Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Ecology

Life cycle of Agriotes wireworms and their effect on maize cultivation

– From a Swedish perspective

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Agriculture Programme – Soil and Plant Sciences
Bachelor's thesis
Uppsala 2017

Independent project/Degree project / SLU, Department of Ecology 2017:3

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Credits: 15
Level: G2E
Course title: Independent Project in Biology – Bachelor's thesis
Course code: EX0689
Programme/education: Agriculture Programme – Soil and Plant Sciences

Place of publication: Uppsala
Year of publication: 2017
Cover picture: Chris Moody
Title of series: Independent project/Degree project / SLU, Department of Ecology
Part no: 2017:3
Online publication: http://stud.epsilon.slu.se

Keywords: Elateridae, Agriotes, lifecycle, control, maize

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Sammanfattning

Majsodlingen i Sverige har ökat med nästan 60% det senaste årtioendet. Med ökad majs odling finns det en möjlighet att problem med knäpparlarver ökar i denna produktion. Knäpparlarver är vanliga i Sverige och de arter som räknas som skadegörare är *Agriotes lineatus* (L.), *Agriotes obscurus* (L.) och *Agriotes sputator* (L.). I Sverige har ingen forskning gjorts på knäppares livscykel. Detta kan vara problematiskt när kontroll av dessa larver behövs. Knäppare gynnas i gräsmarker, exempelvis i vallar, där de har stor tillgång på underjordiska växtdelar som de äter, i denna typ av marker är också markfuktigheten högra vilket är viktigt för att egg och larver ska kunna utvecklas. Under dessa förhållanden tenderar knäpparlarv populationer att öka. Skada som leder till skördeförlust på majs kan ses från groning tills det att det åttonde bladet utvecklats. För att kontrollera knäpparlarver kan flera åtgärder göras. En av dessa är att plöja drabbade fält när larverna finns högt i markprofilen, i Sverige händer detta mellan april och juni och från slutet av augusti till oktober. Ett annat sätt att undvika skador i majs är inte så majs 1 till 3 år efter att en vall har brutits. Under och strax efter en vall bryts kan antalet larver i en population vara hög men minskar årligen på grund av ogynnsamma förhållanden.

Nyckelord: Elateridae, *Agriotes*, wireworm, click beetle, biology, maize, control and antagonists

Abstract

Maize production has increased by almost 60% in Sweden over the last decade. Given this increase in maize cultivation there is a possibility that problems with wireworm increase. Wireworm species that are present in agricultural settings in Sweden are *Agriotes lineatus* (L.), *Agriotes obscurus* (L.) and *Agriotes sputator* (L.). There is little in-depth research made on the life cycle of these wireworm species which is problematic when control of these pests is needed. Species from the genus *Agriotes* have a long life cycle and control measures need to be long term and considered in the entre crop rotation. *Agriotes* favour grassland, such as ley, due to the availability of underground plant part which their major a source of food. These types of arable land also have high moisture content which is needed for eggs and larvae to develop. When these conditions are met populations tend to increase. Damage in maize from germination to the 8-leaf stage can lead to yield loss. To control a wireworm population several agronomic practices can be used. One of these is to mechanically control populations by ploughing when wireworms are close to the soil surface, which in Sweden is from April to middle of June and late August to October. Another way to decrease the risk of damage in maize is to not sow maize 1 to 3 years after a ley is broken for other cultivation. During and directly after a ley is removed can the number of wireworms in a population be high but will decrease yearly due to more unfavourable environment.

Keywords: Elateridae, *Agriotes*, wireworm, click beetle, biology, maize, control and antagonists

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1. Introduction

Maize is one of the most cultivated crops in the world and since 1992 production has doubled, in 2014 total harvested area of maize was 185 million hectare and total production was of 1,038 million tonnes in the world (Figure 1) (FAO 2016). In Sweden, maize is a relatively new crop with specific records of maize from the Swedish board of agriculture dating back to 2007. Its production has also been increasing from 10850 hectares in 2007 to 16977 hectares in 2015, almost 60 % (SCB 2016). With this increasing cultivation of maize, where the crop appears more continuously in the crop rotation, there is also the possibility of yield reductions due to increase of pests (Fogelfors 2015).

Figure 1. World maize production from 1961 to 2014. Source: FAOSTAT (2017)

One pest on maize is wireworm, the larvae of beetles from the genus *Agriotes*, which are polyphagous insects. Because of their ability to feed on various kinds of plants wireworms can be problematic in several different cultivated cops but most damage can be seen in crops that have a low number of plants per area unit, such as maize (Andersson 2008). In Sweden three wireworm species have been identified as agricultural pest, *Agriotes lineatus* (L.), *Agriotes obscurus* (L.) and *Agriotes sputator* (L.) (ibid.) and are viable insects in Sweden (Artdatabanken 2017).

In conventional agriculture neonicotinoids have been used in the whole world as a pesticide against several insects and in several crops, such as maize, potato, rape seed and sugar beet. Against wireworms the neonicotinoid thiamethoxam has been used as a seed coating and it has a good and long-lasting effect against wireworms (Maienfisch et al. 2001). A problem with neonicotinoids is that some are toxic to bees and the neonicotinoids that have been used as seed coating are generally very toxic to bees (Jorbruksverket 2016). In 2013 the European Commission, EC, implemented a prohibition on some neonicotinoids and one of them was thiamethoxam. Another active ingredient that have been used in Sweden as a seed coat against wireworms is methiokarb but is prohibited since 2013 (Kemikalieinspektionen 2016)

In addition to the prohibitions of chemicals that have been used against wireworms in Sweden European Parliament implemented in 2009 on a directive, Directive

2009/128/EC, to achieve a sustainable use of pesticides called integrated pest management, IPM (Directive 2009/128/EC of the European Parliament and of the Council). This has led to a need for knowledge on how to control wireworms in Swedish agriculture.

With a change in climate or a further increase of maize cultivation problems with wireworms could increase. If problems with wireworms would increase advisors and famers need to know how to act to reduce the risk of damage in cultivated maize.

Purpose

With the knowledge mentioned above, with increasing maize cultivation, prohibition of chemicals and the EC directive, the purpose with this thesis is to provide a review of 1) the biology of click beetles, 2) how wireworms and adult click beetles can be monitored, 3) what it does as a pest in maize and 4) what can be done to control this pest in Sweden.

Disposition

In this thesis the main text is composed in three parts. In the first part the biology of wireworms is described. The second part contains an overview of maize cultivation and how wireworms can be monitored and different methods of how wireworms can be controlled in maize cultivation.

2. Method

This thesis is a literature review of scientific articles published on the biology and the control of wireworms and adult click beetle. In total around 110 articles, 5 books and several different websites, based on the keywords for this thesis, have been reviewed. Articles, books and websites that have not been put in the thesis have been taken away on the basis of similar or the same information/research or reliability has not been adequate enough.

Literature has been found in library SLU Ultuna and on the databases which the library of SLU has access to, for example Web of Knowledge, Primo, Google Scholar and Scopus. Search words that were used are: *Elateridae*, *Agriotes*, wireworm, click beetle, biology, maize, control and antagonists. When also “Sweden or Swedish” were used as a search word little information was found and most of it was based on research made in other countries. Examples of these articles are Anderson (2008). Only one article was found on research made in Sweden which was Nilsson (1972) which does not go in deeply on the click beetles life cycle in Sweden.

No studies have been carried out on the lifecycle of wireworms and adult click beetles in Sweden. Therefore the review on the lifecycle of *Agriotes spp.* has mostly been based upon two articles by Furlan (1996, 1998), *Agriotes ustulatus* Schäller and *Agriotes sordidus* Illiger, and one dissertation from Sufyan (2012) about, *A. obscurus*. These articles are based on wireworms from Italy and Germany, which means that this information cannot be directly related to Swedish conditions but can give indications on how wireworms live in Sweden.

To obtain more knowledge of problems with wireworms in Swedish maize production questions were mailed to advisors and persons responsible for crop protection from the Swedish Board of Agriculture. Questions that were given concerned whether or not they have encountered problems with wireworms and what they would recommend as an appropriate control measure. These references are mentioned as personal contact and can be found in the reference list.

3. Biology of *Agriotes spp.*

Elateridae, commonly known as click beetles, is a family of beetles that is distributed worldwide and includes about 9000 species (Nationalencyklopedin 2015). The family comprises 27 genuses (Iowa state university 2015), however most of the significant arable pests belong to the genus *Agriotes* (Tullgren 1929). *Agriotes* are mostly found in the Holarctic and oriental areas and there are about 280 species worldwide (Global Biodiversity Information Facility 2016). In Sweden eight different species of *Agriotes* have been found of these three are the most abundant (Artdatabanken, 2017). Those three are *A. lineatus*, *A. obscurus* and *A. sputator*.

Morphology

Click beetles range in size from 10 to 37 mm and have an elongated oval or elliptic shape, antennae are thread like or serrated, short legs with 5-membered feet and back corners of the pronotum are extended backwards into small points (Figure 2) (Jones & Jones 1984, Tullgren 1929, Douwes et. al. 1998). Most click beetles are black or brown but some can have a metallic green colour and some have red elytron (Douwes et.al. 1998)

The most prominent characteristic of click beetles is a spine between pro- and mesothorax. The spine is attached to prothorax and fits into a cavity in mesothorax (Jones & Jones 1984). This structure is used when a click beetle is on its back to get back on its feet. When this structure is used it gives out a click noise, that feet has given the beetle family its name both in English, Click beetle, and Swedish, Knäppare (Tullgren 1929).

Wireworms, the larvae stage of the click beetle, are soil dwelling and feed on underground plant parts. The larvae can range in size from 13 to 37 mm (Jones & Jones, 1984). They have an elongated cylindrical body and have a yellow to yellow-brownish coloured exoskeleton. The head capsule of the wire worm has large dark coloured jaws and the last body segment is shaped like tongs or a cone (Jones & Jones 1984, Nilsson 1972).

Figure 2. Close up of adult *A. obscurus beetle*.
Source: Chris Moody - Microphoto.co.uk

Lifecycle of Agriotes spp.

Egg and embryonic development

Eggs of *Agriotes spp*. are laid between May and early June (Furlan 1996, 2004, Sufyan, 2012). Eggs are usually oval or ovoid in shape but the shape and size are often irregular which is assumed to depend on soil resistance against the ovipositor. The surface of eggs is smooth and their colour can vary from white to grey-brown. During hatching the egg collapses so larvae can emerge (Furlan 1996, 2004, Sufyan 2012). The size of click beetle eggs differs between species, for example eggs from *A. obscursus* are smaller than eggs from *A. ustulatus* (Sufian 2012, Furlan 1996, Sufyan et al. 2014).

Eggs are laid in moist soil and can be laid singly or in clusters where clusters can be made up by 2 to 39 eggs (Sufyan 2012). Where eggs can be found depend on how moist the soil is. In a laboratory study by Furlan (1996) on *A.ustulatus* it was found that when adult female beetles were put in plastic boxes with moist soil 64% of the eggs were laid in the upper 0.5 cm of the soil, 28% in the layer 0.5-1 cm, 7% in the layer 1-4 cm, 1% in the layer 4-6 cm and no eggs were found deeper. At field capacity most laid eggs can be found down to 10 cm under soil surface (Furlan 1996). Eggs that are laid in dry soil or very close to the soil surface cannot develop and die due to dehydration (Tullgren 1929, Sufyan 2012).

Embryonic development varies between species of *Agriotes*, temperature, degree days and in what kind of climate the species comes from. Estimated time from the time that an egg is laid until the larva hatches is 3-4 weeks (Jones & Jones 1984). A study of *A.obscurus* by Sufyan (2012) showed that eggs could complete their development in an average of 22.5 days when kept at 20ºC and viability and hatching of eggs ranged from 95-100%. A laboratory study by Furlan (1996) on *A.ustulatus* showed that on average, development time was 23.9 days at 20ºC while the shortest development time was 12.5 days at 27.5ºC and the viability and hatching was about 95-100%. However, a study by Furlan (2004) on *A.sordidus* showed that embryonic development depended not only on temperature and degree days but also where the ovipositor came from. Eggs laid by *A.sodidus* from southern Italy took on average 6 days longer to develop than eggs laid by beetles from northern Italy, this imply on local adaptation.

Larvae

Development

Larvae hatch in late summer (Furlan 1996). Newly hatched larvae are vulnerable if no available food source of underground plant parts is near they will starve to death within 4-5 weeks if no food source can be found (Sufyan et al. 2014).

Development of wireworms is divided into several instars and between each instar the larvae moult (Figure 3) (Allaby 1998). Before, during and after each moult the larvae stops feeding (Sufyan, 2012). This behaviour has been studied also by Furlan

(1998) where he divided instars into three phases: (1) darkening and hardening of the mandible, (2) feeding and (3) pre-moulting. The first phase where the larva's mandible gets dark and hard is just after the moulting and the larva does not feed. During the feeding phase the larvae feeds continuously with a few interruptions and it is during this point when larvae can damage plants. The third phase, pre-moulting, the larvae prepare to moult and feeding decreases and later stops before the moulting starts.

Young larvae wireworms are about 1 mm long and moult for the first time after about a month. From hatching to first over wintering wireworms can go through 6 to 7 instars (Sufyan 2012) Number of instars differs between species and temperature in the soil. Studies show that *A. obscurus* larvae can go through 8 to 13 instars, *A. lineatus* can go through 3-12 instars in in field conditions (Sufyan 2012, Sufyan et al. 2014) and larvae of *A. ustulatus* can go through up to 13 instars in laboratory conditions (Furlan 1998). Soil temperature has a strong impact on the larvae development even if the soil moisture and amount of food was adequate. The average temperature needed for the whole larvae development of *A. obscurus* is about 9.248 degree days above a base of 9°C which corresponds to almost 841 days (Sufyan 2012). But in general, development takes 2-5 years for wireworms (Jones & Jones 1984).

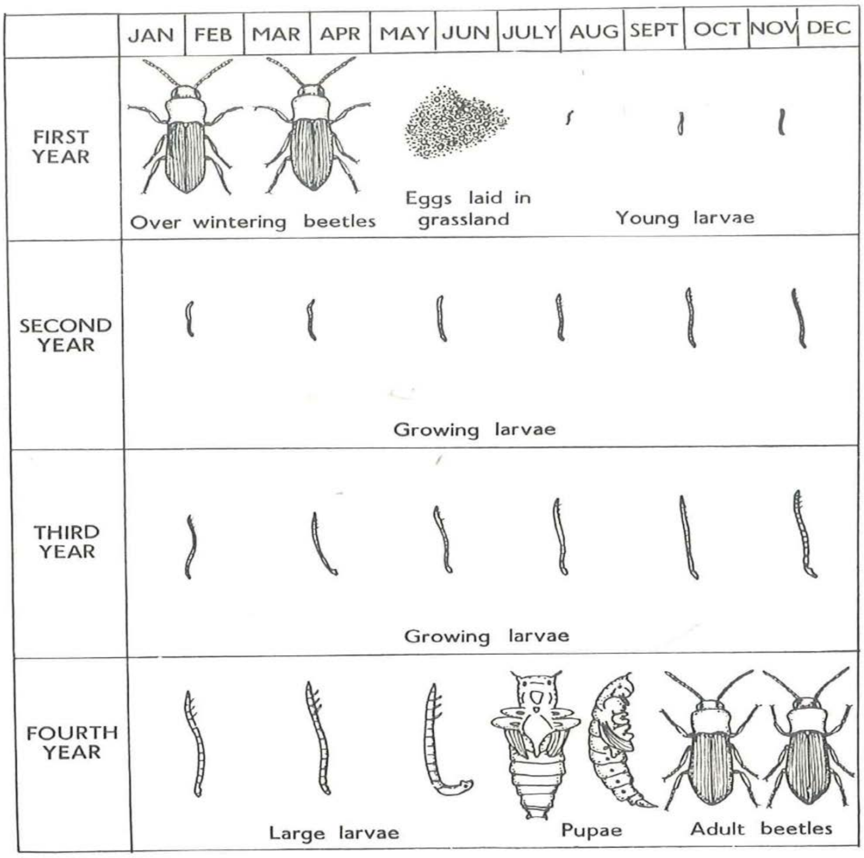

Figure 3. Lifecycle of *Agriotes*. Source: Jones, F.G.W and Jones, M.G (1984)

Wireworms feed on plant exudates from the wounds they make with their large jaws. Since larvae live in the soil, wounds made by wireworms can be found on underground plant parts, seeds, stems and roots (Jones & Jones, 1984). Dead organic material is not suitable as a food source for wireworms for wireworms to survive, neither are germinating seeds for newly hatched larvae since they cannot feed on hard tissues (Furlan 1998). Cannibalism can occur if food availability is low and if that occurs it is the older and larger larvae that eat younger and smaller ones (Sufyan 2012, Furlan 1998).

Mortality of larvae is high during the first overwintering and can reach 56% for *A. obscurus*. Larval mortality rate, due to starvation, decreases as the larvae gets older but can still be as high as 50% after the second overwintering (Sufyan 2012). After overwintering the larvae start to feed and develop as soon as the temperature reaches 9ºC usually sometime between March and May depending on species and location (Sufyan 2012, Furlan 1998).

Larval migration in soil

Larvae follow the changes of temperature and moisture in a soil. They stay closer to surface in the spring and autumn when the moisture and temperature is high in the soil profile and move downwards in the summer when the soil dries up and in the winter and mid-autumn when soil temperature gets too cold for the larvae (Jones s& Jones 1984). Wireworms that overwinter migrate to parts of the soil that do not freeze. Larvae that overwinter are 2nd to 13th instar. Behaviour differences can be seen between young (2nd to 6th instar) and older larvae (7th to 13th instar). Older larvae can be found deeper in the soil and migrate upwards faster than young larvae. In the winter fully grown larvae can be found in the soil as deep as 60-80 cm (Furlan 1998).

Pupae

When larvae are fully grown in late summer, at about 2-5 years of age and are ready to pupate, they burrow themselves lower in the soil profile (Jones & Jones 1984). Where in the soil profile the pupae's can be found depends on soil moisture (Furlan 1998). The colour of the pupae is milky white. Just before the larvae change to adult the body transforms to a light yellow colour and eyes darken in the final stages of pupal development (Sufyan 2012).

The time needed for development from pupae to adult beetle depends on the species and temperature in the soil. For *A. obscurus* it takes 15.4 days at 20ºC to develop into adult beetles which corresponds to about 169.5 degree days (Sufyan 2012). *A. ustulatus* can develop from pupae to adult in 13 days at 20ºC (Furlan, 1998).

Adult

Newly developed adult click beetles darken within a couple of days and are fully developed with hard skin and coloured in about 2 weeks (Sufyan 2012). Adult click beetles can be found on the soil surface on covered lands where they feed on leaves. The damage from adult beetles is small and they are therefore not considered as pests (Jones & Jones 1984). After mating oviposition start in April and peaks in May through early June (Sufyan 2012, Sufyan et al. 2014). Eggs can be laid anywhere in the landscape but female click beetles prefer grasslands over arable land for their oviposition. The reason that grass land is preferred can possibly be because of the cover at oviposition time (Gough & Evans 1942, referenced in Parker and Howard 2001). After eggs are laid the adults of some species die shortly after oviposition, e.g. *A. ustulatus*, and some species can survive for a longer time, overwinter and continue laying eggs the coming season, e.g. the most common species in Sweden *A. lineatus*, *A. spurator* and *A. obscurus*. (Furlan 2005, Jones & Jones 1984).

Distribution of Agriotes

Wireworms often appear unevenly distributed and aggregated into clusters in the landscape and in fields. In fields and in a landscape there can be areas with a low density of wireworms and other areas with a high density (Blackshaw & Vernon 2008, Benefer et al. 2010, Burgio et al. 2012). Adult click beetles can be found in a similar way in the landscape (Blackshaw & Vernon 2006, Blackshaw & Hicks 2013) but no clear relationship between above ground adults and underground larval abundance have been found (Benefer et al. 2012).

Population effects

Where wireworms can be found, the populations are composed of larvae of different instars and generations. In a population, small larvae (less than 9mm) are in the majority and the amount of individuals progressively decrease with the larvae length (Salt & Hollick 1944). Diversity of a population, in a field, has been shown to be an important factor to predict damage. Large wireworms do more damage to single plants than smaller larvae. If a population contains a lot of large wireworm the potential for damage is therefore generally higher (Salt & Hollick 1944).

Landscape effects

The structure of a landscape also has an effect on wireworm damage. Studies show that there is a link between wireworm damage and landscape context (Benefer et al. 2012, Blackshaw & Hicks 2013, Hermann et al. 2013, Saussure et al. 2015). One example of this is the availability of grasslands where *Agriotes* are favoured because of the food availability and increased soil water content (Blackshaw & Vernon 2006, Salt & Hollick 1944, Saussuer et.al 2015) Neighbouring grasslands and field margins provides a source of adult click beetles that will, in turn colonize and oviposit in cultivated crops, which can lead to damage in the field (Saussure et al. 2015, Hermann et al. 2013). A study by Hermann et al. (2013) on damage caused by *Agriotes spp.* in Austria concluded that field margins can explain up to 50 % of the wireworm damage distribution. Another example of how landscape context can affect damage caused by wireworms is the presence of hedges around a field, which increase the probability of damage in a field. But hedges may also lower the intensity of damage since wireworms and click beetles can be more efficiently controlled by natural predators due to the increase of biodiversity in the landscape (Saussure et al. 2015).

Climate effects

Climate affects occurrence of different species depending on temperature and air humidity. Areas where the climate is warmer and drier are dominated by some species while areas that are more humid and have lower temperatures have other dominant species (Staudacher et al. 2013). Even though climate affect occurrence of wireworm species climatic factors such as mean annual temperature do not have the same importance when predicting potential damage. However, Hermann et al. (2013)

showed in their study made in Austria that mean annual precipitation was positively correlated with wireworm damage.

Local scale effects

Soil characteristics can affect wireworms since different wireworm species prefer different types of soils (Furlan 2014, Staudacher et al. 2013). *Agriotes brevis* larvae have been found to prefer soils that are more permeable and *A. obscursus* and *A. lineatus* larvae have been found to prefer soils that have a higher water holding capacity (Staudacher et al. 2013) like soils rich in organic matter (Eriksson et al. 2011). How characteristics of a soil affect potential damage is still not completely understood. One study by Parker & Seeney (1997) showed that the only soil characteristic that significantly predicts damage is bulk density, where a lower bulk density increases the probability of infestation of field. A study made by Hemann et al. (2013) show that damage is higher in soils that have high sand content. Others have found that soil properties do not explain damage (Saussuer et al. 2015). However, no differentiation between species were made and effects that soil properties might have could have been masked. Another soil characteristic that affect wireworm populations is its possibility to hold water. Soils that are covered with vegetation all year around tend to have higher soil water content due to less evaporation and a high content of organic matter that can hold water in the soil. This environment is preferable to wireworms since the development of eggs and larvae is dependent on soil moisture (Furlan 1996, Sufyan 2012, Nilsson 1995).

4. Wireworms in maize

Wireworm damage can be seen from germination until eight-leaf stage (Taupin 2007, referred in Saussure et.al. 2015). Larvae attack germinating seeds, stem base and young roots of maize (Figure 4). Damage made by wireworms can lead to growth reduction of plants, abnormal tillering and discolouration of leaves. In severe attacks damage can cause death of maize plant which lead to total yield loss (Chaton et al. 2003, Larroudé unpublished data, refered in Sausseure et.al. 2015). In fields, damage can be seen in patches (Erichsen 1944, refered in Sausseure et.al 2015) which can be explained by the population distribution of wire worms in the landscape which also appears in patches (Blackshaw & Vernon 2008, Benefer et al. 2010, Burgio et al. 2012). Crop loss due to wireworms can be severe. In North America 100% crop loss has been reported (La Gasa et al. 2006) and in Germany up to 90% in fields with severe infestation (Hurle 2005, referred in Andersson 2008).

Figure 4. Maize plant damage by wireworm. Source: Kerstin Andersson

Possible damage in a field depends on where wireworms are during their migration in the soil profile. The feeding periods that occurs in the spring, when wireworms have migrated upwards in the soil profile, is the most harmful for maize since it takes place before many seedlings have reached their compensation point. Damage to crops during the late summer and early autumn feeding period is smaller as the crops are mature (Jones & Jones 1984).

Another factor that affects damage in maize is the existing local species. Furlan (1998) found in a study in Italy that *A. ustulatus* do not cause damage on maize in late spring because larvae are in a non-feeding phase. Further the author found that *A. sordidus* and *A. brevis* can cause severe damage during the same period because those species larvae are in a feeding stage. Another factor that can affect potential damage is the number of years of ley in one field. With increasing number of years of undisturbed ley, the amount of wireworms in the soil increases (Miles 1942).

Maize production in Sweden

Maize, requires temperatures above 10ºC during days and 5ºC during nights to grow (Fogelfors 2015). These requirements mean that maize is rarely sown further north than Uppland, Västmanland or Värmland. Grain production is almost entirely concentrated to the most southern regions and is highest in Skåne, Östergötland, Jönköping and Västra Götaland (SCB 2016).

Maize that is a relatively new crop, records of specific maize cultivation date back to 2007 (SCB 2016). Before 2007 green fodder production was, in the statistics from the Swedish Board of Agriculture, included into the total green fodder production, grain production was described separately but was and is still as small amount of the total production (Figure 5) (SCB 2008). In 2007 maize was grown on 10850 hectares of this 1570 was used for grain production and production has increased to a total of 16977 hectares in 2015 of which 1330 hectares was used for grain production. This increase is almost 60%, but is in comparison with total used area for agricultural crops in Sweden, 2 604 533 ha, maize production small, only 1% (SCB 2016).

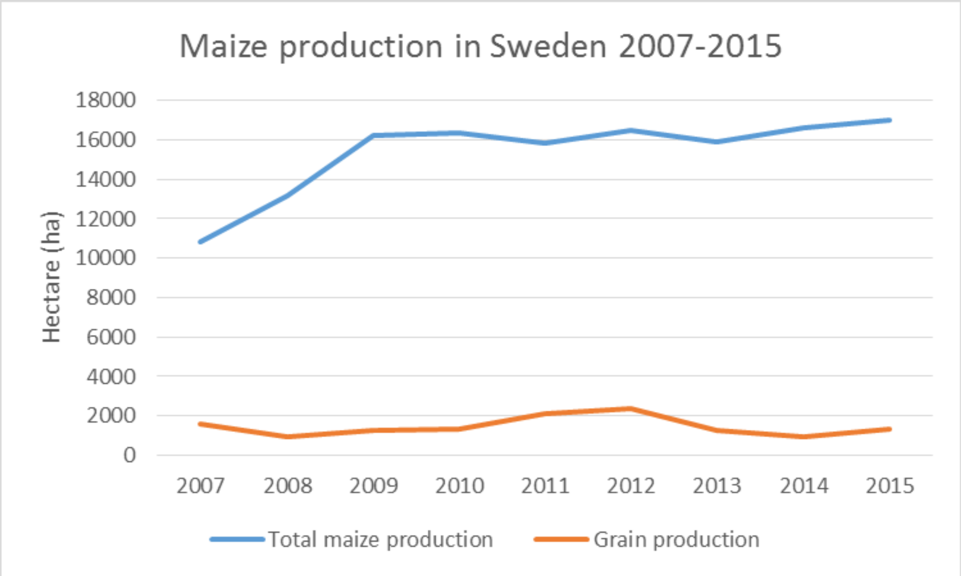

Figure 5. Maize production development in Sweden. Källa: SCB (2016)

Furthermore, maize as a crop that also need high amounts of fertilizer and one recommendation is 160 kg N/ha (Fogelfors 2015). This can be compared with winter wheat produced for human consumption which has the recommendation of 100-185 kg N/ha depending on potential yield and where the wheat crop is grown (Albertson et al. 2014).

Even though maize production has increased and today is stabilised in Sweden, wireworms are rarely seen as a serious issue (personal communication from, Andersson 2015, Berg 2015, Håkansson 2015, Lindgren 2015, Orvendal, 2015, Pålsson 2015). However, erratic problems with wireworm have been reported when maize is sown one to three years after a ley but can also be problematic in crop rotations with a lot of cereals. If a crop is exposed to a lot of damage, yield loss can be substantial. The general recommendation from advisor, Swedish University of Agricultural Sciences and the Swedish Board of Agriculture is to not sow maize 1 to 3 years after a ley (Jordbruksverket 2014, personal communication, Andersson 2015, Berg 2015, Håkansson 2015, 2014, Lindgren 2015, Orvendal, 2015, Pålsson 2015).

Monitoring wireworms

Monitoring and sampling of wireworms can be done with soil samples, bait traps and to monitor adult beetles pheromone traps can be used. Using a single method to monitor larvae or beetles in a field does not necessarily reflect the true amount and distribution of species within a soil. Because wireworms appear unevenly and patchy in a field traps can be put in places where no or a lot of larvae are which can give an inaccurate result (Benefer et al. 2012). Results from traps do not always show the actual probability of potential damage in that field. Damage is not only connected to the number of wireworms but also to climatic and agronomic conditions and also which species have been caught in that specific location (Furlan 2014). Furlan (2014) made a field trail on *A. brevis*, *A. sordidus* and *A. ustulatus*. Wireworms were captured with bait traps between 1993 and 2011. In the study the author found that thresholds for damage was when populations were lower than 1 larvae/trap for *Agriotes brevis*, 2 larvae/trap for *A. sordidus* and 5 larvae/trap for *A. ustulatus*.

Soil sampling and bait traps

Soil sampling is a method where soil cores are taken and later examined for the presence of wireworms. This method is good for estimating number of wireworms per area unit (Parker 1994). Examinations of soil cores are mostly done by soaking each core and retrieving larvae by flotation (Jones & Jones 1984, Parker 1994). This method is time consuming (Parker 1994) and to obtain a correct result, seasonal migration and possibility of newly hatched eggs must be taken in consideration (Jones & Jones 1984).

Bait trap is a method used to monitor and sample wireworms that can be faster than soil sampling. Wireworms are attracted to CO_2, this is important to consider when choosing bait, different baits can exude different amounts of CO_2 (Doane et al. 1975). In a field study by Parker (1994) it was shown that cereal baits such as wheat, maize and barley are better at attracting wireworms than vegetable baits such as potato and carrot and therefor better to use as bait. The traps can consist of baits freely placed in soil or bait in a beaker that is placed in the soil (Parker 1994). At what depth and when baits are placed is important due to the seasonal migration of larvae in the soil (Furlan 1998).

One limitation with bait traps was found in a field study by Parker (1994). The author found that there were a lot of wireworms in the soil just around the traps. If those wireworms are added to the number of wireworms from the baits the total wireworm count could almost double. When soil from around baits is included the processing time would also increase and processing time would be same as processing time for soil cores.

Another limitation with bait traps is that the bait does not cover a constant area (Parker 1994). Laboratory studies show that wireworms may move up to 20 cm to reach a CO_2 source (Doane et al. 1975) but how far a wireworm is able to move in natural soil conditions has not yet been studied. Bait traps also have potential abiotic limitations. Field studies by Ward & Keaster (1977) and Toba & Turner (1983) suggest soil moisture and soil temperature limit the efficiency of bait traps.

Pheromone traps

Pheromone trapping is a method were female-produced pheromone is used to monitor male click beetle. The method has not been studied much but could in the future be a tool for long-term monitoring of click beetles which is needed due to the *Agriotes* long life cycle (Burgio et al. 2012, Hicks & Blackshaw 2008, Tóth et al. 2003). Pheromone traps have also been suggested as a method for pest management where mass trapping of male click beetles are trapped to prevent mating (El-Sayed et al. 2006).

What is needed to be considered when using pheromone traps is what species of beetle is expected to be found, spatial location of traps and for how long the traps are going to be used. Depending on what species is expected to be found in an area it is important to know that different species of *Agriotes* are attracted to different pheromones (Tóth et al. 2003).

The length of time a trap is used can affect which beetles are trapped. Traps that are used for a longer time have a higher probability of gathering beetles that do not originate locally (Blackshaw & Hicks 2012). This interference could be solved be using traps for a short amount of time (Blackshaw & Hicks 2013, Blackshaw & Vernon 2008). Depending on species and for how long the traps are going to be used the trap spacing can be determined (Blackshaw & Vernon 2008). In the study by Blackshaw & Vernon (2008) it was concluded that optimal spacing for traps for *A. obscurus* should be 29-59m apart and the spacing would be larger for *A. lineatus*. The authors also estimated that the maximum range for sampling is 51m for *A. obscurus* and 82m for *A. lineatus*.

Controlling wireworms in maize

Wireworms can spend up to 5 years before pupation and later become adult beetles (Jones & Jones 1984) therefore long term strategies are needed to control the larvae. Below methods to control wireworm infestation are presented.

Mechanical control

Soil tillage can have a direct effect on wireworm populations (Saussaure et.al. 2015). Salt & Hollick (1949) made a survey of a newly cultivated field and found a 15 to 22 % larval mortality due to ploughing. One indirect effect from tillage that the authors mention is predation of larvae by above ground animals. Larvae that are moved up on the soil surface, due to ploughing, become accessible for predators, such as birds. When soil tillage is a part of yearly agriculture practice the number of wireworms present in a field can decrease each year (Miles 1942).

The best control from mechanical methods is obtained during the period when larvae are active high up in soil profile. In Sweden this is from late April to middle of June and late August to October (Andersson 2008). Ploughing during these periods can disturb the larvae. Best effect from ploughing appears when a ploughing is done late in the spring shortly before seeding. Ploughing during the autumn can have a lesser effect due to downwards migration of larvae due to temperature (Andersson 2008, Saussure et. al. 2015). Mechanical breaking of a ley with follow-up with repeated soil tillage also has a good effect on decreasing wireworm abundance. Best results with this method are gotten when a ley is taken away just before upwards migration in late summer and when continuous tillage is made afterwards when larvae are in a feeding phase. When this method is used in a ley migrating larvae, newly hatched beetles and not yet hatchet pupae will be affected (Andersson 2008, Salt & Hollick 1949).

Crops and crop rotation

Crop rotation is one of the most important factors affecting wireworm abundance (Furlan 2007, Miles 1942) and different crops can affect a wireworm population in different ways. Crops with a high number of plants per area unit are favourable in the same way a ley is, but for a shorter time period (Miles 1942,). Crops with low number of plants per area unit tend to decrease wireworm populations. These crops leave the soil surface bare for a long time and therefore do not have the favourable effects that crops with high plants per area unit have (ibid.).

Crops or systems which leads to long time surface coverage increase wireworm population, such as a ley (Furlan 2007, Sassure et al. 2015). This long periods of surface coverage leads to increased access to food, shelter for eggs and larvae due to less evaporation, shelter against predation and more favourable conditions for overwintering (Furlan 2007, Miles 1942, Benefer et al. 2010, Parker & Howard 2010). Miles (1942) noticed that in Britain leys that remain for 5 years or more have a higher risk of building up populations with high numbers of wireworms and leys that remain for 3 years or less tend to keep wireworm populations low.

Trap crops

A trap crop is a plant that can divert a pest from a cash crop and can be used in inter cropping systems (Ratnadass et al. 2012, Shelton & Badenes-Perez 2006). Wireworms' dietary choice can also affect the risk of damage (Schallhart et al. 2012, Staudacher et al. 2013). Schallhart et al. (2012) tested how diversity affected choice of diet. With higher diversity, in this case maize, forbs, grass and legumes, wireworms were less inclined to feed on maize and forbs and preferred grass and legumes. With decreasing plant diversity more damage was seen on maize plants (ibid.). Also Brunner et al. (2009) found that buckwheat grown together with maize might decrease damage on maize plants. This effect with decreased damage from wireworms on a cash crop has also been seen on other crops such as strawberries (Vernon et al. 2000 in Brunner et al. 2009). Though trap cropping has been shown to have an effect on damage from wireworms it has limitations. One is that a trap crop can work as a source for food and oviposition sites which can keep a population at a level that could cause damage in later years. Another limitation is the possibility of competition between the trap and cash crop for light, nutrients, water and space (Ratnadass et al. 2012). Another limitation has been shown by Staudacher et al. (2013) were some trap crops were fed on and some not. Further the authors found that if several trap crops were used in the same field feeding behaviour differed over time. A plant that was fed on during one point in the season was not fed on during another point. From these results Staudacher et al. (2013) concluded that a mixture of catch trap is important and can affect how a catch crop can control wireworm damage on a cash crop.

Biofumigant meals

Soil fumigation can be used against many soil dwelling organisms, including wireworms. Against wireworms mostly plants from the family *Brassicaceae* are used. These contains the substance known as glucosinolates which can be toxic to wireworms. Elberson et al. (1996) tested, in laboratory, the toxicity of rape seed meal against wireworms from the species *Limonius californicus.* In the experiment the authors tried different doses varying from 41.7 to 500 g seed meal/kg soil and mortality from the different doses varied from 15 to 95% after 7 days. However, to obtain the highest mortality large amounts of seed meal would be needed which would be too high for a practical use. Furlan et al. (2010) preformed a field experiment with seed meals made from *Brassica carinata* and *Brassica juncea*. Seed meals made from both *B. carinat*a and *B. junicea needed* a concentration over 1 g/l to get a desirable mortality. Further the author found that five different conditions are needed to be met for biofumigant meals to be practically successful. These conditions are (1) suitable dosage of glucosinolates, (2) homogeneous broadcast application of the seed meal, (3) effective soil incorporation, (4) suitable soil temperature and humidity and (5) presence of wireworms in soil layer where seed meal is incorporated.

Wireworm antagonists

Wireworms have many different antagonists (Kleespies et al. 2013) and many studies try to find if these antagonists can be used as a biocontrol agent, BCA, against wireworms. Below research preformed on bacteria, nematodes and fungi as BCA will be presented.

Bacteria

There have been reports of bacteria as pathogens on wireworms. Examples of these are *Pseudomonas fluorescens*, *Pseudomonas aeruginosa*, *Rahnella aquatilis* and some *Bacillus spp*. species (Traugott et.al. 2015). In a study about bacterial pathogens on *A. lineatus* Danismazoglu et al. (2012) concluded that there is a possibility to use bacteria as a biological control agent, BCA, but further research is needed. A problem with pathogenic bacteria as a BCA against wireworms is that pathogenicity can vary depending on soil moisture, larval instar and moulting cycle (Traugott et.al. 2015).

Nematodes

Nematodes have been found to parasitize both adult click beetles and wireworms (Traugott et.al. 2015). Reduced wireworm damage in maize has been found when *Heterorhabditis bacteriophora* and *Steinernema* species have been applied to wireworms in laboratory studies (Kovacs et al. (1980) in Ansari et al. (2009). Even if positive results have been found, nematodes have, in most cases, been shown to provide insufficient control of *Elateridae* species (Traugott et.al. 2015). In a laboratory assay Ansari et al. (2009) tested different species of entomopathogenic nematodes as a controlling agent. In all cases less than 70% control of wireworms was found. Nematodes’ poor ability to infect click beetles and wireworms is due to physical barriers, the hard integument, and immune system of the larvae (Rahatkhan et al. 2015, Traugott et.al. 2015, Edit & Thurston (1995) in Ansari et al. 2009).

Nematode pathogenicity of wireworms has been shown to depend on nematode and wireworm species (Traugott et al 2015, Ansari et al. 2009)

Fungi

Several fungi have been shown to be naturally pathogenic for wireworms. *Metarhizium anisopliae*, *Beauveria bassiana, Metarhizium brunneum* are well known pathogenic fungi. These fungi infect by penetrating larvae or beetle integument during moulting (Madelin 1966). It has been shown that latent fungal infection can occur and wireworms and mycosis can happen when environmental conditions change (Kabaluk et al. 2007a).

Conidia of entomopathigenic fungi have, in research, been used both as a seed coating and been mixed into the soil. Kabaluk & Ericsson (2007a) found that plant density was higher when maize seed were treated with conidia of *M. anisopliae* than not treated. This impies that less herbivory occurred when seeds were treated with conidia, probably due to either causing wireworm mortality or repulsion (Kabaluk & Ericsson 2007b). This has also been shown by Kabaluk et al. (2007a) who in their treatments mixed conidia into the soil and found that in the field high doses are needed, more than 4×10^6 conidia per cm^3 soil, to get a desirable control. Virulence of fungi has been found to be affected by temperature, both low and to high temperature can reduce fungi virulence (Rath et al. 1995).

Wireworm susceptibility depends on fungal species, larval instar and region where larvae live (Eckard et al. 2014). One example is showed by Eckard et al. (2014) who found that the strain ART2825 of *M. brunneum* caused 80% mortality in eight weeks against *A. obscurus* and 73% mortality against *A. lineatus*. Susceptibility can also be affected by species local adaptation between regions. Where one strain of a fungus can be virulent towards a wireworm species in one region and less virulent towards wireworm from same species but from another region (Kabaluk & Ericsson 2007a). Fungal virulence can also be effected by temperature (Fargues & Bon 2004). One example is *M. anisopliae* which does not affect wireworm mortality at soil temperatures below 12^oC (Kabaluk & Ericsson 2007b). If conidia is applied to a field, rainfall can affect the efficiency of conidia to infect larvae and beetles (Kabaluk 2014).

A few studies adress the shelf longevity of a BCA. Eckard et al. (2014) assessed the virulence of *M. brunneum* when produced on artificial media. In their study they found that inoculum produced for ten subcultivations caused mortality rates of wireworms close to inoculum harvested directly from a host.

5. Discussion

Even though wireworms are a known on pest on several crops including maize in Sweden (Fogelfors 2015, Nilsson 1995, Nilsson 1972, personal contact Berg 2015) little research has been done on these pests up till today and knowledge gaps needs to be filled in. In this section these knowledge gaps will be raised and discussed.

Wireworm biology

Due to the little to no research of life cycle of *Agriotes* in Sweden it is not known how long the larval stage can be in Sweden. This makes it difficult to predict how long and when a wireworm population can become a problem. We could guess that it is similar to Germany and Italy where both Furlan (1996, 1998) and Sufyan 2012 have made studies on wireworm lifecycles since damage is noticed around the same periods (Andersson 2008) but we cannot be sure until research is made on the subject due to differences in climate but also Agriotes species between different areas. According to advisors' that were contacted wireworms are not a common or generally problematic pests on maize. If damage occur, it happens if maize is sown 1-3 years after a ley or if a crop rotation contains a lot of cereals (Andersson 2008, personal communication from, Andersson 2015, Berg 2015, Håkansson 2015, Lindgren 2015, Orvendal, 2015, Pålsson 2015). Even if wireworms do not cause severe damage and total yield loss each year, wireworm damage can cause reduced growth. This growth reduction might not be ascribed to wireworms but other agronomic practices or pests and could, if it is so, lead to inaccurate estimations of wireworm damage.

Threshold values

Maize is a crop that has high requirements both for temperature and nutrients (Fogelfors 2015). Because of these requirements it can be a risk for a farmer to produce maize in Sweden and success with growth and development is important. To estimate the risk of damage from wireworms monitoring populations with soil samples, bait and/or pheromone traps are a good option (Furlan 2014, Parker 1994). Even if existing methods of monitoring wireworms have limitations and little is known about damage thresholds, it is one way to find fields or parts of fields where the risk of damage is high and farmers then have the choice of taking the risk of sowing maize and possibly have crop losses due to damage or choose another field for maize cultivation.

Control

How to control wireworms might not be a knowledge gap but recommendations can and do differ between advisors, the Swedish Board of Agriculture and also research. Example of differences is when to cultivate a soil and how many years to wait between breaking a ley and sowing maize (Andersson 2008, Furlan 2007, Jordbruksverket 2014, personal communication from, Andersson 2015, Berg 2015, Håkansson 2015, Jordbruksverket 2014, Lindgren 2015, Orvendal, 2015, Pålsson 2015). The problem with control might therefor be a communication problem between advisors, farmers and the researching community that not spread what information they have or what new research that have been done.

To control wireworms in maize control measures should be applied during weak points in the wireworm lifecycle, as much as possible, and best effect from these agronomic practices is when all of them are used when maize is produced and throughout the whole crop rotation.

Control of wireworms through tillage is as mentioned above a good way to manage a wireworm population (Andersson 2008, Miles 1942, Saussaure et.al. 2015) and is often applied yearly as a part of the farming system. In the app Växtskyddsinfo made by the Swedish Board of Agriculture wireworms are mentioned as a pest in maize and it recommended that a soil should be cultivated in the autumn after taking away the ley and after harvest of cereals (Jorbruksverket 2014). These recommendations are important to control a wireworm population (Andersson 2008, Salt & Hollick 1949). Research concludes that mechanical control have the best effect when it is made in the spring when wireworms have migrated higher in the soil profile (Andersson 2008). One aspect of tillage that have not been researched is the effect reduced tillage or direct sowing have on wireworms. Probably can both reduced tillage or direct sowing have small effects on wireworms or could also lead to an increase of wireworms.

One weak point in a wireworm's lifecycle is after the egg is laid. Since an egg needs moisture to develop and survive (Tullgren 1929, Sufyan 2012) influencing soil moisture can be one way to decrease a population. Influencing soil moisture can be done by managing irrigation time (Furlan 2007). After eggs are laid they are vulnerable and if the soil layer where eggs are laid is let to dry up eggs will not develop and hatch. Maize might not be an irrigated crop in Sweden but if a farmer has crops that are irrigated in the crop rotation that season this could be a proper time to decrease a population before the maize is sown.

Another factor that is important to avoid increasing a wireworm population and by that avoiding damage, is the crop rotation. As mentioned above is that the risk of damage increases in crop rotations that contain a lot of cereals and leys that are kept for several years (Berg 2015, Anderson 2008, Furlan 2007, Sassure et al. 2014). These problems can be avoided by not sowing maize until 3 years after a ley or having a diverse crop rotation. A way that is less discussed but can create a similar soil environment is to have cover crops. Even though cover crops have good effects in a farming systems, which is not brought up in this paper, a cover crop can lead to an environment that can be favourable for wireworms (Andersson 2008). If a field that is used for maize cultivation have known problems with wireworms or risk of infestation is high, cover crops should be excluded from the crop rotation. Another way to use the crop rotation to control a wireworm population is to grow crops that can also be used as biofumigant meals (Furlan et al. 2010). Even if it might not have as good effect as a grown crop as it could have as a biofumigant meal, a little effect would probably still be seen.

By using these methods the requirement of having an IPM approach when cultivating crops would also be full filled for when maize is cultivated.

Antagonists

Biological control of wireworms by using BCAs is an interesting subject that requires further research. If a BCA would be commercially available, this would offer a natural and specific method of control. One possibility with a BCA is to use together with soil sampling or bait traps to find patches of wireworms and use the product only on that place to minimize cost and unnecessary use. But research on BCA is still in its cradle and much of the research is based on laboratory studies and not in fields (Traugott et al. 2015). More research is needed before they could be used in commercial farming and be economically beneficial.

6. Conclusions

Even though maize production in Sweden has increased damage from wireworm does not seem to follow that pattern. Little is known about the life cycle of wireworms in Sweden and research needs to be made on this topic to know if wireworms have the potential to become more problematic. Control measures that can be used in fields that are infested needs to be long term and not only done before maize is sown, to decrease risk of damage. To control damage maize should not be sown 1 to 3 years after a ley and the soil should be tilled during late spring and late summer to early autumn when wireworms have migrated high in the soil profile. A diverse crop rotation is another way that can decrease a wireworm population which then can lower the risk of damage when maize is grown.

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