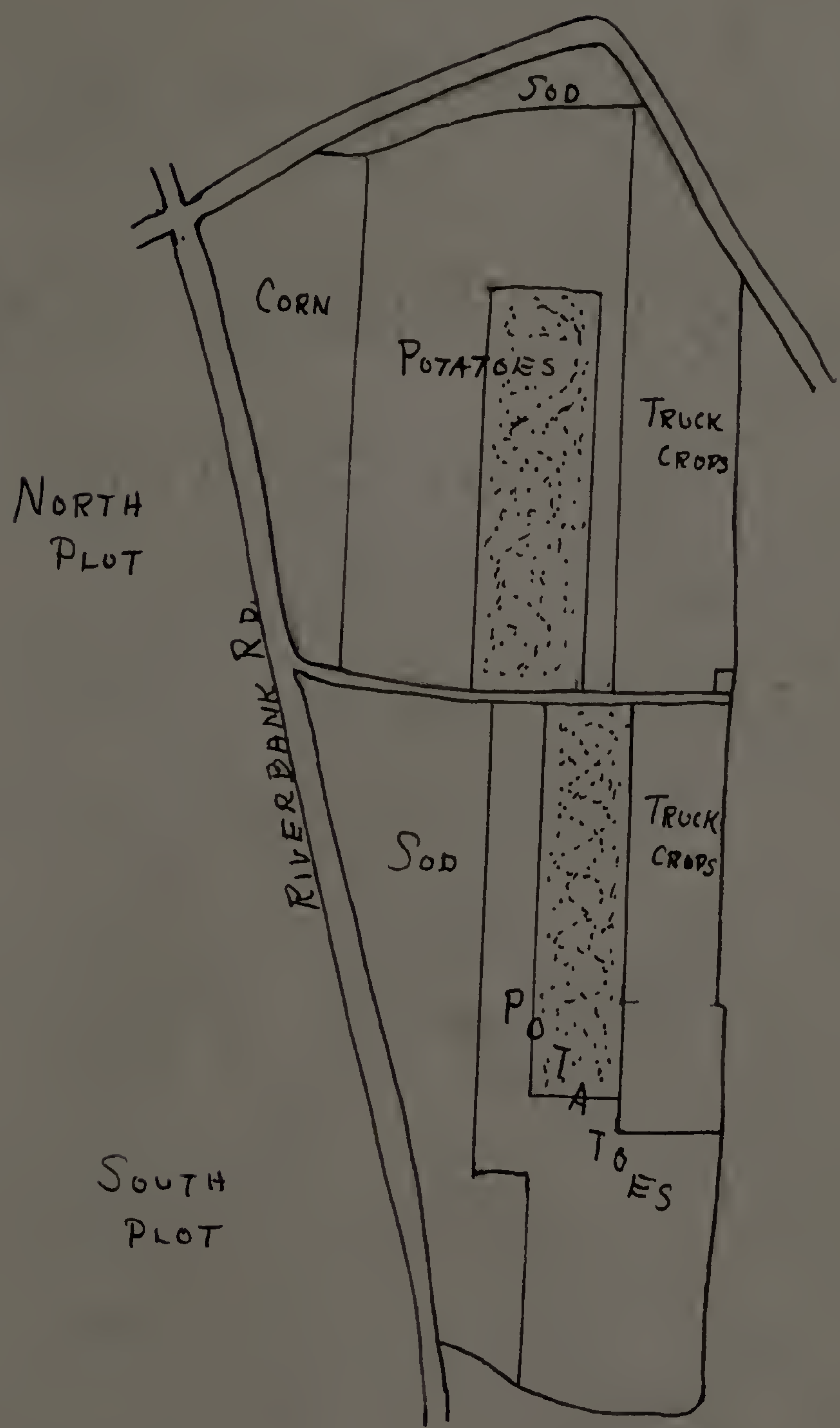


FIGURE VII

MAP OF PARSONS FIELD SHOWING DOTTED AREA TREATED WITH TOBACCO STEMS, APRIL, 1941.



planting could be attempted. In 1940, parts of the South plot were under water but no noticeable amount of debris or sand was left behind after the water had receded.

Preliminary soil sampling in 1939 revealed numerous species of Elateridae. The most abundant species, both adults and larvae, was Limonius agonus Say, the eastern field wireworm. Other species included Ludius cylindriformis Hbst. and Melanotus spp. All of these genera were taken in various parts of the field but the Melanotus spp. were more common in sod areas or sections of the field recently turned over from sod.

Physical Environment

Topography

The Parsons field is almost flat throughout. It slopes imperceptibly from north to south. A slight depression runs longitudinally through the central part of the area. This depression is 100 ft. wide and has a slope of about 1 ft. to 50 ft. of width. All parts of the field except the north end of the depression, drain well. The north end may remain moist for a longer time after snow melts than do other sections of the field. Another depression is located at the western side of the field. This portion of the field as well as the southern end of the field, may become flooded at the time of spring high water. Consequently, these areas remain moist for a few weeks longer than other parts of the field after the snow melts or after flooding.

The eastern side of the field, bearing a windbreak of deciduous trees for three-quarters of its length, is 6 ft. above the adjacent field. Its position in respect to the Connecticut River can best be determined by referring to the map (Fig. I). The western side of the field rises gradually up a 6 ft. terrace. There is no windbreak on this side. The northern end of the field is bounded by a road sunken throughout its length to a depth of 1 to 3 ft. below the level of the northern edge of the field. The land across the road from the north end of the Parsons field continues on the same level to the west bank of the Connecticut River.

When the Connecticut River is at flood, the Parsons field may become inundated either by the backing up of water from the south or by the flooding over of the river from the north. If the banks are flooded, the strong current of water causes silt, sand, and debris to become deposited on the field. This happened in 1936 and left considerable sand.

Exact data concerning past floods are not available but the nature of the soil indicates that flooding has been frequent. Some sections of the field are almost all sand. The low parts of the field have soil of a sandy loam type. For the most part, the soil can be classified as a light sandy loam. In an early soil report by

Flippin (1903), this soil is classified as a dark silt loam. Mechanical soil analyses in this report showed the soil to be of the following composition: (figures stand for percentages) organic matter 1.45, gravel (2 to 1 mm.) 0.06, coarse sand (1 to 0.5 mm.) 0.48, medium sand (0.5 to 0.25 mm.) 0.30, fine sand (0.25 to 0.1 mm.) 1.12, very fine sand (0.1 to 0.05 mm.) 6.52, silt (0.05 to 0.005 mm.) 78.94, clay (0.005 to 0.0001 mm.) 12.42.

Temperature of Soil

Temperature is one of the important factors limiting the activity and development of wireworms. Rise of soil temperature is the determing factor in stimulating wireworm activity and feeding in the spring. Lowering of soil temperature limits wireworm activity and feeding in the fall.

High soil temperatures may occur in mid-summer which are responsible for the drying of the upper soil layers and the consequent downward migration of wireworms. In late summer, soil temperatures are lower and there may be an upward migration of wireworms with increased feeding as a result.

Survival of wireworms during adverse winter conditions is dependent upon soil temperatures and the manner in which these winter soil temperatures are affected by such factors as type of ground cover, snow, and weather conditions. the subterranean existence of wireworms protects them from low temperatures. The soil itself acts as a blanket, and a covering of sod and snow increases the insulating effect against outside temperature and weather conditions.

In the present study, soil temperatures were taken with a view of trying to correlate wireworm activity with the temperature changes throughout the year. At first the pipe system of taking soil temperatures was used. Iron pipes of various lengths, closed at the bottom, were sunk in different parts of the field to depths of 6" to 36", leaving only an inch or two of the pipe exposed above the surface of the ground. A standard thermometer was introduced through the open exposed end to the required depth. The open end of the pipe was then plugged and after a suitable interval the thermometer was pulled out and the temperature recorded. When not in use, the pipe was plugged to prevent rain or snow from entering.

The chief disadvantage to the pipe system is the fact that water can seep into the pipe either through the upper end or the lower. The plug at the upper end may become loose and permit leakage or the lower opening may not be closed tight enough to prevent the seepage of water. When cold weather comes, seepage water in the pipes may freeze and block the introduction of a thermometer or the plug may freeze in the empty hole. Another objection to the use of a pipe is the possibility of the pipe and the air in it being warmed by the sun.

Another method of acquireing soil temperatures was by the thermocouple method. This is based on the principle of measuring the electromotive force set up by two different metals in contact with one another. This electromotive force is proportional to the temperature at which the two metals come in contact. By means of a potentiometer, the electromotive force can be measured and transposed to read in degrees of temperature. The apparatus used in this study was a Leeds and Northrup "student" potentiometer, which measured the current of the electromotive force. By means of a resistance box and two No. 6 dry cell batteries, the apparatus was balanced against a standard cell of known voltage. An outside galvonometer was used in taking readings.

The method of obtaining soil temperatures with this equipment was as follows: two wires, one iron and the other constantan, were twisted together and soldered, forming what is known as the unknown temperature junction. This junction is buried in the soil at the depth required leaving the free ends of the wires far enough above ground so that they can be connected to the potentiometer. In taking a reading, the wires are attached to the potentiometer as shown in Figure VIII. After balancing the potentiometer against the standard cell, readings are taken directly with the potentiometer. This reading, plus the corresponding e. m. f. reading for the air temperature at the binding posts, equals the e. m. f. reading at the depth at which the wires are in contact in the soil. A table for the temperatures corresponding to the various e. m. f. readings for an iron-constantan junction gives the proper temperature reading in degrees centigrade. For example, the potentiometer reading of the e. m. f. of a thermocouple is 1.46 millivolts at 6 inches and the temperature reading at the binding posts is 24°C. The corresponding millivolt reading in the iron-constantan table for 24°C. is 1.25. This is added to the observed reading, 1.46 millivolts, making a total of 2.71 millivolts, which on the table corresponds to 52°C., the temperature at the junction in the soil.

For more accurate work a known reference junction of 0°C. was used instead of the temperature of the air at the binding posts. In order to keep the reference junction at 0°C. it was necessary to immerse the thermo-

FIGURE VIII

DIAGRAM OF LEEDS-NORTHRUP STUDENT POTENTIOMETER.
AIR TEMPERATURE USED AS REFERENCE JUNCTION.

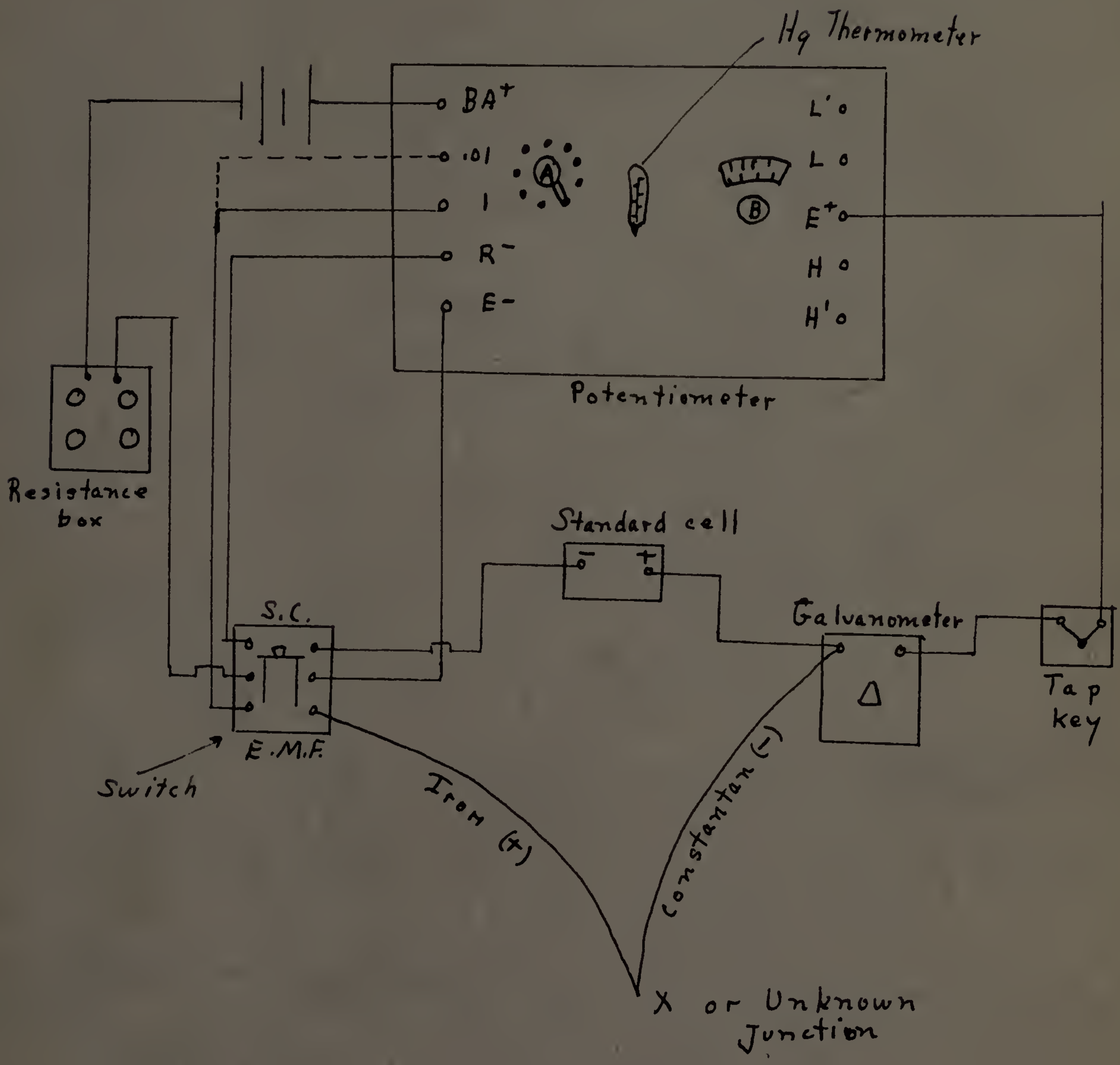
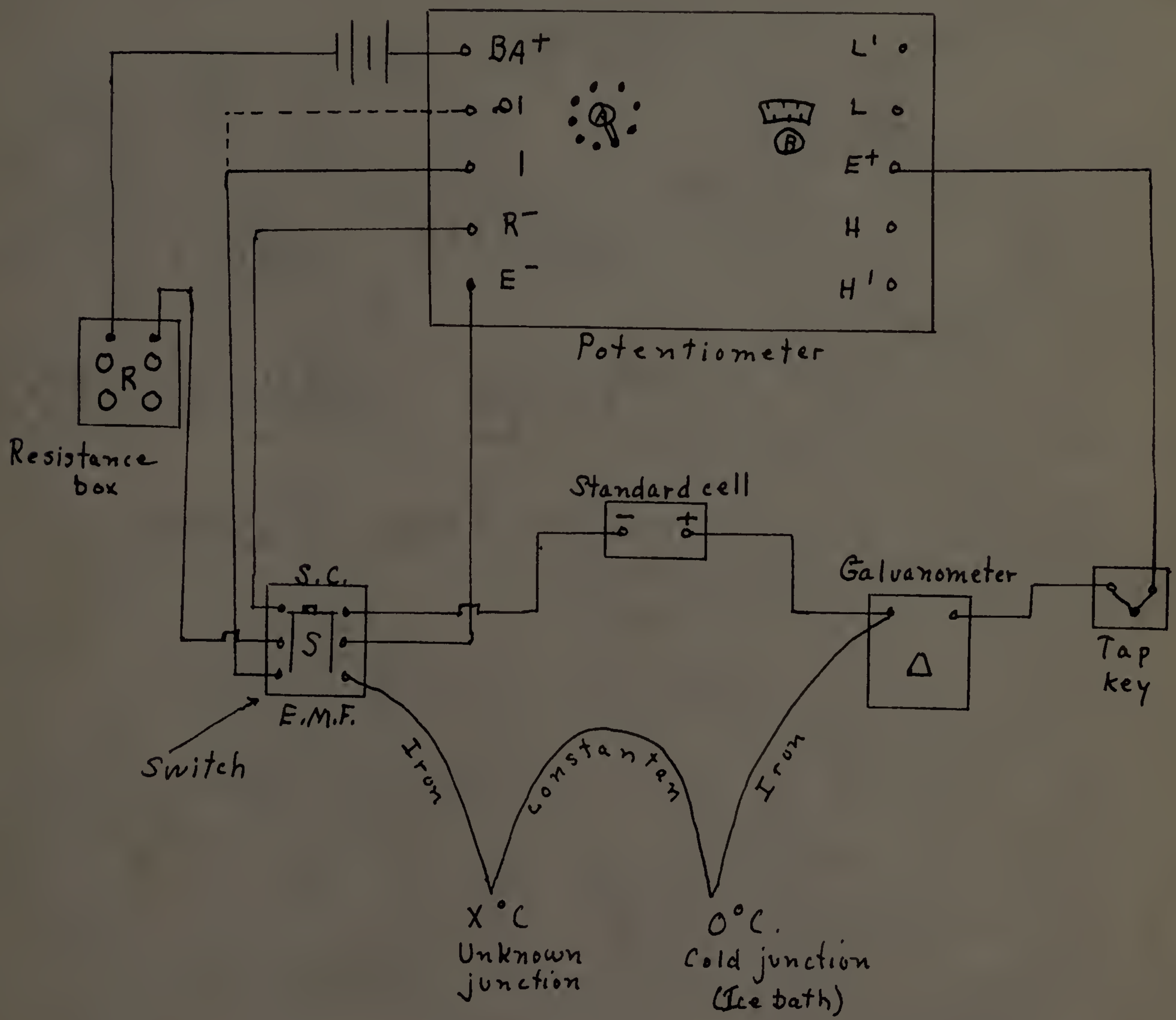


FIGURE IX

DIAGRAM OF LEEDS-NORTHRUP STUDENT POTENTIOMETER WITH REFERENCE JUNCTION AT 0°C.



couple in an ice bath contained in a vacuum bottle. This assured a constant temperature of 0°C. at the level of immersion of the reference junction. This type of reference junction was frequently used and is shown in Figure IX.

A third method of taking temperatures was to simply insert a standard thermometer into the soil to the required depth. This method was used chiefly in connection with soil sampling. Holes dug for sampling permitted easier introduction of the thermometer to the required depth. Temperatures to a depth of 6" were obtained by this method, inserting the thermometer to the depth desired. Below 6", temperatures were taken by inserting the thermometer horizontally for an inch or two into the vertical wall of the pit dug for soil sampling. Thus, if it was desired to take a reading at a depth of 9", the thermometer was inserted into the side of the hole at this depth.

Soil temperatures were taken at least once a week throughout the duration of this study, with the exception of an omission of eight weeks in February-April, 1940. Temperatures taken by the pipe method cover most of the period and potentiometer readings were taken from fall to spring in 1939-1940 and 1940-1941.

The temperatures were usually taken in the early afternoon. Some readings were taken two or three times in the course of a day, one reading in the morning, one in the early afternoon, and sometimes one in the late afternoon. Weather conditions and general soil conditions were noted at the time of the soil temperature readings. Air temperatures were also recorded.

During the season of 1939-40, pipes were placed at different locations in the field. The thermocouple wires were located 500 ft. south of the Middle Road in the South plot, midway between the east and west boundaries of the plot. During the fall-winter season of 1940-41, pipes and thermocouple wires were placed at the northeastern corner of the North plot. In the summer seasons of 1940 and 1941, pipes and thermocouple wires were located 5 ft. south of the shed on the eastern boundary of the field.

It was not possible to obtain complete weekly temperature records by the three methods throughout the year. Freezing of the soil in winter prevented the introduction of thermometers directly into the soil. During the summer, the thermocouple equipment was not always available and pipe and soil thermometer readings had to be resorted to. A complete comparison of the three methods during the entire year is not possible

TABLE II

SOIL TEMPERATURES IN °C. AT DIFFERENT DEPTHS

Date	Thermo-couple			Pipes			Air Temp
1939	6"	12"	18"	6"	12"	18"	
Oct. 14				12.5	12.0		13.5
Oct. 21				15.0	16.0	13.0	20.0
Nov. 5						6.6	2.5
Nov. 12				4.0	5.5	4.0	5.5
Nov. 18		2.3	4.0		2.0	4.0	9.0
Nov. 25		3.5	3.0			2.0	2.0
Nov. 26	1.1	1.2	1.8		2.3		4.0
Dec. 3	3.4	3.2	3.2		4.0		12.0
Dec. 9	2.0	2.6	4.0		2.3		3.0
Dec. 16	1.2	2.3	3.1	0.5	1.6		4.0
Dec. 24	0.6	1.8	2.1		1.0		-4.0
Dec. 29	1.0	2.2	2.8		0.5		-2.0
1940 Jan. 7	0.0	1.2	2.5		-1.0		-9.0
Jan. 13	0.4	0.6	1.7		0.5		3.0
Jan. 21	-5.0	-4.0	-2.0				-7.5
Jan. 28	-8.2	-6.5	-5.0				-4.5
Feb. 4	-5.0	-4.7	-2.5				-1.5
Feb. 11	-0.1	-0.3	0.3				3.0
Apr. 25	7.6	6.3	5.3				13.0
Apr. 28	6.8	6.8	6.6		9.0		14.0
May 2	10.3	9.8	8.7		10.0		17.0
May 12	11.4	11.0	11.0		10.0		12.0
May 16	12.0	10.9	10.5				17.0
May 25	13.5	13.2	12.3		13.0		17.0
June 1	16.0	14.4	14.0		16.0		21.0
June 8					17.0		23.0
June 16					19.0		21.0
June 21					16.0		21.0
June 27					14.0		23.0
July 2							24.0
July 14					16.0	16.0	25.0
July 22					20.5	20.0	29.0
July 28					24.0		24.0
Aug. 3				20.5	18.5		27.0

Date	Thermo-couple			Pipes			Thermometer in soil				Air Temp.
1940	6"	12"	18"	6"	12"	18"	1"	3"	6"	12"	
Aug. 10				21.0	20.0						31.5
Aug. 24				17.0	16.0						19.0
Sept. 28				15.0	12.0						24.0
Oct. 11				15.0	14.0	12.0					19.5
Nov. 11									4.0	4.5	6.5
Nov. 16				6.5	7.0	7.5					3.0
Nov. 22				7.0	6.5	6.5					23.0
Nov. 30				7.0	8.0	8.5					5.0
Dec. 14	0.0	0.0	1.4	1.0	1.5	2.5					-1.0
Dec. 31	0.8	0.8	1.8	1.0	1.0	1.5					5.0
1941 Jan 22	-1.0	0.6	1.0	-2.0	-0.5	1.0					0.0
Feb. 21	1.3	0.7	-0.7	-1.0	-1.5	-1.0					3.0
Mar. 27	-0.4	0.8	0.4	3.0	5.0	6.0					11.0
Apr. 4	5.4	0.6	0.6	8.0	7.0	5.0		15.0		5.0	16.0
Apr. 10	8.6	6.0	3.7	8.5	6.0	3.0					19.0
Apr. 14	3.8	3.6	3.7	12.0	6.0	4.0					23.0
Apr. 18	6.1	5.0	2.3	12.0	7.5	5.5					23.0
Apr. 21	11.3	10.7	7.2	13.5	11.0	9.0					23.0
Apr. 26	8.2	7.8	7.3	8.5	7.5	6.5					14.0
May 8	12.2	11.2	10.2	13.0	12.0	10.0					20.0
May 16	10.6	10.0	9.2	14.0	11.0	11.0					27.5
May 23	16.7	13.9	12.8	19.0	16.0	14.0					33.5
May 31	13.0	13.5	13.0	14.0	14.0	13.0					24.5
June 7	15.2	15.2	14.4	17.0	16.0	14.0					27.5
June 12				16.0	14.5		23.0	19.0	17.5	16.0	26.0
June 20				20.5	18.5						32.0
June 25				18.5	19.0		26.0				27.0
July 7				20.0	19.0	18.0					27.0
July 11				20.0	19.0	18.5					28.0
July 18				19.0	18.5	18.0					27.0
July 25				22.5	20.5	19.5	38.5	29.0	25.0	24.0	32.5
Aug. 21				31.5	20.0		28.8	22.7	20.5	20.0	24.3
Sep. 12				16.5	16.0		22.8	15.9	17.0	16.6	16.6
Oct. 21				11.2	12.1		19.5	16.9	12.3	12.4	17.0

TABLE III

AVERAGE TEMPERATURES FOR THE SIX, TWELVE AND EIGHTEEN INCH DEPTHS BY THE PIPE AND THERMOCOUPLE METHODS

Date of readings	Number of readings		Average temperature °C. 6"	12"	18"	Air temperature	Variations between individual readings
Nov.18,1939 to Jan.13,1940	9	Thermo-couple		1.9		2.2	0.2 - 2.2
		Pipe		1.4			
Apr.28,1940 to June 9,1940	6	Thermo-couple		10.9	10.3	18.2	12", 0.2 - 2.2
		Pipe		12.5	11.0		18", 0.0 - 1.7
Apr.26,1941 to June 7,1941	6	Thermo-couple	12.6	11.9	11.1	24.2	6", 0.3 - 3.4 12", 0.3 - 2.1
		Pipe	14.2	12.2	11.4		18", 0.0 - 1.8

Mail (1930) stated that daily variations of temperature are not noticeable below a depth of 2 to 3 ft. Monthly variations, however, can be noticed to a greater depth and annual variations can be observed as deep as 40 ft.

The effect of solar heat upon soil temperature is influenced by many factors such as type of soil, the soil covering, precipitation, color of soil, and others. In this study, no attempt was made to determine the influence on soil temperature due to different types of soil or soil covering because the Parsons field was uniform in these two factors.

Soil temperature is, of course, closely correlated to air temperature and weather conditions. Sometimes this correlation is disturbed by extremes in air temperature. For example, a short period of extreme cold averaging 0°C. may not affect soil temperature at a depth of 1 to 2 ft. until several days after the cold wave has passed. Then, although the air temperature may rise, soil temperature at 1 to 2 ft. may still be going down. Such variations were often noticed and will be discussed later.

Seasonal changes in soil temperature have been compared to the temperature changes found in lakes. Mail (1930) noted that there is a fall and spring inversion of temperatures of lower depths of 3 to 24 inches. During late fall and winter there is a reversal of this temperature gradient and the soil at the lower depths is warmer than the soil at the surface or a few inches below the surface.

The role of temperature in regard to wireworm control is difficult to determine. Wireworms undergo a hardening process during the gradually cooling fall months which lowers their freezing and undercooling points (Mail, 1930). This enables the larvae to withstand the low winter temperatures and to survive even after long periods in frozen soil. It is possible, however, that many larvae may be killed by sudden changes in temperature during the winter or early spring. For example, a mid-winter thaw followed by freezing weather of several days may be responsible for a high mortality among larvae.

The effect of cold weather on larvae placed at different depths was tested in the winter of 1940-41. Five flower pots ranging in depth from 5" to 7" were used in these experiments. Each pot was filled to the half-way point with soil. Five wireworms and a thermocouple junction were placed at this depth. Each pot was then filled with soil and planted in the field so that the soil level in the pots was the same as that of the field. Depth of the wireworms in the pots was 2" in the smallest pot and 5" in the largest pot. Two thermocouples were planted near the pots, one at 6" and the other at 10". The pots were planted in the field on December 18, 1940 and the soil therein did not begin to freeze until January 5, 1941, and was completely frozen a week later. Lowest temperature recorded in any of the pots was -1.0°C. on January 22, 1941. The soil remained frozen until mid-March and perhaps lower temperatures were reached but they were not recorded in this experiment. By March 25, the top inch of soil in all pots and in the field had thawed. A week later, all the soil was thawed. On April 18, the soil in all pots was examined and the depth and condition of larvae noted.

Of the total of 25 wireworms planted on December 18, 1940, 19 were recovered when the pots were examined on April 18, 1941. The other six larvae had either been lost in the process of soil sifting, because of cannibalism, or death from natural causes and subsequent decomposition. Of the 19 larvae recovered, three were dead. Data for this experiment are presented in the following table:

Pot No.	No. wireworms recovered Alive	Dead	Depth in inches
1	3	0	2-4
2	3	2	2-4
3	1	1	3 (pot broken by frost)
4	4	0	2-6
5	5	0	4-6

The percentage of larvae surviving these tests was 64. This percentage might reasonably be higher if it were definitely known what happened to the other six larvae. It is reasonable to assume that the three dead larvae found in the pots on April 18 died from the effects of the winter cold. However, definite reasons for the disappearance of six larvae cannot be given unless it is assumed that they were lost because of any of the factors mentioned above. Regardless of the reasons for mortality in the winter, a survival of 64 per cent. can be considered as sufficient to perpetuate the population for the coming season and for several seasons to come, provided that the population does not die more rapidly under natural conditions.

Soil Moisture

Wireworms are noticeably affected by the amount of moisture in the soil. Various species are limited in their range by soil moisture. For example, Agriotes mancus Say is found chiefly in low-lying, wet, clayey soils, Limonius spp. are found in higher and drier localities. Limonius agonus Say, the most abundant species in the "Meadows", is in greatest numbers in the low places of the field. Melanotus spp. are sometimes found with Limonius agonus larvae but they are more often found in heavy, loamy soils, particularly in sod areas and areas recently turned over from sod.

Soil moisture, in conjunction with soil temperature, plays an important role in the migration and development of the larvae. In the spring, the soil is wet and wireworms are undergoing an upward migration. During the warm days of July and August, the upper layers of soil may become dry and the larvae may undergo a downward migration in order to escape dessication. This migration may continue through the latter part of August but if an unusually wet season is encountered, there may be no evidence of a downward migration at all because the factors that encourage it are missing. If no downward migration takes place in the summer, the grower may expect greater damage to his crops because there will be more feeding in the upper layers of the soil.

There may be an upward fall migration following the downward summer migration. This may be the result of increased soil moisture at the upper layers in combination with more favorable soil temperatures. Later on in the fall, there is another downward migration that is no doubt due to unfavorable soil temperatures.

Larvae can survive in very dry soil but their development is doubtless impaired. Larvae retained in six-dram vials of air-dry soil survived for several months without the addition of water eventually succumbed. Larvae were

TABLE IIIa

AVERAGE DEPTH OF WIREWORMS IN THE PARSONS FIELD COMPARED TO THE AVERAGE TEMPERATURE AND MOISTURE CONTENT OF THE SOIL

Date	No. of soil samples	No. of wire-worms	Aver. no. wireworms per samp.	Aver. depth inches	Aver. soil temp. to 12 " in °C.	Aver. moisture content percent.
1940						
May	12	30	2.5	4.7	8.9	
June	23	34	1.5	4.4	16.3	
July	11	9	0.8	3.4	18.3	
August	27	42	1.5	6.5	19.7	
September	18	25	1.4	9.2	16.2	
October	4	2	0.5	7.5	12.0	
November	18	14	0.8	10.0	6.4	
December	8	7	0.9	8.1	0.4	
1941						
Jan.-March	8	5	0.6	6.2	0.3	13.0
April	100	77	0.8	6.2	7.0	16.2
May-June	62	97	1.6	7.5	16.2	12.0
August	46	220	4.8	8.1	20.2	8.6
September	25	138	5.5	9.0	16.5	9.6
October	32	32	1.0	9.4	12.2	9.6
November	13	13	1.0	9.7	7.8	15.6

factors such as soil composition, moisture, crops, etc. A suitable combination of such factors may be the ideal condition for wireworms and the consequent soil reaction may be incidental only.

Lacroix (1935) found no correlation between wireworm population and the hydrogen-ion concentration. In the case of the eastern field wireworm, Limonius agonus Say, he noted a tendency of the larvae to congregate at soil levels having a pH of 5.15 to 5.20. In the Parsons field, soil conditions are comparable to the Connecticut Valley field of Lacroix's studies.

Samples of soil for pH determinations were taken during the 1940-41 seasons of crop growth. The purpose was to determine if there was any correlation between wireworm abundance and soil pH and if the various levels of soil were characterized by different degrees of pH, couldthis variation be correlated with the abundance of wireworms at such depths.

Numerous pH tests were made on soil from various parts of the Parsons field. The hydrogen-ion concentration was definitely acid, ranging from 4.62 to 6.5. Soil sampling for wireworms at the same time revealed no correlation between wireworm abundance and soil reaction. Wireworms were found throughout the field in equal abundance in soils having a pH of 4.62, as well as in soils with a pH of 6.5.

Some types of soil show a variation in soil reaction dependent on the depth or soil level. Leaching of the surface soil may cause a lowering of the soil pH and the consequent downward movement of the leaching products may cause a variation in the soil reaction at lower levels. This holds true for soils not subject to frequent cultivation. In an area such as the Parsons field, however, there is no noticeable variation in soil reaction at various levels to a depth of 12". Frequent cultivation tends to keep the soil well mixed and the soil reaction is consequently about the same to a depth of 12". This apparent lack of variation in soil reaction at different depths made it impossible to attempt a correlation between wireworm abundance and soil pH .

Chemical Analysis of the Soil

During the month of July in 1940 and 1941, various samples of soil from different sections of the field were analyzed by the Agronomy Department, Massachusetts State College. The results of these analyses are presented in the table below. Analysis No. 3 was made from samples submitted from a section of the potato field that had been treated with dichloroethyl ether two weeks before the date of sampling. The other two analyses were made of soil taken from parts of the field that had undergone the normal seasonal, cultural and planting practices.

Analysis Number	Ca	Mg	P	K	NO_3	NH_3	Al
1	L		VL	MH			
2	L	L	L	H	H	L	H
3	VH	L	VVH	VVH	VVH	VH	L

Biotic Environment

Vegetation

The biotic environment of the Parsons field is favorable for the development of many species of subterranean insects. According to the present owner of the field, wireworms have been in the field for many years, probably as far back as the early 1900's. In addition to the wireworms, many other species of larvae are here, including some Staphylinidae (scavenger beetle larvae), Carabidae (ground beetles), and Diptera (flies). Many of these might be pests of seasonal crops or of grassland.

In 1941, about 30 out of a total of 35 acres of the Parsons field were in cultivated crops (Fig. VII). Approximately 20 acres were in potatoes, 6 in vegetable crops, 4 in field corn, and the remaining 5 acres in grassland. For the past twenty years the eastern half of the field has been used for growing cultivated crops. In the early 1920's the eastern half of the field was used almost exclusively for growing onions. Onions did not do so well at that time in this section of the field and potatoes were grown instead. The acreage given over to potatoes was gradually increased by turning over the sodland on the western side of the field. During this period, parts of the potato acreage may have been in grass for one year but the extent and the date of this change is not known. However, only a small part of the potato acreage was in grass and it is safe to say that the greater part of the cultivated area of the field has been in continuous use for cultivated crops for the past ten years. It is interesting to note that the wireworm infestation is heavier in the eastern part of the field, the section that has been in continuous cultivation longer than any other section of the Parsons field.

Approximately 10 acres of land on the western side of the field have been used for growing hay for at least twenty years. Ocassionally, a few acres of this grassland in the North plot would be used for corn. In 1939, about 2 acres of the western part of the North plot were in corn. In 1941, the entire western section of grassland in the North plot (approximately 5 acres)was in corn.

The western part of the South plot has been in continuous use as hayland for nearly 20 years. The soil in this section is a light sandy loam and the grass grown on this section is usually sparse. An acre of this section has been planted to alfalfa. Grassland adjacent to the cultivated part of the South plot is overgrown with dandelions. The peak of click beetle emergence comes about the time the dandelions are in bloom and beetles have often been seen on the blossoms and probably feeding on them.

Important Insect Life of the Parsons Field

The most common species of wireworms inhabiting the Parsons field is Limonius agonus Say. Other elaterid species here are Ludius cylindriformis Hbst., Melanotus sp., and Limonius sp. The larvae of Limonius agonus Say, the eastern field wireworm, are in greatest abundance in the cultivated portion of the Parsons field. The other species are frequently found in the same localities as the eastern field wireworm. Larvae of the genus Melanotus however, are more frequently in areas recently turned over from sod.

Wireworms have been collected in plowed land and in grassland but usually all species are more numerous in land that has been under cultivation for a number of years. A series of soil samples taken at various periods throughout the season of 1940 showed an average wireworm population per 1/2-cu. ft. of soil in the grassland was 0.8 larvae. Soil sampling at the same time in cultivated areas showed the average wireworm population was 1.5 larvae. The reason for this wide difference in population of the two areas is not very definite. It would seem that the grassland would present more suitable conditions of food supply and physical environment than does the cultivated area. Food, such as small roots of grasses, clovers, and other plants, is more abundant in the grassland than in plowed land. Humidity and temperature of soil of the grassland is more favorable to wireworm activity than is the humidity and the temperature of the soil in the cultivated land. Furthermore, these factors are not subject to as much variation in the grassland as they are in cultivated land. Miles (1942) noted some of these factors in explanation of the abundance of Agriotes obscurus larvae in sodland. However, these factors favoring wireworm abundance in sodland seemingly do not hold true for larvae of Limonius agonus in the Parsons field. The reason for the greater population of wireworms in the cultivated portion of the field might be a food preference for crops grown here, such as potatoes, or the general nature of the soil, or reduced competition from other soil insects.

Larvae of Staphylinidae (scavenger beetles), Carabidae (ground beetles), Scarabaeidae (June beetles), Tipulidae (crane flies), and Diptera (flies) were in areas infested by wireworms. Adult Staphylinidae, Carabidae, and Formicidae (ants) were also in soil infested by wireworms. Although some of these soil inhabiting species may utilize the same type of food as do the wireworms, they are not in sufficient numbers to make them serious competitors of the wireworms. However, there may be localized instances where wireworms and other species of larvae compete for food. A section of the South plot bearing beets was seriously attacked by what the grower supposed to be wireworms. Investigation showed the injury was produced by white grubs and no wireworms were found. This does not mean that the white grubs acted as competitors and drove the wireworms out of this section.

Wireworms in the cultivated section of the Parsons field do not compete with other larvae for their food supply. Sufficient organic matter is in the soil to support not only the wireworm population but other insects as well without bringing the various species into direct competition.

The grassland harbors many more species and greater numbers of insects than does the cultivated land. This is to be expected for there is considerably more food in the grassland than in the plowed or fallow areas of the field at the time when most insects are feeding. Soil sampling in grassland revealed a greater number of scarabaeid and carabid larvae than were in plowed land. White grubs were common in sodland and were less common in areas recently turned over from sod. With few exceptions, white grubs were not in soil samples taken in land under cultivation for three or more years. Carabid larvae were likewise common in sodland but scarce in plowed areas. The number of other types of larvae in the cultivated areas was insignificant compared to the number of wireworms in the same areas. Observations indicate that the practice of plowing, by making the land unsuitable for grass-loving species of larvae, makes the environment of the plowed field more suitable for wireworm activity and development. Furthermore, there is less competition from other larvae and as long as the food supply remains adequate the plowed areas will remain a suitable habitat for wireworms. In plowed areas the source of food supply is assured by the planting of seasonal crops which usually are excellent food for wireworms. The use of rye, sown as a winter cover crop, provides an additional supply of organic matter to the soil and this serves as food for wireworms. Young wireworm larvae are said to be especially dependent on organic matter and humus as their food supply. The grassland has an abundance of such a food supply and this might be sufficient for young wireworms. Older wireworms, however, are known to require a different food supply and this they find in the potatoes and other crops grown in the cultivated areas (Strickland, 1939).

Parasites and Predators

Except in unusual and rare instances, parasites or predators have not figured very prominently in the control of wireworms in the soil. It may be said that parasites and predators are a negligible factor in the biotic environment of the experimental plot of the "Meadows" and that no marked degree of control can be ascribed to them.

Examination of hundreds of wireworms has not revealed the presence of parasites, either plant or animal, attacking them. Several larvae were infested with white mites which were usually attached to the last abdominal segment of the larvae. Mites attached in this fashion were not considered to be parasitic, since wireworms bearing mites were retained for several months and were normal in their behavior and development.

There is probably more predatism in the Parsons field than parasitism. Wireworms of the genus Limonius and Melanotus were observed to be cannibalistic on one another, especially if they were confined in small vials or if starved. In the field, conditions of crowding and starvation were not observed and cannibalism was negligible.

Larvae of <u>Limonius agonus</u> are known to be attacked by staphylinid larvae. In the field, staphylinid larvae were seen to attack wireworms weakened following treatment with dichloroethyl ether. In one instance, a wireworm in a treated hill of corn was being fed on by several staphylinid larvae. Staphylinid larvae were often in soil which had been treated with the ether compound, having probably migrated to the treated areas in search of weakened wireworms.

Adult elaterids are known to be eaten by birds, frogs, toads, and other predators. It is reasonable to suppose that crows, starlings and meadowlarks feed on a considerable number of adult beetles but not enough to control them.

<u>Wireworm Population</u>

The wireworm population of a given area is best determined by sampling that area. It is not feasible to actually count the wireworms in every foot of a given area of land unless this area consists of only a few square feet. Consequently, soil samples, if they are randomized, can be considered as an index of the number of different species of wireworms in a given area.

Population studies of wireworms have been continued in the field since the beginning of the project. Estimates based on counts taken at various seasons of the year indicate the total population of the field at various depths, how the population changes from season to season, and migration of wireworms from one soil level to another. Population counts can also indicate the effect of various environmental factors upon the wireworms. Thus, the effects of temperature, moisture, freezing, etc., can be determined by actual soil examination. The efficiency of chemical or cultural controls can best be determined by actually sampling the soil and observing the number of wireworms.

Wireworm population counts may serve as the basis for future land-use planning. If an area is supposed to be infested with wireworms, it would be foolish to plant it to susceptible crops without first ascertaining what pests are in the soil. A preliminary sampling of wireworms may reveal a situation wherein it would be inadvisable to plant certain crops.

It is true that using a certain number of sample counts as a basis for the determination of the wireworm population of a given area may not be the most accurate method. Wireworm populations obtained by the sampling method are at least a scientific estimate and can be relied upon much more than a mere guess as to what is actually in the field.

Method of Sampling

Much of the early work on soil sampling for wireworms has been of a hit-or-miss nature. Usually the purpose of the early work was to determine the presence or absence of wireworms. There was no studied or planned method of taking samples with a definite purpose in view. Recent workers have done better than their predecessors in this regard and the results they have obtained have justified the efforts they have made (See Jones, 1937; Miles, 1937, 1938; Lacroix, 1933; Jewett, 1939; Hawkins, 1936a).

Lacroix (1933) sampled areas of soil 2 ft. sq. and 2 ft. deep, half under tobacco rows and half between rows. These samples were taken at various times during the season in two different localities of the field. Successive soil horizons were examined for presence of larvae. His purpose was to determine the depths and seasonal feeding period of the wireworms.

Hawkins (1936) described wireworm population studies in Maine. He suggested determining the wireworm population in early spring or fall when small wireworms or eggs were not in the soil. He recommended taking samples first on areas suspected to be heavily infested and then sampling over the entire area until enough samples were taken to determine the extent and amount of infestation. Poorly drained areas, such as flat spaces and surface depressions, are likely to be heavily infested. During 1934, Hawkins took 54 samples of soil, each sample being 9 sq. ft., and 54 30-sq. ft. samples in experimental plots extending over 1-1/2 acres. Soil samples were taken down as far as wireworms could be found. Most of the wireworms were in the upper 6" and none were below 8". Hawkins suggests that samples 1 ft. sq. in area might be a more representative method of sampling.

Jewett (1940) described a method of sampling for wireworms infesting tobacco fields in Kentucky. The unit sample was 1 ft. wide, 3 ft. long, and 8 inches deep. Thirty or thirty-six samples were taken in sodland during the fall preceeding the planting of tobacco.

Morrill (1939) stated, in an interview, that soil samples in Connecticut tobacco fields near Windsor Field Station were taken diagonally across the field. In such a manner, a more representative sampling of the field was obtained. Samples were 1 ft. sq. in area taken to a depth of 6 - 9".

Jones (1937) presented an extensive and able account of field sampling of soil for wireworms. As far as is known, this is the most extensive account of soil sampling for wireworms. He took samples of 1, 1/4, and 1/16 sq.ft. at random from one end of the field to the other. The data obtained were subjected to statistical analyses. Jones concludes that 1 sq. ft. units are more accurate in estimating the mean than the smaller units. Fifty samples are considered sufficient to determine the number of wireworms per sq. ft. of soil at low population levels and fewer samples, if population levels are higher. All samples were taken to a depth of 1 ft.

Soil sampling in the "Meadows" was conducted throughout the entire year. In the spring, samples were taken at random from one corner of the field, diagonally across to the opposite corner. Usually the sampling was done on both diagonals so that a map of samples taken would resemble a huge X. During the summer, samples were taken in the same manner in rows and outside of rows. Soil samples were also taken after controls had been applied in order to determine the effect of various controls.

In the fall, soil samples were taken to determine if any correlation existed between wireworm population and amount of injury to potato tubers. Samples were also taken later in the fall to find the wireworm population after the crops had been harvested.

In the winter, soil sampling was difficult because of the frozen soil. The purpose of winter sampling was to determine at which soil levels wireworms were located and the effect of freezing on the larvae.

In deciding upon a unit sample, Jones' (1937) work on soil sampling was taken into consideration. This investigator found that 25 units of 1 sq. ft. or 1/4 sq. ft. were required to obtain a 20 to 40 per cent. error range. A 1-sq. ft. or 1/4 sq. ft. sample was easy to handle and more of these smaller samples could be taken resulting in a more representative sampling of the soil population.

The Unit Sample

At the beginning of the field work, 1-sq. ft. samples down to a depth of 1 ft. were taken. As the season progressed, samples of 1/4-sq. ft. were used. The smaller sized sample proved to be more convenient and economical of time that could be allotted to wireworm population study.

Each sample was taken to a depth of 12" no matter what the season of the year or condition of the soil. Many samples were taken to a greater depth. Usually it was not necessary to go below 12" to get all the wireworms. The area to be sampled was first measured and marked out and the soil removed to a sieve with a trowel. The depth at which wireworms were collected was noted with other relative facts such as size of wireworm, activity, condition, etc.

In order to facilitate soil sampling, a sampling device, modeled after that of Jones' (1937) was constructed. This sampler was made of iron, 3/16" thick, made to enclose 1/4-cu. ft. of soil when driven into the soil to a depth of 12". The inside top measurement of the sampler was 6-1/4" square and the bottom inside measurement was 6" square. A collar of steel, 1" wide, was welded on the outer top edge which served as a support for the sampler as it was hammered into the soil. The bottom edge of the sampler was filed to a sharp edge so that it would enter the soil more easily. The sampler was 12" long.

In collecting a sample of soil, the sampler was dropped on the ground with the sharp edge downward. By hammering on the collar it was driven to the required depth and then removed with its column of soil. Frequently, it was necessary to hammer the edge of the collar in order to loosen the sampler in the ground. This did not distubb the soil within the sampler. The smaller dimensions of the sampler at the bottom prevented the soil from sliding down when the sampler was removed from the ground. This device was found to work satisfactorily in loose soil but it was difficult to use in compact clayey soil. In frozen soils it was impossible to use.

If the sampler was not used a convenient amount of soil was removed with a trowel and sifted. This procedure was repeated until the required depth in the soil had been reached. If the Jones type sampler was used, layers of soil 1" to 3" in thickness were removed and sifted at a time.

Sifting

Numerous methods of soil sifting have been recommended by various investigators. These methods vary from the use of simple hand sieves to elaborate, power-driven sifters. The hand sieve has its advantages when used in certain instances. A simple hand sieve with a screen of the proper mesh might prove adequate for determining the population of the larger wireworms in the soil. Hawkins (1936a) stated that a simple sieve of 1/4" mesh proved adequate for his needs. In addition he found that a rotary ash screen could be used satisfactorily. These two types of screens may be suitable to use where one worker sifts the soil and another watches the sifted soil for wireworms. However, it would hardly be possible throughout the season to get an accurate count of all wireworms in a sample by using 1/4" mesh screen. Many of the smaller larvae, no doubt, fall through the screen unobserved. By using a series of gradually finer sieves, greater accuracy in obtaining the number of wireworms in a sample can be reached. Jones (1937) describes a method of sampling by washing the soil through a series of sieves, one placed directly above the other. The bottom sieve has the finest mesh screen in the series. Lane and Shirck (1928) described a mechanical sifter operated by hand. In 1936 they published an account of a power-driven sifter, capable of handling approximately 5 cu. ft. of soil per hour.

In soil sampling work in the "Meadows" various methods of sifting have been tried. At first, a circular hand sieve of 1/4" mesh, 6" deep, and 10" in diameter was used. This proved to be unsatisfactory because sifted soil passed through it too rapidly and many larvae were not observed. Another simple sieve of 10 meshes to the inch was constructed, 6" deep, 14" wide, and 17" long. This sieve was used with the 1/4" mesh sieve already described. Good results were obtained by first breaking up and sifting the soil through the larger mesh sieve into the finer box-like sieve. The soil was then resifted through the finer mesh sieve.

A series of screens similar to those described by Jones (1937) was constructed with the idea of washing the soil sample instead of sifting it. Several tests with this set of screens showed that there would be no saving of time or labor in using them. It was difficult to find the wireworms after the soil had been washed because of the debris and other matter left on the screens in the process of washing. This method might prove satisfactory for sampling wireworm eggs and its use for this purpose has been suggested by Jones (1937).

Another method of treating the unit sample of soil was tried. Instead of sifting the soil, the sample was introduced into a Berlese type funnel for heat treatment. This method caused the soil to dry out and the larvae to go downward in order to escape the heat and consequent drying of the soil. The larvae were collected at the small end of the funnel in water or alcohol. Two screens insdie the funnel sefved to keep falling soil out of the collecting vial.

This method is very effective in collecting insects from humus, fine debris, or duff, but it is not advantageous to use for soil collecting unless some modifications are made. The funnel used is too small to accomodate an entire 1/4-cu. ft. sample. The type of soil in the "Meadows" is a sandy loam, and when placed on the top screen of the

Berlese apparatus, is easily disturbed by the efforts of the larvae to escape the heat and drying. Screens, fine enough to prevent the fall of an excessive amount of soil into the collecting vial, prevent the passage of larvae through them, and the heat kills the larvae thus caught on the screens.

Field Work - Fall, 1939

Preliminary soil sampling to determine the extent of wireworm damage to potatoes and the wireworm population at the time of harvest was begun in August, 1939. Several hills of potatoes were selected at random and the soil in each hill, one square foot in area taken to a depth of 12" was examined for wireworms. The number of potatoes in each hill was noted and also the number of wireworm holes and larvae.

It was soon discovered that the number of wireworms on or in the potatoes upon removal from the hill could not be relied upon as a true index of the number of wireworms that actually were in the hill. Many larvae were shaken off in the process of removing the potatoes from the hill and others were probably hidden in the potatoes. The number of wireworm holes per potato might serve as a better index of the population per hill. This figure usually corresponded with the actual number of wireworms found in the hill by soil sampling methods.

Twenty-three hills of potatoes, selected at random throughout the field, were examined for the presence of wireworms and the amount of damage done to potatoes. Results of these early examinations showed that three hills had no wireworms and the remaining hills had as many as 19 wireworms per hill. These results are listed in Table IV. The number of potatoes per hill ranged from 1 to 9, the average being 4.7. The average number of wireworm holes per tuber was 3 and the average number of wireworms per hill was 4.6. On the basis of these figures, it was estimated that each wireworm was responsible for making 3 holes per potato.

An estimated population of the wireworms in the Parsons field was based on the results of the soil sampling shown in Table IV. The total of 105 wireworms obtained in 23 cu. ft. samples equaled an average of 4.6 wireworms per cu. ft. of soil. On an acre basis this would total 200,376 wireworms for the first 12" of soil. Roebuck (1924) considered that 200,000 wireworms per acre as the utmost limit for safety as regards wireworm damage to crops. Hawkins (1936a) found 3 out of 7 plots with a wireworm population of 91,000 to 100,000. In these plots, 95.1 to 100 per cent. of the tubers were injured. The percentage of injured tubers in the samples taken in August, 1939, was 84.

TABLE IV

NUMBER OF WIREWORMS AND WIREWORM HOLES PER POTATO AND NUMBER OF WIREWORMS PER HILL

Date	Hill no.	No.pots in hill	No.wire-worm holes per potato	No.wire-worms in or on potato	No.wire-worms in hill only	Total no. wireworms
Aug.16,1939	1	4	10	1	0	1
	2	5	11	0	1	1
	3	3	9	3	4	7
	4	3	13	2	4	6
	5	7	17	2	8	10
Aug.17,1939	6	6	17	1	5	6
	7	5	4	1	5	6
	8	3	6	4	4	8
Aug.24,1939	9	4	0	0	2	2
	10	4	0	0	1	1
	11	1	0	0	1	1
	12	3	0	0	1	1
	13	2	0	0	0	0
	14	7	8	0	2	2
	15	5	0	0	0	0
	16	5	9	0	2	2
	17	4	1	0	0	0
	18	3	6	0	2	2
Aug.28,1939	19	9	29	1	15	16
Aug.29,1939	20	8	32	1	2	3
	21	7	100	5	14	19
	22	5	24	2	8	10
	23	5	29	0	1	1
Total	23	108	325	23	82	105
Averages		4.7	3			

Migration

After the 1939 potato harvest, random soil samples were taken to determine the extent of the downward migration of wireworms. Eight out of nine cubic foot samples showed wireworms. Twenty larvae of various sizes and three adults were collected at depths ranging from 6" to 12". No wireworms were found above 6" or below a depth of 12". Soil sampling before the time of harvest showed that wireworms were at depths of 4" below the soil surface. Six weeks had elapsed between the dates of these two samplings.

This preliminary sampling was indicative of a downward migration of larvae in the fall. Observations in the field indicated that there were two factors which could be responsible for this downward migration.. After the harvest, the field is usually disced and harrowed to a depth of 4-6". Furthermore, soil temperatures after the time of harvest are usually on the down grade. These two factors might work together and the downward migration of the larvae is a result of their interaction. Below a depth of 6", larvae are not subject to the discing and harrowing practiced after the harvest. Temperatures at the lower depths are more favorable to wireworm activity and survival. Although the discing may help to drive the larvae down, no doubt lower temperature of the soil is the chief factor.

During the winter months soil sampling was discontinued and was resumed in May, 1940, at the time when truck crops were beginning to come up out of the soil. Wireworm infestations could readily be recognized by the appearance of the newly planted field. The damage in heavily infested areas caused many plants to die so that in many cases replanting (reseeding) was necessary. Out of a total of 14 1/4-cu. ft. samples taken in infested beets during May-June, 1940, 12 samples had 22 wireworms. These larvae averaged 1/2 inch in size and were in the soil at depths varying from 2" to 10" below the soil surface, the average depth being 2.5". Compared to the results of the soil sampling the preceding fall, this spring sampling showed a definite upward migration of the larvae.

Wireworms continued to be found at shallow depths of 2" to 5" until the end of July. After this date, there evidently began a downward migration of wireworms. During August, 1940, 26 soil samples of 1/4-cu. ft. had wireworms in 14 samples. Of the 40 wireworms in these 14 samples, 36 were 4" or more below the soil surface.

September soil sampling revealed a deeper migration of wireworms. Eleven our of 17 soil samples had a total of 23 wireworms. These were collected 5" or more below the surface of the soil, the average depth being 9.2".

Lacroix (1933) in Connecticut, found larvae of <u>Limonius plebejus</u> and <u>Pheletes ectypus</u> at depths of 6" to 9" during the growing season and at 3" to 6" during October-November. Bryson (1934), in Kansas, noted a downward migration in late June and mid-July. He suggested that this migration was either for the purpose of pupating or escaping the heat. Bryson noted an upward migration in mid-September and a downward migration below the 6" plow line in autumn.

The number of samples taken during October was not large enough to get a true average depth of larvae. During October, November, and December, 27 1/4-cu. ft. samples were taken. The total number of larvae in the samples was 24 and their average depth was 9.1". These figures would indicate that the larval population had ceased its downward migration in the late fall months. The soil was not frozen up to December 1, 1940.. The top inch or two of the soil had frozen during mid-December but the warm weather and rains of late December kept the soil soft. By January 22, 1941, the soil was frozen to a depth of at least 12".

268,804 wireworms. The total for these two months was 65 wireworms collected in 35 samples or an estimated acre population of 337,144. During July, the estimated acre population was 132,124, and during August it was 291,564. It is interesting to note at this point, Hawkins (1936) stated that he found a decrease of 45 per cent. in the populations from spring to fall. Pupation and other factors (not mentioned) were given as reasons for this decrease. A comparison of the spring and fall populations obtained in this study showed a decrease of approximately 16 per cent. in the fall population. After potatoes were harvested, the estimated acre population for September was 232,356 wireworms, a reduction of about 31 per cent. from that of the spring population.

In the overwintering experiments conducted in pots, a decrease of 36 per cent. was recorded in the number of wireworms surviving the winter. Based on soil samplings in the field, a decrease of 31 per cent. in the spring (April) population was noted when compared to the preceding fall (September, 1940) population. The populations for various periods of the year, estimated on the basis of random sampling, are given in Table V.

TABLE V

AVERAGE NUMBER OF WIREWORMS PER CUBIC FOOT, AVERAGE DEPTH AND ESTIMATED ACRE POPULATION

Date	No. of samples	Total no. wireworms	Aver. depth of wireworms in inches	Aver. no. wireworms per cu. ft.	Estimated acre population
May, 1940	12	31	4.7	10.3	469,268
June, 1940	23	34	4.6	5.9	268,804
May and June, 1940	35	65	4.6	7.4	337,114
July, 1940	11	8	3.4	2.9	132,124
Aug. 1940	27	43	6.5	6.4	291,584
Sept. 1940	18	23	9.2	5.1	232,356
Oct., Nov., and Dec.'40	30	24	8.0	3.2	145,792
1941					
April	100	77	6.2	3.1	141,236
May-June	62	97	7.5	6.3	287,028
Aug.1-15	21	128	7.6	12.2	555,832
Aug.26-29	25	92	8.8	7.4	337,144
Aug.1-29	46	220	8.1	9.6	437,376
Aug.26 - Sept.12	50	230	9.1	9.2	414,596
Sept.2-12	25	138	9.0	11.0	501,160
Aug.1 - Sept.12	71	353	8.5	9.9	451,044
October	20	8	8.0	1.6	72,896
Oct. 31	12	24	9.3	8.0	364,480
November	13	13	9.7	4.0	182,240

Soil sampling was resumed in the spring of 1941. The April soil samples preceeded the spring pre-plowing of the Parsons field. The cover crop of rye, planted the preceding fall, was 6" to 8" high. Compared to the estimated populations of other months, the April estimate seemed rather low. This may be explained by the fact that the April samples were taken at random under an even cover of rye. Other samples taken that year, including those as late as September 12, were beneath plants that had been planted in late April or early May. Therefore, the April samples represent the entire field whereas the later samples represent only the area beneath the growing crops. For example, samples taken under the dates of August 1 to August 29 were taken in potato rows and not between the rows. These rows constituted only one-half or less of the entire surface area of the soil in the field. Furthermore, the area between the rows had very few wireworms, in most samples--none. Therefore, a true estimate of the total population of the field would be more accurate if these factors were taken into consideration in making the estimate. The population of the Parsons field during August is based on 46 1/2-cu. ft. soil samples taken in the rows of potatoes (See Table IV). If, however, it is assumed that these samples represent only one-half or one-third of the soil capable of being inhabited by wireworms, then some factor of calculation would have to be introduced which would give weight to the area (i.e., the soil between the rows) which is not represented by these 46 soil samples. Without the basis of further soil sampling data and experience, it is difficult to say how much weight this factor should be given. The estimated populations in Table IV were based on the number of wireworms found in the stated number of samples taken in the row.

Reference is again made to Hawkins' (1936a) observation that there is a decrease of 45 per cent. in the wireworm population from spring to fall. Comparison of the April, 1941 soil sampling with that of October-November, 1941 showed that there was an increase of approximately 44 per cent. in the wireworm population during the summer.

The purpose of comparing the fall wireworm population with that of the previous spring is to determine what increase or decrease of wireworm abundance had occurred in this period. The accuracy of the results obtained depends on various skills and techniques in obtaining and interpreting soil sampling results. Although soil sampling may show a decrease in the larval population from spring to fall, this does not necessarily mean that all of this change has been due to actual mortality among the wireworms. Methods of sampling, the areas sampled, personal error and other factors might be partially responsible for such an increase or decrease. Furthermore, cultural practices and seasonal variations might be active in bringing about a decrease or increase in the populations from spring to fall and the importance ofsuch factors is often difficult to evaluate. Therefore, in order to get a truer picture of the changes occurring in the wireworm population of a given field, it would be better to compare the data of one particular season with the data for the same season one year hence.

Lacroix (1933) reported that larvae of Pheletes ectypus and Limonius plebejus were at 6" to 9" depths during the growing season. In the Parsons field, the average depth for larvae of Limonius agonus during the months of April to September, 1941, varied from 6.2" to 9.0". Lacroix noted an upward migration of wireworms during October and November and this fact was corroborated to a slight degree, in the studies of larvae in the Parsons field. Wireworms were found nearest the surface during April at an average depth of 6.2". During the succeeding months wireworms were found at increasingly deeper soil levels reauhing an average depth of 9" in September. In October, the average depth was 8.6" and in November, the average depth increased to 9.7".

In the course of sampling various fields in the "Meadows" section it was evident that the wireworm population of adjacent fields was not as great as that of the Parsons field, and as was to be expected, the amount of injury to potatoes was consequently less in these adjacent fields. The fields sampled were all within a half mile radius. Two of them, fields No. 2 and 5 (see Fig. I), were only 300-500 ft. west of the Parsons field. However, these fields are on a terrace 5 ft. higher and are not subject to flooding or poor drainage as are parts of the Parsons field. Fields No. 2 and 4 are of the same sandy loam type as is the Parsons field. The other fields are a little darker in color and of a heavier loam type.

All of the fields sampled have been used for potato growing for a number of years. Occasionally a part of one of these areas may be in sod for a year or two. One field has had onions on it for one season. Usually these fields are not sown to a cover crop in the fall.

The results of soil sampling in these fields presented in Table VI show that the number of wireworms is greatest in the Parsons field. The reasons for the smaller populations in the other fields may be due to the different type of soil and to the use of grassland as part of the rotation.

TABLE VI

COMPARISON OF WIREWORM POPULATION AND DAMAGE TO POTATOES IN THE PARSONS FIELD WITH THAT OF OTHER NEARBY FIELDS

Field no.	Date	Number of soil samples	Number of wireworms	No.of potatoes	No. of wireworm holes	Aver.no. wireworms per samp.	Aver. no. wireworm holes per potato
	1941						
1	Aug.11	5	2	29	10	0.4	0.3
2	Aug.11	5	3	30	15	0.6	0.5
3	Aug.11	5	4	31	19	0.8	0.6
4	Aug.22	5	11	28	30	2.2	1.1
5	Aug.11	5	6	33	49	1.2	1.5
6	Aug.7	5	91	29	59	1.8	2.0
7	Sep.11	5	13	27	75	2.6	2.8
8	Aug.-Sep.	70	359	402	2,027	5.0	5.0

Adult Sampling

The insect population of a certain area can be estimated by the use of various sampling methods. Sampling of the adult insect population of any given area is merely a scientific measure of what is on the ground or at certain heights at a given time. Total population can be sampled by sweeping the vegetation at a certain height with an insect net (of known size). A given area is covered by a pre-arranged number of sweeps. This sample is supposedly indicative of the total number of different species in the particular stratum of the area being examined. This method can be modified to include only a particular species of insect.

Population counts of adult elaterids were taken with an insect net in various sections of the Parsons field. The purpose of these counts was to determine at what time of the season adults emerged, the peak and end of adult appearance, species of elaterids, and the most densely populated areas.

Samplings were made by sweeping from early May to mid-June and in some cases much later. Some samples taken before May were made by examining likely hiding places of the beetles, such as under stones and boards, in heavy vegetation, and other places. As the weather became warmer, sweepings were taken and continued until after no more adults could be collected.

Records were also made of beetles taken in the soil at the times of sampling for larvae.

Adult sampling records for 1940 show that the peak of beetle activity occurred in mid-May. Complete sweeping records for 1940 are not available but field observation notes reveal that adult flight and mating was in full progress by May 19, 1940. On that date, beetles were observed in the sodland west of the South plot potato area. Air temperature at the time of observation, 10:30 A.M. to 12 noon, was 22°C. to 25°C. Beetles were very active in a sandy patch of soil in the grassland, making short flights and attempting to mate. Several matings and deposition of eggs were observed. Eggs were deposited by the females in soft sandy areas, small cracks and crevices. The posterior abdominal segments were gradually worked into the soil and in some cases the beetles were covered by the soil. Later observation of the soil revealed a few eggs. These eggs were transferred to the laboratory but only one newly hatched larva was obtained.

Soil examination of May 18, 1940, in the cultivated area of the South plot showed that emergence of beetles was still in progress. One beetle was found at a depth of 6". The soil temperature at this point was 13.0°C.

No standard method of sweeping had been decided upon in the 1940 adult collection. Some collections by sweepings were made in the grassland west of the South plot potato area as well as in the cultivated South plot. No adults were collected in the cultivated area on May 19, 1940, but 50 adult beetles were collected in the grassland area in a hundred complete sweeps taken in an area 6 ft. wide and 500 ft. long. On June 7, 100 complete sweeps in an area the same size in the grassland section of the South plot netted 10 adult beetles. Most of these beetles collected on these two dates were Limonius agonus Say, and probably 10 were Ludius sp. (hieroglyphicus?). On June 23, only 1 beetle (probably Melanotus sp.) was netted in 100 complete sweeps.

Observations of the beetles at twilight and early evening were made in the field. No adult activity was noticed at twilight time although 100 sweeps in an area 6 ft. x 500 ft. netted 10 beetles. No beetles were attracted to the lights of a motor car parked in the field. This, however, does not necessarily mean that all beetles are inactive throughout the hours of darkness. Previous studies of night flying insects attracted to light traps show that some elaterids are caught at night.

From July 25 to August 22, 1934, a total of 50 adult elaterids was collected in a light trap operated in a field behind Fernald Hall, Massachusetts State College. From July 24 to August 3, 1935, the total number of click beetles caught in this trap was 54. In 1937, 33 beetles were collected from May 23 to June 25. It should be noted that these figures, compared to the total catch of all insects for the same periods, are very small.

Observations in the Parsons field would indicate that this nocturnal activity was very small compared to the activity at other periods of the day, particularly in mid-afternoon when air temperatures are optimum for adults.

Adult collecting was started again in the spring of 1941. Sweepings in late March did not net any adults. Stones, sticks, and other objects under which the adult beetles might hide, were examined but no adults were found. None were collected by these methods until April 22, 1941 (adult elaterids were collected in Amherst as early as April 15, 1941). The next collection was made on May 8, 1941 and 59 click beetles were collected in an area 6 ft. wide and 500 ft. long. This collection was made in grassland 20 ft. east of the mid-section of the South plot. In grassland west of the South plot, 63 adults were collected in 50 sweeps taken over an area 6 ft. wide and 250 ft. long.

On the basis of collections made in 1940 and early 1941, a standard for sampling adult populations was decided upon. A cone shaped net, measuring 12½" in diameter at the mouth and 18" long , was used in all the sweeping collections. The handle on the net was 3 ft. long. In actual sampling, the net was swung 3 ft. on either side of the body. A complete sweep was considered as one swing of the net from right to left and back again. The forward motion of the body would be 5 ft. during the time of one complete sweep. The net was swung as close to the ground as the vegetation would permit. This method was used throughout the period of adult collection from May to July, 1941.

Most of the samples were taken in the grassland area adjacent to the potato land of the South plot. This section was selected as a matter of convenience and economy. The North plot had no grassland bordering it directly.

The upper or north end of the South plot is bordered by the road dividing the Parsons field in two parts. In sampling, the usual precedure was to take 100 complete sweeps alongside the potato field, starting from the Middle Road and going south 500 ft. This would constitute one sampling unit. The second sampling unit was taken 50 ft. west of the line followed in the first unit back towards the Middle Road.

General observations were made at the time as to the condition of vegetation in the areas sampled. Also, the relative abundance of other species of insects was noted. Air temperature and weather conditions at time of sampling were recorded.

Results of the 1941 sampling are shown in Table VII. The data show that the peak of adult abundance came in mid-May when 169 click beetles were collected in 100 complete sweeps on May 16, 1941. Adult collections after that date showed an irregular decline until June 24, when no beetles were collected. Sweepings in July netted no beetles.

The greatest number of beetles were collected in the grassland next to the cultivated potato land of the South plot. The number of beetles collected further west of the cultivated area diminished seemingly in proportion to the distance from the cultivated area, that is, the further away from the cultivated area, the fewer the beetles. Soil samples for wireworms in the cultivated area should be indicative of the number of adults inhabiting the area. Adult samples were taken in the cultivated portion of the North and South plots but no click beetles were collected there. Sweeping in the grassland next to the potato land of the South plot netted several adults but sweeping in the cultivated land, 5 to 10 ft. east of the grassland, netted no adults.

Larval sampling data showed that newly turned sod in the western sections of both the North and South plots did not yield as many wireworms as the central portion of the field. This would seem to indicate that cultivated areas were more suitable for wireworm development than the sod areas. It should be noted, however, that the greatest number of beetles were collected in grassland and not the cultivated area of the South plot. Beetles have been collected in the cultivated areas but not above the soil. Numerous specimens have been taken in the soil either before the time of spring emergence or after pupation in late summer.

TABLE VII

NUMBER OF CLICK BEETLES (ELATERIDAE) COLLECTED IN THE GRASS LAND OF THE SOUTH PLOT OF THE PARSONS FIELD

Date	Temperature in °C.	Number beetles collected in 100 complete sweeps
1941		
April 4	14.5	0
April 10	16.0	0
April 22	15.0	0
May 8	18.0	63
May 13	20.0	35
May 14	21.0	18
May 16	28.0	169
May 20	28.0	53
May 23	32.0	55
May 31	28.0	27
June 6	24.0	18
June 23	25.0	1
June 24	26.0	0
July 11	26.0	0

Control of Wireworms

Ecological Methods

Wireworm control can be based on three different types of soil treatment, ecological, mechanical, and chemical. The ecological means of wireworm control is discussed first. Under this heading the mechanical methods of control should be included because the mechanical methods referred to were usually dependent upon certain cultural practices. In the control of adult beetles however, mechanical methods were not dependent upon cultural practices and hence were a separate method of control.

Many of the early recommendations for wireworm control stated the advisability of fall or spring plowing. The purpose of plowing at either one of these seasons was to disturb the environmental conditions enough to injure the larvae or pupae. Fall plowing was frequently recommended as a control for elaterid pupae because it injured or turned the pupae up on the surface of the soil, exposing them to adverse weather conditions. Larvae were also supposed to be harmed in the process of fall plowing.

Soil samples taken in the fall in the Parsons field showed that pupae were usually at a depth of about 10" at the time of fall plowing. The depth of the plow line was 6 - 7" only. Adults were also found at depths averaging 9.0". Hence it can be seen that fall plowing to the depth usually practiced in this locality, would not reach the pupae and would reach only those larvae down to 7" in the soil. It is felt that the early recommendations for fall plowing were made without sufficient knowledge of the activities of the wireworms at the time of plowing.

Fall plowing is not practiced in the Parsons field except in a few acres given over to truck crops. The usual practice followed in the potato areas of this and other fields is to sow the land after the harvest to a cover crop of rye. This cover crop serves the double purpose of a green manure which is turned under in the spring and holds the soil in case of high winds or severe floods. The truck crop area of the Parsons field is usually plowed in the late autumn. The truck crop area of the North plot has undergone fall plowing for the past three years and that of the South plot area, for the past two years. In the spring, the truck crop areas of both North and South plots are harrowed before planting.

The cultural practices followed in the truck crop areas, in addition to the summer cultivating and weeding, leave a minimum food supply for wireworms. Infestations of wireworms in the spring are apt to be more noticeable in these areas than in the potato land, probably because the soil of the truck crop sections is kept freer of organic matter the wireworms are not so well fed, and consequently feed more in the spring. Furthermore, germinating seeds and young plants are very attractive to larvae and their feeding is concentrated upon this source of food.

Results of soil sampling in the fall of 1940 showed the average depth of wireworms to be approximately 9". Out of a total of 23 larvae collected in 21 1/4-cu. ft. samples during September-October, only 2 wireworms were at a depth of 5" or less. The other 21 larvae were 6" or more below the soil surface. The average depth of wireworms in September-October, 1941, estimated on the basis of 57 soil samples, was 9". A total of 170 wireworms were collected in these 2 months and only 31 were at a depth of 6" or less below the soil surface. The practice of fall plowing to a depth of 6" would have reached only 18 per cent. of these larvae.

Spring plowing for the control of wireworms is not now considered an effective measure of control. Larvae turned up by plowing at this time are not subject to any great variations of temperature and, unless injured, they immediately burrow down into the soil. There is a possibility that more larvae are injured by spring plowing than by fall plowing. The reason for this is that more larvae are nearer the soil surface at the time of spring plowing. Larvae have been collected near the soil surface in spring, feeding on the turned under roots of rye. Harrowing and discing of the field when the larvae are thus feeding may result in some degree of control.

Spring plowing in the Parsons field usually takes place before the first of May. The potato land, bearing its cover crop of rye is plowed to a depth of 6". What effect spring plowing of the potato land has on wireworms infesting it can be judged by taking into consideration the depth of the larvae at the time of this plowing. One hundred soil samples were taken a few days before the spring plowing of 1941. Out of a total of 70 wireworms collected in these samples, only 30 were 1 to 6" below the soil surface. This amounts to 42 per cent. of the larvae present to a depth of 12" in the soil. Comparing these figures with the fall population depth counts it is evident that spring plowing reached a greater percentage of the wireworms. It is problematical though, if very many of the larvae upturned in spring suffered any damage.

Discing, Harrowing

Discing or harrowing of the soil prior to spring planting or after the fall harvest cannot be recommended as a control measure for wireworms. Based on the estimates of the spring and fall soil sampling it was found that the majority of the wireworms were 6" or more below the soil surface. Discing and harrowing disturbed the soil to a depth of 4" only. On the basis of the results of the above mentioned, discing or harrowing the soil in the fall to a depth of 4" would reach only 7 per cent. of the wireworms present in the first 12" of soil. In the spring, 33 per cent. of the larvae might be affected by discing or harrowing. This does not mean that 7 per cent. of the wireworms in the fall or 33 per cent. in the spring would be killed by these cultural methods, but merely that these percentages would be subject to the probable injurious effects of discing and harrowing.

Truck Crop Areas versus Potato Areas

In the eastern part of the North plot approximately 4 acres are used for truck crops. This area has had various vegetable crops for 4 years while the remainder of the cultivated portion of the North plot has been in potatoes for several more years. Estimates based on preliminary soil sampling showed that the truck crop area had a lower wireworm population than the land used for potatoes. The truck crop area does not differ markedly from the potato land in respect to soil structure, moisture, pH, or topography. Certain sections of the potato area may be more moist than the truck crop area. However the chief differences between the two are in the cultural treatment of the soil and the crops grown in these areas. It is felt that these differences are probably the real reasons for the wide variation in the number of wireworms in the two areas.

The truck crop area is usually harrowed after the harvest in the fall. Excess surface vegetation such as weeds, plant stalks and so forth are raked off before harrowing. Late in October, the area is plowed to a depth of 6" and undergoes no further treatment until spring. In the spring, it undergoes a second thorough harrowing before planting. Frequent hand cultivation during the growing season is practiced followed by cultivations at periodic intervals during the summer season for the purpose of keeping the weeds down. Thus it can be seen that the truck crop area of the North plot is well cultivated and free of weeds. The lack of a cover crop reduces the amount of food available for wireworms. Also, the practice of raking the excess vegetation from the field at the end of the growing season leaves that much less organic matter available as a source of food for wireworms. Constant cultivation during the growing season dries out the upper layer of soil and creates conditions unfavorable to wireworms, driving them deeper into the soil where they are less likely to attack plants.

Superficial examination of wireworm damage in the truck crop area of the North plot in the spring may lead to the conclusion that the wireworm population here is much greater than that of the potato land. This may be explained by the reasons noted above, chiefly the lack of excess vegetation and consequently the greater attractiveness of newly germinated plants. In the potato area, there is no concentration of food as there is in the truck crop area early in spring. The green cover crop of rye of the potato area is an abundant supply of food for wireworms. After the rye has been turned under and the land set to potatoes, there still is no concentration of larvae about the sprouting potato seed because rye roots and other organic matter in the soil are an adequate source of food. Consequently, spring soil sampling in the truck crop area is likely to show a greater number of wireworms because the sampling was done near growing plants. Evident lack of such concentration in the potato area is revealed in the smaller number of wireworms obtained in spring soil sampling.

Soil sampling at other periods of the year showed that there was a larger wireworm population in the potato area than in the truck crop area. The following table presents soil sampling data for the three seasons of the year 1941. As a matter of convenience, the seasons have been arbitrarily divided as follows: spring season consisting of March, April, May, and June; summer season consisting of July and August and part of September before harvest; fall season consisting of the remainder of September, October, November and December.

TABLE VIII

COMPARISON OF WIREWORM POPULATIONS IN TRUCK CROP AND POTATO AREAS

	Truck Crop Area			Potato Area		
Season	Ave. samp. pop.	Total no.of wws.	Total no.of samp.	Ave. samp. pop.	Total no. of wws.	Total no.of samp.
Spring	1.3	59	44	1.06	74	73
Summer	0.96	26	27	5.45	311	57
Fall	0.50	12	24	1.08	62	57

Reference to Table VIII shows that the potato area had a greater population than the truck crop area during the summer and autumn seasons. This difference in population is very marked for the summer season. There are probably several reasons for this, chiefly the difference in the cultural methods practiced and the different plants grown in the two areas.

The potato area is cultivated every 2 or 3 weeks. Beginning about the first week in June the potato foliage affords some shade. By the end of June the foliage is about full, providing plentiful shade to the soil and thereby helping to keep the soil cool. At this time, the new potatoes are forming and for the next 6 weeks, conditions are very favorable for wireworm development. In hills not shaded by potato foliage, larvae can escape adverse temperatures by boring into the tuber or by going deeper into the soil. Wireworms in the hills are not injured or disturbed by the infrequent soil cultivation are able to do considerable damage to potatoes before the harvest.

The cultural practices outlined above are not followed in the truck crop area. Cultivation here is more intense and frequent, and hand weeding is done often. These practices tend to pack the soil between the planted rows. At the beginning of the season there is not much shade in the truck crop area and unless there has been excessive rain, the soil is dry and hot. The growing plants will offer more shade later on in the season but the frequent cultivation will tend to disturb the soil and thus make it unfavorable for wireworm activity. Furthermore, most of the crops grown here have a comparatively short season and there is usually more than one harvest on the same area during a season. For example, early beets, radishes, and spinach may be harvested in approximately 4 weeks and acreage occupied by them may be planted to a second or third crop of vegetables. This practice disturbs the soil, making it more unfavorable for wireworms.

Thus it can be seen that the truck crop area and the potato area, although similar in soil type, topography, etc., are very different in the way in which they are used and cultivated. The differences in cultural treatment of the two areas are no doubt responsible partially for the smaller wireworm population in the truck crop area. The treatment of the truck crop area indicates that clean fallow and frequent cultivation might be efficient methods of control. The chief objection to letting the land remain fallow in the "Meadows" region is the loss resulting from the non-use of the land.

Sod Land versus Cultivated Land

Another cultural method of avoiding wireworm damage in the Parsons field might be the planting of crops in land newly turned over from sod. It has been noted that crops planted in sections recently turned over from sod were less likely to show wireworm damage than if they were planted in areas which had been under cultivation for a number of years. For example, in 5 hills of potatoes sampled at random in areas planted the first season after sod, there were 6 wireworms. In these 5 samples there was a total of 26 potatoes with a total of 27 wireworm holes, or an average of about 4 holes per wireworm. An equal number of samples was taken in the cultivated area. These had a total of 29 larvae and 41 potatoes with 204 wireworm holes. Each potato averaged about 5 wireworm holes and there was approximately 9 holes to each wireworm. On the basis of this sampling, the estimated wireworm injury to potatoes grown in areas which had been in cultivation for several years was five times as great as that done to potatoes from areas newly turned from sod. It should be noted that the sod areas never had more than 3 larvae per sample in any of 40 samples taken in one season. Samples taken from the cultivated area has as many as 18 wireworms per sample.

In general, the potatoes from the area newly turned from sod were cleaner and not so scabby as the potatoes from adjacent cultivated areas. However, potatoes grown in sodland were subject to greater attack by white grubs than were those grown in land which had been under cultivation for a number of years.

Sod areas showed a smaller wireworm population than the cultivated fields. Forty soil samples taken in the sodland before the harvest of potatoes netted a total of 33 wireworms or an average of 0.57 wireworms per sample. An estimate of the total population, based on this figure, is only one-tenth of the total population of wireworms in the cultivated land, which estimate was also based on 40 soil samples.

Thus it would appear that land newly turned over from sod offers more suitable conditions for growing potatoes comparitively free of wireworm injury. This phase of cultural control requires further study over a longer period of time before more definite recommendations can be made.

It is of interest to note here the differences in the larval and adult populations of the sod and cultivated areas. Sampling for adult beetles, as already explained, showed that the greatest number was in sodland close to the potato field. Soil sampling for larvae, however, revealed that the greatest number of larvae was in the cultivated areas, particularly midfield of both the North and South plots.

Rotations and Fallow Land

Other types of cultural control which might be of some value in keeping down wireworm populations are crop rotations and summer fallow.

Most of the "Meadows" growers are not in a position to practice intense rotation methods because of the type of farming in which they are engaged. These growers are interested in a one-crop farm and rotation is practiced only an a very small scale. Any rotation, however, which would require large areas to be kept in sod or hay land for a number of years would not be practiced. The "Meadows" grower has no need for a large acreage of hay land because he is not in the dairy business. For the same reason the grower would not be interested in planting large areas of corn. A rotation of sod, corn, and then potatoes, might be a very good way to reduce wireworm population. The summer of 1941 has demonstrated the advisability of growing crops other than potatoes in some parts of the Parsons field because of the intensity of wireworm attack therein. Beginning in the fall of 1941, rotation of part of the Parsons field was under way.

Summer fallow has been tried with varying degrees of success as a control for wireworms in other sections of the country. It has not been attempted in the "Meadows" because of the intensity of the agricultural program. This land is valued very highly and every acre suitable for cultivation is planted to potatoes and vegetable crops. Loss of any acreage due to summer fallow represents a real monetary loss and for this reason, growers are reluctant to practice this form of control. Furthermore, summer fallow might result in loss of the top soil in case of high winds or flooding. Despite the possibility of these losses, a season or two of summer fallow might materially reduce the wireworm population and result in better potato and truck crops.

Control of Adults by Light Traps

Control of adult Elateridae by attracting them to lights has not been very successful. Most species are not thus attracted. A few species have been noticed near lights. Comstock and Slingerland (1891) listed a few species collected at trap lanterns. Gibson (1916) reported adults of *Horistonotus uhlerii* Horn were collected at lights. The females are evidently above ground for only a very short while. Stear (1918) said trap lights had no value in catching elaterid beetles. Thomas (1930) stated *Melanotus* sp. and a few other elaterid adults are attracted to lights but Pheletes agonus, an important economic species of Pennsylvania, is diurnal and seldom seen about lights.

Langenbuch (1932) found Agriotes obscurus adults were not attracted to lights. McDougall (1934b, 1935) found the same true for Lacon variabilis. Cockerham and Deen (1936) said adults of Heteroderes laurentii are active only at night but only a few seem to be directly attracted or caught at lights. Vereshchagin (1932) stated that males of Harminius dauricius in Russia, are easily trapped at lights.

Trap lights of the electocutor type, bulb and pan, and of an automatic collecting type were operated for several seasons in South Amherst and at the Massachusetts State College. The South Amherst electrocutor trap was located in an apple orchard. Records from this trap show that 9 adult Elateridae were collected from May 19 to June 12, 1936. The bulb and pan trap consisted of a bulb suspended over a pan of kerosene. During the period May 19 to June 12, 1935, only 3 click beetles were collected in this trap.

The automatic light trap at the Massachusetts State College consisted of 12 cyanide bottles mounted on a revolving platform. This platform was enclosed in a box with a funnel through the top. The large mouth of the funnel was directly under a 200-watt bulb. An electical relay system operated to move the platform with its jars so that each jar received one hour's catch. The trap was located on a wooded side hill, 1000 ft. east of Fernald Hall.

In 1934, a total of 50 elaterid specimens were collected from July 25 to August 22. In 1935, 54 click beetles were collected in a much shorter period, from July 24 to August 3. During 1937, a total of 33 elaterids was caught from May 23 to June 25. Compared to the total catch of all insects for these periods, the numbers of adult elaterids caught was small. Nightly catches of insects averaged hundreds of specimens, except during very wet nights.

Observations in the field at Northampton show that the maximum period of adult activity during the day is during the hours of maximum temperature. Very few beetles were taken by sweeping after dark.

Chemical Controls

Three general types of insecticides are available for use as soil insecticides for the control of wireworms. These three types are classed as fumigants, contact insecticides, and stomach poisons. The type of soil insecticide which can be used most efficiently depends, of course, on the insect to be controlled and the area to be treated. Generally speaking, fumigants have been the most effective insecticide used in wireworm control on a large scale. Because of greater penetration, there is more possibility of killing the larvae by using a fumigant than by using a contact or a stomach poison. Contact insecticides are of no use unless they acutally hit the wireworm and this is difficult to do when the larvae are deep in the soil. Stomach poisons for wireworm control are of questionable value. Recent reports already mentioned in this paper have stated the ability of wireworms to reject unsuitable substances in their food. Consequently, objectionable stomach poisons, mixed with the food of wireworms, are rejected.

Much of the work done on chemical control has been unsatisfactory because of failure to control, the high cost of materials, or injury to growing plants. In looking for insecticides suitable to use in the "Meadows", it was necessary to choose those not injurious to plants. Also, soil insecticides used in the "Meadows" in early spring should be effective at the soil temperatures at this time of the year. Naphthalene and paradichlorobenzene, used with good results by some investigators, in other parts of the country, could not be used in the "Meadows" because of low soil temperatures. A soil temperature of 15°C. or higher is necessary in order to get a satisfactory kill with these materials. Soil temperature before spring planting in the Parsons field averaged less than 8°C. At this low temperature, the diffusion of gases is retarded, resulting in a poor kill of wireworms.

There are several good soil insecticides on the market but their use in soil bearing crops is limited because of the danger of injuring plants. One compound that shows promise as a wireworm control is chloropicrin, commonly known as tear gas. It is injected into holes 4" deep on 10" or 12" squares. Injection of 2 cc for every hole should control wireworms to a depth of at least 12". Chloropicrin should be used after the soil has been properly prepared for planting. After applying the material, the soil is watered down and covered with wet burlap bags to prevent escape of the gas. Crops should not be planted sooner than 10 to 14 days after treatment. The cost of this material would make its use on a large scale prohibitive. In case of severe damage in selected spots the use of chloropicrin could be recommended. Chloropicrin was tried by the writer on a small scale but results are not definite enough to make any conclusions.

Carbon disulphide, alone or emulsified with some other material, has been tried by numerous workers. In general, it is agreed that this material is too expensive for field use but may be used advantageously on small areas in the greenhouse or in choice garden plots. The same holds true for calcium cyanide which is often recommended for use in connection with a trap crop.

Recently, the compound known as beta-beta dichloroethyl ether has come to the fore as a wireworm control. This compound has already been described in the section "Review of Literature", under "Chemical Control". Because of the possibilities of this compound as a suitable wireworm control it was decided to test it in the laboratory and in the field.

Correspondence with other workers, interested in the problem of soil pest control, revealed the fact that there was really no adequate efficient and inexpensive chemical that could be used as a soil ånsecticide. Dr. Harry Dietz of the E. I. du Pont de Nemours and Company, suggested that two inorganic mercury compounds, manufactured by du Pont, might prove effective in wireworm control. These two compounds bore the code numbers, FD-2A and LF-5. They were tested in the laboratory and in the field. Another du Pont product, a powder form of a chlorinated toluene compound (coded IN-3102) was also tried.

These four compounds were tried in the laboratory and in the field during the growing season of 1940 and 1941. Dichloroethyl ether appears to be the most promising of these compounds and will be discussed first.

Dichloroethyl Ether

Dichloroethyl ether, as a soil insecticide, can be properly classed as a fumigant. Some investigators at first regarded it as a contact insecticide. During 1940, laboratory and field experiments with dichloroethyl ether were carried on simultaneously. In the first laboratory test, the same aqueous concentration of the ether compound was tried on larvae placed at varying depths in a 5-qt. container full of soil. The concentration used in this experiment was 1 cc of dichloroethyl ether to 1 qt. of water. In order to bring the ether into solution rapidly it was first emulsified with an aqueous solution of "Aresklene", and this stock solution was then added to the proper amount of water. The solution was then poured over the soil in the 5-qt. can at the rate of 1 pint to each can. Previous to treatment, two wireworms had been placed at a different depth in each can. The treated cans were examined three days later and the number of dead larvae recorded. The first test resulted in a kill of 70 per cent. (Table IX). The two wireworms at the 6" depth and one of the two at the 5" depth were not killed.

The experiment was repeated a second time, using a concentration of 2-2/3 cc per qt. of water with an aqueous solution of "Ultrawet" as the emulsifier. In this experiment, a kill of 50 per cent. was obtained. Use of 1 qt. of this solution to each can resulted in a kill of 100 per cent., as was shown in the third experiment. In the first two tests, larvae were found 1" to 2" above or below the depth at which they were originally placed. This would indicate that the larvae were attempting to escape.

Results of these tests indicate that the material has fairly rapid killing powers and that it is effective if used at rates of application high enough to saturate the soil.

TABLE IX

RESULTS OF PRELIMINARY LABORATORY TESTS WITH DICHLOROETHYL ETHER AND WIREWORMS

Test no.	Can no.	Concentration of dichloroethyl ether	Rate of application	Depth of wireworms in soil (inches)	No. of wireworms	Condition after 72 hrs.
1	1	1 cc per 1 qt. H_2O with "Aresklene"	1 pt. per 5-qt. can of soil	1	2	dead
	2	"	"	3	2	dead
	3	"	"	4	2	dead
	4	"	"	5	2	1 dead 1 alive
	5	"	"	6	2	2 alive
2	1	2-2/3 cc per 1 qt. H_2O with "Ultrawet"	1 pt. per 5-qt. can of soil	1	2	1 dead 1 alive
	2	"	"	2	2	1 dead 1 alive
	3	"	"	4	2	1 dead 1 alive
	4	"	"	6	2	1 dead 1 alive
3	1	"	1 qt. per 5-qt. can of soil	1	2	dead
	2	"	"	2	2	dead
	3	"	"	4	2	dead
	4	"	"	6	4	dead

In the field, dichloroethyl ether was tested 13 different times during the growing season of 1940. Beets showed considerable wireworm damage and for this reason they were chosen for the first series of tests. Concentrations of 1 cc to 2-2/3 cc of dichloroethyl ether to 1 qt. of water were used. Both "Aresklene" and "Ultrawet" were used as emulsifiers. The required amount of ether was first added to the proper amount of either one of these and then shaken until it had emulsified. This stock solution was then added to the required amount of water and shaken until it was thoroughly dissolved.

The beets used in these preliminary experiments received 1 pint of solution to each plant. Prior to treatment, the soil in a 3" radius around the plant was loosened with a trowel and hilled up slightly so that the liquid would not run off. The plants were not disturbed for three days, after which time soil samples were taken to determine the number of wireworms killed. Observations were made to see if the treatment affected plant growth or material. The same procedure was used in treating other plants such as carrots, spinach, and potatoes. Results of these 1940 field experiments are presented in Table X. The rate of application was 1 pt. of solution to each plant except in tests No. 7 and 11, where it was one qt. to the plant, and in tests No. 12 and 13, where it was 1 pt. to each lineal foot of row.

TABLE X

RESULTS OF 1940 FIELD TESTS WITH DICHLOROETHYL ETHER IN THE PARSONS FIELD

Test no.	Concentration ($cc/qt.H_2O$)	Test Plants	Soil Condition	No. of samps.	No. wws.	Depth of wws.	Alive or dead	Per cent. kill
1	1 cc with Aresklene	Beets	Soil hard had to be loosened	5	2	2" 4"	A. A.	0.0
2	1 cc with Ultrawet	Beets	ditto	2	2	2" 4"	D. A.	50.0
3	1 cc with SS-3	Beets	ditto	2	2	2" 2"	D. A.	50.0
4	1-1/4 cc with Ultrawet	Beets	ditto	3	9	2" 3" 4"	3 D. 1 A. 5 A.	33.3
5	2-1/4 cc with Ultrawet	Beets	ditto	5	11	2" 4" 5" 6" 8"	1 D. 2 A. 2 A. 4 A. 2 A.	9.0
6	2 cc with Aresklene	Carrots	Soil porous	2	0	-	-	-
7	2-1/4 cc with Ultra.	Potatoes	ditto	2	4	6" 12"	2 D. 1 A.	75.0
8	ditto	Carrots	Soil hard	1	1	8"	1 A.	0.0
9	ditto	Beets	As in 1	1	0	-	-	-
10	ditto	Beets	ditto	2	3	4" 6" 8"	1 A. 1 A. 1 A.	0.0
11	ditto	Potatoes	Porous moist	3	1	10"	1 D.	100.0
12	3-3/4 cc with Ultrawet	Carrots	As in 1	3	8	2" 6" 11"	1 D. 1 A. 6 A.	12.5
13	1-1/4 cc with Ultrawet	Spinach	Shallow furrow alongside plants	4	1	6"	1 A.	0.0

The results of the 1940 field tests with dichloroethyl ether showed a wide variation. Soil samples were taken in the 13 areas treated and wireworms were found in 11 areas. The percentage of kill obtained in these tests varied from 0 to 100 per cent. of the wireworms found in 32 soil samples. Test No. 1, for example, showed a kill of 0 per cent. based on the wireworms found in two soil samples. Test No. 11 showed a kill of 100 per cent. based on three soil samples. Such a wide variation in control can be explained by several factors such as the condition of the soil, the time and rate of application, the concentration of the solution, the activity of the larvae, and limitations of the soil sampling technique.

The condition of the soil at the time of treatment with the insecticide greatly influences mortality. In order to reach the wireworms in the soil, there should be a conditioning of the soil and the proper time for making applications should be carefully considered. The soil was likely to be packed in truck crop areas because of cultivation processes. Before treating such areas with a liquid insecticide it is best to loosen the soil around the plants so that the solution may penetrate the soil quickly and with as little loss as possible due to run-off and evaporation.

Applications should not be made in the heat of the day when evaporation reduces the amount of liquid that penetrates the soil. Furthermore, such applications of dichloroethyl ether may have a harmful effect on plant growth.

The concentration of solution and the rate of application have a direct effect on the degree of control of wireworms. These preliminary tests were not conclusive enough to demonstrate the differences in kill due to different concentrations of dichloroethyl ether or due to different rates of application. It is reasonable to assume, however, that the greater the amount of solution that is applied to the soil, the greater the penetration of the solution and consequently the greater the possibility of affecting a a larger number of wireworms.

It is not possible to fully describe the activity of wireworms in an area which has just been treated with dichl roethyl ether. The normal wireworm is an active creature and should it be disturbed by chemical treatment of the soil, no doubt would show increased activity in escaping from such an area. It is possible for wireworms to escape from treated soil provided the dichloroethyl ether has not reached them in sufficient quantity to stop their activity. In the field tests described here, no attempt was made to determine how many larvae did escape from treated areas. Soil samples were taken in the treated areas 3 days after treatment. Wireworms which escaped were not, of course, included in the reckoning of the percentages of kill obtained. Perhaps some did escape and died in soil not included in the soil sample. This factor might be considered as one reason for the wide variation of kill obtained by using dichloroethyl ether.

The limitations of the soil sampling technique and the possibility of error arising therefrom, are important in determining the percentage of kill. It may be argued that the small number of samples used in determining the mortalities listed in Table X is not sufficient to overcome errors due to sampling. It should be pointed out, however, that by using a small number of tests, it was possible to examine all samples very carefully. The number of samples actually used showed the effectiveness of dichloroethyl ether under certain conditions and for this reason the samples can be considered indicative of the results to expect in using this compound.

In summarizing the first season's work with dichloroethyl ether it is apparent that this material shows some promise as a soil insecticide against wireworms. The efficiency of dichloroethyl ether is affected chiefly by its ability to penetrate the soil far enough and quickly enough to kill wireworms. Soil conditions at the time of application may retard the penetration powers of dichloroethyl ether. Therefore, it is best to loosen the soil around the plant before the solution is applied. Furthermore, plants should not be treated in the heat of the day.

Tests with dichloroethyl ether were resumed in 1941. Several types of experiments were tried for different purposes.

One of the first experiments tried during this season was for the purpose of testing the toxicity of dichloroethyl ether upon wireworms contained in soils of different moisture content. Soil from the Parsons field with varying amounts of moisture was placed in 5-qt. cans to a depth of 5". Five wireworms were then placed in each can and 4" more of soil was added. The same concentration of dichloroethyl ether was used in each can and the rate of application was the same, 1 pint of a 2-1/4 cc / 1 qt. water solution/ Tergitol Penetrant 7 was used as an emulsifier. The solution was poured evenly over the top of the soil in each can. The wireworms were collected a few days preceding the experiment. The cans were examined three days after treatment to check on the condition of the wireworms. The soil conditions and results of these tests are indicated in Table XI.

These tests indicated that wireworms in dry soil were more quickly affected by dichloroethyl ether than were wireworms in moist soil. The mortality was highest in the soil having the least amount of moisture. Under normal atmospheric conditions the soil of the Parsons field is just about at the "sticky point". The "Sticky point" is used to designate the moisture content of the soil if it sticks together when a handful of it is squeezed. The toxicity of dichloroethyl ether to wireworms under moisture conditions existing at the "sticky point" is variable, probably because of the nature of the soil. A loose soil would permit greater penetration of the solution and consequently a greater kill ofwireworms would be expected whereas a tightly packed soil would not allow such a favorable rate of penetration and the kill would be smaller.

Toxicity due to dichloroethyl ether in soils having a greater moisture content than at the "sticky point" is considerably reduced. This is probably the direct result of excessive dilution by the increased moisture content of the soil.

It would appear from these tests that the most favorable moisture condition for applying dichloroethyl ether to the soil is that when the soil is very dry. Plant growth under such extreme dry conditions would be greatly reduced and there would be no need of protecting plants from wireworm injury.

TABLE XI

TOXICITY OF DICHLOROETHYL ETHER IN SOILS OF DIFFERENT MOISTURE CONTENT

Test no.	Condition of soil	No. of wws.	Condition of wws. after 72 hours	Mortality 1st. treat. (per cent.)	Mortality 2nd. treat. (per cent.)
1	Very dry. Sifts through 14 mesh screen easily	6	5 dead 1 alive	83.3	
2	Dry. Sifts through 14 mesh screen with difficulty	5	2 dead 3 alive	40.0	
3	Moist. Goes through 14 mesh scfeen after much sifting	5	2 dead 3 alive	40.0	
4	Near saturation does not sift	5	1 dead 4 alive	20.0	
5	Saturated	5	5 alive	0.0	100.0
6	Super-saturated	5	5 alive	0.00	100.0

Dichloroethyl Ether and Germination

Another series of tests with dichloroethyl ether was conducted in 1941 to determine the effect of various concentrations of this insecticide upon seed germination.

Three rows of corn, 7 hills to the row, and 5 kernels to the hill, were planted in soil prepared in the ordinary manner by plowing and harrowing. In the first row, 3 fluid oz. of a 1-1/4 cc / 1 qt. water solution of dichloroethyl ether was poured into each of the 7 holes dug for the planting of corn. Five kernels of corn were then placed in each hole and covered over with soil. Over each group of kernels, another 3 fluid oz. of the dichloroethyl ether solution was poured. In the second row, the same procedure of wetting the soil before and after planting was used except that ordinary tap water was used instead of dichloroethyl ether. In the third row, the planting was done in the normal fashion without the use of water of dichloroethyl ether. The hills in each row were spaced 20" apart and the rows were 30" apart. Corn in all rows was planted to a depth of 3".

The results of these different methods of planting are shown in Table XII. It is clearly evident that the corn in untreated hills appeared first above ground and had a greater percentage of germination than did the hills treated with water or dichloroethyl ether. The

TABLE XII

EFFECT OF DICHLOROETHYL ETHER ON THE GERMINATION OF CORN

Treatment	No. of hills showing plants after:			Height of plants after:			Per cent. Germ.
	10 days	14 days	20 days	10 days	14 days	20 days	
none	7	7	7	1-2"	3-4"	5-6"	62.5
H_2O	7	7	7	½-1"	2-3"	3-5"	57.1
Dichloro-ethyl ether	2	6	7	½-1"	½-2"	1-4"	60.0

application of dichloroethyl ether at the concentration of 1-1/4 cc / 1 qt. water definitely retarded the germination of corn. Plants in one hill did not appear above ground until 20 days after treatment. It may be, however, that a more dilute solution of dichloroethyl ether would not retard the germination of corn.

Plants in the untreated and water-treated rows appeared more vigorous and healthier than did those treated with dichloroethyl ether. Plants treated with the dichloroethyl ether solution were yellower than those in the other rows, and they remained green for a longer time than did the others, thus showing later maturation.

Dichloroethyl ether was used also to test its effect when applied to newly set potatoes. Ten days after planting, potatoes were treated with a 1-1/4 cc / 1 qt. H_2O solution of dichloroethyl ether applied at the rate of one pint of the solution to each hill without disturbing the soil. Potato shoots at the time of treatment were just beginning to appear above the surface of the soil. Examination of the treated hills one week after treatment showed that they were stunted when compared to check hills. In another test, an equal number of hills were treated with a 2-1/4 cc / 1 qt. H_2O solution of dichloroethyl ether applied at the rate of one pint to each hill. Examination of these hills one week after treatment showed that they had attained a normal growth. There was no yellowing of leaves or any evident indication that the treatment was injurious to plant growth or material. One month after treatment, hills in both of these tests appeared the same and there was no apparent difference in size.

The second test was repeated on fresh hills of potatoes, the insecticide being applied 16 days after the potatoes had been planted. Examination of the potatoes 10 days after treatment showed that they were normal and did not differ in size or appearance from the check plants.

Indications obtained from these tests are that dichloroethyl ether is harmful to the germination of potatoes and corn if it is applied at the time of planting or shortly after. Plant growth may be slowed up and weakened and permanently stunted plants may result from this treatment. Based on these tests, the use of dichloroethyl ether should be avoided at the time of planting and for a period of several days after planting.

1941 Field Tests with Dichloroethyl Ether

Field tests with dichloroethyl ether were resumed in the middle of May, 1941. One of the early experiments was with the cabbage maggot, and is mentioned here by way of introduction to this season's work.

Cabbage set early in May in a field near Fair Street in the "Meadows" section of Northampton was heavily infested with cabbage maggots. A total of about 300 plants had been treated with a solution of corrosive sublimate (1 oz. / 1 gal. H_2O) applied at the rate of 3 fl. oz. per plant. A few days later no appreciable control had been obtained. A section of one row, nine plants 2" to 4" high, was treated with a 1-1/4 cc / 1 qt. water solution of dichloroethyl ether. This was applied around the base of the plant at the rate of 1 pint per plant. Previous to the application, the soil around the plant was loosened so that a greater amount of the liquid could penetrate the soil more readily. Two plants were partially wilted at the time of application, and these were dead three days after treatment. The soil around the roots of the dead plants had been heavily infested with mites and cabbage maggots, but they were all dead. Three other plants at this time showed a small amount of yellowing, one leaf in each plant being slightly yellow, probably because it had been touched by the dichloroethyl ether in the process of application. Ten days after the treatment, another plant died and at the end of 18 days, a fourth plant died. The remaining 5 plants were in good healthy condition 25 days after treatment while the plants that had received only the corrosive sublimate treatment were wilting and dying despite a second treatment with corrosive sublimate. Damage done by the maggots was too severe to overcome, and the entire field of cabbage was ploughed under.

This test showed that the early application of dichloroethyl ether would have controlled the cabbage maggots. The conditions for the application of dichloroethyl ether in the field were ideal, namely, a loose type of soil situated in a shady portion of the field.

Field tests in the Parsons field were carried on throughout the summer. Various types of crops were treated, including radish, carrots, corn, spinach, and potatoes. Soil around the plants was loosened before the test solution was applied. Results of these tests are listed in Table XIII, except the tests on potatoes which are summarized in another section of this paper.

Reference to the table shows that the percentages of kill were based on a relatively small number of samples. Previous sampling experience has demonstrated that is is possible to obtain a fair knowledge of the efficiency of the dichloroethyl ether by taking a relatively few tests. In choosing a small number of tests for determining the efficiency of this compound, other factors were taken into consideration, such as the time available, the seriousness of the infestation, and

TABLE XIII

THE RESULTS OF TREATING TRUCK CROPS WITH DICHLOROETHYL ETHER IN 1941

Concentration in ccs. per quart and emulsifier	Rate of application	Crop	No. of samples	No. of wire-worms	Depth in inches	Alive or dead	Percent. of kill
1¼ ccs. Aresklene	1/3 pt. per plant	Spinach	12	3	1-4	3 a	0.0
Ditto	Ditto	Raddish	10	0	-	-	-
1¼ ccs. Tergitol Penetrant 7	1 pint per hill	Corn, 1-3 in. high.	5	1	6	1 d	100.0
2¼ ccs. Tergitol Penetrant 7	1 pint per hill	Ditto	4	3	4-9	2 d 1 a	66.6
1¼ ccs. Tergitol Penetrant 7	1 pint per hill	Ditto	6	7	4-11	7 a	0.0
2¼ ccs. Tergitol Penetrant 7	1 pint per lineal ft. of row	Carrots	6	2	3-10	1 d 1 a	50.0
Ditto	1 qt. per lineal ft. of row	Ditto	6	6	3-7	3 d 3 a	50.0
Ditto	3/4 qt. per lineal foot of row	Ditto	6	6	3-4	5 d 1 a	83.3

the size of the treated plots. It was deemed better to take fewer samples and to check these more carefully and completely than to risk errors in trying to check over a large number of samples.

The percentage of kill in the 1941 field tests varied from 0 to 100. The reasons for this wide variation are the same as those mentioned in the similar field tests of 1940, namely, the ability and the speed of penetration of the soil by the dichloroethyl ether solution, the nature of the soil, and the concentration and rate of application of the test solution.

There is no doubt that some wireworms are able to escape the harmful effects of dichloroethyl ether provided they move out of treated areas fast enough, In the fifth test of Table XII, wireworms were found at depths of 4" to 11". The soil above the 4" depth was riddled with wireworm burrows, out of which the larvae had vacated when applications of dichloroethyl ether were made.

The concentration and rate of application of test solutions of dichloroethyl ether were important factors influencing the killing power of this insecticide. A weak solution or a solution applied to very wet soil was ineffective as was shown in laboratory experiments.
In field work, a solution of 2-1/4 cc / 1 qt. H_2O was

adequate for killing wireworms to a depth of at least 4", and was probably more effective at greater depths than were weaker solutions.

The rate of application should be such that the soil is saturated deep enough to affect the majority of wireworms. This depth can probably be defined as the level of the plant roots where most of the larval attacks occur. Usually, this depth is not more than 10" and 1 pint to 2 pints of a solution are enough to reach this depth.

Tests with dichloroethyl ether on potatoes were continued in 1941. In the potato experiments, treatments were repeated a second, and in one instance, a third time. Observations in regard to plant growth, effect on wireworms, and effect on the taste of potatoes, were more complete than those made in the truck crop experiments. The method of treatment was the same in the potato tests as in the truck crop tests.

Five sections of rows in five different rows were used for these tests. Five similar sections were selected as check plots which received no treatment. Plot No. 3 received one treatment, plots No. 1, 2 and 4, two treatments, and plot No. 5, three treatments. The concentration of the test solution was the same in all cases, 2-1/4 cc / 1 qt. H_2O, with Tergitol Penetrant 7 as the emulsifier. Most plants were 12-14" high by the end of June and were beginning to blossom. More complete data pertaining to these tests are given in Table XIV.

TABLE XIV

DICHLOROETHYL ETHER TREATMENT OF POTATOES IN 1941

Plot no. and date of treatment	Rate of application per hill	No. of samples	No. of wireworms	Alive or dead	No. live wireworms in equal no. of check plot samples	Depth of wireworms (inches) Treat.	Check.
Plot 1 June 14	1 pint	3	11	7 d 4 a	7	4-7	4-7
Plot 2 June 18	1 pint	3	1	1 a	21	7	2-11
Plot 3 June 24	3/4 qt.	2	3	3 a	4	9-11	9-11
Plot 4 1st. treat. June 24	1 pint	2	4	4 a	2	5-6	5-6
2nd. treat. July 22	3/4 qt.	1	2	2 a	3	9-10	9-10
Plot 5 1st. treat. June 24	1 qt.	2	3	3 a	9	6-10	6-10
2nd. treat. July 7	1 qt.	(no samples taken)					
3rd. treat. July 22	1 qt.	1	4	2 d 2 a	6	5-9	5-10

Results of these tests with potatoes were somewhat similar to the results obtained in previous experiments. The test solution penetrated the soil of potato hills to a greater depth and more readily than it did the soil of truck crop areas. The soil of potato hills was usually in a loose condition whereas that of the truck crop area usually packed because of trampling and frequent hand cultivation. This loose nature of the soil in potato hills permitted rapid penetration of the solution into the soil but at the same time it was also more favorable for the escape of larvae from treated areas. Drying of treated plots was probably more rapid in loose soils than in well packed soils.

Plot 1 yielded a high percentage of kill, probably because of the loose nature of the soil as explained above. Wireworms were found at depths of 4 to 7 inches. When the soil was very loose, kills to a greater depth have been recorded. For example, in plot 5, one dead wireworm was collected at a depth of 15 inches.

None of the wireworms were dead in plots 2, 3, and 4 when examined. This did not mean that the test solution did not kill any wireworms. Soil samples from these plots were not taken until 6 to 24 days after treatment. Wireworms killed by the dichloroethyl ether might have become decomposed by this time. However, it was evident from these three test that wireworms could safely re-enter a treated area probably as soon as 6 days after treatment.

Treated areas did not appear as favorable to wireworm activity as did untreated check areas. In a total of 14 1/2-cu. ft. soil samples taken in treated plots, a total of 28 wireworms were collected, 9 dead and 19 alive. In an equal number of samples taken in the check plots, a total of 52 live wireworms were collected. Comparing the total number of larvae found in these two areas, it seemed evident that the treated area was not an attractive environment for wireworm activity. Because of the small number of wireworms in the treated areas, even as late as 24 days after treatment, it was suspected that dichloroethyl ether might be acting as a repellent. The odor of dichloroethyl ether was in the soil 30 days after treatment. Workmen plowing the field noted the odor when the soil was turned over. The taste of dichloroethyl ether in treated potatoes lasted as long as 5 months after treatment. Treated potatoes were accidentally cooked for table use and the taste was very noticeable to people who had never experienced dichloroethyl ether before. The number of wireworm holes per potato in the treated area was less than that for potatoes from the check area.

Based on observations made in these tests, the efficiency of dichloroethyl ether as a soil insecticide depends on the ability of this compound to penetrate the soil rapidly. Observations indicate that treated areas can probably be reinfested by wireworms 6 days after treatment without any apparent injury to the wireworms. More efficient control can be obtained by repeating the treatments at frequent intervals. This practice, however, is apt to result in plant injury or to affect the taste of the underground portion of the plant, as in the case of potatoes. In order to determine the effect of repeated treatments with dichloroethyl ether on the same plants, 3 of the 5 potato plots mentioned above, were treated a second time and 1 plot was treated three times (Table XIV).

Plot 1, treated with dichloroethyl ether 2-1/4 cc / 1 qt. H_2O, showed no harmful effects as late as two weeks after treatment. This plot was again treated two weeks after the first treatment. Four days after the second treatment, 4 hills showed moderate yellowing of leaves and 1 hill had 50 per cent. of its leaves yellowed. Six days later, a few of the leaves in this hill had died. The plants in the check hills were normal.

Plot 2 showed no yellowing following the first treatment. It was treated a second time 10 days later and in four days, 3 hills out of 8 showed moderate yellowing of leaves. Eight days after the second treatment a few of the leaves were dead. All check plants were vigorous and green.

The effect of dichloroethyl ether in the remaining 3 plots was more noticeable after only one treatment. Yellowing of leaves occurred in these 3 plots within a week after the first application of dichloroethyl ether. Plots 3, 4, and 5 were treated June 24, while plots 1 and 2 were treated June 14 and June 18, respectively. This difference in time of treatment may have been responsible for the early yellowing of leaves in plots 3, 4, and 5.

Plot 4, treated a second time a month after the first treatment, showed additional yellowing of leaves 3 days later. Plot 5, treated a second time 7 days after the first treatment, showed a slight yellowing of leaves 3 days later. Two hills had about 25 per cent. of their leaves showing yellow. A third treatment was applied to plot 5 two weeks after the second treatment. Three days later 2 additional hills had yellow leaves. The shoots in this plot were the first to dry up.

The effects of dichloroethyl ether on potato growth and production were just as marked as the damage to the foliage. Potatoes from 5 hills in each of plots 3, 4, and 5, were compared to potatoes from an equal number of hills in untreated check plots. Potatoes from both plots were harvested at the usual time. Results of this comparison are listed in Table XV.

TABLE XV

COMPARISON OF POTATOES IN TREATED AND CHECK HILLS

	15 hills Treated	Check
Weight of U.S.No. 1 potatoes (lbs. and ozs.)	3:5	12:1
Weight of U.S.No. 1 potatoes damaged by wireworms (lbs. and ozs.)	5:11	6:13
Weight of "pig" potatoes (lbs. and ozs.)	3:3	2:10
Total weight of all potatoes (lbs. and ozs.)	12:3	21:8
Total no. of potatoes	66	89
Total no. of wireworms	54	55
Total no. of wireworm holes	230	330
Ave. no. of wireworm holes per potato	3.4	3.7

The 15 hills in the check rows produced a significantly greater number of pounds of potatoes than did the hills treated with dichloroethyl ether. U. S. Grade No. 1 potatoes in the check hills weighed more than three times as much as those in the treated hills. The weight of small potatoes, commonly called "pig" potatoes, was considerably less in the check hills than in the treated hills. Furthermore, the average number of wireworm holes in treated and untreated potatoes did not differ significantly.

On the basis of these observations, dichloroethyl ether was evidently not a very efficient soil insecticide against wireworms. Use of this material in concentrations strong enough to kill wireworms injured and retarded plant growth, resulting in a greater number of smaller potatoes. The action of dichloroethyl ether was not strong enough to keep wireworms from re-entering treated areas and again attacking potatoes. Treated hills showed nearly as much wireworm damage as did untreated hills. The taste of dichloroethyl ether was noticeable in most of the potatoes treated. Two weeks after the digging of potatoes, they were tested, cooked and raw, for the presence of dichloroethyl ether. All plots except plot 2 had potatoes in which the taste and odor of dichloroethyl ether was definitely noticeable. Cooking of the potatoes only accentuated the taste and odor of the test solution. Treated potatoes, when cooked, had a sickening, sweetish taste.

Inorganic Mercury Compounds FD-2A and LE-5

In addition to dichloroethyl ether, two other soil insecticides were tested during the 1940 season. Both were inorganic mercury compounds obtained from the Insect Pest Control Station of the E. I. du Pont de Nemours Company of Wilmington, Delaware. As far as is known, these materials have not been offered for sale under any general trade name. They were known by the code numbers FD-2A and LE-5.

FD-2A is a heavy liquid, light brown in color, which separates into two layers upon standing. The recommended concentration for this material is 1 part to 500 parts of water. In the laboratory it was tried at twice this concentration without any injury to wireworms. The procedure for testing this material in the laboratory was similar to that used in testing dichloroethyl ether.

In the field, FD-2A was tried at a concentration of 4 cc to 1000 cc of water and applied to beet plants at the rate of 1 pint to each plant. It was given 3 tests in the field. Ten soil samples from treated areas yielded 5 active wireworms. An equal number of untreated samples yielded 11 wireworms. This indicated that the material was inefficient for wireworm control at concentrations much higher than those recommended. No injury to plant growth was noted.

The inorganic mercury compound LE-5 was similarly tested in the laboratory and in the field. LE-5 is a dark brown liquid which separates into two different shades of brown upon standing. Recommended concentrations for this material were 1 part LE-5 to 1000 parts of water.

In the laboratory, LE-5 was tested at concentrations of 1 to 4 cc per 1000 cc water, with no control of wireworms. In the field it was tried at concentrations of 1 and 2 cc per 1000 cc of water, with no apparent control. As in the case of FD-2A, no injury to plant growth was noticed.

It may be noted that the tests given both these materials were probably not conclusive enough to pass on their worth as soil insecticides. However, it could be gathered, not only from the above mentioned data, but also from general observations and from comparisons with results from dichloroethyl ether, that these materials were not satisfactory at the concentrations used. For these reasons further tests with these two inorganic mercury compounds did not seem to be warranted. Results of tests with FD-2A and LE-5 are presented in XVI and XVII.

TABLE XVI

LABORATORY TESTS, 1940, WITH LE-5 AND FD-2A
At rate of 1 pt. of solution per can

Test no.	Can no.	Material used	Concentration	Depth of wws. (in.)	Condition after 72 hours	Condition after 3 months
1	1	LE-5	1 cc/1000 cc H_2O	2	2 A.	2 D.
	2	"	"	3	2 A.	2 D.
	3	"	"	4	2 A.	2 A.
	4	"	"	6	2 A.	2 A.
2	5	LE-5	4 cc/1000 cc H_2O	1	2 A.	(1 A. (1 D.
	6	"	"	2	2 A.	{1.A. (1 D.
	7	"	"	4	2 A.	2 A.
	8	"	"	6	2 A.	{1 A. (1 D.
3	9	FD-2A	"	1	2 A.	2 A.
	10	"	"	2	2 A.	2 A.
	11	"	"	4	2 A.	2 A.
	12	"	"	6	2 A.	2 A.

TABLE XVII

FIELD TESTS, 1940, WITH LE-5 and FD-2A
At rate of 1 pt. of solution per plant

Test no.	Material used	Concentration	No. of samps. exam.	Tot. no. fws.	Depth (in.)	Alive or dead	Per cent. kill
1	LE-5	1 cc/1000 cc H_2O.	6	0	-	-	-
2	"	"	2	0	-	-	-
3	"	2 cc/1000 cc H_2O.	2	1	3	A	0.0
4	FD-2A	"	2	2	3	A	
					4	A	0.0
5	"	4 cc/1000 cc H_2O.	6	0	-	-	-
6	"	"	2	3	5	A	
					6	A	
					8	A	0.0

Experiments with IN-3102

During the growing season of 1941, a new soil insecticide, IN-3102, was tested. This material, a chlorinated toluene product, had been recently manufactured by the E. I. du Pont de Nemours Company. The material was in powder form and could be used as such, mixed with the soil, or could be prepared in an aqueous solution and poured over the soil. This material had been recommended as a control for termites in the soil.

Preliminary tests with this material in the laboratory were made on wireworms located at various depths in soil contained in 5-qt. cans. In one test, the bottom half of the can contained soil mixed with 5 level teaspoonfuls of IN-3102. Five wireworms were placed on top of this treated soil and the can was then filled with untreated soil. Examination of the can three days later showed that all the wireworms were killed, and two had turned black, indicating early death. The soil from this can was thoroughly mixed after this test and used again without the addition of more IN-3102. Five wireworms placed at a depth of 4-1/2" in the can and then covered with another 4-1/2" of soil were all dead in three days.

In another test, 5 level teaspoonfuls of IN-3102 were dissolved in one pint of water. This solution was then poured over a 5-qt. can of soil which contained wireworms at a depth of 4-1/2". At the end of three days, all wireworms were unharmed and active. These results indicated that the powder form of IN-3102 was more effective than a similar amount dissolved in water.

IN-3102, in the dry form was used at the rate of 1 or 2-1/2 level teaspoonfuls to each 8-qt. can of soil containing five wireworms at a depth of 4" to 5". At the end of three days both cans had a mortality of 100 per cent. Examination of the soil indicated that IN-3102 killed quickly for wireworms were found at approximately the same levels in the cans as originally placed.

Two other laboratory tests were conducted, using aqueous solutions of IN-3102. As before, 5 wireworms were put in untreated soil at a depth of 4" to 5". The cans were then filled and a solution of 1 or 2-1/2 teaspoonfuls of IN-3102 per pint of water was poured into each can. The rate of application was 1 pint of the solution per can. The two cans thus treated were examined three days later. The soil in all sections of the can was moist from the test solution but the wireworms were found active.

The action of this material upon soil and plant life was tested. The soil from the four last mentioned experiments was retained and corn was planted in each at a depth of 2". There was no germination of corn in any of the cans.

Corn planted in check cans germinated in about 10 days. Similar tests, using potatoes and pole beans, were carried out . Soil had previously been treated with 5 level teaspoonfuls of IN-3102 (dry or in 1 pint of water) to a 5-qt. can of soil. Examination of the cans ten days after planting showed that the beans had swelled but had failed to sprout. Others were beginning to rot. The potatoes had begun to shrivel and the eyes had dried. Beans and potatoes in untreated check cans showed a normal growth.

The effect of IN-3102 upon the germination of potatoes, corn and beans in the field was tested. The soil was first prepared to a depth of 3" by treatment with 3 level teaspoonfuls of IN-3102 to a unit area of 12" x 6". The powdered material was dusted evenly over the soil and then mixed with it to a depth of 3". The soil was then planted to beans, corn and potatoes. Ten days later treated plots were examined. By this time, potato seed pieces had begun to rot. The beans had swelled but had not sprouted, and many were rotting. The corn had failed to sprout. All check plots showed normal growth ten days after planting. Potato foliage was beginning to break through the soil, and beans and corn were already 1" or 2" above ground.

The use of IN-3102 at any of the rates mentioned above was definitely harmful to plant life. Experimental areas in the field thus treated did not support any plant life at all for the rest of the growing season. For this reason, the use of IN-3102 cannot be recommended in fields that are to be planted the same year.

Sulphur Treatments, 1940

Sulphur was used on a large scale in 1940 (Fig. VI). The grower had heard that sulphur might control wireworms and decided to use it on soil heavily infested with wireworms. It was applied to approximately 6 acres of potato land in the North and South plots about 1 week before the time of planting. These 6 acres were considered, on the basis of the previous year's crop, to be the most heavily infested with wireworms.

The sulphur was applied with a fertilizer spreader at the rate of 400 lbs. to the acre. The treated areas were then plowed to a depth of 9" and harrowed in order to mix the sulphur with the soil. A week after the treatment, potatoes were planted in the usual manner.

Soil sampling taken at random throughout the treated area showed no recognizable effect on wireworm activity. Seed pieces were found riddled with wireworm holes and wireworms were quite active. No dead wireworms were found. Treated areas were compared with untreated areas at the time of harvest. From observations made in the field it was evident that sulphur did not repel or control wireworm attacks. Soil samples taken in treated areas showed just as many wireworms and just as many damaged potatoes as did untreated areas. No beneficial wireworm control could be ascribed to the sulphur treatment. During the following year it was not used.

Tobacco Treatments, 1941

In 1941, the grower decided to use tobacco stems as a control for wireworms. It had been rumored that good results had been obtained by other growers in using tobacco stems for wireworm control. These stems were the center ribs of the tobacco leaves and not the stalks of the tobacco plants themselves.

During the latter part of April, approximately 4 acres of potato land in the North and South plots were treated with tobacco stems (See Fig. VII). These were spread over the soil with a manure spreader at the rate of 500 lbs. to the acre. The field was then plowed and the tobacco stems turned under to a depth of approximately 9".

Soil samples in this area were taken before treatment and again after treatment in order to check on the amount of control obtained. In the North plot, 20 soil samples were taken in the area to be treated, which yielded 10 wireworms or an average of 4 wireworms per cu. ft. Soil samples were taken at random shortly after treatment. Wireworms were found to be active and unharmed. In many cases the larvae were found adjacent to tobacco stems. At the time of harvest, 15 1/2-cu. ft. soil samples were taken in the treated area of the North plot. Each sample had wireworms in it and the number of wireworms per sample varied from 2 to 18. The total number in the 15 samples was 122, or an average of 16.2 wireworms per cu. ft.

These figures and observations show that the tobacco stem treatment was ineffecutal. In fact, it would seem a better policy not to have treated the soil in this manner. Any addition of organic matter into the soil is likely to favor wireworm growth, and since the tobacco stems did not act as a control, they probably favored wireworm development because of their incorporation into the soil.

Immersion Experiments

All the soil insecticides used in the field experiments were tested for the speed with which wireworms were killed when immersed in them. One ounce of each insecticide was used for each test and each wireworm was immersed separately. Wireworms used for these tests had been collected shortly before the date of testing. The time when the wireworm became inactive was recorded. In many cases, wireworms were left in the test liquids for 20 to 60 seconds after they became inactive. After immersion, each wireworm was removed to a 6-dram vial of fresh soil and retained for further observation. The results of these tests are listed in Table XVIII.

Chloropicrin killed in the shortest time and none of the 3 wireworms survived these tests. Dichloroethyl ether ranked second in regard to the speed with which it inactivated larvae. One wireworm recovered after being immersed for 60 seconds but after another immersion of 60 seconds, succumbed. All wireworms treated with LE-5 recovered 30 minutes after immersion and remained active for 5 days after treatment. In the case of FD-2A, a heavy brown liquid, it was not possible to see when wireworm activity ceased. Consequently wireworms immersed in this solution were removed after various periods of immersion. After an immersion of 1-1/2 minutes and 2 minutes, wireworms were inactive and died 1/2 hour after treatment. An immersion of 1 minute failed to inactivate the larvae used in this test, and it was active for at least a week after the test was made.

TABLE XVIII

IMMERSION EXPERIMENTS - 1941

Material used	Test no.	Inactive in (seconds)	Period of immersion (seconds)	Active in (min.)	Condition after 3 days	Condition after 6 weeks
Dichloro-ethyl ether	1	50	50		d	d
	2	60	60		d	d
	3	70	70	1	d	d
Chloropicrin	1	50	110		d	d
	2	70	130		d	d
	3	50	80		d	d
LE-5	1	60	120	30	a	d
	2	60	120	30	a	d
	3	60	90	30	a	d
FD-2A	1	120*	120		a	d
	2	90*	90		a	d
	3	60*	60		a	a
Tergitol Penetrant	1	45	45		d	d
	2	50	50		a	a
	3	120	120		a	a
Alcohol C_2H_5OH	1	90	90		a	d
	2	80	80		a	a
	3	135	135		a	d
Water	1	20 min	20 min	10	a	a
	2	21 "	21 "	10	a	a
	3	22 "	22 "	10	a	a

* Due to color of liquid, it was not possible to see when activity ceased. Figures here refer to time wireworms were in liquid.

Tergitol Penetrant 7, an emulsifying agent for dichloroethyl ether, showed the widest variation in killing time of any of the insecticides used. One wireworm became inactive after an immersion of 45 seconds and this larva failed to recover. The second wireworm became inactive in 50 seconds but it recovered 30 minutes after treatment. The third larva was inactive in 2 minutes after immersion. Three days later it showed signs of life. These last 2 larvae were active for at least 6 weeks after the time of treatment.

Wireworms immersed in 95 per cent. alcohol became inactive in 80 to 135 seconds, but they recovered within 24 hours. All were active 3 days after treatment. Six weeks after treatment the larva that had been immersed for 135 seconds had died but the other 2 were active.

Wireworms can evidently withstand long periods of immersion in water. All three wireworms used in the water immersion test were inactive in 20 or 21 minutes but all had recovered within 10 minutes after immersion. No injury to these wireworms was noticed and all were active 6 weeks after immersion.

SUMMARY

Numerous wireworms are serious pests of truck crops, potatoes, and tobacco in the Connecticut River Valley. The J. W. Parsons field in the "Meadow" section of Northampton has had a serious infestation of wireworms affecting truck crops and potatoes for many years. The chief elaterid species in this field is Limonius agonus Say. Another species, Ludius cylindriformis Hbst. is found in this same locality. Lafvae of Melanotus sp. are frequently found in grassland adjacent to the cultivated portions of the field.

Estimates of wireworm populations were obtained at various seasons of the year by the use of soil sampling. The unit sample was 1/4 of a cu. ft. taken to a depth of 12". Fifty of these units were considered enough for an estimate of wireworm population in a 5-acre field.

The cultivated portion of the field had a greater wireworm population than the grassland. The reasons for this difference are not definitely known but it is suspected that cultivated crops are a preferred source of food, and, furthermore, might present better conditions for egg-laying than does the grassland.

The wireworm population undergoes seasonal vertical migration initiated by temperature and moisture conditions. Hibernation of overwintering larvae occurs at depths averaging 6" to 9". Upward migration of the larvae begins in April after the soil is thawed. Downward migration of larvae takes place when temperatures in the upper soil levels rise and moisture content decreases, This downward migration may occur from July to August, and if the season is a moist one, such a migration may be negligible.

The hydrogen-ion content of the soil ranged from 4.6 to 6.2. There was no correlation between soil reaction and the abundance of wireworms.

Four different soil insecticides were tested in the field and in the laboratory as controls for wireworms. Two of these were inorganic mercury compounds, LF-5 and FD-2A, which proved to be ineffective. A third compound, IN-3102, a chlorinated toluene product, was very effective as a soil insecticide but it could not be used in the presence of plants.

Dichloroethyl ether was effective, especially in loose types of soil. Control was not possible with one application and repeated applications imparted an objectionable flavor to potato tubers. Because of this, its use as a soil insecticide is limited.

Observations on cultural control show that cleanly cultivated areas of the Parsons field had a smaller wireworm population than did other areas, such as the potato bearing plots. Indications are that clean cultivation as practiced in the truck crop area reduces the wireworm population of the soil.

CONCLUSIONS

The average wireworm population of the Parsons field varied from 100,000 to 250,000 per acre. Damage to potato tubers was very evident at the higher population levels, which were characteristic of the areas usually used for potato growing. The truck crop areas of the field had a wireworm population of less than 100,000 per acre. Damage to root crops in truck crop areas was negligible.

Wireworms undergo vertical migrations in the soil which are initiated by temperature and moisture changes in the soil. The upward migration in the spring is the result of favorable temperature changes which warm the soil. The downward migration in July-August is the result of lessened moisture content of the upper soil levels, occasioned by higher temperatures.

Chemical control of wireworms in the Parsons field with any one of the four compounds tested was not successful from a practical standpoint. The most promising soil insecticide used was dichloroethyl ether but its use is limited because of the flavor it imparts to root crops.

The use of sulphur did not result in any noticeable control. Tobacco stems, harrowed into the soil, did not control wireworms.

Cultural control, especially clean cultivation, reduced the wireworm population of the soil. Clean cultivation, plus a system of clean summer fallow and a rotation of crops might be the answer to an inexpensive and effective wireworm control program in the Parsons field.

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