Biology of the Diamondback moth (*Plutella xylostella*) and its future impact in Swedish oilseed rape production
– a literature review

Kålmalens biologi och dess framtida inverkan på svensk oljeväxtproduktion

– en litteratursammanställning

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Abstract

The biology of the Diamondback moth, *Plutella xylostella*, and its impact on oilseed rape production is reviewed. The Diamondback moth, DBM, is a serious, migratory, pest and a problem worldwide because its larval stage has a ravenous appetite, which causes major economic losses in *Brassica* crops. With the effect of global warming and models predicting an increase in temperature an assessment of the future impact of this pest in Swedish oilseed rape production is performed. Sweden is possibly facing a major problem in the future having the DBM at its doorstep as an overwintering seasonal pest with the potential for several generations throughout the growing season. DBM pest status in Sweden varies with memory depending on how serious our sporadic infestations have been. Historical information on the infestations of the DBM in Sweden and reviews of scientific articles concerning DBM biology and control around the world, in particular Canada that shares the same Köppen climate classification, and future problems with the pest are presented. Given the right abiotic conditions it is plausible that DBM has a future as an overwintering pest in Sweden. Integrated pest management practices and creative cropping systems with *Brassica* crops will play an important role in controlling the pest.

Sammanfattning

Kålmalens (*Plutella xylostella*) biologi och dess framtida inverkan i Svensk oljeväxtodling är presenterat och granskat. Kålmalen är en allvarlig insekt som migrerar med vindar världen över. Kålmalen är en fruktad skadegörare i hela världen med sitt larvstadiums glupska aptit som orsakar stora ekonomiska förluster i *Brassica* grödor. Med effekten av den globala uppvärmningen och modeller som förutspår en ökning av temperaturen så granskas de framtida effekterna på svensk oljeväxtodling. Sverige står möjligen inför ett framtida stort problem med kålmalen utanför sin tröskel som en övervintrande skadeinsekt med ett flertal generationer under växtsäsongen. Kålmalens status som skadeinsekt här i Sverige varierar med minnet om-, och, hur omfattande de sporadiska angreppen var. Tidigare information om angreppen av kålmal i Sverige och recensioner av vetenskapliga artiklar om kålmalens biologi och bekämpning runt om i världen, i synnerhet kanadensiska som delar en likadan Köppen klimatklassifikation och framtida problem med skadeinsekten, presenteras. Med de rätta abiotiska förhållanden så är det troligt att kålmalen har en framtid som övervintrande skadeinsekt i Sverige. Integrerat växtskydd och kreativitet i odlingssystem med *Brassica*-grödor kommer spela en avgörande roll i bekämpandet av kålmalen som skadeinsekt.

Introduction

The Diamondback moth, DBM, *Plutella xylostella* (Linnaeus) (Plutellidae), is a serious pest in *Brassicaceous* crop worldwide (Talekar and Shelton, 1993; Furlong, Wright, Dosdall, 2013). Oilseed rape and turnip rape (*Brassica napus* ssp. *napus* and *Brassica rapa* ssp. *oleifera*) are important crops in Swedish crop rotation throughout the country because of their value as break crops and preceding crops (Wallenhammar & Bågenholm, 2004). The DBM has historically been a sporadic migrating pest coming in to Sweden and has caused great economical damage for farmers in some regions (Borg, 1946; Johansson, 1958; Ekbom, 1995; Sandström *et al.,* 2011; Karlsson *et al.*, 2013). Due to the ravenous appetite of the larvae, infestation by the DBM can destroy entire cropping systems and render regions unsuitable for production (Talekar and Shelton, 1993).

Brassicaceae is an economically important family of dicotelydonous herbs consisting of over 3500 species. The natural host range of the DBM are the Brassicaceae that are characterized by the so called 'mustard oils', or glucosinolates, and can be both wild and cultivated varieties (Warwick *et al.*, 2003). These mustard oils are harmful to generalist insects and acts as an evolutionary defence for the Brassicaceae but the DBM has become a specialist on these kinds of secondary compounds and use it for their advantage when it comes to oviposition and larval feeding (Sarfraz *et al.* 2006). Much like the comma butterfly lays its eggs on the stinging nettle (*Urtica dioica*) for its protection of the larval stages and molting (Janz *et al.*, 1994).

The pest is considered to be incapable of overwintering in areas with cold climate and harsh winter months have been an important natural mortality factor reducing the DBM population annually in Sweden. This prevents it from being a constant seasonal pest with an early development in some regions to which migration occurs. Whether the DBM can overwinter in Sweden is uncertain and there is no record of this. Considering only the mean temperature during the WMO (World Meteorological Organization) normal period 1961-1990 of the winter months in Sweden (Dec., Jan., Feb.) specifically Götaland and Svealand (SMHI, 2009) and the articles written about the DBM on development and reproduction depending on temperature, both fluctuating and constant, it indicates that it is plausible the DBM can overwinter in Sweden today (Liu *et al.*, 2002; Golizadeh *et al.,* 2007; Gu, 2009).

With the potential problem of global warming and thus the increase of average temperatures globally (IPCC, 2007), Sweden is facing a major future problem with having the DBM at its

doorstep as an overwintering seasonal pest with the potential of having several generations throughout the growing season (Liu *et al.*, 2002; Golizadeh *et al.,* 2007; Altermatt, 2009; Gu, 2009; Pöyry *et al.,* 2011). Parts of Canada face the same problem with their extensive oilseed rape production (Dosdall, Weiss, *et al.* 2006) and share the same latitude and Köppen-Geiger climate classification as Sweden (Peel *et al.,* 2007). Implementations of Canadian situations, techniques and experience can serve as a good reference for Sweden.

The objective of this literature review is to show the DBMs future importance in Swedish oilseed rape production and to portray a scenario for the DBMs overwintering possibilities in parts of Sweden using simple day-degree models and life tables. Some of the control methods and integrated pest management (IPM) that have been tested and the capability of resistance to insecticides the DBM has built up over the decades are also reviewed (Furlong, Wright, Dosdall, 2013). The review is aimed at crop advisors and interested farmers highlighting the future problem and to serve as a reference next time an infestation occurs.

Biology of the Diamondback moth

Life cycle

The diamondback moth, DBM, has four stages in its life cycle (figure 1): Adult, egg, larva and pupa (Talekar and Shelton, 1993). The duration of each stage is dependent on temperature (Sarnthoy *et.al.*, 1989; Golizadeh *et al.* 2007). Its life cycle begins as an adult. The adults are around 9mm long and greyish brown and somewhat ochreous. Antennae are around 5 mm long. Wings range also from ochreous to brown with black spots and when folded the upper part form three or four diamond-shaped, whitish-grey areas (CABI, 2015). Adult moths are most active at dusk and at night. Mating occurs at dusk and the DBM starts mating the same day as the adults emerge; if host plants are easily available the females lay their eggs only a few hours after mating (Talekar and Shelton, 1993; Åsman, Ekbom, Rämert, 2001). The life expectancy of an adult is 16 days for female and 12 days for male moths. Females lay their eggs up to 10 days and 95% start laying on the day of emergence (CABI, 2015). The preferred site for oviposition on *Brassica napus* seems to be the lower first, second and third true leaves (Silva and Furlong, 2012). They can lay up to 200 eggs and they are laid on both the upper and lower leaf surfaces but preferably on the lower surface away from direct sunlight and where there is protection from the wind and the rain (Talekar and Shelton, 1993). The DBM does not seem to prefer to oviposit on the stem of *B. napus* like other hosts in the Brassicaceae family; for example wild cabbage plants (*Brassica oleracea*) where tests have shown that

eggs are just as well laid on the stem as on the leaves (Silva and Furlong, 2012). Eggs are not laid on smooth surfaces of the leaves but in concavities often on the base of the leaf or close to the veins (Talekar and Shelton, 1993; Silva and Furlong, 2012). The incubation time before the larval stage is temperature-dependent and varies between 15 to 3 days with temperatures ranging from 10-28°C. There is not a linear connection between days and temperature. For example the time of incubation drops from 15 to 7 days with only a temperature increase of 5°C (10-15°C) (Sarnthoy *et.al.*, 1989; Golizadeh *et al.*, 2007).

The eggs are small and yellowish round spheres that can be seen clearly using a hand lens (CABI, 2015). As soon as the eggs hatch the first instar larva makes its way into the spongy mesophyll of the leaves. The first instar does not consume the waxy surface on the leaves instead it creates a window-like type of damage (Talekar and Shelton, 1993). The second instar begins with what it's famous for as a pest which is its larval stage ravenous appetite and nonstop consumption of foliage (Talekar and Shelton, 1993). The duration of development between the four instar larval stages is dependent on temperature and increases with rising temperatures up to around 30°C at which it reaches a high point and falls, it reaches zero and mortality is absolute at temperatures around 40°C, although the temperature could vary a few degrees between different strains (Liu *et al.*, 2002; Golizadeh *et al.*, 2007). The later instars appear on the surface of the leaves and continue to consume foliage including the waxy surface and no longer creating the window-like type of damage. This is later in the season recognized as oval holes in the leaves (Talekar and Shelton, 1993).

After the fourth instar the larva stops consuming foliage and before it begins to enter the pre-pupal stage, which lasts between 1 and 3 days in temperatures between 10-20°C (Golizadeh *et al.*, 2007), it constructs a loosely woven cocoon, usually fastened near the buds hidden away in crevices, and then it moults (Talekar and Shelton, 1993; CABI, 2015). Thereafter it enters its pupal period which varies between 3 to 20 days, or around 130 day degrees, DD, depending on the host plant and temperature (10-30°C). Tests have shown that DBM reared on cauliflower and cabbage showed that development time on cauliflower was shorter. This was estimated to depend on host plant quality such as nutritional value and ovipositional advantages (Sarnthoy et.al., 1989; Talekar and Shelton, 1993; Liu *et al.*, 2002; Golizadeh *et al.*, 2007; CABI, 2015).

Once the pupal period is over the DBM has gone through complete metamorphosis and becomes a short lived adult moth that feeds on dew and water drops and soon starts mating

and begins the cycle all over again (Talekar and Shelton, 1993). The lifecycle can be measured in day degrees, DD, and around 260 DD is needed for a complete cycle. It takes around 80 days for a complete cycle to be made with a base temperature of 7°C and a mean temperature of 10°C. The number of days is reduced by half with an increase in mean temperature by 4°C (Sarnthoy *et.al.*, 1989; Golizadeh *et al.,* 2007).
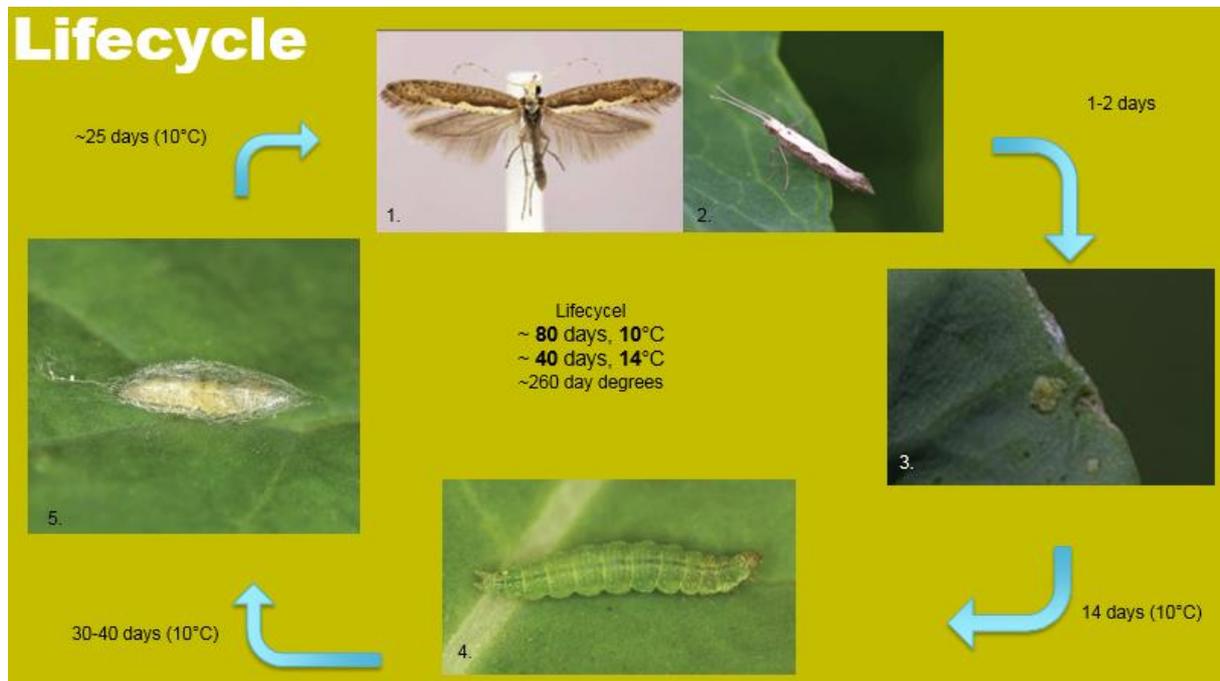

Figure 1. Lifecycle of the diamondback moth with the number of days for each stage, considering a mean temperature of 10°C and a base temperature of 7°C. The number of days is reduced by half with an increase of 4°C.

Host plant interaction

Brassicaceae plants are characterized by containing glucosinolates, also commonly called 'mustard oils', a secondary sulphur-containing compound (Sarfraz *et al.* 2006). Glucosinolates are an evolutionary defence against herbivores but have, over time, attracted specialists, such as the DBM, who have adapted and through certain detoxification methods are able to feed on the plant (Wheat, 2007) making it attractive for oviposition (Sarfraz *et al.* 2006). It's been shown that in the absence of host plants containing glucosinolates the DBM can choose other hosts (Löhr & Rossbach, 2001) and therefore glucosinolates are not an absolute requirement for food acceptance but a strong stimulant for oviposition, mating, and larval feeding (Li, Eigenbrode *et al.,* 2000; Sarfraz *et al.* 2006; Müller, 2010). The host shift occurred in 1999, Kenya, and the new host was sugar snap peas, or snowpeas, (*Pisum sativum* L.) (Löhr & Rossbach, 2001). It was earlier thought that the DBM was restricted to Brassicaceae only (Talekar and Shelton, 1993) but this find confirmed that the DBM had adapted to another host in the absence of the original host. A special pea strain has developed called 'DBM-P' and Löhr & Rossbach reared the new strain larva on kale (*Brassica oleracea var. acephala* L.) and on peas (*Pisum sativum*). The DBM-P was compared to a strain originating and adopted from cabbage, DBM-C, and tests show that the DBM-P survived on both plants but DBM-C survived poorly on peas (Löhr & Rossbach, 2001).

The toxic products in Brassicas, the most common being isothiocyanates, are released when damage to the leaves occurs through feeding mixing glucosinolates and the enzyme myrosinase that is stored separately in intact plant tissue (Ratzka *et al.,* 2002; Sarfraz, 2006). The DBMs gut lumen contains an enzyme called 'glucosinolate sulfatase' that through hydrolysis reactions manages to desulphate glucosinolates rendering them harmless and ineffective to prevent larval feeding (Ratzka *et al.,* 2002; Müller, 2010).

Because of the enzyme´s broad range of detoxification the DBM have many hosts to choose from in the Brassicaceae family (Ratzka *et al.,* 2002; Sarfraz, 2006).

The DBM has complex and sometimes unpredictable interactions with its host. Rational decisions for landing and oviposition, based sometimes on physical characteristics occur. Studies show that the DBM makes its choice based on volatile aliphatic glucosinolates and non-volatile indole glucosinolates and the plant bouquet of compounds. But it seems that a combination of many different morphological factors determines the susceptibility and fitness of the plant for the DBM and DBM density as well as occurrence in the field could sometimes

be random (Sun *et al.*, 2009; Silva and Furlong, 2012). The example with the host shift to peas addresses the problem that the DBM is adaptable and in a short period of time able to develop new strains more suitable for a specific host (Löhr & Rossbach, 2001; Müller *et al.,* 2010).

Overwintering

There has been no proof that overwintering occurs in Sweden today. Old publications from 1946 tells us that it was believed the DBM, because of its several life stages occurring at the same time in the field, were capable of overwintering and that a small portion did so prior to years with large infestations (Borg, 1946). The climate in Sweden is comparable to the climate in certain parts of Canada where oilseed rape production is extensive specifically southern –Ontario –Manitoba –Saskatchewan -Alberta (Peel *et al.,* 2007).

There have been field experiments carried out in Canada; Alberta, Vegreville (53°N) and Saskatchewan, Saskatoon (52°N), that tested the DBM capability of surviving the winter under different field conditions. These regions have the same Köppen climate classification: Dfb. The climate at these locations can be compared with the current climate in the south of Sweden with the climate border located above Lake Vänern stretching towards the city of Uppsala (Peel *et al.,* 2007). The specimens used were 3rd generation reared under lab conditions from collected field moths. The conditions were varied levels of tillage and varied thickness of cover, including simulated snow coverage for insulation. The experiment took place during three years and the results were that no DBM survived under any conditions (Dosdall, Mason, Olfert *et al.*, 2001).

There have been laboratory studies on milder temperatures where the DBM has shown possible signs of survival and reproduction. The studies took place in southeastern Australia where climate temperatures varies between +5°C to -5°C during the relatively mild winter period. The DBM strain was collected in the nearby areas from oilseed rape and turnip rape (*Brassica napus* L. & *Brassica rapa* spp.) and placed in insect cages/environmental rooms along with water for the DBM to consume. The study showed that the DBM survived alternating temperatures between 0°C and 5°C, with 15-20% of the adult moth group surviving and around 70% of the larva- and pupae group surviving for 60 days. The test with exposure to constant -5°C showed bleaker results with second-, third- and fourth instar larvae and pupae surviving for 2 ,4 ,6 , 13 days respectively and around 30% of the adult moths were still alive at the end of the test period of 20 days. The fertility after exposure to both

conditions was relatively unchanged (Gu, 2009). This shows that in temperatures similar to southern Sweden the DBM has some prospects to overwinter as an adult moth during ideal conditions if it were to hibernate like the butterfly 'common brimstone' (*Gonepteryx rhamni*) which overwinters as imago (complete metamorphosis) in shrubbery and leaves (Nationalnyckeln, 2005).

So far the only proven way the DBM has been found in areas where climate is not favourable is through long distance migration. This is also the DBMs migratory behaviour to flee when colder temperatures are present (Chapman *et al.,* 2002).

History

The DBM has caused great damage to Swedish oilseed rape production previously. Early records date back to 1946. The following years of significant impact were 1958, 1995, 2010 and 2013 (Borg, 1946; Johansson, 1958; Ekbom & Wærn, 1995; Djurberg & Gustavsson, 2010; Sandström *et al.*, 2011; Karlsson *et al.*, 2013).

Back in 1946 the DBM was estimated to complete at least 2 life cycles, about the same as today, and was also suspected of having overwintering populations, which has not been confirmed today. The recommended pesticide back then was DDT, which showed the best result in controlling this pest. Another active substance tested was nicotine but the effect was poor. The specific DDT product used was Gesarol, which was one of the first pesticide products based on DDT and marketed in 1942 (Borg, 1946; UNIDO, 2015). It showed great effectiveness even to adult moths. Years later, 1953, the DBM was reported resistant to DDT (Talekar and Shelton, 1993). It was the first reported resistance to a pesticide and also the first agricultural pest to become resistant to DDT.

In 1958 there was another large scale infestation by the DBM. This time crop advisors were aware of it having several generations at once in the same field and advisors knew that treatment was most effective against the larval stage, but many sought it as an especially resistant insect and sprayed with 'parathion' among other very effective and poisonous pesticides even then believed to be damaging to human health. This was recommended instead was DDT which showed great effectiveness and no immediate threat to one's health (Johansson, 1958).

It was not until 43 years later, in 1995, that Sweden had another infestation of great significance. By then the research around the world had gotten further and more knowledge of

the DBM existed and was published. The pesticide products used then still exist today but the DBMs resistance to them is a bit more widespread. Lambda-cyhalothrin, in the form of the product *Karate,* and *Bacillus thuringiensis*, *Bt*, were tested and showed positive results (Ekbom & Wærn, 1995).

There has been a tendency to forget the DBM as a possible pest. In 2010 it came yet again and also as a bit of a surprise after years of insignificance. It came from the east and for those unfortunate to not have an affect against them in combination with the control treatment for the Brassica pollen beetle, *Meligethes aeneus,* could find their fields completely devastated by the damage caused by a second generation of the larval stage of the DBM (Djurberg & Gustavsson, 2010).

Yet again in 2013 the DBM migrated in with the winds, this time from the southeast. Those who used indoxacarb, in the form of the product *Avaunt*, a relative new active substance released in the early 2000, showed a tendency to a better result (Karlsson *et al.*, 2013).

Local movement and migration

The DBM is not a strong flyer and rarely moves long distances locally, although occasionally there is a great deal of movement in field and between neighbouring weeds or refuge vegetation (Schellhorn *et al.*, 2008). The great majority (95%) of the DBM local population in the field does not exceed the flight distance of 110 meters, and the near total (99%) does not exceed the distance of 200 meters, therefore individual moths rarely move to neighbouring fields (Mo, *et al.* 2003). Active flight in the field usually occurs at dusk to dawn if not disturbed by animals or humans during the day (Goodwin & Danthanarayana, 1984; Talekar & Shelton, 1993). The DBM has a peak in active flight when there is a small breeze and has problems flying and controlling its direction and movements when winds exceed 2.2 ms^{-1} (Goodwin & Danthanarayana, 1984). Rainfall reduces flight activity almost completely (Talekar & Shelton, 1993; Tonnang, Löhr, Nedorezov, 2014). The lower temperature threshold for flight found in a study from 1984 was 7°C (Goodwin & Danthanarayana, 1984) and this number correlates with recent studies of the DBMs lower temperature threshold for development which is 7.06°C (Golizadeh *et al.,* 2007). The preferred temperature for optimal flight capability is 23°C (Shirai, 1991).

The DBM shows up as a pest wherever Brassica is grown and originates from warmer countries/regions and the DBMs long range migratory capability is what has made it a cosmopolitan pest (Talekar & Shelton, 1993; Furlong, Wright, Dosdall, 2013). The DBM is

known to migrate with winds up to 1000 km per day (Talekar & Shelton, 1993) and seasonally move in to regions where it cannot survive year round (Talekar & Shelton, 1993; Furlong, Wright, Dosdall, 2013).

The Canadian Meteorological Centre which has generated backward trajectories in order to help studies, show the DBMs movement from southern Texas and California in the United States, as well as Central America, to regions in the Canadian prairies (Dosdall, Mason, Olfert *et al.*, 2001; Hopkinson & Soroka, 2010). The DBM has been shown to migrate from continental Europe through Belgium and the Netherlands up to southern England using combined methods with radar, aerial netting and traps (Chapman *et al.,* 2002). Although the origin of the DBM in southern England is discussed because of the climate temperature is at the lower limit of the DBM´s survival and development opening a window for an overwintering population (Furlong, Wright, Dosdall, 2013). The DBM´s arrival in Sweden and Finland back in 1995 was reported by the Finnish weather service to have arrived with winds crossing over the Baltic and Russia going north towards northern Sweden and then turning to a more southerly direction across the middle of Sweden (Ekbom & Wærn, 1995; Leskinen *et al.*, 2011). And recently that same migration trajectory over Finland and Sweden has been proven using similar but updated methods as those used in the UK in 2002 (Leskinen *et al.*, 2011).

Forecasting the DBM

There have been methods developed to forecast the DBM in-flights using radar (Chapman *et al.,* 2002; Leskinen *et al.*, 2011). In Canada developed methods are put in practise on a seasonal basis of predicting the size of the larval populations early in the season using commercially available traps and pheromone lures (figure 2) (Gavloski 2005; Evenden & Gries, 2010; Miluch *et al.*, 2013). The method is to get pheromone traps with sticky walls out early in the field, at best before the crop is seeded. The traps are then used to catch adult migrating moths flown in from southern populations. It is not the number of moths that is most relevant; it is the time of arrival. The time of arrival is then evaluated along with the weather and conditions at the time. This then gives an indication of the expected size of the larval population and vitality (Gavloski 2005; Miluch *et al.*, 2013). The importance of interpreting the data collected is stressed by John Gavloski. Gavloski explains it: "The intention of insect forecasts is not to determine if control is necessary in a particular field, but to provide an early warning of the risk of subsequent stages or populations being economical threats within the general region." (Gavloski, 2005). This method of collecting data on adult

moths is based on the assumption that the southern upwind occurs on a seasonal basis (Hopkinson & Soroka, 2010) which Miluch, Dosdall and Evenden have given strength to with their experiments in Alberta, Canada, where they compare different commercially available pheromone-baited traps (Miluch *et al.*, 2013). They also came to the important conclusion that the predictions made pre-growing season did not tell the size of larval population in the late growing season and that models combining this method with larvae samples roughly two weeks after the first catch could predict population size mid-season (Miluch *et al.*, 2013). Pheromone lures and traps for the DBM in Sweden are currently being sold by Biobasiq Sverige AB (Biobasiq, 2016).

Canada has similar Köppen-Geiger climate classification as Sweden (Peel *et al.*, 2007) and can be served as a good reference module for future implementation of the same techniques of forecasting the DMB.

In addition to pheromone lures and traps here could be a use of an already applied method in Sweden to predict the potential development time of the DBM and its generation cycles. It is to

Figure 2. Commercially available pheromone-baited traps used in field to predict the seasonal population of the DBM caused by migrating moths (Knodel & Ganehiarachchi, 2008).

monitor the number of day-degrees. Combining this with field scouting to keep records of the arrival of the first adult moths gives a good prediction of when the first instars will appear but not the size of the potential damage or if control is necessary.

Field scouting is important along with the setup of pheromone lures and traps. It should be done regular and especially if the traps indicate that there are DBMs present in the area or region. The fields should be checked at a couple of random locations at least twice per week. A rule of thumb is that at least 5 locations per field should be checked and you remove plants in an area of about $0.1m^2$ carefully and count the number of larvae. The action threshold recommended in Canada is 20-30 larvae in $0.1m^2$. That indicates around 2-3 larvae per plant if the plant density is around $100/m^2$ (Canola Encyclopedia, 2015).

Resistance

Table 1. Insecticide resistance (Furlong, Wright, Dosdall, 2013).

Insecticide class;	Year of introduction (IRAC);	Reported resistance, country;
Organophosphates	1944	Australia, China, Costa Rica, India, Nicaragua, Pakistan, Philippines, South Africa, South Korea
Carbamates	1950	China, India, South Africa, South Korea, Taiwan
Pyrethroids	1977	Australia, Brazil, China, India, Japan, Malaysia, Mexico, New Zealand, Nicaragua, Pakistan, Philippines, South Africa, South Korea, United States
Indoxacarb (oxadiazines)	1997	Australia, Brazil, Malaysia, United States, Pakistan
Avermectins	1978	Brazil, China, Malaysia, Pakistan, Taiwan
Cyclodiene organochlorines	1950	India
Phenylpyrazoles	1989	China, Malaysia, India, Taiwan
Spinosyns	1997	Malaysia, United States, Pakistan, Taiwan
Nereistoxin analogue	1965	China, India, Taiwan, Nicaragua
Neonicotinoids	1990	Malaysia
***Bt* (*kurstaki,* Cry1A)**	1970	Central America, China, India, Malaysia, United States, Taiwan, Thailand
***Bt* (*aizawai,* Cry1C)**	1970	Malaysia, United States, Taiwan, Thailand
Chlorfenapyr	1992	China, Taiwan
Benzoylureas	1975	Brazil, China, Japan, Malaysia, Nicaragua
Diacylhydrazines	1993	China
Azadirachtin	1995	Taiwan
Anthranilic diamides	2008	China

One of the great problems in managing the DBM is its resistance to a broad range of insecticides. Different strains of the DBM have, over the past 70 years, from when insecticides were introduced, developed near total resistance to all of them (Talekar & Shelton, 1993; Furlong, Wright, Dosdall, 2013). However, it is important to know that not all strains of DBM are resistant to the same group of active substances, it depends on where the moth originates from and what active substances that have been previously used as control agents (Gonzalez-Cabrera *et al.,* 2001). It is also worth noting that cross resistance between these substances occurs, meaning that developing resistance can lead to an increase in tolerance, or resistance, to other active substances (Furlong, Wright, Dosdall, 2013). Table 1 shows how long some active substances have actually been in use and the many years the

DBM has been exposed to it depending on various uses. It was the first insect to report resistance to novel active substances such as *Bacillus thuringiensis, Bt,* and some of its different Cry-toxins, both in genetically manipulated crops and spray-products (Talekar & Shelton, 1993).

The reason for its broad resistance is the extensive use of pesticides, i.e. calendar spraying, where *Brassica* crops are grown on a nearly year-round basis creating a green bridge for the DBMs life stages. This is frequent in the tropics and subtropics where *Brassica* is an important cash crop and there are few alternative hosts in the wild, so the local strains of the DBM gets exposed frequently to the active substances in the insecticides. The high average temperature in the tropics allows rapid development and the DBM can manage many generations per year, increasing the rate of resistance development (Furlong, Wright, Dosdall, 2013).

Integrated Pest Management

Integrated pest management is going to play an important future role in managing the DBM. In Sweden where the weather is not always favourable for insecticide treatment at the right time, a combined treatment strategy of the DMB such as preservation of natural enemies, intercropping and dead end trap crops etc. can compensate and reduce reproductive success/rate 'R_0'. R_0 represents, under ideal conditions, the average number of offspring produced by an individual in its lifetime (Holland, 2007).

This has been carried out in practise for as long as 30 years in the region 'El Bajio' in central Mexico (Shelton, 2001). 'El Bajio' is a region with extensive broccoli production, up to 40,000 ha. They started to notice great resistance against their most commonly used insecticides in the pyrethroid class. This led to control failures and quality loss. The advice given, and what also solved the production problems, was to back away from the extensive use of pyrethroids and start planting *Bt* genetically modified crops and stop the use of pyrethroids. This let the natural enemies population, which had been a victim of the broad spectrum insecticides, be restored. A threshold was set for when crop spray was motivated and sampling in the field occurred regularly. By doing in-field sampling you get an overview of the DMB local movements and if resistance is present. The most important control measure they implemented was to break the green bridge between growing seasons and thus breaking the life cycle of the DBM (Shelton, 2001).

Intercropping

Intercropping is a well-known method for reducing pests. It is based on multispecies cultivation and biodiversity where you combine two or more crops in one field to achieve an additive positive effect from either the fertilizer point of view or reduction of pests (or both) resulting in a higher quality or, in some cases, increase in yield (Tilman et al., 2002; Muschler, 2001; Mucheru-Muna, 2010).

Experiments in order to reduce damage by the DBM have been carried out with intercropping non-host together with species from the *Brassica* family;

Experiments were carried out in the year 2000 in both laboratory- and field conditions with intercropping white cabbage (*Brassica oleracea var. capitata*) with high- and low growing red clover (*Trifolium pratense*) in the meaning of vegetational diversity. It was compared with monoculture of white cabbage. The idea was that the DBM were to get visually confused and disrupt its immigration- and emigration behaviour so that the main cash crop avoided damage. The results were that only intercropping with high growing red clover showed some reduction in eggs laid. High clover also showed differences in immigration and emigrational behaviour concluding that the DBM might be controlled by intercropping (Åsman, Ekbom, Rämert, 2001).

In Ghana, in 2010, white cabbage (*Brassica oleracea var. capitata*) was intercropped with several non-hosts in different tests; cabbage-tomato, cabbage-pepper and cabbage-onion. There were two controls with monoculture of white cabbage, one sprayed with the insecticide Dursban from the class organophosphates and one without any control measures. The tests showed, in this case, that intercropping with all these three different non-host plants was as effective in reducing damage to the leaves and heads as spraying with this particular crop spray Dursban, and that intercropping with onion and tomato resulted in less damage than intercropping with pepper (Asare-bediako *et al.*, 2010). However, in 2012 another test was carried out in Ghana with intercropping cabbage (*Brassica oleracea*) with onion and it showed no significant reduction in damage compared to its control with sole crop (Baidoo *et al.*, 2012).

To continue with intercropping with the family *Allium,* there have been tests in China regarding intercropping Chinese cabbage (*Brassica rapa L. subsp. chinensis*) with garlic (*Allium sativum*). The same study also tested lettuce (*Lactuca sativa*) intercropped with Chinese cabbage. The study looked at larval and pupal growth, development, and mortality.

Results were that in both tests pupal development slowed down and mortality increased with statistical significance. They conclude that the DBM can possibly be suppressed in the long term since this prolongs its life cycle (Cai *et al.,* 2011).

Trap cropping

There are many varieties of methods, similar to intercropping, called trap cropping and "dead end" trap cropping. The idea of these methods is to attract the DMB and its ovipositional choice towards these trap crops and not to the current cash crop. Concentrating the immigration, oviposition, and damage caused, to the trap crops. Dead end trap crops are to act as a sink rather than as a source for future generation by decreasing larval and pupal survival (Shelton, Badenes-Perez, 2006).

These trap crops can be wild species either grown within the field or preserved at the edges of the field through herbicide-free spray zones.

Evaluation of different species used as trap crops, their attraction characteristics, and why they are effective has been done. Badenes-Perez, Shelton and Nault (2004) evaluated and wrote a report and review on different trap crops for the DBM. In the study in 2004 they compared glossy and waxy collards (*Brassica oleracea var. acephala*), Indian mustard (*Brassica juncea*) and yellow rocket (*Barbarea vulgaris*) on the conditions of ovipositional preferences, attraction and larval survival. They did statistical analysis on the adult moths' preferences for attraction based on volatiles and morphology of the different plants. A comparison with cabbage (*Brassica oleracea var. capitata*) acting as the cash crop in a two-choice test was done and a comparison to the trap crops themselves, as well as the cabbage, in a multiple-choice test against each other. The tests were performed in outdoor screen houses.

The results can be summarized as the trap crops having the most potential were Indian mustard and yellow rocket and the potential plants for dead end trap crops were glossy collards and yellow rocket. Yellow rocket has been shown to be resistant and lethal to other larvae of the *Pieridae* family and beetles of the genus *Phyllotreta* making it a promising choice of dead end trap crop (Badenes-Perez, Shelton, Nault, 2004). Larval survival in this test was significantly lowest on glossy collards (6.7%) and yellow rocket (0%) hence suitable for dead end trap cropping (Badenes-Perez, Shelton, Nault, 2004).

In the multiple-choice test Indian mustard and yellow rocket stood out in ovipositional preference for the DBM. In the two-choice test compared to cabbage, acting as the cash crop,

the only one that didn't show significant results were waxy collards (Badenes-Perez, Shelton, Nault, 2004). One should be aware that in other tests result indicate that the presence of Indian mustard elicits more eggs to be laid by the diamondback moth during their reproductive lives, causing potential for the cash crop to receive more eggs compared to trap cropping with a less attractive plant species (Shelton, Hatch *et al.,* 2008).

In the case of yellow rocket the low larval survival is caused by the high content of saponins which is harmful to DBM larvae when consumed. Low survival on glossy collards is not due to saponins, since it is not known to contain a substantial amount, but is rather due to some behavioral changes of newborn larva caused by the reduction of wax. Waxy collards do not show this low percentage of survival (18.9%) (Badenes-Perez, Shelton, Nault, 2004; Badenes-Perez, Reichelt M. *et al.*, 2014). The ovipositional attraction is based on many combined factors but this study puts volatiles in the center and visual preferences and total leaf area as 2nd (but still important) after experiments with ovipositional preferences conducted in Plexiglas tubes were no total leaf area and visual bais was present (Badenes-Perez, Shelton, Nault, 2004).

Insecticide use

Crop spraying with insecticides is going to continue to play an important role in managing the DBM because of its effectiveness when used correctly. It is also going to keep being important in controlling the DBM and be an essential part in IPM. These past decades there is an increasing demand for spray products that are more selective and preserve natural enemies. Although they are usually being introduced in a combination of older more broad insecticides that already have resistance present in many strains of the DBM. This causes resistance to quickly develop to the newly introduced substances and ruin future good use in IPM as a specific insecticide and conservation of natural enemies (Furlong, Wright, Dosdall, 2013).

The timing of application and choosing the right product are important factors. When it comes to specific insecticides the DBM larvae are often targeted in such a way that it either has to hit the larvae directly or be consumed. The first instar larva is protected against contact insecticidal products because it lives and feeds in the mesophyll. Timing so that the application hits the great majority of all the second instar that live on the surface of the leaves can be crucial to reduce the reproductive rate in potential females of the population (Furlong, Wright, Dosdall, 2013).

Monitoring when to spray using sex pheromone lures and traps to get the catch threshold has been done in cole crops in India. This was done to evaluate the potential to prevent unnecessary calendar applications of insecticides. There were no optimum trap catch number or timing established but the data gave a good indication of the optimum period of which applications hit a large part of the population and gave good end results in reducing damage to the cash crop at the same time as insecticide applications were reduced (Venkata *et al.,* 2001).

Changing, or sometimes mixing, the products used and active substances as often as possible is recommended to prevent resistance development but cutting away from broad spectrum insecticides can be just as important in order to preserve natural enemies such as predators and parasites (Weinzierl, 2009). In mid-western USA an example of IPM is in practice by farmers growing Brassica; the goal is to stay away from broad spectrum insecticides and only use specific targeted against lepidopteran larva such as *Bt* (which is not an insecticide) allowing natural enemies to develop and control the DBM. Then in a later stage use fewer applications of pyrethroids if control threshold is reached or to control other pests (Weinzierl, 2009).

If the timing is successful there are other factors that can be a challenge such as hitting the targeted insect. In oilseed rape there are a range of crop spray techniques that you can apply in order to fully cover the crop and get to the majority of larvae that live and feed on the underside of the leaves. One examples of these techniques is an air assisted spray boom that with the help of air jets propel the spray mist at 35-40 m/s into the crop making air turbulence as it hits the ground and projects droplets back up so that the complete foliage gets covered. Another technique is using a Cropsurfer (patent by Viby Teknik in Sweden) which is a semisoft shield or a boom in front of the spray boom that causes the crop to flex forward revealing parts of the underside of the top foliage and getting the spray droplets further down into the crop. Combining treatment timing with a well thought through application technique the dosage can be reduced and also the number of times applied (Hagenvall & Nilsson, 1997; Viby teknik, 2015).

Irrigation modification as an alternative control measure

The DBM is sensitive to abiotic stress and rainfall is a big mortality factor. It can disrupt the DMB from flight but also dislodge the larva from the plant. Tests have been done in the 80's where three different irrigation methods were evaluated for alternative control of the DBM on cabbage and Chinese cabbage: furrow irrigation, central point (Rainbird-type sprinkler)

irrigation, and overhead irrigation. The sprinklers were on frequently at dusk during three to four weeks. The sprinkler systems manage to reduce the amount of damage done but are not sustainable for conventional or organic farming in brassicas found in temperate climate due to cost and the risk of fungal infections (Talekar, Lee, Huang, 1985; Talekar and Shelton, 1993).

Bacillus thuringiensis

Bt, Bacillus thuringiensis, is a soil bacteria that can produce a crystalline protein (cry protein) during sporulation. This protein is an insecticidal toxin and active against most species of Lepidopteran larvae including the DBM larvae. It is also active against some dipteran and coleopteran species. Because the toxin is so host specific it does not target beneficial insects like broad spectrum insecticides do (Höfte & Whiteley, 1989).

The genes that produce this toxin are called cry-genes and are located on the plasmid of the bacteria, making it more available for extraction than if it were located on its DNA. This has been taken advantage of and there is a transgenic way to implement this gene into a desired crop and create dead end trap crops mentioned above. Although this method is only suitable outside of Europe due to EU regulations concerning genetically modified organisms, GMO (Sarfraz *et al.,* 2005).

There have been recent studies showing that DBM natural enemies help slow down the DMBs development of resistance for the Cry-toxin produces by induced *Bt* crop, hence providing a favourable environment for natural enemies that is a great implement in IPM (Liu *et al.*, 2014).

Natural enemies

The DBM has many different natural enemies ranging from viruses, pathogenic fungi, pathogenic bacteria (such as *Bt*), generalists predators and parasitoids. Over 135 species of natural enemies have been recorded to attack various stages of the DBM worldwide (Sarfraz *et al.,* 2005). Different viruses have been tested for controlling DBM and some are successful as, for example, granulosis virus PlyxGV, but no products are available outside of China and therefore not implemented in any control strategy or IPM-program (Grzywacz *et al.,* 2010). Proteins or spores from fungi can often have pathogenic characteristics against insects. A fungus effective against whiteflies (*Pieridae*); *Isaria fumosorosea*, has been evaluated for its protein's antifeedant- and insecticidal actions. There were 7 isolates tested and results showed some differences in the 7 isolates of this fungus, two of those showed promising results as a

potential insecticide. However, it is long before there is an available product in the form of a biological spray on the market (Freed *et al.,* 2012).

Other more well known but different types of fungi used as insecticides are *Zoophthora radicans* and *Beauveria bassiana*. *Zoophthora radicans* has been isolated from the DBM and can cause epizootics when environmental conditions are beneficial for the fungus. It is even reported to reduce the local populations completely to zero. Infected adult moths laid significantly fewer eggs and infected larvae have shown to consume 44% less foliage than healthy ones. *Beauveria bassiana* is available as a market product for insect management and reported to successfully reduce the local population and effectively spread between contaminated moths and healthy moths (Sarfraz *et al.,* 2005).

The generalist predators have not yet been seen as primary control although they do attack the DBM. The parasitoids are considered the most important natural enemies and can provide considerable control if provided with beneficial environmental conditions (Sarfraz *et al.,* 2005).

There are three main parasitic wasps that are well known and recorded to attack DBM; *Diadegma insulare*, *Microplitis plutellae,* which attack the larval stage, and Diadromus subtilicornis which attacks the pupal stage (Sarfraz *et al.,* 2005; Canola Encyclopedia, 2015). These three are also the most important natural enemies in biological control of western Canada, which is similar to Swedish environmental circumstances, and are recorded to parasitize in field up to 50% of the DBM in Canada. In Minnesota, USA, *D. insulare* are recorded to parasite up to 80% of DBM (Wold-Burkness *et al.,* 2005). They migrate from the south along with the DBM in springtime and the population size development rate goes hand in hand with the DBM with some delay (Canola Encyclopedia, 2015).

Even if *Diadegma insulare,* for example, is known to parasitize the DBM in Canada it is not officially recorded yet to occur in Sweden but there are several species of the genus Diadegma that live and reproduce in Sweden and one of them who do is Diadegma majale (Dyntaxa, 2015). In Iran this is also a known parasite of the DBM in oilseed rape and according to field test with six commercial cultivars it parasitizes up to 88% (cultivar Opera) (Fathi, Sarfraz *et al.,* 2011).

During the infestation in 1995 in Sweden some parasitoids on the DBM were collected in field. These were larval parasitoids: *Cotesia plutellae* (earlier known as *Apanteles plutellae*)

from the family *Braconidae; Diadegma semiclausum* from the family *Ichneumonidae*. Pupal parasitoids: *Diadromus subtilicornis* from the family *Ichneumonidae*. All of these parasitic wasps are native in Europe and probably also Sweden (Barbara Ekbom, personal communication 2016).

It is also important to note that different strains of a specific parasitoid attack a specific host which means that if *D. insulare* were to occur in Sweden it depends on the DBM strain and origin if it has coevolved with the natural enemy and evolved as a preferred host (Sarfraz *et al.,* 2005). Also the cultivar planted has influence on the parasitoid's preference on the host plant (Fathi, Sarfraz *et al.,* 2011).

As mentioned before the parasitoid population size follows the DBM in parallel but with some delay for the DBM population size increase. Refuge crop or refuge area is a good way to allow parasitoids and other natural enemies to increase in number and establish a decent sized population before colonizing the cash crop and thereby reducing the delay in which the DBM increases in number (Schellhorn *et al.,* 2008).

An increase in natural enemies and predation of DBM can have a great effect in controlling the pest and a good implementation in IPM practice (Furlong, Ju *et al.,* 2008; Furlong, Shi *et al.,* 2004).

It is essential to plan a management strategy as a whole when relying on natural enemies as an integrated pest management and consider what you spray with later on since it has been shown in a study carried out in California, USA, that Bt induced crop producing the Cry-toxin does not affect DMBs parasitic insects and allows it to fully develop and kill its host (Chen *et al.,* 2008). Synthetic insecticides such as Pyrethroids, and organic based insecticides such as Spinosads, consumed by DBM larva will not only kill the DMB but also its parasitoid (Chen *et al.,* 2008).

Parasitoids are not the only insects that are a threat to the DBM; flies, lacewings, plant bugs, pirate bugs, beetles, spiders, and birds also prey on the diamondback moth larvae (Sarfraz *et al.,* 2005; Canola Encyclopedia, 2015).

Life tables

To provide some examples of reduction of DMB population either through control measures, natural cause of death, rainfall/irrigation, natural enemies etc. a series of life tables were put together displaying the reproductive success 'R_0'. The goal is to maintain R_0 below 1 and thereby decreasing the population. Results are displayed in table 2, and the basic model representing the 'IPM system' in table 2 is presented in the appendix.

Table 2. Displaying the results of the reproductive success, R_0, from the life tables. 'Happy face' designates a positive result indicating reduction of population and 'sad face' designates negative results indicating an increase in population.

Main mortality cause	Adult females age in days			Result
	1	5	10	
R_0				
Parasitized 3rd instars 70%	0,4	0,8	1,0	☺
Crop spray 2nd instars 90%	0,2	0,4	0,6	☺
Rainfall 3rd instars 80%	0,9	1,8	2,3	☹
Control failure	1,2	2,3	3,0	☹
IPM system	0,0	0,0	0,0	☺

Variables that represent the mortality in percent for the different life stages are: crop spray, rainfall, fall of plant, low temp., disease, predators, parasitized, egg mortality/infertility, failure to reproduce and various/unknown. The life stages include: Eggs, 1st - 4th instars, pupas, and adults (female). Number of initial eggs was set to 130 as a reasonable estimate considering that the female DBM can lay up to 200 eggs but not every individual is certain to do so (Talekar and Shelton, 1993). 20% of the adult females were set to fail to reproduce after 5 days of age.

'Parasitized 3rd instars 70%' show how much R_0 is reduced when the DBM population is parasitized by natural enemies slowly beginning the population development at the DBMs 2nd instars and reaching population maximum at the 3rd instars. The reproductive success is reduced below 1 even after adult female moths reach 5 days of age.

'Crop spray 2nd instars 90%' show that an effective well timed spray application well enough reduces the reproductive success. The population of natural enemies is affected by the insecticide application and barely recovers until the last instar of the DBM.

'Rainfall 3rd instars 80%' shows no population reducing factor or active control method. Heavy rainfall hitting the 3rd instars reduces the population by 80% yet the rain comes too late and reproductive success rapidly reaches 2

'Control failure' showing the effects of an incorrect timing of crop spray application and a attempt to correct it afterward. The 1st instars are located in the spongy mesophyll of the leaves and not affected by contact of any spray applications. The error is attempted to be corrected at the 3rd instars although the timing is too late and reproductive success is not reduced below 0 and rapidly staggers above 3

'IPM system' show how effective a well-established IPM-system can have on reducing a DBM population. The population of natural enemies is promoted through a favourable environment and given a head start at the season. No broad spectrum crop sprays is used and the natural enemies can pray in the DBM throughout the season. The reproductive success is well below 1 and the DBMs population is wiped out.

Climate data

As explained in the 'overwintering' section the DBM has limited cold tolerance and probably does not manage to overwinter in climates like the climate we have in Sweden at the moment (Gu, 2009). The climate is changing and becoming warmer and has done so for the last climatic normal period (official climatic normal cover a 30-year period of record, 1961-1990) and we can expect an increase during this ongoing period that we are in (SMHI faktablad nr 29, 2006; smhi.se/klimatdata, 2016). What are the climate temperature and the possibilities for the DBM to overwinter going to look like in Sweden for the next 100 years? And during the years of early migration how many generations can we expect, as well as reduction in time between generations (increased growth rate)?

The temperature predictions used are based on data from different climatic scenarios: RCP 4.5 and RCP 8.5 (Representative Concentration Pathways). The RCPs are trajectories of future greenhouse concentrations and created from a collection of 9 different global climatic models summarized in a mean temperature increase or decrease for each year to the year 2100.

RCP 4.5 is characterized by

- Population around 9 billion
- Extensive reforestation

- Lower energy intensity

- Strongly driven global climatic politics

- Greater efficiency in agriculture in terms of area need

- Change in consumer patterns

RCP 8.5 is characterized by

- CO_2 emissions are three times the values of today

- Population over 12 billion

- Large demand for fossil fuels

- Slow development in technology towards energy efficiency

- High energy intensity

- Methane emissions drastically increase

- No further development in global climatic politics

The district in Sweden provided data for is eastern Svealand which includes Uppland and Södermanland.
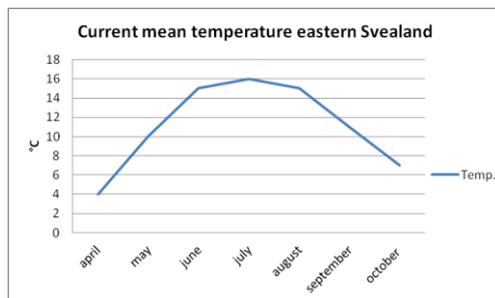

Figure 3. Graph displays the current mean temperatures during the spring, summer and autumn that are relevant for the lifecycle of the DBM in Sweden, eastern Svealand (smhi.se/klimatdata, 2016).

(SMHI- RCP, 2013; SMHI.se/klimatdata, 2016).

With climate data from SMHI about the RCP scenarios graphs were generated, see figure 4 & 5, with temperature series. The data provided were means of temperature predictions for Eastern Svealand for all the years between 2014-2100 according to the model scenarios RCP 4.5 and RCP 8.5. The scenarios provided predictions on a yearly basis and for each season (winter, spring etc.). The series do not originate from zero because the data is displayed as a comparison to the mean temperature value of the climatic normal period 1961-1990. Also shown are the average temperatures, in all series an increase, and those are based on the mean from all predicted temperatures of the RCP model between the years 2014-2100.

Figure 4. Graph displays mean temperature according to climatic scenario RCP 4.5 between years 2014-2100. The District is eastern Svealand. The series are not originating from origin because it is a comparison to the mean temperature for each year of the climatic normal period 1961-1990. The average increase in mean temperature for each series is also shown.
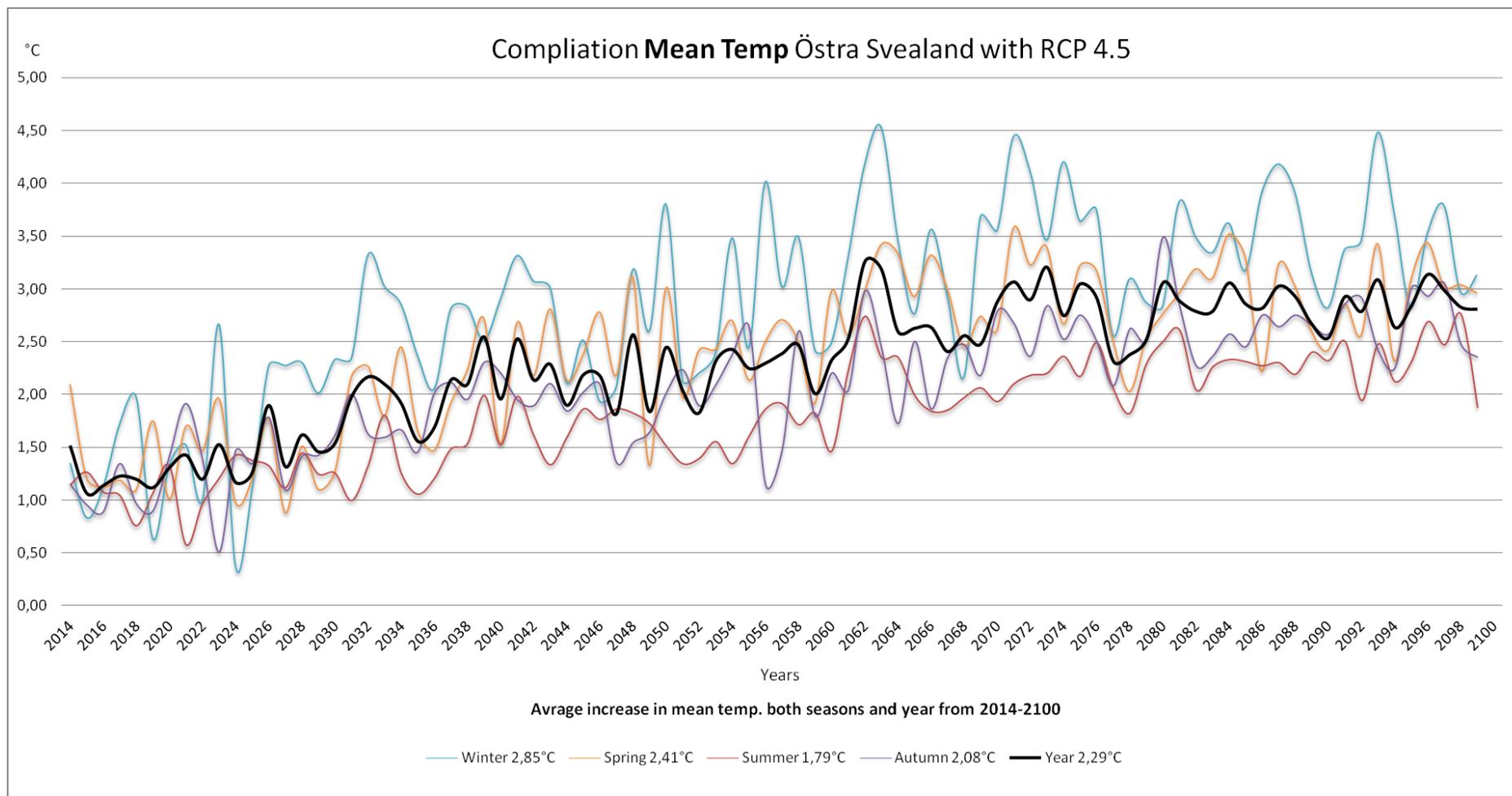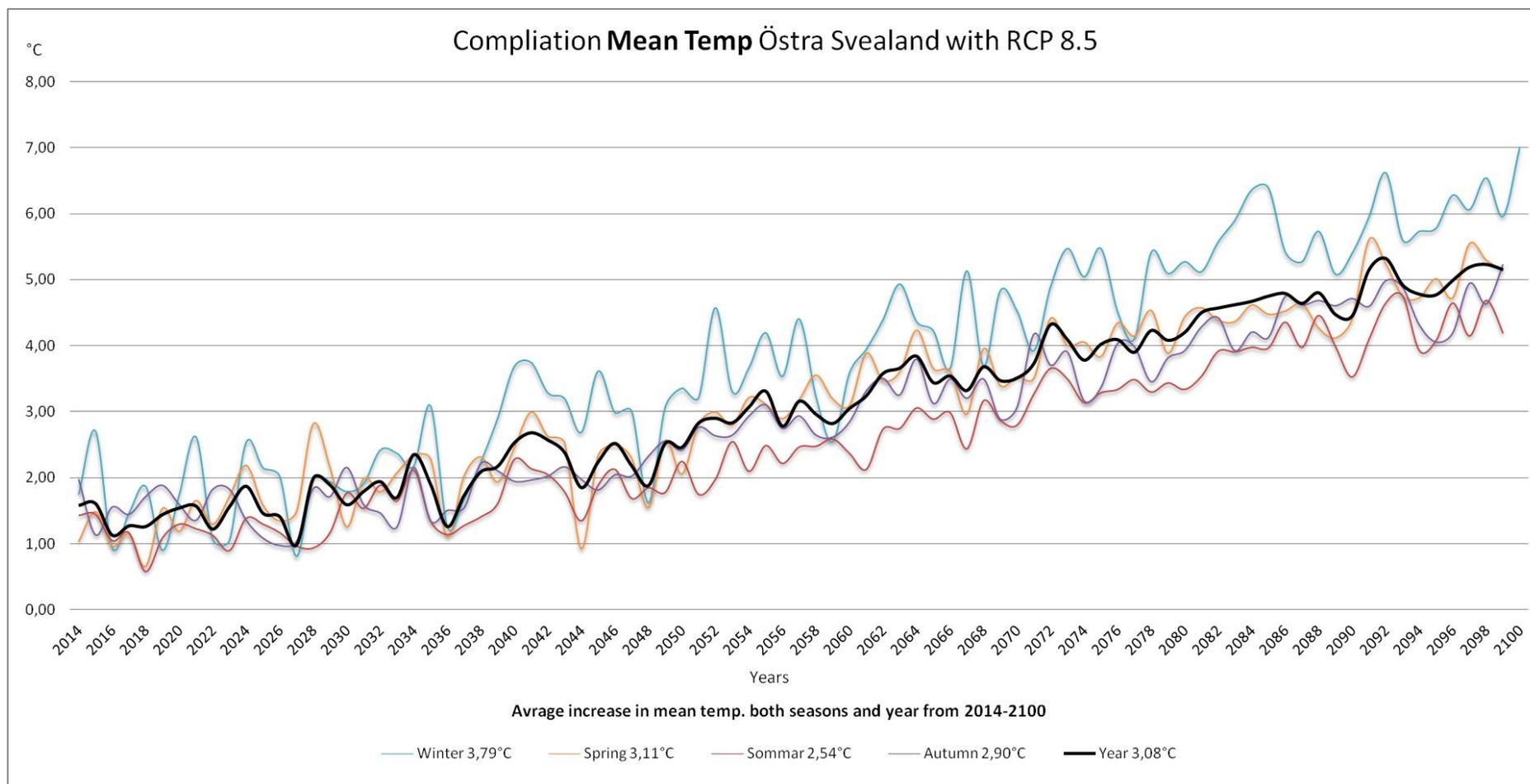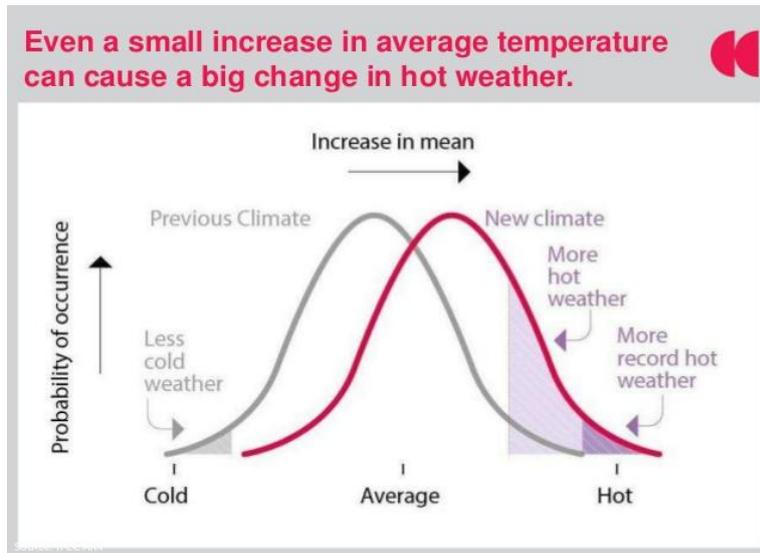
Figure 5. Graph displays mean temperature according to climatic scenario RCP 4.5 between year 2014-2100. The District is eastern Svealand. The series are not originating from origin because it is a comparison to the mean temperature for each year of the climatic normal period 1961-1990. The average increase in mean temperature for each series is also shown.

During the course of 86 years the average temperature increases in all series and both scenarios. Even though it is only a small increase it makes a significant difference in the

overall climate as illustrated in figure 6 (IPCC, 2007). The data is presented both as per year and the different seasons. Spring months are March, April, and May. Summer months: June, July, and August. Autumn: September, October, and November. Winter: December, January, and February.

Figure 6. Graph illustrates that even a small change in mean temperature causes overall warmer weather (IPCC, 2007).

The relevant months for the DBMs development (temperature baseline above 7°C) in this report are April to October so these are the months taken in consideration in 'figures 8-10' but April is only presented in 'figure 10' because only in RCP 8.5 does the DBM accumulate DD that month (figure 7). The temperatures during the winter months are also important when speculating overwintering possibilities and probabilities. With the data from the future mean temperature, figure 4 and figure 5, and today's current mean temperature, figure 3, one can calculate the number of days the DMB lifecycle is reduced and how many generations per year it is plausible that the DBM can manage. This is done based on the DBM lifecycle of 260 DD (Sarnthoy *et.al.*, 1989; Golizadeh *et al.,* 2007).

In figure 8, showing the number of days it takes for the DBM to complete its generations today, the first generation takes 52 days to accumulate 260 DD. This stretches between 1st of May that has an average temperature of 10°C, to 21st of June that has an average temperature of 15°C (figure 3). Generation 2 and 3 takes 30 and 26 days respectively. The generation development for the DBM today stops in late September due to the average temperature for October being below the temperature development baseline of 7°C (figure 7).

		Current, °C	Increse RCP 4.5, +°C	Future temp. ÖS RCP 4.5, °C	Increse RCP 8.5, +°C	Future temp. ÖS RCP 8.5, °C
Spring	April	4	2,41	6,41	3,11	7,11
	May	10	2,41	12,41	3,11	13,11
Summer	June	15	1,79	16,79	2,54	17,54
	July	16	1,79	17,79	2,54	18,54
	August	15	1,79	16,79	2,54	17,54
Autumn	September	11	2,08	13,08	2,9	13,9
	October	7	2,08	9,08	2,9	9,9

Figure 7. Current mean temperatures in eastern Svealand (ÖS) for the spring, summer and autumn months. And the mean temperature increase for each month from climate scenarios RCP 4.5 & 8.5 added to the current temperature and showing future predicted temperatures in eastern Svealand (ÖS).
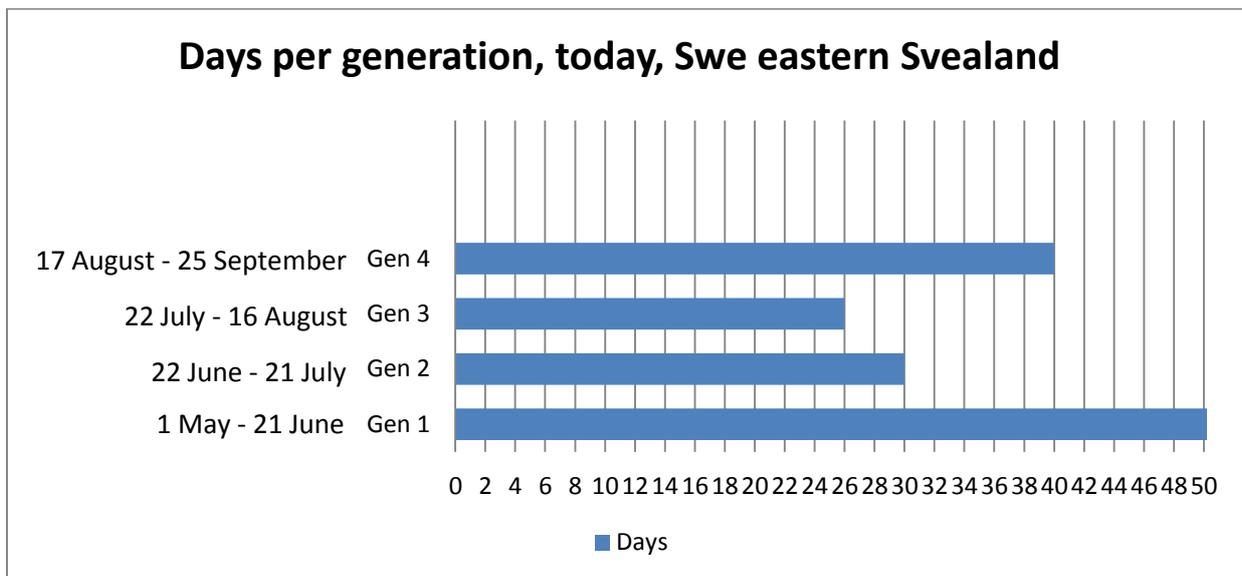

Figure 8. The number of days it takes for the DBMs generations to complete with the current mean temperature in eastern Svealand. It can manage four generations in total during the months May to September and the dates for each generation are presented.

'Figure 9 & 10' are based on the predicted climate data from figure 4 & 5. According to the RCP 4.5 data and 8.5 data the DBM manages 6 generations as the temperature is above development baseline (figures 7, 9, 10). The months differ between the figures because in RCP 4.5 the DBM does not reach the development threshold in April but in RCP 8.5 it does, but only by 0.11°C (figure 7). It is still important to show, even though it barely accumulates DD, because the climate change could cause earlier establishment of migration and inflight, and thereby an earlier start of the DBMs season. The DBM reaches the 6th generation in October (figure 9) at RCP 4.5 and September (figure 10) at RCP 8.5. Both scenarios show a temperature in October above the baseline 7°C (figure 7) but it is not enough for a 7th generation for either of them so RCP 8.5 in figure 10 only presents development too late September. It is worth noticing that in RCP 8.5 the predicted temperature for October is almost 1°C more than in the scenario RCP 4.5.

Figure 9. The number of days it take for the DBMs generations to complete with the mean temperature during climate scenario RCP 4.5 in eastern Svealand. It can manage six generations in total during the months May to October and the dates for each generation are presented.
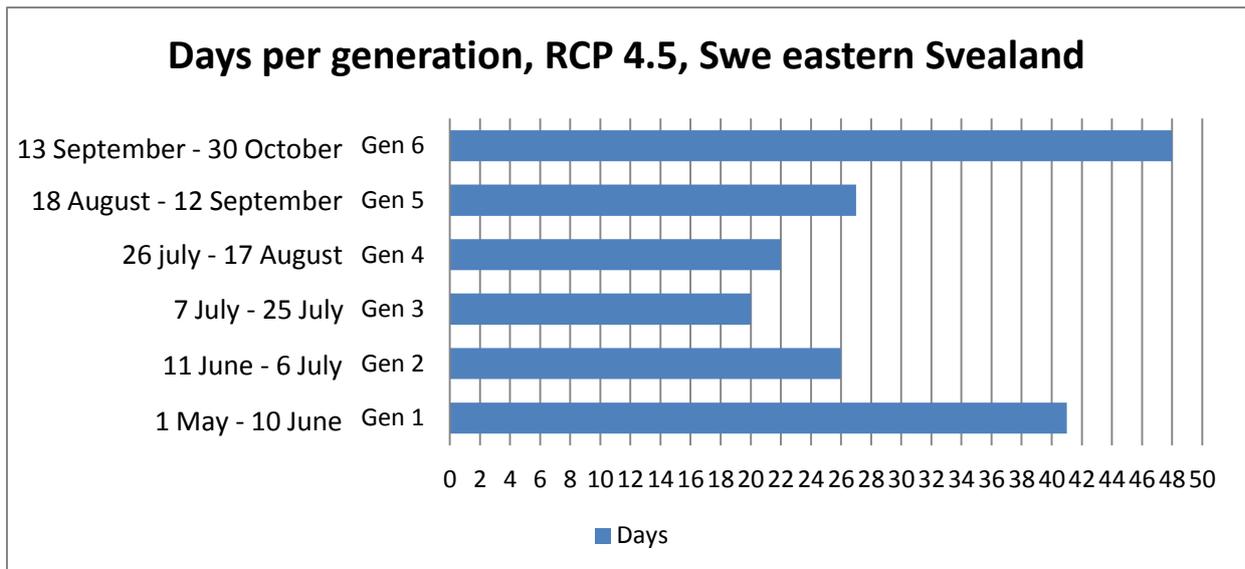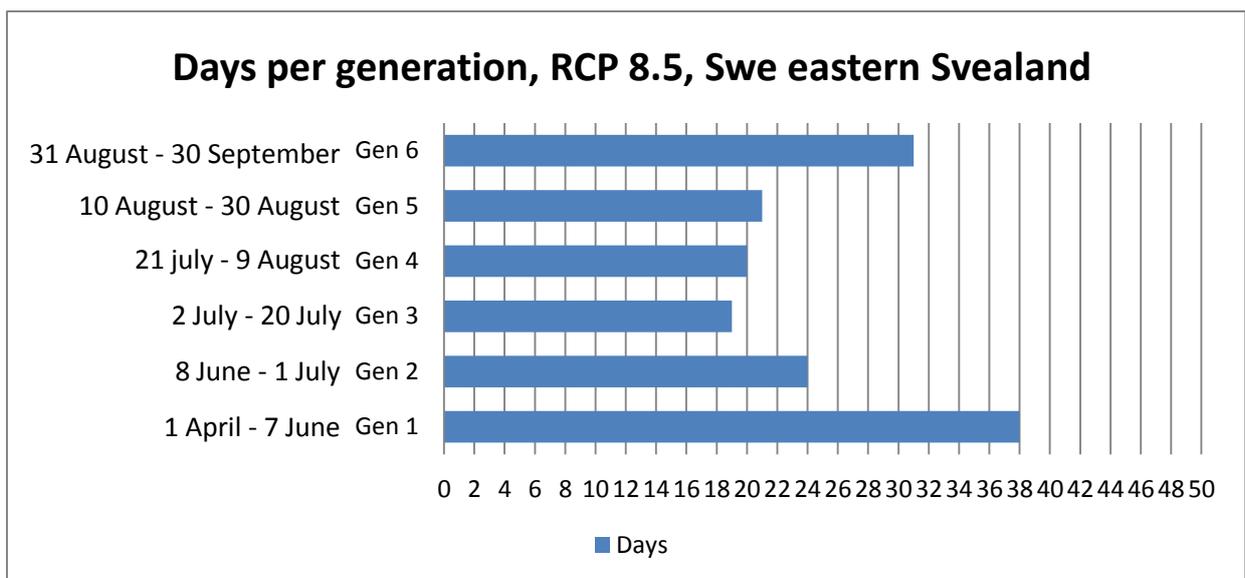

Figure 10. The number of days it take for the DBMs generations to complete with the mean temperature during climate scenario RCP 8.5 in eastern Svealand. It can manage six generations in total during the months April to September and the dates for each generation are presented.

Discussion and Conclusions

One of the bigger questions about the DBM and its future is its overwintering capabilities and prospects. As of today, in Sweden, we have not found any documented specimen or results that indicate that the DBM overwinters in our current climate. Even in regions of Götaland (southern parts of Sweden) where we have the mildest winter months with relatively high average temperatures (SMHI, 2009) have we had populations proven that it originates from the previous growing season. Studying only the average temperatures during the winter months in Sweden it is plausible that some years the DBM can survive between growing seasons given the optimal conditions (Gu, 2009; SMHI, 2016).

An important factor to consider when discussing the possibilities of overwintering is abiotic conditions such as, for example, precipitation during the late period of the year and also weed management around the field (Talekar and Shelton, 1993; Schellhorn *et al.*, 2008). When temperatures for survival, or even development and reproduction, are at the limit the DBM has high requirements on the local area to provide food and shelter in order for a population to sustain itself into the next growing season. Refuge vegetation and nearby shrubbery is important when the main host plant, mainly the cash crop, is harvested. Even during optimal coverage from precipitation, predators etc. the development for the 4th and last generation stops mid-September to late late-September (figure 8) and cold today in Sweden will help reduce the population's reproductive rate, R_0, below 1 so that the population will not establish enough in the spring to be a threat during the growing season. So for now our rainy autumns and cold winter months are protecting us.

Introducing the future climatic scenarios RCP 4.5 & 8.5 that show an average increase in temperature the next coming decades (figure 4 & 5) DBM chances of surviving the winter become a whole lot different. The relatively small increases can make a huge change in climate and weather (IPCC, 2007). With the warmer temperatures we introduce 2 more generations (figure 9 & 10) and prolong the season where the DBM can be active. Combining this with higher average temperatures during the winter months chances for surviving increase and we can expect the DBM to overwinter in the future decades.

The average temperature will also increase globally and more extreme weather patterns will come with it (IPCC, 2007). The resistance problem will increase where it is already a problem due to an increase in development rate and the need for more intense spraying. It will also

spread to areas where introduction of a continuous generation cycle due to new overwintering capabilities occurs (Furlong, Wright, Dosdall, 2013).

The prolonged DBM season in Sweden (figure 9 & 10), even if overwintering doesn't occur, makes is more difficult to control the pest. The DBMs generations can occur in parallel in one field (Borg, 1946). This could be dependent on different times of inflight or slight differences in development time. An earlier date with a temperature that allows for survival and development also allows earlier establishment when inflight occur. These parallel generations could make spray application timing difficult which is critical if the plants themselves have not yet started building enough biomass to withstand some damage to the foliage.

Integrated pest management, IPM, techniques provide a promising future in controlling the DBM. The effects of insecticides or biological pesticides is important and unless we introduce better management of the usage of them it is likely they will all start to render ineffective in the future due to increase in resistance (Furlong, Wright, Dosdall, 2013). Improved management includes several things: one is applying the right amount at the right time. The right way to start is by choosing an effective product and applying it correctly with the right amount and with a calibrated sprayer that runs at the proper operating pressure for the specific nozzle. Other things to you can do to improve efficiency is to use a crop surfer, which is a shield or a boom that is mounted in front of the sprayers nozzles and flex the plant to an angle exposing more of the lower parts of the plant and underside of the leaves. Another is to use an air assisted spray boom to propel droplets into the crop and get an increased coverage compared to a regular sprayer (Hagenvall & Nilsson, 1997; Viby teknik, 2015).

A basic need for the correct timing of application is a proper monitoring of the pest. Monitoring the DBM inflight with pheromone lures and insect traps is an applied method in Canada, where the DBM is a common pest due to seasonal inflight (Miluch *et al.*, 2013). Pheromone traps give an indication of when the DBM arrive and thus when field scouting should intensify. With the help of counting day degrees from the beginning of the season and continuous field monitoring it can give a good estimate of the time scale of the DBMs development and when to spray (Venkata *et al.,* 2001). In Sweden today the first application of insecticides against *Meligethes aeneus*, rapeseed pollen beetle, in late May to early June often correlates with the timing of the first application against DBM (Ekbom & Wærn, 1995; Karlsson *et al.*, 2013) although this is not a guaranteed control of the DBM if inflight occurs

after this period or if the population is big. Regular monitoring and field scouting throughout the season is recommended.

Field scouting techniques and action thresholds recommendations vary a bit but putting those in practice regularly is the most important. Acting one step ahead or in parallel with the inflight population of the DBM is a huge advantage in managing the pest.

When discussing IPM management tactics further a big component is natural enemies and intercropping or trap crops. Having the knowledge of these species and their preferences of habitat helps in shaping the cropping system on a landscape level and that is a key to reducing the use of insecticides and controlling the DBM in a sustainable way.

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Figures:

Figure 1 images:

1.

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Figure 2:

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Personal Communication. Barbara Ekbom, February, 2016.

Appendix

Basic life table displaying results of R_0 of an IPM system:

DBM Stage	Age in days x	Number alive S(x)	Prob. birth to X l(x)	Prob. survive X to X+1 g(x)	Prob. death X to X+1 d(x)	expect. nr new fem. m(x)	death cause	#dead	%mortality	expect. offspring l(x)m(x)	Repr. rate R_0
Eggs		130	1	0,95	0,05		crop spray	0	0		
							eggs infertile	0	0		
							fall of plant	0	0		
							parasitized	0	0		
							unknown	6,5	5		
							SUM	6,5	5		
First instar		123,5	0,95	0,55	0,45		crop spray	0	0		
							predators	37,05	30		
							disease	0	0		
							parasitized	12,35	10		
							fall of plant	0	0		
							rainfall	0	0		
							unknown	6,175	5		
							SUM	55,575	45		
2nd instar		67,925	0,5225	0,2	0,8		crop spray	0	0		
							predators	20,3775	30		
							disease	0	0		
							parasitized	27,17	40		
							fall of plant	0	0		
							rainfall	0	0		
							unknown	6,7925	10		
							SUM	54,34	80		
3rd instar		13,585	0,1045	0,2	0,8		crop spray	0	0		
							predators	2,717	20		
							disease	0	0		
							parasitized	8,151	60		
							fall of plant	0	0		
							rainfall	0	0		
							unknown	0	0		
							SUM	10,868	80		
4th instar		2,717	0,0209	0,1	0,9		crop spray	0	0		
							predators	0,2717	10		
							disease	0	0		
							parasitized	1,9019	70		
							fall of plant	0	0		
							rainfall	0	0		
							unknown	0,2717	10		
							SUM	2,4453	90		
pupae		0,2717	0,00209	0,9	0,1		crop spray	0	0		
							predators	0	0		
							disease	0	0		
							parasitized	0	0		
							fall of plant	0	0		
							rainfall	0	0		
							unknown	0,02717	10		
							SUM	0,02717	10		
adult females	1	0,24453	0,001881	1	0	0,122265				0,00022998	
							crop spray	0	0		
							low temp.	0	0		
							fail reproduce	0	0		
							disease	0	0		
							rainfall	0	0		
							unknown	0	0		$R_0=$
							SUM	0	0		0,000
adult females	5	0,24453	0,001881	0,8	0,2	0,122265				0,00022998	
							crop spray	0	0		
							low temp.	0	0		
							fail reproduce	0,048906	20		
							disease	0	0		
							rainfall	0	0		
							unknown	0	0		$R_0=$
							SUM	0,048906	20		0,000
adult females	10	0,195624	0,0015048	1	0	0,097812				0,000147187	
							crop spray	0	0		
							low temp.	0	0		
							fail to reproduce	0	0		
							disease	0	0		
							rainfall	0	0		
							unknown	0	0		$R_0=$
							SUM	0	0		0,001