Scent traps and trap crops for broad bean weevil (*Bruchus rufimanus*) control

Doftfällor och fångstgrödor för kontroll av bönsmyg (*Bruchus rufimanus*)

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Popular Science Summary

Imagine you are out for a walk in the Swedish countryside a sunny summer day. You are approaching a field of faba beans and notice something strange. At the margins all around the field, sticks with water-filled containers are set up. When you get closer you also notice that test tubes are placed in the center of the containers, from which a fresh scent is emitted. You look up and see the farmer walking towards you. The farmer explains that these are scent traps, set up to capture an insect pest called broad bean weevil whose larvae cause serious quality damage in beans. The traps have two different scents, synthesized to mimic chemical emissions of faba bean flowers and faba bean pods, and they aim to attract broad bean weevils into the traps. To further increase the attractive effect, the farmer grows a strip of an early flowering faba bean cultivar, called Sampo, at the field margins. Since broad bean weevils colonize early flowering faba bean cultivars first the Sampo strip should pull broad bean weevils away from the later flowering faba bean cultivar inside the field and thus work as a trap crop. This control system does not rely on pesticides to secure bean quality, which makes it a great alternative in organic farming and/or in implementation of integrated pest management.

In this experiment, scent traps with flower- and pod scent combined with a Sampo strip were tested and evaluated as a potential means of control of broad bean weevils. The study focused on evaluating how the egg laying and bean damage of faba beans by broad bean weevils are affected and to evaluate if there is any difference in attraction to the two scents between broad bean weevil males and females. The study also aimed to investigate if the total area of potential overwintering sites for broad bean weevils (forest and previous faba bean fields) affect broad bean weevil densities and if they have a particular inflight direction. Five field pairs in Östergötland, Sweden were used, consisting of one treated field with scent traps and Sampo strip and one control field. The results of the study showed that scent traps combined with a Sampo strip has potential to reduce bean damage in faba beans and that egg laying can be reduced in field edges. The results also show that weevil densities are not affected by distance to potential overwintering sites, and they do not seem to have a certain inflight direction. This might be due to reinfection from damaged seed or simply because too few fields were used to give significant results. Due to few samplings of weevils, we could not determine if males and females show a certain preference to one of the two scents. The results of the study show that scent traps combined with a Sampo strip has some potential in broad bean weevil control, however, further investigations are needed to better evaluate the effect.

Sammanfattning

Bönsmyg (*Bruchus rufimanus*) är en skadeinsekt vars larv orsakar skada i åkerböna (*Vicia faba minor* L), vilket reducerar bönornas kvalitet och kommersiella värde. Detta projekts syfte var att testa och utvärdera doftfällor i kombination med fångstgrödor som en biologisk kontroll mot bönsmyg. Två olika dofter användes, en med baljdoft och en med blomdoft, framställda för att locka till sig bönsmyg. Dofterna bestod av kemiska substanser kallade kairomoner som naturligt emitteras av åkerbönor och påverkar bönsmygens livscykel. Blandningen med baljdoft antogs främst attrahera honor och blandningen med blomdoft antogs främst attrahera hanar. Fångstgrödan var en tidigt blommande åkerbönssort vid namn Sampo. I studien användes fem fältpar i Östergötland, Sverige, bestående av ett behandlat fält med en 12m Sampo-remsa kombinerat med doftfällor, och ett kontrollfält. Resultaten visade att doftfällor i kombination med en fångstgröda har potential att minska bönsmygens bönskada i fältkanten (17-21m inne i fältet) och fältets mitt (42-46m inne i fältet). Resultaten visade dock att antalet ägg per balja endast har potential att minskas i fältkanten, inte i fältets mitt. Densiteten av vuxna bönsmygar verkar inte påverkas av avståndet till potentiella övervintringsplatser (skog och tidigare åkerbönsfält) och de verkar inte ha en specifik inflygningsriktning. Resultaten var inte tillräckliga för att avgöra om bönsmygshanar och -honor har en viss preferens för en av de två dofterna.

Nyckelord: Åkerböna, Vicia faba minor, Semiokemikalier, Kairomon

Abstract

Broad bean weevil (*Bruchus rufimanus*) is an insect pest whose larva cause damage in faba bean (*Vicia faba* minor L), reducing bean quality and commercial value. This project aimed to test and evaluate scent traps in combination with trap crops for broad bean weevil control. Two different scents were used, one with faba bean pod scent and one with flower scent, synthesised to attract broad bean weevils. The scents consisted of chemical compounds called kairomones, which are naturally emitted from faba beans and affect the life cycle of the broad bean weevil. The attractant with pod scent was assumed to predominantly attract broad bean weevil females and the attractant with flower scent was assumed to predominantly attract males. The trap crop was an early flowering faba bean cultivar named Sampo. Five field pairs in Östergötland, Sweden each consisting of one treated field with a 12m Sampo strip combined with scent traps, and one control field were used. Results showed that scent traps combined with a trap crop has potential to reduce bean damage in field edges (17-21m inside the field) and field center (42-46m inside the field). However, results show that eggs per pod only have potential to be reduced in field edges not in field center. Broad bean weevil adult densities do not seem to be affected by the distance to overwintering sites (forests and previously grown faba bean fields) and they do not seem to have a certain inflight direction. Results were not enough to determine if males and females show a certain preference to one of the two scents.

Keywords: Faba bean, *Vicia faba minor,* Semiochemicals, Kairomones

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Abbreviations

DW	Dry weight
EFA	Ecological focus area
INRAE	French national research institute for agriculture, food and environment

1. Introduction

Vicia faba L is a leguminous crop of the family Fabaceae and consists of two genotypes, variety major, commonly called broad bean, and variety minor, commonly called faba bean or field bean (Bodner et al. 2018; Fogelfors 2015; Röös et al. 2020). Faba beans, like all legumes, have high value in both human and animal nutrition by being a good source of protein, carbohydrates, minerals and vitamins and there are several benefits to include them in cropping systems (Röös et al. 2020). Faba bean serves as a good break crop in cereal based cropping systems, decreasing crop rotation diseases and increasing soil health due to their deep roots that loosen the soil and their nitrogen fixation (Fogelfors 2015). Faba bean's ability to fixate atmospheric nitrogen increases nitrogen levels in the soil and therefore, nitrogen fertilization to crops grown after faba bean can be reduced up to 100-200 kg N/ha without any yield loss (Jensen et al. 2010). Since production of nitrogen fertilizer emits considerable greenhouse gases through N_2 fixation, growing of faba bean and other legumes can contribute to reduced greenhouse gas emissions (Jensen et al. 2010).

In developing countries, faba bean serves as an important source of protein in the human diet while in most industrial countries it is mostly fed to animals (Röös et al. 2020). However, legumes have great potential to support global protein production by partially replacing meat and dairy products in the human diet, which would contribute to reduced environmental impact and benefit human health (Multari et al. 2015; Röös et al. 2020). If 50% of the current Swedish meat consumption would be replaced by legumes, climate impact would be reduced by 20%, agricultural land use associated with the Swedish diet would be reduced by 23% and there would be less need of nitrogen fertilization (Röös et al. 2020). The interest in faba bean cultivation is growing due to increased interest in local production of protein rich fodder, as an alternative to imported soy (Åkerfeldt & Wivstad 2020). In Sweden, faba bean cultivation has increased drastically since the year 2000 (Jordbruksverket 2020), the cultivation increased about 16 000 ha between 2010 and 2018, however, due to the drought in 2018 the cultivation decreased about 12 000 ha, and in 2019 the faba bean cultivation was 39 390ha (31 140ha conventional and 8250 ha organic) with a total of 2609 producers (Fogelfors 2015; Jordbruksverket 2020). However, due to increased demand of faba bean as animal fodder and new cultivars adapted to a Swedish climate, faba bean cultivation is estimated to increase again (Åkerfeldt & Wivstad 2020).

What is currently constraining faba bean productivity in Europe is the crop's susceptibility to several diseases and insect pests as well as sensitivity to low temperatures (Åkerfeldt & Wivstad 2020). Because of this sensitivity to low temperatures, only spring sown faba beans are sown in Sweden while in other countries like France, winter sown faba beans occur as well (Jordbruksverkent 2020; Åkerfeldt & Wivstad 2020; Hamidi et al. 2021). One of the insects constraining faba bean productivity is the broad bean weevil, *Bruchus rufimanus* Boheman, whose larvae consume bean endosperm, decreasing bean quality, commercial value and the potential to use the beans as food for humans (Epperlein 1992; Roubinet 2016). Broad bean weevil originates from southern Europe and was probably introduced to Sweden with infested imported beans (Ekbom 2012). Broad bean weevils overwinter as adults in sheltered places or as diapausing larvae or pupae in stored beans and re-infest new fields of faba bean in the next growing season (Ekbom 2012; Roubinet 2016). Percent beans damaged by broad bean weevil varies between years but can reach up to 100%, and with the increased faba bean cultivation, damage by broad bean weevils is increasing (Ekbom 2012; Roubinet 2016). Because of limited effects of chemical control against broad bean weevils, as well as the lack of control measures in organic faba bean and ecological focus areas (locations which aims to improve life quality for plants and animals (Jordbruksverket 2021a)), alternative control measures need development (Roubinet 2016). One alternative management method against the broad bean weevil that is under investigation is mass trapping by scent traps. This method uses kairomones (organic compounds emitted by one species that favor another species) that attract broad bean weevil adults into related traps and it relies on trapping as many individuals as possible, before they mate or oviposit, to reduce or eradicate the pest population (Smart et al. 2014; Segers et al. 2021). There are two different kairomonal attractants under investigation, one with flower scent thought to be more attractive to broad bean weevil males, and one with pod scent, thought to be more attractive to broad bean weevil females (Bruce et al. 2011). Another management method could be to use early flowering cultivars of faba bean as trap crops. This method uses the fact that broad bean weevils prefer early flowering cultivars over later flowering cultivars and aims to lure broad bean weevils to an early flowering cultivar grown around a protected later flowering cultivar and thus reduce their inflight and damage in this protected cultivar (Szafirowska 2012; Växtskyddscentralen personal communication 2020). In this study, a combination of kairomonal attractants and trap crops were tested as a possible control measure against the broad bean weevil.

1.1 Purpose

The purpose of the study is to test and evaluate if traps with kairomonal attractants (scent traps) in combination with trap crops is a valid method for broad bean weevil

(*Bruchus rufimanus*) control. The study focuses on evaluating how the egg laying and bean damage of faba beans (*Vicia faba minor*) by broad bean weevils are affected when using scent traps and trap crops in faba bean. Further, the study aims to investigate if the total area of potential overwintering sites for broad bean weevils (forest and previous faba bean fields) affect broad bean weevil densities and if they have a particular inflight direction. The purpose is also to evaluate if there is any difference in attraction to the two kairomonal attractants, flower scent and pod scent, between broad bean weevil males and females.

1.2 Hypothesis

The hypothesis is that the scent traps will attract and capture broad bean weevil adults, stopping them from flying further into the field. The hypothesis is also that the early blooming faba bean cultivar (trap crop) sown as strips at the edge of the field will attract broad bean weevils early in the season, pulling them away from the later flowering cultivar in the field. The combined effect of the scent traps and trap crop will thus hopefully reduce egg laying and bean damage caused by broad bean weevils at the faba beans inside the main field, compared to the faba beans in the trap crop strip and the faba beans grown at the control fields (fields without scent traps and trap crops).

Since broad bean weevil adults overwinter in forest areas and close to previously grown faba bean fields it is expected that faba bean fields situated at locations with a greater area of forest and old faba bean fields will have greater densities of broad bean weevils. Thus, faba bean fields at such locations will likely catch more broad bean weevils in their scent traps. The hypothesis is also that broad bean weevils will colonize the faba bean field from overwintering sites and thus scent traps situated at the same direction as previous years faba bean fields should catch more broad bean weevils compared to other traps.

It is expected that broad bean weevil females will be more attracted to the kairomone attractant with pod scent and males will be more attracted to the kairomone attractant with flower scent. This would imply that scent traps with pod scent catch more broad bean weevil females and scent traps with flower scent catch more broad bean weevil males.

2. Background

2.1 Biology of broad bean weevil

Broad bean weevil, *Bruchus rufimanus* is a Coleoptera that belongs to the family Chrysomelidae, subfamily Bruchinae (Hamidi et al. 2021). There are two ecological groups of bruchids: multivoltine species that have more than one generation per year, and univoltine species that only have one generation per year (Roubinet 2016). The broad bean weevil is a univoltine species, mainly living on *Vicia spp*., where the larvae live inside the beans and consume the endosperm (Hamidi et al. 2021; Medjdoub-Bensaad et al. 2018), adults mainly feed on pollen and nectar (Ekbom 2012). Broad bean weevils overwinter as adults, either free living in sheltered places like holes in the ground, inside old wood or lichens, or they can enter reproductive diapause inside the beans (Ekbom 2012; Tran et al. 1992). When spring temperatures reach 15 degrees Celsius, adults start to colonize crops (Ekbom 2012). First, broad bean weevil males enter the crop at the flower bud stage (BBCH 51) where they feed on extrafloral nectaries (Pölitz & Reike 2019). A day length of 16h is required to terminate their reproductive diapause, which in southern and central Sweden occurs in early May (Roubinet 2016). A day length of 18h is optimal for diapause termination and at a day length below 15h and/or temperatures below 9 degrees Celsius, broad bean weevil adults do not emerge (Ward 2018). Later at the flowering stage (BBCH 65) and when day temperature reach 20 degrees Celsius, females colonize crops (Tran et al. 1992; Pölitz & Reike 2019). There is no information on broad bean weevil flight distance published to my knowledge, however the adults are thought to be able to move over quite far distances (Hamidi et al. 2021).

The females are still in reproductive diapause when they enter the crop but become sexually mature within a few days depending on photoperiod (at least 18h) and pollen consumption (Tran et al. 1992). Before faba bean flowering, post overwintering broad bean weevil adults can temporarily feed on pollen from alternative host species such as wild chervil (*Anthriscus sylvestris L)*, oilseed rape (*Brassica napus* subsp. *Napus L)*, wild Prunus *(Prunus sp., Rosaceae L)* (Hamidi et al. 2021) white clover (*Trifolium repens* L*)*, chamomile *(Matricaria recutita L)*, mustard (*Sinapis arvensis* L*)*, radish (*Raphanus sativus* L *var. oleiformis)*, dill *(Anethum graveolens* L*)*, sunflower *(Helianthus annuus* L*)*, mallow *(Malva* sp L), lacy phacelia (*Phacelia tanacetifolia* L*)*, cornflower (*Cyanus segetum* L*)* and buckwheat *(Fagopyrum esculentum* L*)* (Pölitz & Reike 2019; Hamidi et al. 2021). However, the pollen from faba beans seem to be especially important for sexual maturation of broad bean weevil females (Hamidi et al. 2021). For males, diapause termination mainly depends on photoperiod while for females, long photoperiod alone cannot induce sexual maturation as food resources have to be sufficient as well (Tran et al. 1992). The mating of broad bean weevil adults is thus dependent on the abundance of food resources at the colonization phase (Medjdoub-Bensaad et al. 2018). The mating spans 2-3 weeks and is optimal at 20-25 degrees Celsius; if temperatures go below 20 degrees Celsius or the weather is rainy or windy, mating and oviposition is delayed (Medjdoub-Bensaad et al. 2018). After mating, broad bean weevil males leave the crop while females stay to lay eggs on green pods, thus broad bean weevil males dominate in the crop field in early crop stages and females dominate in later crop stages (Pölitz & Reike 2019).

Females lay eggs on green pods regardless of pod growth stage, thus predominantly the first pods at the lower part of the plant are more damaged since they exist longer throughout the ovulation period compared to the later developed pods on higher nodes (Szafirowska 2012). The females lay between 50-100 eggs with a maximum of ten eggs per pod (Medjdoub-Bensaad et al. 2018). However, egg mortality is around 2-55% and larval mortality is around 64-98%, caused by parasitism (for instance by *Triaspis thoracicus)*, cannibalism, rain and unknown factors (Seidenglanz & Huňady 2016). After ovulation, adult females either die or migrate towards overwintering sites (Medjdoub-Bensaad et al. 2018). After 1-3 weeks the eggs hatch and larvae bore holes through the pod walls and enter the beans where they feed on endosperm (Ekbom 2012). One larva feeds on the same bean the whole season but two to three larvae can feed on the same bean (Ekbom 2012; Segers et al. 2021). There are four larval stages that last 2-3 months in total after which the larvae cut a circular cap before entering the pupal stage (Roubinet 2016). After around ten days, adults emerge from the beans and search for overwintering places (Pölitz & Reike 2019). However, if temperatures go below 20 degrees Celsius, some larvae and pupae might enter diapause and overwinter inside the harvested beans (Ekbom 2012). Figure 1 is an overview of the broad bean weevil life cycle.

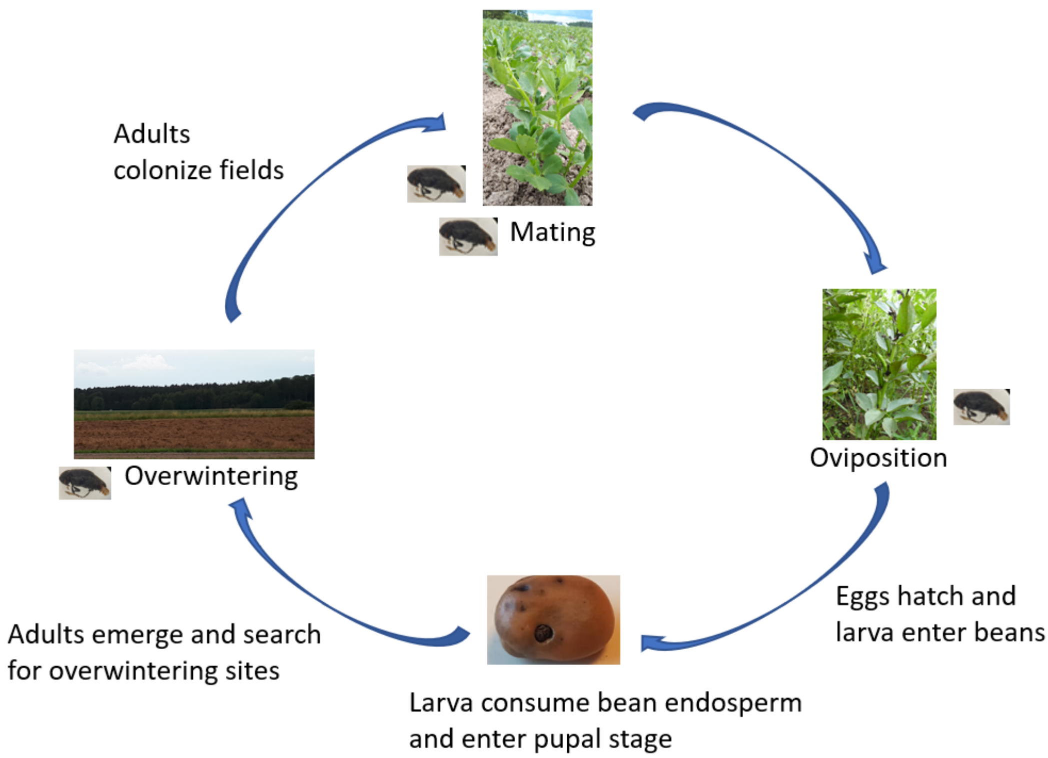

Figure 1. Life cycle of the broad bean weevil, Bruchus rufimanus. Photos: Ylva Johansson

2.2 Damage caused by broad bean weevils in faba bean (*Vicia faba minor*)

The damage in faba bean is caused by broad bean weevil larvae, which consume bean endosperm, while adults are not directly harmful to the crop (Ekbom 2012, Riggi et al. 2021). There are uncertainties whether germination capacity of infested beans is negatively affected (Ward 2018). Some experiments show that faba bean cultivars with small beans or beans stored for longer periods have reduced germination rate when infested by broad bean weevils (Ward 2018). Swedish germination experiments show that infested beans have on average 26% lower germination rate and 9,5% lower thousand seed weight (Wikström 2020). However, other experiments show that damaged beans have increased germination rate because the loss of bean volume (about 3% volume loss) increases water absorption of the bean (Epperlein 1992). Either way, damaged beans used as seed have increased susceptibility to rust and root diseases which might reduce the yield up to 45-70% compared to undamaged beans (Epperlein 1992). In the absence of pollinators, damage by broad bean weevils can increase faba bean yield by inducing reallocation of resources from the roots to pods and beans, which increases pod production or bean weight (Riggi et al. 2021). This is thought to be an overcompensation to both the pod damage and the insufficient fertilisation, however, when pollinators are present this overcompensation is not detectable, suggesting there is a connection between damage by broad bean weevils and cross-pollination on faba bean yield (Riggi et al. 2021). Further, broad bean weevil adults have the potential to increase the number of beans per plant, by acting as cross-pollinators themselves (Riggi et al. 2021). This means that damage by broad bean weevils can increase faba bean yield when pollinators are absent, however, damaged beans have lower commercial value because -beans are not allowed for export due to the presence of insects (Riggi et al. 2021; Röös et al. 2020). The damage threshold for human consumption is 3%, thus the possibility to use the beans for human food is reduced by damage of broad bean weevil (Riggi et al. 2021; Röös et al. 2020). However, damage by broad bean weevil in faba beans intended for local animal feed is not considered an issue since the visual quality is not important (Ward 2018).

2.3 Control measures against broad bean weevils

2.3.1 Preventive control methods

Since 2014, all farmers in the EU must implement integrated pest management (IPM), which strives towards a more sustainable use of pesticides (Jordbruksverket 2021b). This means that preventive methods should be combined with direct action and adaptation of needs to create a more environmentally friendly control of various weeds and pests (Jordbruksverket 2021b). For broad bean weevil, the main preventive method is to use healthy seed to avoid spreading of the pest from storage facilities (Jordbruksverket 2014). Damage by broad bean weevil depends on sowing and harvesting date and faba bean cultivar (Szafirowska 2012; Bachmann et al. 2020). There is a positive correlation between early sowing date and damage by broad bean weevil; by delaying sowing date for 10 days the damage can be reduced by up to 36% in organic production and up to 10% in conventional production (Szafirowska 2012). The delayed flowering and pod setting restrict oviposition by broad bean weevil females, which explains the reduced damage in late sown fields (Szafirowska 2012). However, because of the short growing season in Sweden and faba bean's slow development, early sowing is recommended (Jordbruksverket 2014). By harvesting early before adults emerge (~70% bean dry weight), the adult's life cycle can be interrupted given that the damaged beans are consumed and not used as seed, and reinfection on adjoining land can be reduced (Bachmann et al. 2020). There are uncertainties if increased plant density affects broad bean weevil damage intensity positively or negatively (Ward 2018). The argument that greater plant density increases broad bean weevil damage is that increased plants per m^2 indicate more flowers per m^2 that attract broad bean weevils at a higher level (Ward 2018). However, the argument that a reduced plant density increase broad bean weevil damage is that fewer plans per m^2 can lead to reduced pod density which might lead to higher levels of oviposition on a fewer number of pods (Ward 2018). The optimal commercial plant density for spring sown faba bean is 55 plants per m^2 so it is also likely that the reduction in yield due to a reduction in plant density is not economically favorable for broad bean weevil control (Ward 2018). Experimenting with plant density might therefore not be a good option to prevent broad bean weevil infestation (Ward 2018).

The difference in damage susceptibility to broad bean weevil among cultivars depends on plant morphology, time of flowering and pod setting and involvement of different defense mechanisms (Carrillo-Perdomo et al. 2019; Szafirowska 2012). If the time of flowering and pod setting of the faba bean cultivar benefits broad bean weevil life cycle the damage will increase. Broad bean weevil females have a lower tendency to move from a flowering plant that provides pollen, and thus more eggs are laid on faba beans that still have flowers when the first pods are set (Medjdoub-Bensaad et al. 2018). When grown together, early flowering cultivars (i.e SU-BT and Divine), attract broad bean weevil females earlier than later flowering cultivars (i.e Melodie and Merkur), which makes oviposition in the early flowering cultivar start earlier and last longer (Seidenglanz & Huňady 2016). Cultivars with stronger and more complex pod valves and bean tissue (i.e Divine and Merkur) have greater egg and larval mortality compared to those with weaker tissues (i.e SU-BT and Melodie) (Seidenglanz & Huňady 2016). The difference in damage susceptibility among cultivars is likely mostly due to differences in plant architecture, flowering period and abundance, and the timing of pod formation

(Ward 2018). However, faba bean accessions partially resistant to broad bean weevil infestation have been found in the faba bean cultivars Côte d'or, Nova gradiska and 223303 (Carrillo-Perdomo et al. 2019). The resistance comes from antibiosis and or antixenosis mechanisms i.e. thickness, hardness and texture of pod valves which creates a mechanical barrier against larvae and/or prevents attachment of eggs and biochemical defense barriers in the bean coat (i.e alkaloids, polyphenols, lectins, proteinase inhibitors, α-amylase inhibitors, etc.) which may reduce the fertility and/or oviposition and increase the development time and/or larvae, pupae and/or adult mortality (Carrillo-Perdomo et al. 2019). Resistant accessions might also be present in the faba bean cultivar Fuego since it showed significantly less bean damage compared to Fury in a field experiment made in UK despite similar time of flowering and pod setting in the two cultivars (Ward 2018). The difference in damage susceptibility between cultivars is not well understood but research is in progress (Seidenglanz & Huňady 2016; Ward 2018). A Swedish experiment show that in organic farming, the faba bean cultivar Boxer have significantly more eggs per pod compared to Aurora and Gloria and in conventional farming, Capri and Boxer have significantly more eggs per pod compared to Gloria and Daisy (Wikström 2020). There was a strong positive correlation between pod length and number of eggs as well as between early cultivars and/or early sowing date and number of eggs (Wikström 2020). However, the differences between the cultivars might also be due to antibiosis and/or antixenosis and thus are in need of further investigation (Wikström 2020). There are currently no faba bean genotype showing complete resistance and thus there is a need for more breeding programs (Carrillo-Perdomo et al. 2019).

2.3.2 Chemical control

Because the larvae of broad bean weevils live inside the beans, they are hard to treat with insecticides. Chemical management methods therefore focus on the ovulating females (Ekbom 2012). The critical stage of damage by broad bean weevils is when pods are at 2cm length (from finished bloom and 10-15 days thereafter) (Biarnes et al. 2019). The commercialized insecticides against broad bean weevil adults in Europe are pyrethroids and neonicotinoids (Roubinet 2016). However, because of these insecticides' negative effects on pollinators, there are restrictions in their use (Roubinet 2016). In Sweden, only the two pyrethroids Mavrik (active substance tau-flauvinate 240g/l) and Fastac (active substance alphacypermethrin 50g/l) are currently authorized for use in bean production (Jordbruksverket 2021b). The effect of these two insecticides against the broad bean weevil is unclear and there are therefore no recommendations in their use (Jordbruksverket 2021b). An experiment in Sweden in 2019 showed that early treatments with Mavrik and an earlier used neonicotinoid (Biscaya, active substance thiacloprid 240g/l) increase bean yield compared to untreated fields, however, the economic gain is low because the increased yield income does not compensate for the cost of insecticide use (Eriksson 2019). Another Swedish study in 2017 showed no effect on broad bean weevil damage when using Biscaya (Raderschall et al. 2021). The small effects of chemical control on broad bean weevil might be due to difficulties in determining optimal spraying time (Raderschall et al. 2021). Since broad bean weevil biology is highly influenced by the weather, current economic thresholds are based on temperature rather than pest density (Ramsden et al. 2017). In Sweden, no economic threshold for broad bean weevil control is set, however, the current economic threshold in the UK is when adults are present, and temperature has reached 20 degrees Celsius on two consecutive days during pod setting (Ramsden et al. 2017). This threshold does not provide farmers with useful guidance on at which weevil densities application of insecticides is justified, thus there is a need for new economic thresholds in order to improve insecticide use (Ramsden et al. 2017). Fumigation of faba bean beans in storage facilities is used as broad bean weevil control in some countries, particularly California and Australia (Roubinet 2016). However, several of the fumigant gases e.g. phosphine are highly toxic to animals and plants and therefore there are strict regulations in their use (Roubinet 2016). In Sweden no chemical fumigants against the broad bean weevil are registered for use (Kemikalieinspektionen 2020).

2.4 Semiochemicals for pest monitoring and control

In order to detect and monitor broad bean weevil presence, semiochemical traps can be used (Bruce et al. 2011). Semiochemicals are volatile and non-volatile organic compounds sent out by organisms causing chemical signals that make communication with other organisms possible (Law & Regnier 1971). Semiochemicals that are used for communication within a species (intraspecific) are called pheromones and semiochemicals that are used for communication between different species (interspecific) are called allomones and kairomones (Law & Regnier 1971). Allomones are interspecific semiochemicals that favor the producer and kairomones are interspecific semiochemicals that favor the receiver (Law & Regnier 1971). Investigations show that faba beans transmit kairomones that favor the broad bean weevil, which are released by faba bean flowers, providing food localization signals and by faba bean pods providing oviposition signals (Segers et al. 2021). There are also pheromones transmitted from broad bean weevil males, attracting females (Bruce et al. 2011). Kairomones transmitted from faba bean and pheromones from broad bean weevil males have been sampled and specific blends based on natural ratios have been elaborated to develop effective attractants to use in semiochemical traps (Bruce et al. 2011).

There are nine identified kairomones emitted by faba bean flowers that attract broad bean weevil: myrcene, (R)-limonene, (E)-ocimene, (R)-linalool, 4-allylanisole, cinnamyl alcohol, cinnamaldehyde, α-caryophyllene and β-caryophyllene (Bruce et al. 2011). Studies show that a combination of three of these kairomones, (R)-linalool (17,7 mg/day), cinnamyl alcohol (0,4 mg/day) and cinnamaldehyde (0,77 mg/day) trap about ten times more broad bean weevils than unbaited traps, and that males are more attracted than females (Bruce et al. 2011). Complex blends containing several kairomones increase broad bean weevil catches about 50% compared to the blend with only three kairomones, however, because of the increased cost, this is not justified for commercial use (Bruce et al. 2011).

The value of semiochemical monitoring of the broad bean weevil is limited because the pesticide use efficiency is low anyways (Segers et al. 2021). Furthermore, the faba bean's strong floral odors reduce the attraction to the semiochemical traps (Segers et al. 2021). To outcompete the faba beans´ strong flower scent, the French national research institute for agriculture, food and environment, INRAE, have developed a kairomonal attractant with the scent of a faba bean pod (Ene Leppik personal communication; Segers et al. 2021). This kairomonal attractant is thought to be useful in semiochemical mass trapping (Ene Leppik personal communication). Mass trapping is a management method that relies on trapping as many individuals as possible, before they mate or oviposit, to reduce or eradicate pest population (Smart et al. 2014). The semiochemical traps must be more effective than natural sources of attraction throughout the entire reproductive stage of the insect pest to reduce damage, and the yield benefits must overcome the cost of the traps for them to be a suitable management option (Smart et al. 2014). Mass trapping can also be combined with insecticides in a lure and kill technique or with insect pathogens in a lure and infect technique (Smart et al. 2014). This means insecticide use is limited to a smaller area, which reduces environmental impact compared to regular insecticide use (Smart et al. 2014).

Another implementable semiochemical control method for broad bean weevil is "push pull" which consists of manipulating the pest behaviour via the integration of stimuli that act to make the protected crop unattractive (push) while luring them toward an attractive source (pull) from where the pests are collected and removed (Cook et al. 2007). The repellant could for instance be botanical oils of *Artemisa campestris* L, nigella and mustard, which have repellence/oviposition-deterring/insecticidal effects on the broad bean weevil, and the pulling agent could be synthetic kairomones associated with traps in the field margins (Segers et al. 2021).

2.5 Trap crops

Another IPM management strategy against insect pests is to use trap crops. Trap crops are crops grown to attract insect pests, or other organisms like nematodes, to protect target crops from pest attack (Hokkanen 1991; Shelton & Badenes-Perez 2006). The trap crops prevent the pests from reaching the protected target crop by concentrating them in a certain part of the field (Hokkanen 1991). The principle relies on using a trap crop that the insect pest shows distinct preference to (i.e certain plant species, cultivars, or a certain crop stage) in order to prevent them from moving into the target crop (Hokkanen 1991). If the insect pest significantly prefers the trap crop, damage in the main crop can drastically be reduced (Shelton & Badenes-Perez 2006). For instance, flea beetles significantly prefer turnip rape over cauliflower (about 96% preference to turnip rape in greenhouse and 97% preference in open field) (George et al. 2019). By growing borders of turnip rape around cauliflower, flea beetle damage can be reduced by 40% (George et al. 2019).

To increase the efficiency of a trap crop, insect preference can be altered, for instance through cultural management (i.e. sowing date) or breeding programs, to develop cultivars with enhanced attractiveness to the insect pest and or natural enemies or cultivars with enhanced larval/egg mortality (Shelton & Badenes-Perez 2006). In Arkansas (USA), the early soybean cultivar *Glycine max L.* were sown as a trap crop for stink bugs around a later soybean cultivar (Smith et al. 2009). However, the trap crop was not sufficient to reduce stink bug populations due to the widespread distribution of early soybean fields in Arkansas that multiply and spread stink bugs (Smith et al. 2009). Additionally, the trap crops were only attractive for stink bug oviposition up to 4-5 weeks, and thus did not protect the main crop all season (Smith et al. 2009). This is also the case when using safflower as a trap crop against mirid bugs in cotton (Wang et al. 2021). Safflower has a flowering period of 4-5 weeks while cotton flowering lasts for 6-7 weeks (Wang et al. 2021). If mirid bugs oviposition is still active when safflower flowering is over, there is a risk that they continue into the flowering cotton and make damage (Wang et al. 2021). Therefore, it is important to customize trap crop species, cultivar and sowing date after the biology of the insect pest and characteristics of the main crop (Hokkanen 1991). Trap crops are mainly grown around the main crop, a method relying on an initial edge effect that reduces/prevents pest dispersal into the main crop (George et al. 2019). This method is insufficient in control of insect pests with undirected/random dispersal patterns (George et al. 2019). For such pests, intercropped trap crops might be a better solution (George et al. 2019). For instance, the trap crop effect of safflower (*Carthamus tinctorius*) in Chinese cotton against mirid bugs (*Lygus pratensis*) increase when safflower is intercropped (sown on two edges and in the middle of the field) compared to Safflower only sown on two edges of the field (Wang et al. 2021). However, this seemed to be rather due to the total area of safflower (12.5% of the crop area when intercropped and 10% when sown on two edges) than sowing pattern (Wang et al. 2021). General guidelines are that about 10% of the total crop area should be planted with a trap crop for it to be efficient (Hokkanen 1991).

The potential to use early flowering cultivars of faba bean as a trap crop in broad bean weevil control has been investigated in Sweden in 2020 (Anders Arvidsson, the Plant Protection Centers of the Swedish Board of Agriculture, personal communication 2021). When early and later flowering cultivars of faba bean are grown together (i.e early flowering SU-BT and Divine and later flowering Melodie and Merkur), broad bean weevil females are more attracted to early flowering cultivars, which make them more damaged than later flowering cultivars (Seidenglanz & Huňady 2016). In the Swedish field experiment, three faba bean fields were grown with a 12m strip of the early flowering faba bean cultivar Sampo as a trap crop, attracting broad bean weevil females early in the season and making them less likely to move further into the field (Anders Arvidsson, the Plant Protection Centers of the Swedish Board of Agriculture, personal communication 2021). The percentage of damaged beans and average eggs per pod in the trap crops were greater than for the field cultivars, (56 % vs 27 % damage and 8 vs 5 eggs per pod (Figures 2-3) (Anders Arvidsson, the Plant Protection Centers of the Swedish Board of Agriculture, personal communication 2021). The broad bean weevil thus seems to prefer the trap crop over the field cultivar, however, the experiment lacked control fields, so it is difficult to say if the use of a Sampo strip reduces damage of the broad bean weevil (Anders Arvidsson, the Plant Protection Centers of the Swedish Board of Agriculture, personal communication 2021). Early cultivars of faba beans also often give lower yields compared to later cultivars, which means that the method might not be economically favorable (Anders Arvidsson, the Plant Protection Centers of the Swedish Board of Agriculture, personal communication 2021).

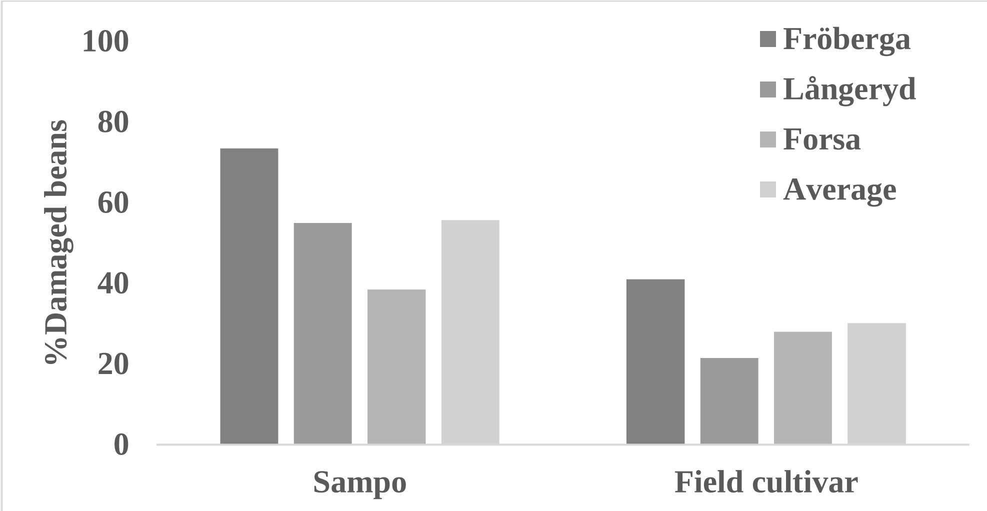

Figure 2. The percentage damaged beans in Sampo (trap crop) and field cultivars in three Swedish faba bean fields (Fröberga, Långeryd and Forsa) (Anders Arvidsson, the Plant Protection Centers of the Swedish Board of Agriculture, personal communication 2021).

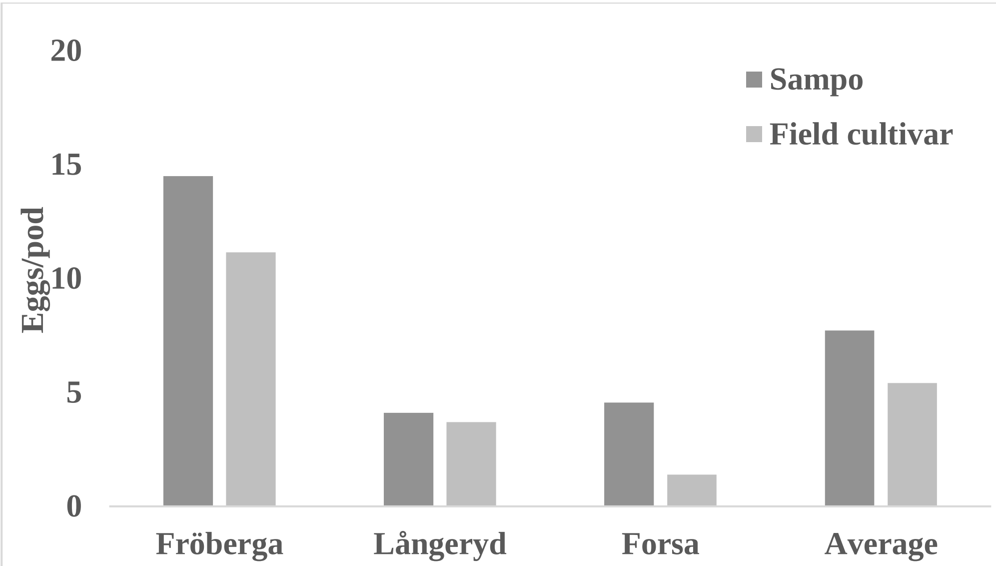

Figure 3. Average broad bean weevil eggs per pod in Sampo (trap crop) and field cultivars in three Swedish faba bean fields (Fröberga, Långeryd and Forsa) (Anders Arvidsson, the Plant Protection Centers of the Swedish Board of Agriculture, personal communication 2021)

2.6 Combining trap crops with attractants or repellents

To make trap crops even more effective they can also be combined with attractive pheromones or semiochemicals and/or repellents in the main crop, creating a push-pull system (Segers et al. 2021). The most famous push-pull system was developed 1994 in sub-Sahara, Africa, where smallholder cereal farming use different types of companion crops with natural semiochemicals that repel the insect pest, a lepidopteran (moth) stem borer, and/or attract insect pest predators (Picket et al. 2014). In order to find the most effective companion crop, samples of the released volatiles were analysed by gas chromatography, coupled with electrophysiological recordings from moth stem borer antennae (Picket et al. 2014). Intercropping maize with "push" plants like silverleaf desmodium (*Desmodium uncinatum*) or greenleaf desmodium (*D. intortum*) combined with borders of "pull" plants like Napier grass (*Pennisetum purpureum*) or *Brachiaria* cv *mulato* II has proven to be an effective push-pull system against lepidopteran (moth) stem borer in the smallholder cereal farming in sub-Sahara (Picket et al. 2014). The system is being further improved by gene-modifying techniques (for instance by providing the crop plant with the push trait itself) to qualify in industrialized farming (Picket et al. 2014). In Georgia, US, push-pull has been tested in cotton sown with two adjacent rows of soybean trap crops with or without pheromone traps for stink bug control (Tillman et al. 2015). Soybean proved to be an effective trap crop for stink bugs, both when used alone and once combined with pheromone traps (12,5% and 10,2% boll injury respectively, compared to the control with 21,7% boll injury), however, pheromone traps alone were not sufficient in stink bug control (20,8% boll injury compared to a control with 21,7% boll injury) (Tillman et al. 2015). This is because stink bug females are not attracted to the pheromone until they mature, which they do not until they find a sufficient food resource, i.e soybean (Tillman et al. 2015).

3. Material and Methods

3.1 Project setup

Five pairs of faba bean fields in Östergötland, Sweden were included in the study. All fields were organic or grown as ecological focus area with no use of pesticides. Six fields were in the northwest part of Östergötland and four in the eastern part. Each pair of fields consisted of one treated field with scent traps and trap crops and one control field without scent traps and trap crops, situated in the same cropping area as their treated field pair. All five treated fields were grown with a 12m (4 fields) or 16m (1 field) strip, about 6-8% of the entire field, of the early blooming faba bean cultivar Sampo along the entire outer edge of the field, this cultivar was considered the trap crop. In the Strip, scent traps were deployed with 20m intervals throughout the fields (figure 4) (35-53 traps per field depending on field size and geometry) from BBCH 50 to 85 and dates 2021-06-04 to 2021-07-23. In all fields, both treated and control, the field was divided into three transects, one in the center of the Strip (at 6m or 8m, Strip transect), one at 5 m from the Strip (17m or 21m from field edge depending on Strip width, Edge transect), and one at 30 m from the Strip (42m or 46m from the field edge depending on Strip width, Center transect) (figure 5). The fields were given an individual two letter code with the first letter pairing the fields (N, F, L, E, and T) and the second being T for treated and R for control. The fields were sown between date 2021-04-11 and 2021-04-29, all field pairs were sown on the same date and had less than 170m apart except for field LT and LR that were sown with one day apart and had a 6km distance. The faba bean cultivars grown were either Fanfare, Fuego, Stella, Aurora or Paloma. The average distance from last year's closest faba bean field, total area of faba beans grown last year and total forest area within a 1km and 2km radius were measured in ArcGIS (table 1).

Figure 4. Field LT at the installation of scent traps (BBCH 50). Photo: Gustaf Tim.

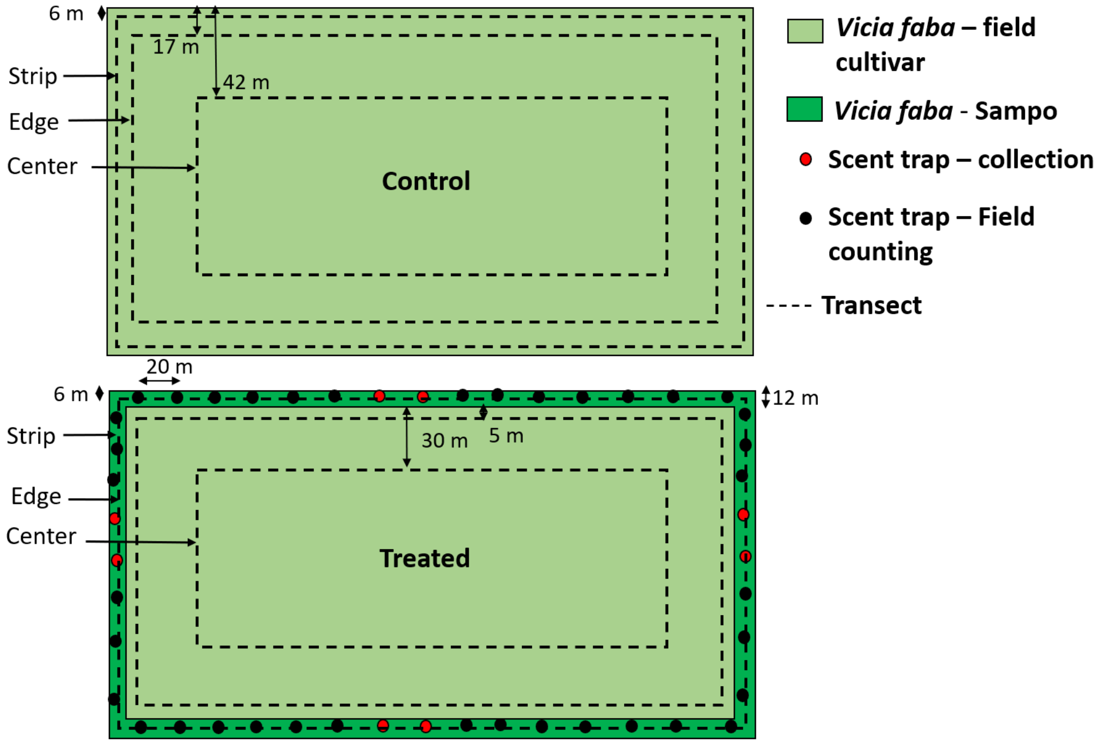

Figure 5. General setup of the control (top) and treated (bottom) fields with transects and scent traps. The top figure of control field include distances of transects to the field edge (6, 17 and 42m) and the bottom figure of treated field include distances between the strip and the edge (5m) and center (30m) transects.

Table 1. Field information with field size, sowing date, faba bean cultivar, if the field were organically grown, average distance from last year's faba bean field in meters (Distance lastfield), the average area of forest and faba beans grown last year within 1km and 2km radius from this year's field in hectares (Forest1km, Forest2km, Beans1km and Beans2km) the distance between fields within pairs in meters and the number of scent traps set up.

Field	Size (ha)	Sowing date	Cultivar	Organic	Distance lastfield	Beans1km	Beans2km	Forest1km	Forest2km	Field pair distance	Scent traps
NT	3,4	2021-04-26	Fanfare	Yes	613,3	12,35	17,50	20,33	57,70	130	44
NR	2,1	2021-04-26	Fuego	Yes	643,9	11,48	17,50	16,10	49,99	130	0
FT	3,4	2021-04-11	Stella	Yes	904,5	2,00	72,06	31,87	241,62	12	35
FR	7	2021-04-11	Stella	Yes	820,5	3,48	75,26	33,85	242,27	12	0
LT	4	2021-04-19	Fanfare	No	820,5	0,00	5,68	6,38	92,92	6000	43
LR	2,5	2021-04-20	Fanfare	Yes	1600	0,00	27,72	45,37	212,43	6000	0
ET	4,2	2021-04-27	Aurora	Yes	925,3	1,45	9,81	54,82	234,67	15	47
ER	11	2021-04-27	Aurora	Yes	607,2	6,79	9,81	46,07	228,47	15	0
TT	4,1	2021-04-29	Paloma	Yes	60,1	31,88	45,39	51,86	182,52	165	53
TR	9,0	2021-04-29	Paloma	Yes	48	31,88	45,39	52,81	191,23	165	0

3.2 Measurements and sampling

3.2.1 Scent traps

The scent traps used in the field experiment were developed by INRAE (the French national research institute for agriculture, food and environment) and are under investigation by the French company Agriodor. In this project two different kairomonal attractants were used: one with the scent of a faba bean flower, developed by Bruce et al. (2011) and one with the scent of a faba bean pod, developed by INRAE. The kairomonal attractant with flower scent contains (R)-linalool (94%), cinnamyl alcohol (2%) and cinnamaldehyde (4%) (Bruce et al. 2011) and the kairomonal attractant with pod scent contains cis-3-hexenyl acetate (30-40%), octamine (15-20%), linalool (10-20%), α-caryophyllene (10-20%) and limonene (15-20%) (Ene Leppik, personal communication). The kairomonal attractants are placed in Eppendorf pipes, green pipes with pod scent and blue pipes with flower scent. The Eppendorf pipes were then placed into circular plastic containers with an attached cylinder that keeps the Eppendorf pipe protected from environmental disturbance. The container was attached at a stick placed in the ground at the edge of the faba bean fields. The container was filled with water mixed with scentless dishwashing detergent, where the insects that are attracted to the scent can be trapped (figure 6). The scent traps were loaded at flower bud stage, BBCH 50 which occurred on the 4th of June in fields FT and LT and on the 10th of June in fields NT, ET and TT. Every other trap was loaded with pod scent and every other with flower scent. At pod set, BBCH 71, on the 1st of July, all kairomonal attractants were exchanged with pod scent. For field TD the new pod attractants were not enough to replace all old attractants so for the five last scent traps two old pod attractant kairomones were placed instead of one new.

Figure 6. Scent trap loaded with kairomonal attractant with pod scent. Photo: Ylva Johansson.

The scent traps were refilled with water mixed with scentless dishwashing detergent once a week in order to not dry out. Once a week the trapped broad bean weevils were counted directly in the field in all traps except the collection traps (see below), and the traps were emptied and refilled with the water mixture. Two scent traps, one of each kairomonal attractant, from each side of the fields (4 or 3 sides depending on if the field had a square or triangular shape) were marked as sampling traps. From the sampling traps, all trapped insects were collected into jars with alcohol and were marked with trap number and from which direction they were placed on the field. If the sampling traps did not contain any broad bean weevils no sample was collected. The sampling and counting of broad bean weevils continued for seven weeks until the 23rd of July at the beginning of bean maturation, BBCH 78-88. In total 103 samples were collected, 14 from traps with flower attractant and 89 from traps with pod attractant. From the collected samples all broad bean weevils were sorted out and the number of females and males were identified using a microscope. Broad bean weevils were defined as males if they had a spur on their middle leg and as females if a spur was lacking (figures 7 and 8) (Hamidi et al. 2021; Segers et al. 2021).

The number of ovulating females per treated and control field was estimated using the average number of broad bean weevil eggs per m^2 (sampling and calculations explained in sections 3.2.2-3.2.3) grouping fields by treatment. The number of eggs per m^2 was multiplied by the average field area to get the number of eggs laid in the whole field and then divided by 100, based on the maximum number of eggs one female can lay in a season (Medjdoub-Bensaad et al. 2018), to get the average number of ovulating females in the field. The average number of broad bean weevils caught per field during all trapping weeks was then divided by the total weevils estimated in the field to estimate the percentage of weevils captured by the traps.

Figure 7. Broad bean weevil male. Middle leg containing a spur. Photo: Ylva Johansson.

Figure 8. Broad bean weevil female. Middle leg lacking a spur. Photo: Ylva Johansson.

3.2.2 Broad bean weevil eggs

The sampling of broad bean weevil eggs was conducted on the 7th of July at BBCH 72-79. Fifty pods per transect were sampled from each field (both treated and control fields), one third from the lower level of the plant, one third from the middle level and one third from the upper level. All pods were put in paper bags marked with the name of the field and transect (Strip, Edge or Center). The samples were put in the freezer overnight and the eggs on the pods were counted the next day by using a microscope or hand lens (figure 9).

Figure 9. Faba bean pod with broad bean weevil eggs. Photo: Växtskyddscentralen Linköping.

3.2.3 Broad bean weevil bean damage

One week before bean sampling (about one week before harvest, BBCH 89), the amount of faba bean plants was counted per square meter in four random places in each transect on all fields. The number of pods per plant were also calculated on ten random faba bean plants per transect. This was done in order to compare the overall broad bean weevil damage per area unit between fields and transects and were used in the calculations of overall price loss caused by broad bean weevil damage. The places of the plant and pod calculation were evenly spread out over the transect and randomly chosen. At one landscape, the treated and control fields were harvested before pods per plant were counted and thus values for these fields are lacking (fields LD and LR).

The sampling of beans was made on the 24th of August at BBCH 89, about one week before harvest. Two treated fields and one control field were already harvested at the sampling, but beans could still be collected from spillage. About 90 pods from each transect (Strip, Edge and Center) were collected randomly selected from lower, middle and upper nodes of the faba bean plant, and put into paper bags marked with field and transect. The pods were kept dry in the laboratory for 1,5 months before analysis in order to give the larvae time to develop into adults that create windows or complete holes in the beans. In each sample, the pods were counted and the proportion of damaged beans with broad bean weevil windows and/or holes were analysed (figure 10). After sorting the beans as undamaged or damaged they were dried for 48 hours in 65 degrees Celsius and weighed to get the bean dry weight which was used in total yield and harvest loss percentage calculations.

Figure 10. Faba bean bean in three stages of damage caused by broad bean weevil. From left: Circular cap "window" is cut by the weevil larva before entering pupa stage; adult emerging; an emergence hole is left in the bean. Photo: Ylva Johansson.

In order to calculate the total harvest, dry weight (DW) in kg/ha, the harvest of undamaged and damaged beans in kg/ha was calculated for each transect of both treated and control fields. These values was then summarized (Formula 1).

Formula 1. Calculations of total harvest dry weight

$$\frac{Total\ DW\ undamaged\ beans\ [kg] + Total\ DW\ damaged\ beans\ [kg]}{Total\ number\ of\ beans} = Average\ DW\ per\ bean\ [kg]$$

$$Beans\ per\ pod * Pods\ per\ plant * Plants\ per\ ha * Average\ DW\ per\ bean\ [kg] = Total\ harvest\ DW\ \left[\frac{kg}{ha}\right]$$

3.2.4 Statistic analysis

The statistical analysis was conducted in R Studio x64 4.1.1. For all data a dot chart and histogram were constructed to investigate if the data was normal, Poisson or negative binomial distributed to further choose the correct model. For models that were considered normally distributed the package lmer was used and for models considered Poisson or negative binomial distributed the package glmmTMB was used. A qqplot was constructed to check for normality and if needed, models that assumed normal distribution was reconstructed with either a square root or logarithmic transformation. All models were tested using Anova type III with a confidence level of 0,95. Significance intervals used was; 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1.

In the analysis of captured broad bean weevil adults, three different models were constructed. The first model investigated if the direction of scent traps and/or the direction of last year’s closest faba bean field affected the number of broad bean weevils captured. The second and third model investigated if the total area of faba beans grown last year and the total forest area within 1km or 2 km radius, respectively affected broad bean weevil catches. Field was used as random effect. All three models assumed negative binomial distribution. The analysis organized generalized directions, north, south, east and west, of all five fields separately, however all traps of one field direction was grouped and their total broad bean weevil catches over the total trapping days was summarized.

The fixed effects used in the egg, bean damage and yield analyses were treatment, transect and their interaction. If the Anova showed a significant interaction effect, a post-hoc test was constructed to investigate which treatment combinations that showed significant differences. If the Anova did not have any significant interactions, the model was reconstructed, not including the interaction and a post-hoc only analyzing the significant main effects was constructed. Figures showing mean and dispersion of values across factors of interest were constructed in R Studio.

In the egg data analysis three different models were constructed. Two with the response variable eggs per pod, where one included all field pairs and one excluded fields LD and LR because of the great distance between this field pair (6km) making the treated and control field less comparable compared to the other four field pairs. These models were considered Poisson distributed with the random effect observation nested within transect, treatment and field pair. The third egg model used the response variable eggs per m^2 to analyse the number of eggs per area unit, rather than per pod, in the field transects. Before constructing this model, a model with the response variable pods per m^2 was constructed to investigate if a greater number of eggs per pod could be due to less pods per m^2 rather than higher overall pest pressure. The average values of pods per plant and plants per m^2 were calculated for each field transects. Only four field pairs were included in this analysis because values for fields LD and LR were lacking. The average values of pods per plant and plants per m^2 were then multiplied in order to get the average pods per m^2. These average values were then analysed with a log normal distribution model with the random effects field and treatment. In order to get average eggs per m^2 to use in the eggs per m^2 analysis, average eggs per pod values for each field transect were multiplied with the average pods per m^2 values. The model was considered log normal distributed with treatment nested within field pair as random effects.

In the analysis of bean damage, the percentage damaged beans were used as response variable. The model was run twice, once including all field pairs and once excluding fields LD and LR. Both models were considered normally distributed after square root transforming the data. Field and treatment were used as random effects. For the yield analysis, the log-transformed total bean yield in kg/ha was used as response variable, assuming normal distribution. Field and treatment were used as random effects. This model excluded fields LD and LR because sampling values of plants per m^2 and pods per plant was lacking and thus the total bean yield could not be calculated for these fields.

4. Results

4.1 Scent traps

During the seven weeks the scent traps were set up, 3852 broad bean weevils were trapped, which on average equals to 2.4 broad bean weevils per trap. The catches started to increase in week 26 with a peak the 7th of July with 1765 broad bean weevils in total (on average 8.0 per trap). The lowest capture was during the last week the 22nd and 23rd July with 74 in total (on average 0.3 per trap) (table 2 and figure 11). The first week, the 10th of June, only two fields had prepared scent traps while the other weeks all five fields were prepared which affects the average broad bean weevils per trap calculations. The statistical analyses show no significant effect on broad bean weevil catches of either trap direction (grouping traps of the same cardinal direction, grouping all fields), the direction of last years closest faba bean field, or the total area of faba beans grown last year or forest area within 1km and/or 2km radius (table 3). The estimation of ovulating females is 394224 per field in treated fields and 637899 per field in control fields. Based on the number of weevils in treated fields and the average catch of 770 weevils per field over the season, 0.2% of the total number ovulating females are trapped by the scent traps.

Table 2. Number of broad bean weevils (Bruchus rufimanus) trapped in the scent traps each week between 2021-06-10 and 2021-07-23

Date	Week	Total broad bean weevils	Average broad bean weevils per trap
2021-06-10	23	42	0.50
2021-06-17/18	24	218	0.86
2021-06-24	25	130	0.56
2021-07-01/02	26	757	3.23
2021-07-07	27	1765	7.98
2021-07-15/16	28	866	3.65
2021-07-22/23	29	74	0.32

Total	3852	2.44

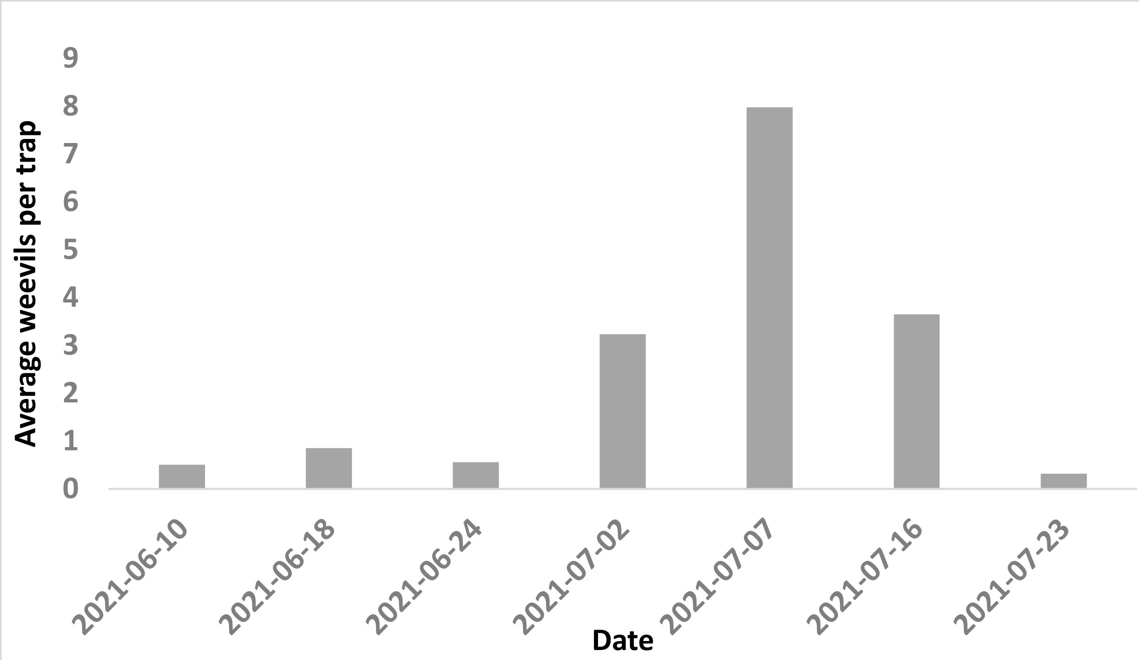

Figure 11. Average captured broad bean weevils per trap and week between 2021-06-10 and 2021-07-23

*Table 3. Chi-Square (X^2) and p-values (p) given from the statistical Anova tests of the broad bean weevil catches. Significance is indicated by 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1. The table include conditional R-square (R2c) to represent the variance explained by the random effects and marginal R-square (R2m) to represent the variance explained by the fixed effects. The fixed effects are direction of last year's faba bean field (Last field direction), direction of traps (Trap direction), forest area within 1 and 2km radius (Forest1km and Forest2km) and the total area of faba beans grown within 1km and 2km radius from this year's faba bean field (Beans1km and Beans2km).*

Response:	Broad bean weevil catches			
	X^2	p	R2c	R2m
Intercept	99.40	<2e-16 ***	0.123	0.0045
Last field direction	0.20	0.653		
Trap direction	0.56	0.90		
Intercept	15.70	7.428e-05 ***	0.072	0.023
Beans2km	1.80	0.17		
Forest2km	1.40	0.24		
Intercept	13.10	0.0003 ***	0.098	0.0049
Beans1km	0.17	0.68		
Forest1km	0.20	0.66		

4.2 Identification of broad bean weevil sexes

In total 581 broad bean weevils were collected for sex identification; 23 from scent traps with flower attractant and 558 from scent traps with pod attractant. Of the collected broad bean weevil adults, 439 were females and 142 were males which corresponds to 76% females and 24% males (table 4). The captures started to increase during week 26 and peaked during week 27 (20201-07-07) with 77% females and 23% males (figure 12). During the remaining two weeks the captures steadily decreased. The data of broad bean weevil sexes were not statistically analyzed because of too few specimens were caught in traps with flower attractant.

Table 4. Broad bean weevil sexes from the sample traps each week between 2021-06-10 and 2021-07-23.

Date	Week	Attractant	Total broad bean weevil	Females	Males
2021-06-10	23	Flower	4	2	2
2021-06-10	23	Pod	2	1	1
2021-06-18	24	Flower	9	2	7
2021-06-18	24	Pod	10	8	2
2021-06-24	25	Flower	10	7	3
2021-06-24	25	Pod	7	3	4
2021-07-01	26	Pod	63	53	10
2021-07-02	26	Pod	32	20	12
2021-07-07	27	Pod	305	235	70
2021-07-15	28	Pod	30	26	4
2021-07-16	28	Pod	95	70	25
2021-07-22	29	Pod	3	3	0
2021-07-23	29	Pod	11	9	2
Total			581	439	142

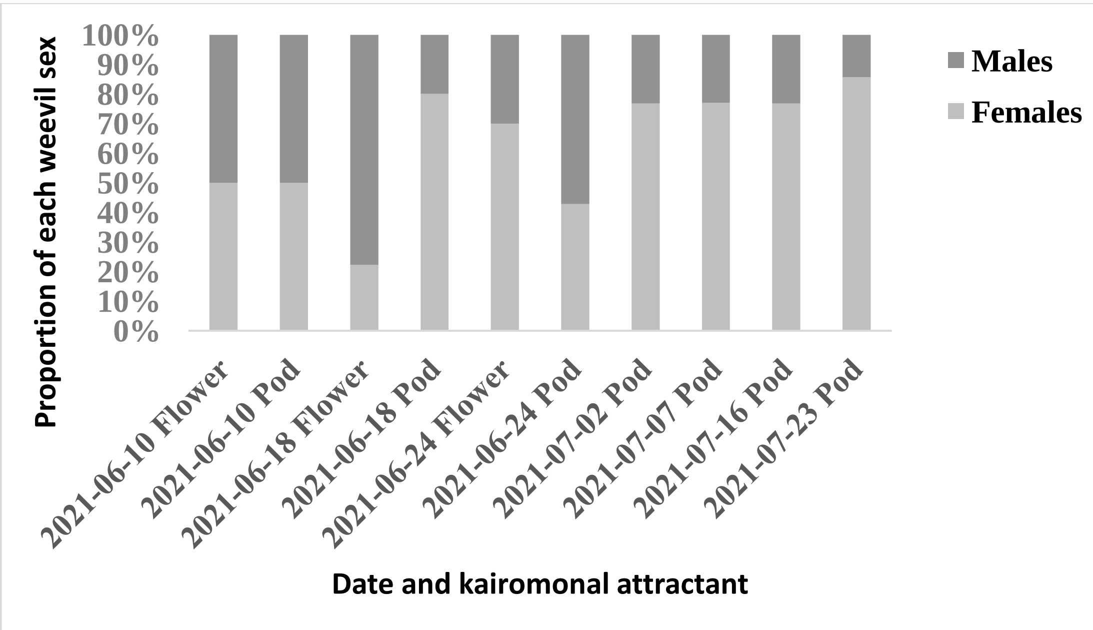

Figure 12. The percentage of males and females collected for sex determination between date 2021-06-10 and 20201-07-23.

4.3 Broad bean weevil eggs

The analysis of eggs per pod showed that there is a significant interaction effect of treatment and transect (table 5). The post-hoc tests show that there are significantly more eggs per pod in the treated strip compared treated edge and center ($p<0,001$) but no significant difference between the treated edge and treated center (figure 13). There is no significant difference between control transects, however, there is significantly more eggs per pod in control edge compared to treated edge ($p=0,0312$) (figure 13a). Once fields LD and LR is excluded from the analysis, there is only a significant effect of transect not treatment or any interaction. The post hoc test show that there are significantly more eggs per pod in the strip compared to edge and center ($p=0.0101$ and $p=0.0168$) (figure 13b).

For the analyses of pods per m^2 and eggs per m^2, there is also only a significant effect of transect, not treatment (table 5). There are significantly more pods per m^2 in the center compared to the edge ($p=0.0080$), however, there are no significant difference between the other transects (figure 14a). There are significantly more eggs per m^2 in the strip compared to the edge ($p=0.0139$) however, there are no significant difference between the other transects (figure 14b).

*Table 5. Chi-Square (X^2) and p-values (p) given from the statistical Anova tests of the broad bean weevil egg models, response variables pods per m2, eggs per m2, and eggs per pod (including all fields and excluding fields LD and LR). Significance is indicated by '***' =p <0.001 '**' =p <0.01 '*'=p < 0.05 '.' =p <0.1. The table include conditional R-square (R2c) to represent the variance explained by the random effects and marginal R-square (R2m) to represent the variance explained by the fixed effects. The fixed effects represent the individual effect of treatment and transect as well as the combined effect of treatment and transect (Treatment*Transect)*

Response	Pods per m^2		Eggs per m^2		Eggs per pod		Eggs per pod (LD and LR excluded)	
	R2c= 0.60	R2m=0.23	R2c=0.82	R2m=0.087	R2c=0.82	R2m=0.086	R2c=0.85	R2m=0.049
	X^2	p	X^2	p	X^2	p	X^2	p
Intercept	69.51	< 2.2e-16 ***	142.17	< 2.2e-16 ***	10.91	0.00096 ***	3.44	0.064 .
Treatment	0.08	0.78	0.06	0.80	1.59	0.21	0.25	0.61
Transect	13.13	0.0014 **	10.83	0.0045 **	21.69	1.945e-05 ***	10.79	0.0045 **
Treatment*Transect					8.37	0.015 *		

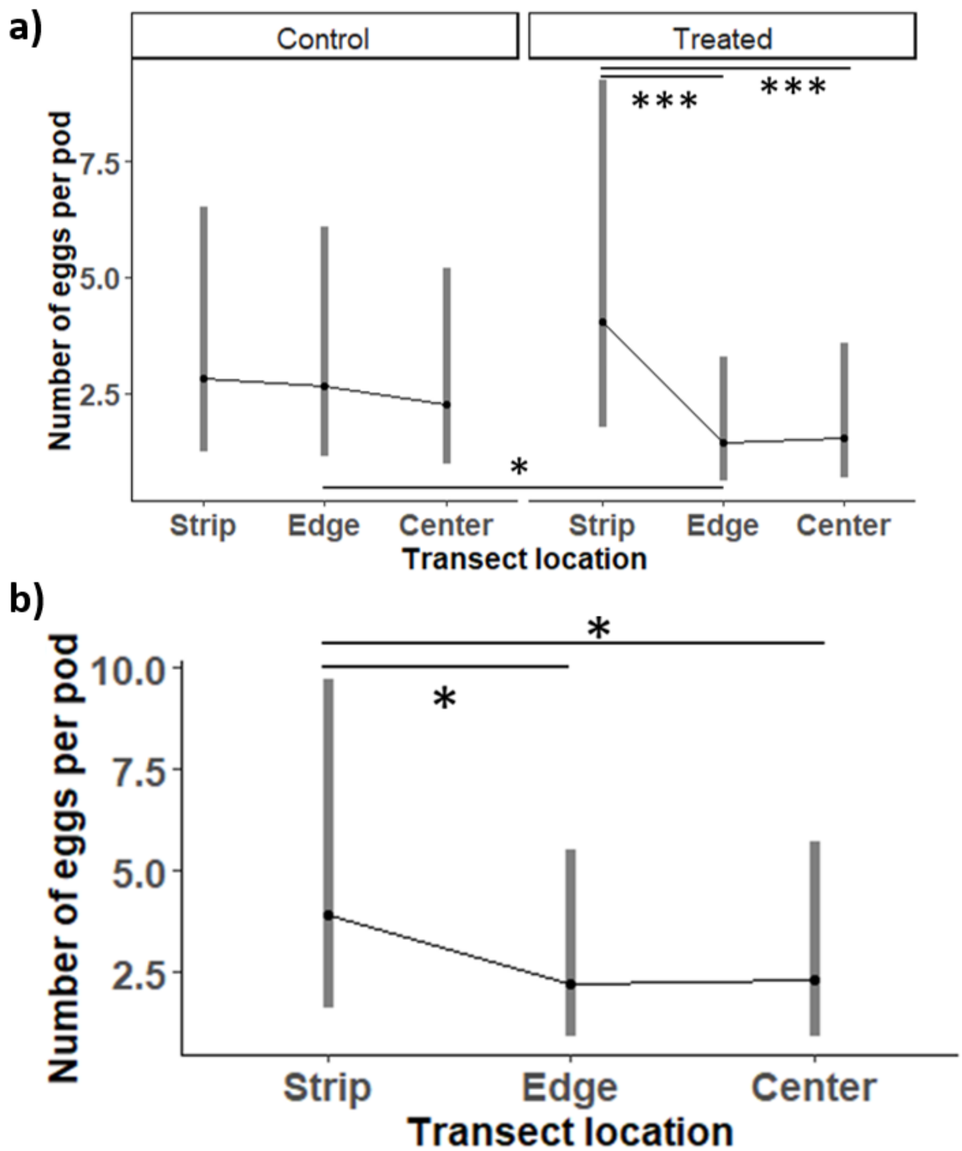

*Figure 13. Estimated marginal means of a) The combined effect of treatment and transect on the number of eggs per pod (all fields included) b) The effect of transect on the number of eggs per pod (fields LD and LR excluded). Whiskers represent 95% confidence intervals and significance is indicated by '***' =p <0.001 '**' =p <0.01 '*'=p < 0.05 '.' =p <0.1. Line endpoints represent significance comparisons.*

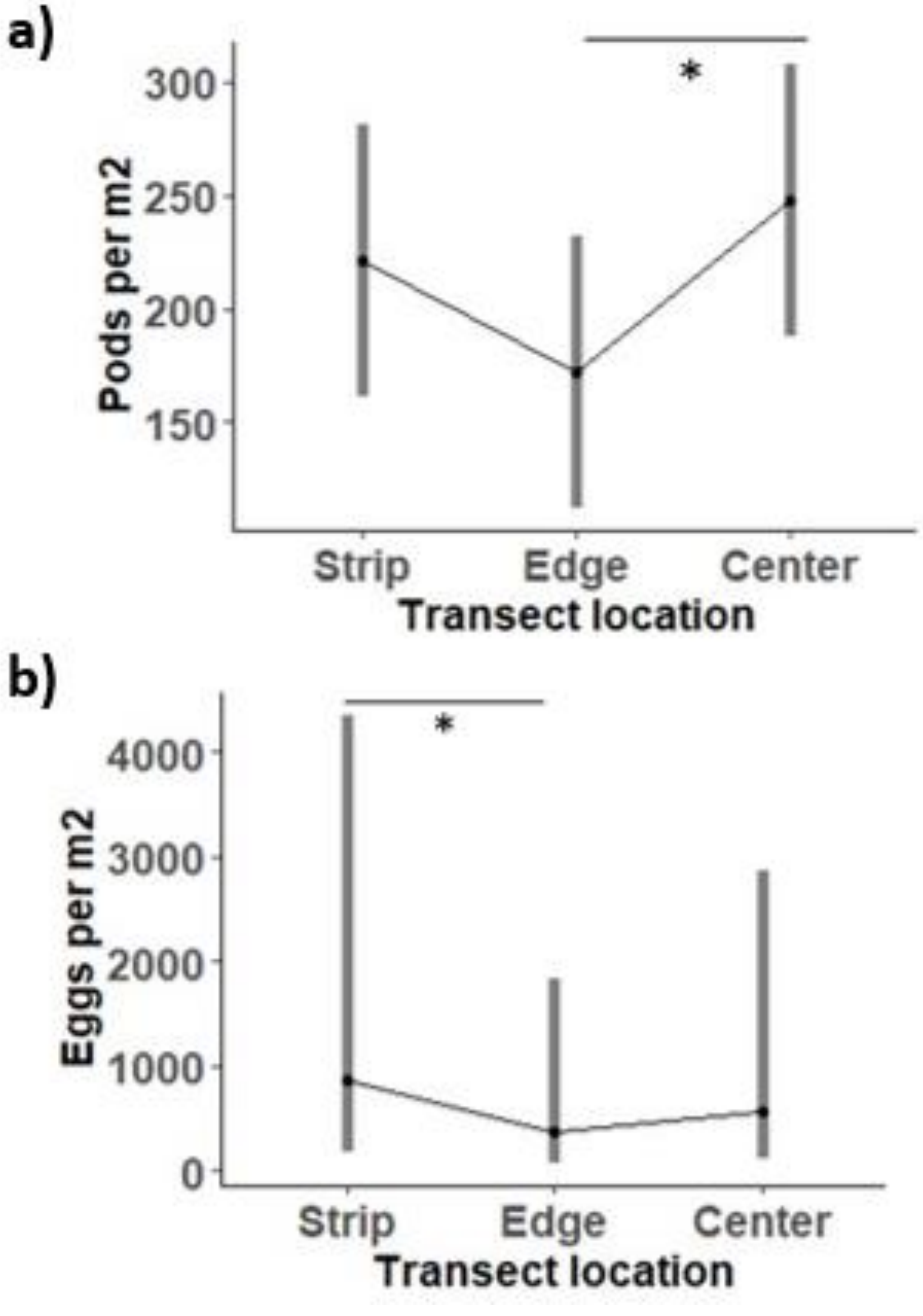

*Figure 14. Estimated marginal means of the effect of transect on the number of a) pods per m2 b) eggs per m2. Whiskers represent 95% confidence intervals and significance is indicated by '***' =p <0.001 '**' =p <0.01 '*'=p < 0.05 '.' =p <0.1. Line endpoints represent significance comparisons.*

4.4 Bean damage and yield

The bean damage analyses show that there is a significant combined effect of field treatment and transect both when including and excluding fields LD and LR (table 6). Post hoc tests show that there is significantly greater percent damage in treated strip compared to control strip (p=0.0299) (figure 15a). In treated fields, the strip has significantly greater percent damage compared to the edge and center (p<0.001), but there is not a significant difference between the edge and center. For the control fields there are no significant differences in percent damage between either of the transects (figure 15a). Once fields LD and LR are excluded, there is still significantly greater bean damage in treated strip compared to treated edge and center (p<0.001). When comparing the two treatments there is significantly greater percent damage in treated strip compared to control strip (p=0.0038) and significantly greater percent damage in control edge and center compared to treated edge and center (p=0.0011 and p= 0.0119) (figure 15b).

As for the yield there is only a significant effect of transect, not treatment or the interaction (table 6), with significantly lower yield in field strips compared to field centers (p=0.0077) (figure 16).

*Table 6. Chi-Square (X^2) and p-values (p) given from the statistical Anova tests of the broad bean weevil bean damage and yield models, response variables bean damage percentage (including all fields and excluding fields LD and LR) and total yield in kg/ha. Significance is indicated by '***' =p <0.001 '**' =p <0.01 '*'=p < 0.05 '.' =p <0.1. The table include conditional R-square (R2c) to represent the variance explained by the random effects and marginal R-square (R2m) to represent the variance explained by the fixed effects. The fixed effects represent the individual effect of treatment and transect as well as the combined effect of treatment and transect (Treatment*Transect).*

Response	Bean damage		Bean damage(LD and LR excluded)		Yield	
	R2c=0.90 X^2	R2m=0.21 p	Rc=0.94 X^2	Rm=0.30 p	Rc=0.51 X^2	Rm=0.31 p
Intercept	83.47	< 2.2e-16 ***	129.74	< 2.2e-16 ***	2108.03	< 2.2e-16 ***
Treatment	7.28	0.007 **	13.37	0.00026 ***	2.18	0.14
Transect	0.27	0.87	102.92	< 2.2e-16 ***	12.64	0.0018 **
Treatment*Transect	25.83	2.46e-06 ***	44.25	2.46e-10 ***		

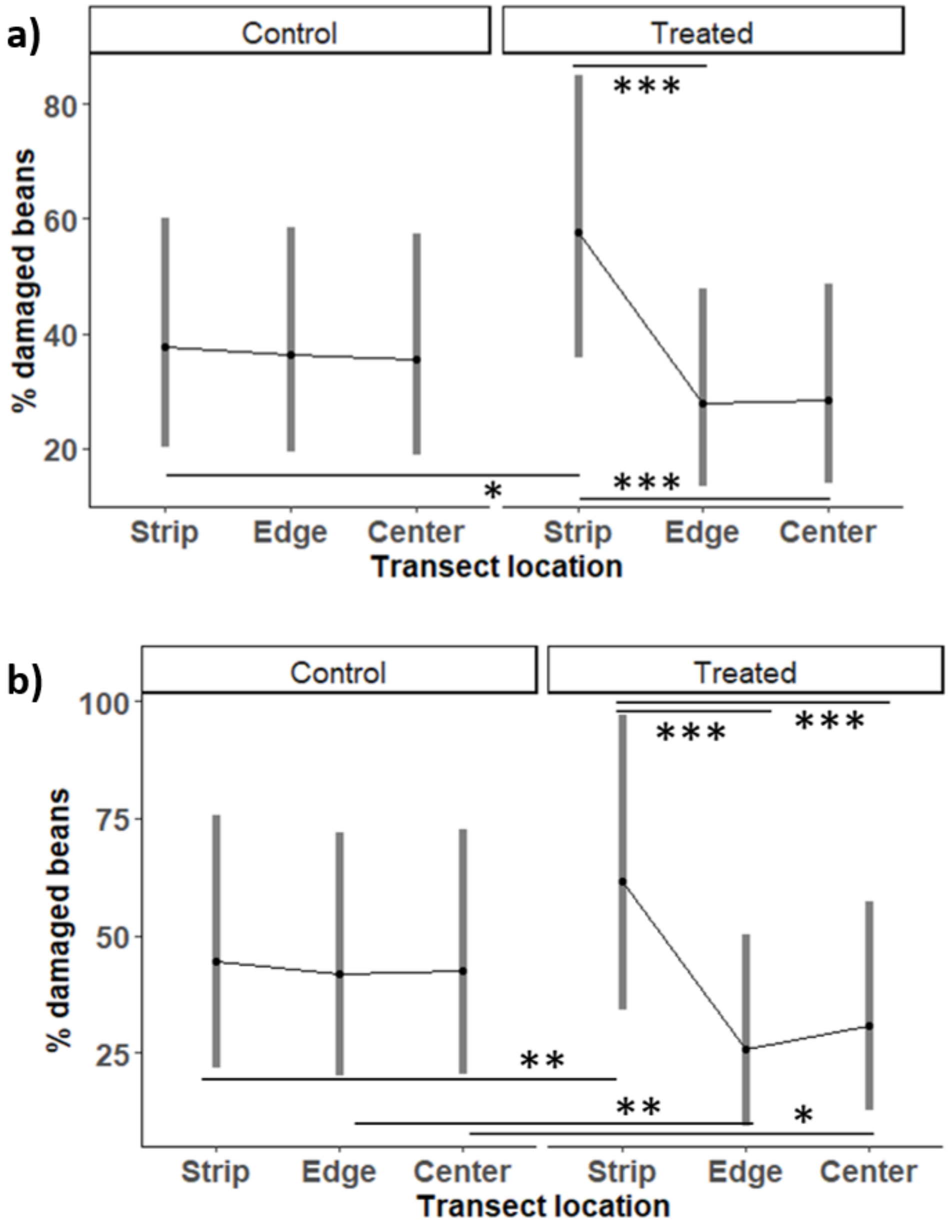

*Figure 15. Estimated marginal means of the combined effect of treatment and transect on the percent beans damaged by broad bean weevils a) All fields included b) Fields LD and LR excluded. Whiskers represent 95% confidence intervals and significance is indicated by '***' =p <0.001 '**' =p <0.01 '*'=p < 0.05 '.' =p <0.1. Line endpoints represent significance comparisons.*

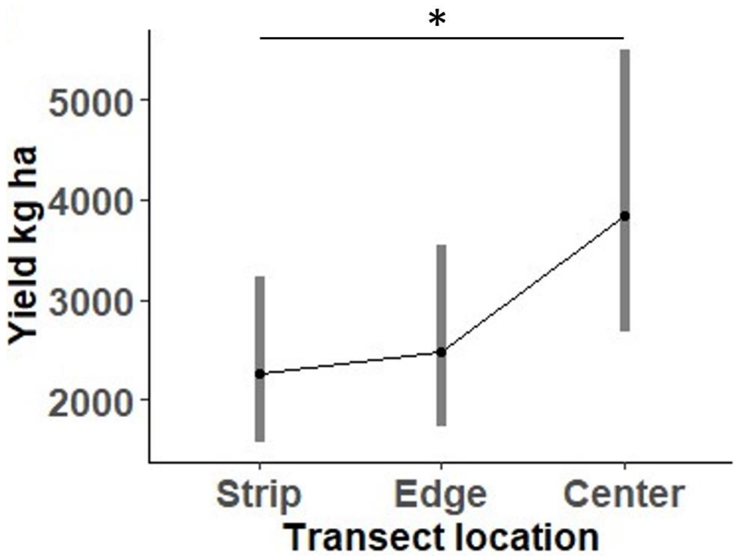

*Figure 16. Estimated marginal means of the effect of transect on the total yield in kg/ha. Whiskers represent 95% confidence intervals and significance is indicated by '***' =p <0.001 '**' =p <0.01 '*'=p < 0.05 '.' =p <0.1. Line endpoints represent significance comparisons*

5. Discussion

The results of this study tell us that once a strip of the early flowering faba bean cultivar Sampo as a trap crop combined with kairomonal scent traps are used in a later flowering faba bean field, broad bean weevils prefer the trap crop compared to the rest of the field. However, it is impossible to say if the effect is predominantly driven by the trap crop or by the scent traps since no control fields were only using a trap crop or scent traps was used. Since previous results show that broad bean weevil females prefer early flowering over later flowering faba bean cultivars once grown together (Seidenglanz & Huňady 2016) it is likely that the greater numbers of eggs per pod in the trap crop compared to the treated edge and center is due to a pulling effect of ovulating females towards the trap crop. Thus, even though data cannot prove this, I believe that the trap crop alone can have an attractive effect on broad bean weevil adults and possibly reduce egg laying and bean damage. However, the greater number of eggs per pod and bean damage in the trap crop might be increased due to an attractive effect of the scent traps. In the same way it is possible that the broad bean weevil catches in the scent traps is greater than it would normally be if using scent traps without a trap crop since the trap crop likely increase the attraction of weevils towards field strips. However, I believe that the scent traps also might have an individual effect on broad bean weevil egg laying and bean damage since insect captures in the scent traps predominantly consisted of broad bean weevils compared to other insect catches. The scents thus seem to target broad bean weevils quite well. Other insects that were trapped was mostly flies and beetles, a few bumblebees were trapped but not enough to believe that the traps could be harmful for pollinators, making the traps an environmentally friendly control measure compared to pesticides. However, in order to tell if the scent traps are effective in attracting broad bean weevils, the trapped number of weevils should be compared with the overall adult density in the field. The weevils are quite hard to detect and count in field, thus the estimation of ovulating females based on the number of eggs per m^2 were made. The greater number of weevils in control fields are due to the greater field area of control fields compared to treated fields rather than preference to the field. Since our estimations indicate that the scent traps only catch about 0.2% of the weevils in the field is not likely that the traps are enough to reduce egg laying and bean damage significantly. This estimate also only detects ovulating females and therefore also assume that all weevils in the traps are females, which they were not. However, since it is the ovulating females that are harmful to the beans it should be the most important sex to detect and capture. However, since the traps did not only capture females the trapping effect is overestimated. Due to the low percentage of weevils captured in the traps, I have a stronger belief that the trap crop is the main contributor to the reduction of egg laying and bean damage rather than the scent traps. However, the estimation of broad bean weevil density is based on several assumptions and the numbers are therefore very uncertain.

Since there were significantly more eggs per pod in treated edge compared to control edge, it seems like the treatment has the potential to reduce egg laying in field edges. However, the effect does not seem to be enough to reduce egg laying in field center. The treatment also seems to be effective in decreasing bean damage. The results show that broad bean weevils significantly cause more bean damage in the trap crop compared to the rest of the treated field which reflect the greater number of eggs per pod laid in the strip. Once including all fields in the study, the results show that broad bean weevils indeed cause greater damage in the Sampo strip compared to the control strip which indicates that the treated strip have an attractive effect on broad bean weevils. However, the treatment does not seem to be enough to reduce bean damage either in field edge or center. This result might be misleading since the fields in one field pair (fields LD and LR) were far from each other (Table 1). The large distance (6km) between those two fields means that they do not share the same local conditions, like initial pest pressure. This argues for the exclusion of this field pair in the statistical analysis. By excluding this field pair, the results indeed show that the treatment has potential to be a sufficient control measure that can reduce bean damage in both field edges and field center.

Since broad bean weevils overwinter as adults in sheltered places of forests and nearby locations of previously grown faba beans (Ekbom 2012; Tran et al. 1992) it would be likely that faba bean fields situated close to forests and fields of previously grown faba beans should have greater inflight of broad bean weevils. However, our results showed no effect of the total forest area or previously grown faba bean area within either a 1 or 2km radius or the distance to the closest faba bean field on the amount of broad bean weevils captured. This indicates that keeping a distance to potential broad bean weevil overwintering places, like forest areas and previous faba bean fields, is not enough to reduce broad bean weevil inflight. It further indicates that broad bean weevils can disperse over long distances (Hamidi et al. 2021) or that they can reinfest faba bean fields when using damaged beans as seed (Bachmann et al. 2020). Our results also do not show that broad bean weevils have any specific inflight direction, however more investigations on broad bean weevil flight patterns should be performed. Previous studies imply that males are more attracted to kairomonal attractants with flower scent and that females are more attracted to kairomonal attractants with pod scent (Bruce et al. 2011). However, in this experiment too few specimens were caught in traps with flower attractant to be able to draw any conclusion about the preference towards flower and/or pod attractant between broad bean weevil males and females. The reason for the few catchments in traps with flower attractant is likely due to low broad bean weevil densities at the beginning of the season, when the flower attractants were set up rather than low attraction towards the flower attractant per se since traps with pod attractant had low catches the first weeks as well. To be able to compare the preference of flower and/or pod attractant between sexes both attractants should be used during the entire trap period. However, since the main purpose of this study was to capture as many broad bean weevils as possible to evaluate the potential control effect, flower attractants was replaced to pod attractants in order to mimic natural kairomonal emissions and have a better effect on the attraction of broad bean weevils.

It seems like the higher plant density in Sampo compensate for fewer pods per plant, which results in a similar number of pods per m^2 in the treated strip and control strip. Since the number of pods per m^2 does not differ significantly between treated and control fields, the number of eggs per pod can be used to compare pest pressure between field pairs. However average pods per m^2 differ between transects with fewer pods per m^2 in the edge compared to the center. This could be one explanation to an increased number of eggs per pod in field edges. However, since the pods per m^2 values do not completely reflect the eggs per pod values (significance only between edge and center for pods per m^2 and significance only between strip and edge for eggs per m^2), egg laying is not only affected by the number of pods per m^2. Because of the greater plant density of the Sampo cultivar, the yield in kg/ha is not considerably lower compared to the strip of the cultivar in the control field. This indicates that there should not be a huge reduction in yield if the farmer would implement a Sampo strip instead of growing the same faba bean cultivar over the whole field if increasing plants per m^2 in Sampo. However, the cost for the increased sowing density in Sampo must not overweigh the yield increase.

One downside with the scent traps was that the water quickly dried out which meant that the traps had to be refilled twice a week on sunny weeks. This craves considerable work from the farmer which does not seem reasonable. However, the company that developed the trapping methodology, Agriodor, are working on a new type of scent trap with adhesive glue instead of waterfilled containers which will save a lot of time and effort (Ene Leppik, personal communication). I also believe that the kairomonal attractants could need some improvement, perhaps a new more effective blend could be developed. I also believe that kairomones are the right substance to use in the traps, not pheromones as in other insect mass trapping because of the dependance of sufficient food resources for broad bean weevil female maturation (Medjdoub-Bensaad et al. 2018). This makes me believe that broad bean weevil females will be more attracted to food localization signals compared to pheromones before they mature, just like stink bug females (Tillman et al. 2015). Because of the work effort, I thus believe that a trap crop is a more valid control measure against broad bean weevils compared to scent traps. However, since we do not know if the single effect of a trap crop is enough to reduce egg laying and bean damage this needs to be further investigated before recommending it as a control measure. In future investigations of trap crops in broad bean weevil control the trap crop effect might be improved by choosing a faba bean cultivar that flowers for a longer period compared to the field cultivar (Wang et al. 2021) to prevent broad bean weevils from continuing their oviposition in the field cultivar. An earlier sowing date of the trap crop cultivar could further attract broad bean weevil females to the trap crop early on (Seidenglanz & Huňady 2016) however, the length of flowering could not be manipulated in this way, which probably would not improve the trap crop effect that much. By growing a greater area of trap crops the effect on damage levels could also be improved (Wang et al. 2021). Our trap crop used 6-8% of the total crop area, however, previous research argues that at least 10% of the total crop area should be planted with a trap crop for it to be efficient (Hokkanen 1991). Since our results show that Sampo does not have significantly lower total bean yield compared to the other faba bean cultivars, once sown at a greater plant density, it should not be a considerable price loss to grow a greater area of Sampo as a trap crop. However, we noticed that due to the low plant height and positions of nodes bearing pods, mechanical harvest of Sampo might be difficult and leave a lot of spillages. The trap crop might also be improved by testing a different sowing pattern. Since broad bean weevils seem to have a randomized dispersal pattern, a trap crop sown around the field might not be enough to reduce the adult densities inside the field. In this case an intercropped trap crop might be more effective (George et al. 2019).

Even though the effect on broad bean weevil egg laying, and bean damage is not remarkable when using scent traps combined with trap crops it is still important to continue the development of IPM strategies against broad bean weevils. Since faba bean cultivation and broad bean weevil damage are increasing in Europe the need for effective control measures will increase as well. The net economical gain from using currently approved insecticides against broad bean weevils is very low (Eriksson 2019) and is also not an option in organic faba bean cultivation, which further argues for the development of other control measures. Additionally, preventive measures and more environmentally friendly control should always be implemented before using chemical control (Jordbruksverket 2021b) which argues that research should focus on finding effective IPM measures. The scent traps might also be effective in monitoring systems rather than mass trapping in order to detect broad bean weevils in the field and evaluate if treatment is valid. Since current economic threshold are based on temperature rather than pest density (Ramsden et al. 2017) monitoring might contribute to development of new economic thresholds in order to improve insecticide use.

I believe that in a current state, a trap crop combined with scent traps is not a valid control measure against broad bean weevils. However, with some improvement I believe that both trap crops and scent traps might have potential in future broad bean weevil control and/or monitoring.

6. Conclusion

The use of a strip of an early flowering faba bean cultivar Sampo combined with kairomonal scent traps has potential to reduce broad bean weevil egg laying in field edges, but the effect does not seem to be enough to reduce egg laying in field center. The trap crop combined with scent traps also has potential to reduce bean damage in both field edges and field center. However, further research is needed to evaluate if a Sampo strip as a trap crop combined with scent traps is a valid IPM control measure against broad bean weevils. It seems like broad bean weevils infest faba bean field no matter of distance to potential overwintering places, which suggests that they are able to infest faba bean fields over large distances and argues for the importance of reinfestation from damaged beans used as seed. No conclusion of the preference towards flower and pod attractants between broad bean weevil males and females can be drawn.

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Personal communication

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