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Biology, Monitoring and Management of Economically Important Wireworm Species (Coleoptera: Elateridae) in Organic Farming
2013 / 124 Seiten / zahlr. farb. Abb. / 19,80 € / ISBN 978-3-89574-822-6
Verlag Dr. Köster, Berlin / www.verlag-koester.de

The range of distribution and apparent speed of movement were greater for older compared to younger larvae. Larger larvae are better able to disperse from the site of oviposition, leading to less aggregation with age (DOANE 1977). This could partly explain the patchy damage behaviour often observed within fields. SALT & HOLLICK (1946) found a non-random distribution of *Agriotes* larval population with very little to heavily infested areas in the same field. SCHALLHART et al. (2011) observed no movement of *Agriotes* larvae between cereal and grassland plots. This study might suggest that elaterid larvae rarely disperse between crops as long as local food supply is sufficient. According to DOBROVOLSKY (1970) & ARAKAKI et al. (2010), wireworms can cover distances up to 240 cm, with some directional movements at small scale from 10 to 20 cm depending on species, soils and cultivation type. Larval movements decreased with increasing soil moisture level and mortality increased to 80% in very moist soil (40-45%) after 5 weeks time (SEAL & JANSSON unpublished).
Agriotes larval feeding behaviour appears to be mediated by short distance mechanisms involving dietary preference (CHATON et al. 2003). According to SALISBURY & LEATHER (1998), wireworms lack efficient receptors that able to elicit a response to the food source attractivity, as also observed for other larval Coleoptera living in confined areas. In contrast to this apparent lack of a food quality detection system over long distances, the larvae seem to possess a gustative system for short-distance food choice, which may be localised on the mouthparts. Moreover, some studies suggest that carbon dioxide is not attractive to the larvae (CHATON et al. 2003), which is in contrast to previous studies in larval attractivity (DOANE 1961, AGUILAR 1962) which involved carbon dioxide released by root respiration. In addition to the forms of attraction above, wireworms appear to show preferences towards different parts of a field. RILEY & KEASTER (1984) found that wireworms are more likely to be found in fresh manure pats and the soil underneath them than in a decomposed manure pat or soil without manure. Certain fields are more susceptible to wireworm damage than others. RILEY & KEASTER (1984) suggest that crops planted in former cow pastures may be especially susceptible due to the increased numbers of wireworms under manure. Fields with native grasses and left fallow for 10 years make ideal habitats for elaterids and may be contributing to the problems observed in arable rotations (HANCOCK et al. 1992, PARKER 1999).

2.3 Wireworm damage to crops

Wireworms, the polyphagous larvae of click beetles (Coleoptera: Elateridae), are serious pests of many different crops all around the world (KLINGER & DOANE 1974, WIGHTMAN & MORRISON 1978, IVASHCHENKO & ADAMENKO 1981). *Agriotes* wireworms are predominantly herbivorous, although some *A. obscurus* larvae individuals feed on animal prey (TRAUGOTT et al. 2008). Crops susceptible to injury are cereals, maize, potatoes, sugar beet, strawberries and vegetables (STAMOPOULOS 1995), causing serious loss of plants if attack occurs in the later stages of the crop after thinning (MILES 1942, ANON 1983). Autumn- and spring-sown oats and wheat are more susceptible than barley and rye, which are less likely to be injured (GLOGOZA 2001). Other crops such as *Brassicas*, leeks, beans, tomatoes and carrots are also attacked at both the seedling stage and in later development, although once established serious damage is rare (MILES 1942a, COCKBILL et al. 1945, GRIFFITHS 1974, ANON 1983). Wireworms primarily feed on underground parts, but the seriousness of the damage depends on a number of factors, including the plant species, growth stage, vigour when attacked, and plant density (ANON 1983). Damage caused by wireworms can result in substantial yield losses and damage to maize can be particularly serious due to its low plant density which may sometimes require crop replanting (SMITH et al. 1981, ANON 1983, FURLAN 1989, 1990, LEFKO et al. 1998a, 1998b, SIMMONS et al. 1998). In some cases up to 35% of maize crop might be lost due to wireworm damage (APABLAZA et al. 1977).

Generally high wireworm populations have been linked to long-term grassland fields (MILES 1942, ANON 1948), as this habitat is usually favourable for wireworm survival. Damaged plants can wilt and die, resulting in thin stands and bare spots may appear. Wireworms may also bore into the underground portion of the stem or feed the roots of the plant, resulting in withering and structural instability (KULASH & MONROE 1955, MUNSON et al. 1986, SIMMONS et al. 1998). Young wireworms smaller than 5 mm (length) are not considered to be capable of causing significant crop damage. As wireworms increase in age and size, they become more capable of destruction and are more readily seen in the soil (PARKER & HOWARD 2001).

The potato is the most important vegetable in Organic Farming and fourth (after rice, wheat and corn) most important agricultural crop worldwide that plays a key role in feeding the growing world population (FAO 2005). There are about 39 species of wireworms from 12 genera that have been recorded as important constraints for potato production and causing serious damage (JANSSON & SEAL 1994). Some of these species are widely distributed, while others are only of regional or local importance. Wireworms cause severe injury to potato tubers, leaving tunnels and small round holes on the surface, reducing crop quality rather than yield; and even low populations (<100,000 wireworms/ha) can cause economic damage (PARKER & HOWARD 2001). Injuries caused by wireworms may facilitate the penetration of *Rhizoctonia solani* (black scurf) into the tuber and assist the formation of drycore symptoms. According to KEISER (2007), drycore symptoms were 2.46 times higher for tubers with wireworm damage than for clean tubers, suggesting that wireworms are important factors for the formation of drycore symptoms on tubers. Cosmetic damage, such as pits, scars or holes, and narrow tunnels to the roots or tubers occurs, resulting in lower market value or total refusal by retailers (PARKER & SEENY 1997).

Typical crop losses in North America caused by wireworm damage range from 5 to 25% (JANSSON & SEAL 1994). However in the last couple of years wireworm damage has become an increasing problem, with damage occurring in fields in all arable rotations even without long-term grassland history (DEMMLER 1999, PARKER & HOWARD 2001). In an investigation under the federal Organic Farming program, an increase of wireworm damage in Germany was observed during the last few years (VUB-RING ÖKOLOGISCHER LANDBAU E.V. – ÖKORING 2009). The share amount of damaged potatoes was about 7%, and the damage to tubers reduced crop quality rather than yield. There is some evidence that crops following long-term set-aside (1-5 years green fallow) provide a suitable habitat for wireworm and this may be contributing to the problems observed in arable rotations (HANCOCK et al. 1992, PARKER 1999). Several factors play an important role in enhancing wireworm problems in potatoes. The most common factor associated with wireworm damage is the cropping history of the field. Potatoes are most vulnerable to wireworm outbreaks when they follow a favourable host in the rotation, such as fodder grasses (SCHEPL & PAFFRATH 2005). Other precrops known to favour wireworm outbreaks in potato rotations include cereals, green fallows, sugar beet and alfalfa (MCSORLEY et al. 1987, JANSSON & LECRONE 1991). Another important factor in enhancing wireworm problems on potato is lack of soil moisture. When soils dry out, wireworms presumably seek moisture from potato tubers. In general, the drier the soil, the greater the incidence of wireworm feeding on potato tubers (JANSSON & LECRONE 1991).

Apparently, wireworm damage may be confounded with slug damage as slug entrance holes are very similar to those made by wireworms. However, slugs often hollow out large cavities within the tuber flesh, whereas wireworms do not. Wireworm holes may also provide initial access for slugs, nematodes or other soil organisms such as millipedes or bacterial rots, further increasing the damage (GRATWICK 1989, PARKER 2005). Larvae of all stages feed periodically on potato tubers as each larval instar passes through different phases during development (FURLAN 2004). It has been found in various wireworm food preference studies (ROBERTS 1919, CHATON et al. 2003, TRAUGOTT et al. 2008), that *Agriotes* larvae preferred to feed on a mixed diet of weeds, cereals, potato tubers and even also seed flour materials. According to CHATON et al. (2003) larval feeding choice may also have been affected over short rather than long distances. The feeding pattern of *Agriotes* larvae appeared to be very sporadic and limited by temperature, relative humidity, and perhaps by endogenous factors. In agro-ecosystems, *Agriotes* larvae feed in the top 5 to 10 cm of soil, but they also migrate very deeply into the soil during extreme (winter and dry) periods, and larvae remain in the resting layer and move between the two layers with relative ease (CHATON et al. 2003).

2.4 Use of sex pheromone traps

Pheromones are natural chemicals produced in the body of an animal known to help in communicating with other members of its species (BEROZE & KYDONIEUS 1982). The first semiochemical to be chemically characterized was the sex pheromone of the silkworm moth (*Bombyx mori*) by BUTENANDT and coworkers in 1959. A considerable advancement has been made in chemical techniques and equipment to identify compounds from ever smaller amounts of material, and the field has progressed rapidly as a result of the identification of the first sex pheromone. The insects world is filled with many odours. Insects use these odours to cue them in a variety of complex social behaviours, including courtship, mating and egg laying. The pheromone-baited trap has become one of the most widely used methods to gather insects from a wide area and thus can be used to sample sparse insect populations (WALL 1989). Pheromone traps are typically very specific in attracting the target species, hence avoiding the need to sort out pests in the samples collected in nonspecific traps that require skill and considerable time. The monitoring of insect populations has long been recognized as an essential component of any successful pest control programme (PINNIGER 1989). With regard to insect pest management, population dynamics and long-term monitoring can help to elucidate patterns in population life cycles. These patterns can then be combined with the known biology of the insect to define parameters and strategies for an effective control campaign (NORTON & MUMFORD 1993). Pheromones can be sub-divided into different categories. For example, sex pheromones are chemicals which mediate interactions between sexes of the same species; most are produced by females and attract males, although some examples of male-produced pheromones are also known. Other types of pheromones include trail pheromones (which guide social insects to distant food sources), aggregation pheromones which may or may not be produced by both males and females to congregate the species for feeding or reproduction, alarm pheromones which may serve to rapidly disperse a group of insects, usually as a response to predation (NORDLUND 1981) and oviposition-deterring pheromones (which deter females from laying eggs in the same resource as another female). Most sex pheromones are not a single compound, but rather a blend of several compounds, with an accurate concentration and ratio to bring about the appropriate behavioural responses to a particular species.

Currently, the most widely used semiochemicals in pest management are the insect sex pheromones, particularly those of lepidopteran pests, which were amongst the first to be identified and synthesized (ARN et al. 1992). Recent progress in pheromone-monitoring traps have made them available for a wide variety of pests, including Coleoptera, Homoptera and Diptera in agriculture, horticulture, forests and other stored products (EL-SAYED et al. 2008). Pheromones have also been successfully applied for control and monitoring of pea moth (MACAULEY et al. 1985), spruce budworm (ALLAN et al. 1986), fall armyworm (ADAMS et