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Integrated pest management strategies for cabbage stem flea beetle (*Psylliodes chrysocephala*) in oilseed rape

Running Title: IPM of CSFB in oilseed rape

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Abstract

Oilseed rape (OSR) is the second largest source of vegetable oil globally and the most important biofuel feedstock in the European Union (EU) but production of this important crop is threatened by a small insect; *Psylliodes chrysocephala* – the cabbage stem flea beetle (CSFB). The EU ban on use of neonicotinoid seed treatments and resistance of CSFB to pyrethroid insecticides have left farmers with limited control options resulting in drastic reductions in production. Integrated pest management (IPM) may offer a solution. We review the lifecycle of CSFB and the current options available, or in the research pipeline, for the eight IPM principles of the EU Sustainable Use of Pesticides Directive (Directive-2009/128/EC). A full IPM strategy for CSFB barely exists. Although there are a range of preventative measures these require scientific validation; critically, resistant/tolerant OSR cultivars are not yet available. Existing monitoring methods are time consuming and there are no commercial models to enable decision support based on predictions migration timing or population size. Available thresholds are not based on physiological tolerances of the plant making it hard to adapt them to changing market prices for the crop and costs of control. Non-synthetic alternatives tested and registered for use against CSFB are lacking, making resistance management impossible. CSFB control is therefore dependent upon conservation biocontrol. Natural enemies of CSFB are present, but quantification of their effects is needed and habitat management strategies to exploit their potential. Although some EU countries have local initiatives to reduce insecticide use and encourage use of ‘greener’ alternatives, there is no formal process for ranking these and little information available to help farmers make choices. We summarise the main knowledge gaps and future research needed to improve measures for CSFB control and to facilitate development of a full IPM strategy for this pest -and sustainable oilseeds production.

Keywords

Insect pest control, *Brassica napus*, sustainable agriculture, pesticides, control threshold, biocontrol.

Introduction

Oilseed rape (*Brassica napus*, L., OSR) is the second largest source of vegetable oil in the world, after soybean (European Commission 2018); grown throughout most of the European continent (Table S1) it is the dominant biodiesel feedstock in the European Union (EU), accounting for 39% of total biodiesel feedstock production (USDA 2019). Its importance as biofuel feedstock has contributed substantially to the rising value of the crop; the additional demand from the energy sector (Directive 2003/30/EC, 2003) expanded the use of the crop, and consequent increase in production from 11.1 Mt in 2003 to 21.4 Mt in 2009 (Faostats 2021). This, however, led to almost unlimited availability of resource for insect pests. OSR is attacked by a suite of insect pests (Williams 2010a), which can significantly impact yield (Zheng et al. 2020) and the cabbage stem flea beetle (CSFB, *Psylliodes chrysocephala* L. Chrysomelidae) has been ranked as the most significant biotic threat to OSR cultivation in Europe (Zheng et al. 2020). Due to severe infestations by CSFB, farmers, especially in the UK and northern Europe, are struggling to grow OSR and are opting to grow alternative crops (Defra 2017; Wynn et al. 2017; Andert et al. 2021). Major reductions in OSR area has led to a decline in production in Europe (Zheng et al. 2020; Andert et al. 2021); the area of OSR harvested in the EU for 2019/20 was the lowest since 2006/07 (USDA 2020). This was mainly attributed to higher pest pressure and decreasing availability of registered active ingredients for chemical control, especially since the ban on neonicotinoid seed treatments (Zheng et al. 2020; Andert et al. 2021).

Ecology of CSFB

Adult CSFB are present throughout most of the European continent (CABI, 2021; Table S1). They are oval in shape, 3.2 - 4.6 mm long (Bonnemaison and Jourdheuil 1954) have 10 antennal segments, and thickened hind femurs to enable them to jump to avoid predators (Furth 1988; Ruan et al. 2020) (see graphical abstract). They are usually black with a blue-green metallic sheen although a brown variant also occurs (Bonnemaison and Jourdheuil 1954). Adult beetles migrate to newly-sown OSR crops in autumn; they are able to fly up to 3-4 km (Bonnemaison 1965). Migration flights generally end in October and once in the crop their flight muscles atrophy (Bonnemaison 1965; Ebbe-Nyman 1952). The beetles feed on the cotyledons and young leaves of plants (Fig 1A); after a period of c.2 weeks, they start to mate and oviposition begins (Bonnemaison and Jourdheuil 1954; Sáringer 1984; Alford et al. 2003). Oviposition usually peaks

in autumn, when temperatures are between 2°C - 16°C, but continues until early spring in mild conditions (Meuche 1940; Bonnemaïson and Jourdheuil 1954; Bonnemaïson 1965; Sáringier 1984; Mathiasen et al. 2015a). Eggs are oval, orange, 0.6 mm long and 0.4 mm wide (Bonnemaïson & Jourdheuil, 1954) (Figure 1B) and are laid in batches in the soil near the host plant (Sáringier 1984; Vig 2003). Eggs hatch from September onwards (Alford 1979; Johnen et al. 2010) but larvae are sensitive to cold winter frosts which could limit their distribution in the furthest north areas of Europe (Mathiasen et al. 2015a,b). The neonate larvae tunnel into the plant and feed and develop gregariously in the plant petioles and stem throughout the winter and into late spring (Alford et al. 2003). There are three larval instars (Bonnemaïson 1965) (Figure 1 C-E). From late February to June, third instar larvae tunnel out of the plant, drop to the ground and create a small cavity a few cm under the soil surface to pupate (Williams and Carden 1961) (Figure 1F). Pupation lasts 8 - 12 weeks depending on temperature; new generation adults start to emerge in May within the OSR crop where they stay to feed on the stems and the exterior of pods (Williams and Carden 1961; Sáringier 1984) (Figure 1G). In late summer adults undergo a period of aestivation (prospective diapause (Sáringier 1984)) where they stop feeding and either remain in the crop (Vig 2003; Sivcev et al. 2016) or migrate to sheltered areas such as hedgerows and woodlands (Bonnemaïson and Jourdheuil 1954) (Figure 1H). By the end of August, when temperatures have cooled, the beetles become active again and migrate into newly-sown crops, reaching the population peak by early September, although this varies with weather conditions (Sáringier 1984; Vig 2003).

[Figure 1 here]

Pest Status

Both adult and larval stages of CSFB are damaging. Adults feed on cotyledons and young leaves of OSR plants giving rise to 'shot-holing' symptoms (Figure 1A). Although in controlled conditions, plants can fully compensate for up to 90% leaf area loss at early growth stages (Ellis 2015; Coston 2021), damage to the hypocotyl at the cotyledon stage or severe and sustained feeding damage to the first leaves can threaten crop establishment. Once plants are beyond the four-leaf stage, they are better able to compensate for leaf area loss and adult feeding damage becomes less important (Ruck et al. 2018). Larvae damage the plants by feeding (mining) within

the petioles and stems (Williams and Carden 1961) (Figure 1C-E), causing reduced plant vigour and increased risk of frost damage and disease, reducing overwintering survival; in spring they can cause stem splitting, death of the growing point, delayed flowering, and even plant death (Bonnemaison and Jourdeuil 1954; Williams and Carden 1961; Evans 2007). Traditionally, neonicotinoid seed treatments were the main method for protecting crops against adult CSFB (Maienfisch et al. 2001). However, since their withdrawal following concerns regarding their effects on non-targets (Blacquièrre et al. 2012; Palmquist et al. 2012), pyrethroids are the only registered insecticidal control option but resistance is an increasing problem (Heimbach and Müller 2012; Zimmer et al. 2014; Willis et al. 2020). The current situation reveals a threat to long-term efficacy of insecticide use, making it necessary to have a broad range of management options available for farmers to combat CSFB in a sustainable and efficient way.

Current EU policy provides a framework for integrated pest management (IPM); defined by the Sustainable Use of Pesticides Directive (Directive 2009/128/EC), IPM offers ‘an approach to reduce the development of harmful organisms where plant protection products and methods are appropriately considered and kept to levels that are economically and ecologically justified and minimise risks to human health and the environment’. This Directive (Annex III) sets out a series of eight IPM principles (described by Barzman et al. 2015); namely: (1) Prevention and suppression of the pest through cultural actions; (2) pest monitoring – to enable: (3) well-judged decision-making based on the actual and/or predicted pest incidence and specific thresholds. If an intervention is needed, IPM strategies offer a sequence of control options, giving preference to: (4) sustainable biological, physical and other ‘non-chemical’ methods. When insecticides are essential to provide control, (5) insecticide selection should favour selective products with fewest detrimental effects on the environment, non-target organisms and human health. Also, IPM aims to: (6) reduce insecticide use and (7) avoid insecticide resistance development. Principle 8 (evaluation) encourages users to evaluate the success of the actions and measures adopted to improve the process. Here we review the current evidence for existing components of IPM strategies to control CSFB in OSR following the structure defined by Directive 2009/128/EC and the principles described by Barzman et al. (2015) and highlight areas of research needed to improve them.

Principle 1. Prevention and suppression via cultural actions

Crop rotation

Crop rotation is used to prevent build-up of pests, weeds and diseases and to maintain soil health; it is one of the fundamental aspects of IPM (AHDB 2020). Initially OSR was grown in c. one-in-five rotations with cereals (ENDURE 2007). Longer rotations tend to result in increased yield (Zheng et al. 2020), but as the value of the crop has risen there has been a trend towards one-in-two or three-year rotations (Berry and Spink 2006; Rusch et al. 2010). The percentage of OSR in a region was shown to be negatively correlated with the proportion of plants with CSFB larvae or damage (Valantin-Morison et al. 2007). However, this study was conducted several years before the peak in OSR production, and it is unknown if this ‘dilution effect’ applies to larger cropped areas and increased populations of beetles. Spatially, crops located close to the previous year’s OSR seem to exhibit more damage than crops sown far from previous crops (Williams and Carden 1961; Alves et al. 2015). However, because CSFB are highly mobile and can easily migrate between fields (Bonnemaison 1965), crop rotation in itself is unlikely to disrupt their distribution unless done on a synchronized area-wide basis (regionalized zoning) in which whole regions break from OSR cropping at the same time (Zheng et al. 2020).

Sowing date and seed-bed conditions

Historically, the sowing window for a successful overwintering OSR crop was mid-August to early September, although the optimum varies with latitude (Williams and Carden 1961; Lääniste et al. 2007; Henke et al. 2009; Ratajczak et al. 2017). However, by sowing at this time, crop emergence coincides with CSFB immigration, making it susceptible to feeding attacks which can threaten establishment. Early sowing can enable crop establishment before CSFB migration, reducing crop vulnerability to adult CSFB (Valantin-Morison et al. 2007; Alves et al. 2015; Wynn et al. 2017). However, early sowing can increase the risk of larval damage by lengthening the period available for CSFB oviposition (White and Cowlrick 2016; Conrad et al. 2021). More research is required to understand the trade-offs between crop establishment and larval damage and the interaction with timing of adult migration and establishment conditions.

Soil conditions at sowing are important. Crops drilled into light and fine soils with adequate moisture (40% by weight of water), particularly during emergence, establish quicker and are more

able to withstand CSFB feeding damage (Blake and Spink 2004; Alves et al. 2015; Wynn et al. 2017).

Cultivation method

There is a wide range of tillage regimes used for OSR, with differential effects on CSFB damage. Larval infestation is reduced when using minimum or zero tillage compared with ploughing (Ulber and Schierbaum-Schickler 2003; Valantin-Morison et al. 2007). In reduced tillage systems the presence of previous crop stubble, particularly tall stubble, reduces adult CSFB infestation (Ulber and Schierbaum-Schickler 2003; United Oilseeds 2020). More work is needed to understand the mechanisms responsible for these observations.

Cultivation method can also impact the natural enemies of CSFB (see Principle 4). Ground dwelling predators react differently to tillage method (Holland and Oakley 2007) and reduced tillage has been found to increase their numbers in OSR (Stinner and House 1990; Büchs 2003; Thorbek and Bilde 2004). Reduced tillage has been found to have positive effects on the abundance and survival of *Tersilochus migrogaster* Holmgren (Ichneumonidae: Tersilochinae) the main parasitoid of CSFB larvae (Ulber and Nitzsche 2006). *T. microgaster* overwinters in diapause in the soil of former OSR fields (Ulber et al. 2010a), therefore, leaving fallow ground or using cultivation methods with minimal soil disturbance can reduce parasitoid mortality caused by ploughing (Nilsson 2010).

Seed rate

Adult CSFB feeding is decreased at higher seed rates (White et al. 2020; Coston 2021), likely due to dilution effects. Similarly, CSFB larval infestation per plant is significantly reduced with increasing plant density (Nuss and Ulber 2004; Coston 2021). However, final crop yield was not affected by seed rates (Nuss and Ulber 2004; White et al. 2020; Coston 2021b). This is attributed to the ability of plants grown at low density to better compensate for larval damage and to produce larger petioles, more leaves and lateral racemes, providing enough food to avoid larval competition thereby reducing migration to the main stem and terminal buds. However by increasing OSR seed rate total larvae/m² could be increased; this may exacerbate problems in

following seasons by increasing the total abundance of adult CSFB emerging from the crop (Nuss and Ulber 2004; White et al. 2020).

Mowing/sheep grazing

The possibility of adapting canopy management techniques used for spring OSR crops such as livestock grazing (Syrový et al. 2016) or mowing (Kirkegaard et al. 2008) for CSFB management has attracted recent interest. By removing OSR leaves infested with larvae, the number of third instar larvae entering stems and subsequent negative yield effects can be reduced. Winter OSR has been shown to compensate from defoliation with minimal impact on yield if occurring prior to stem elongation (Spink 1992; Sprague et al. 2014). Later mowing led to a greater reduction in larval infestation compared to an unmown control: 31% in December, 42% in January and 55% in March (White et al. 2018). However, crops mown in March (close to stem elongation) had the lowest yields. Also, mowing the crop in early March delayed the onset of flowering which increased risk from pollen beetle (*Brassicogethes aeneus*) (Coston 2021); this may have contributed to yield reductions recorded in comparison to unmown crops. In a farmer-led study in the UK, larval numbers were significantly reduced in OSR crops when they were sheep-grazed or mown (c. 75% and 45%, respectively), however, all defoliation resulted in yield loss compared with controls (Pickering and White 2021). Further work is required to optimise timing and grazing intensity to overcome these negative impacts.

Companion planting

Two main companion planting approaches have been tested for CSFB: (1) sowing the crop with a 'nurse crop' i.e. plants which protect the crop and are later removed after crop establishment, and (2) trap cropping, where plants that are more attractive to the pest than the cash crop are grown alongside to divert pest pressure away from the cash crop (Hokkanen 1991; Shelton and Badenes-Pérez 2006; Cook et al. 2007). The species used as 'nurse plants' are ideally fast growing but not highly competitive, frost sensitive and nitrogen providers. Tested species include faba beans, lentils, vetch, fenugreek, clovers, white mustard, buckwheat and nyger (Ruck et al. 2018; Breitenmoser et al. 2020; Coston 2021). Reductions in CSFB adult damage and/or larval infestation have been reported when berseem clover was sown with OSR in France, Switzerland

and UK (Verret et al. 2017; Breitenmoser et al. 2020; White et al. 2020; Seimandi-Corda et al. unpublished data). The presence of cereal volunteers during establishment also reduced CSFB damage (Seimandi-Corda et al. unpublished data). The approach ideally relies on die-off of nurse plants in winter to avoid competition with the crop. However, in regions with mild winters like NW France and UK, removal with herbicide is required. This is problematic when OSR is combined with other Brassicas such as white mustard (*Sinapis alba*) and although use of ‘Clearfield’ cultivars resistant to specific herbicide overcome this, correct timing of removal of the nurse crop is difficult (Coston 2021). Rigorous assessment of the efficacy of these practices is currently lacking.

Trap crops have shown potential to reduce CSFB infestation in OSR. In different field trials, OSR plots with turnip rape (*Brassica rapa*) borders were less damaged by adult CSFB (Coston 2021) and had lower larval infestation (Barari et al. 2005; Coston 2021) than plots without a trap crop. This is probably the result of the beetle’s preference for turnip rape (Barari et al. 2005; Sivcev et al. 2016) but could be due to its fast-maturing nature relative to OSR. Patches of volunteer OSR have also been shown to act as a trap crop reducing CSFB damage and larval infestation in OSR sown in close proximity (White et al. 2020). More research is needed to understand the mechanisms of action of nurse crops and trap crops and how implementation can be optimised by farmers.

Resistant cultivars

Although OSR cultivars resistant to several diseases have been successfully developed and are widely used, there are no insect resistant cultivars currently commercially available for any OSR pest (Hervé 2017). Breeding plants with strong early vigour or good compensation mechanisms could increase plant tolerance to adult and larval infestation. Field data from commercial cultivars suggests that hybrids are generally more successful in withstanding CSFB pressure than conventional varieties, as they develop faster in autumn and/or spring, enabling them to grow away from adult and larval damage, respectively (Bayer 2020; White et al. 2020).

The easiest way to develop resistant OSR cultivars is to identify resistant *B. napus* genotypes that can then be crossed with high-yielding genotypes. Screening for reduced adult feeding has been conducted on limited number of genotypes in the field or in controlled conditions (Åhman 1993;

Giamoustaris and Mithen 1995; Bartlet et al. 1996; Lambdon et al. 1998) but no consistent differences were identified. More recent and ongoing research on larger OSR genotype sets seems to indicate some variability in resistance but results are inconsistent between laboratory and field trials (Cook et al., unpublished data; Thursfield et al. 2020). No differences in larval infestation between genotypes have been found (White 2016; Döring and Ulber 2020; White et al. 2020). However, mechanisms that confer insect resistance in other closely related *Brassica* species can also be used in OSR breeding programs via introgression. Interspecific variability of CSFB adult feeding has been tested (Bartlet and Williams 1991; Lambdon et al. 1998), and CSFB larvae have reduced weight and higher mortality when developing in white mustard compared to OSR (Döring and Ulber 2020). Introgression of resistance to insects from this species to OSR has already been achieved (Gavloski et al. 2000; Kott and Dossdall 2004) and could be possible for CSFB. Resistance mechanisms behind the intra- and inter-specific variation observed remain largely unknown. Metabolites such as the glucosinolates (defence compounds specific to cruciferous plants including OSR) could be involved as these act as phagostimulants to CSFB adult feeding (Bartlet and Williams 1991; Bartlet et al. 1994a; Giamoustaris and Mithen 1995) but contradictory results were found between feeding and glucosinolate levels (Bartlet et al. 1996, 1999).

Genetic modification enables OSR plants to express genes not usually found in the *Brassica* genome which confer resistance to insects (Hervé 2017). Transformed OSR expressing the cysteine proteinase inhibitor (blocking protein digestion in insects) showed no effect on CSFB adults or larvae (Girard et al. 1998). In Canada, OSR transformed with *Arabidopsis thaliana* genes that induce the growth of dense trichomes at the cotyledon stage seems effective against *Phyllotreta* flea beetles and could also deter CSFB (Gruber et al. 2006; Soroka et al. 2011; Alahakoon et al. 2016a, b). Another potential approach is post-transcriptional gene silencing via RNA interference (RNAi), which prevents the manufacture of key proteins in insects, leading to death when ingested (e.g. Baum et al., 2007). However, the EU currently has a restrictive regulation on the use of GM crops (Masip et al. 2013) limiting the adoption of such strategies.

Principle 2. Monitoring

A key aspect of IPM programs is assessing the risk of the crop suffering economically significant levels of damage. This assessment is usually based on the pests' population density in the crop

and/or direct assessment of injury levels via crop monitoring (scouting), and making use of scientifically-based diagnosis and prediction systems when available (Evans and Scarisbrick 1994; Barzman et al. 2015). As both adults and larval stages of CSFB are damaging, there are separate methods for monitoring and assessing the injury levels caused by each.

Monitoring Adults

Yellow water traps are currently the main method of monitoring adult CSFB migration into newly sown OSR crops in autumn. The traps are placed at ground level in the crop and should be checked throughout CSFB immigration phase; the number of CSFB per trap is counted weekly (Walters and Lane 1994). Although somewhat labour intensive for transportation of water and manual sorting (identifying and counting CSFB among by-catch), these were found to be more effective than yellow sticky traps, which are often not sticky enough to trap adult CSFB (Green 2008). Image-based automatic identification applications, which make water trap assessments quicker and easier, are becoming commercially available (e.g. Xarvio scouting app which automatically counts and classifies insects including CSFB in the trap). Other image-based sensor technologies are being developed to provide automatic identification of CSFB flight activity in real time (Hassall et al. 2021; Kirkeby et al. 2021). Use of attractant host plant volatiles (e.g. isothiocyanates (breakdown products of glucosinolates described above) (Bartlet et al. 1992)) or sex/aggregation pheromones could improve monitoring efficacy. Male-produced aggregation pheromones have been identified in *Phyllotreta* flea beetles (e.g. Peng and Weiss 1992; Beran et al. 2011; Tóth et al. 2011). For CSFB, male-specific antennal glands were discovered (Bartlet et al. 1994b) suggesting that they may also secrete a sex pheromone, but this has not yet been chemically identified.

Monitoring larvae

Larval abundance is commonly assessed by dissecting OSR plants using a scalpel and counting the number of larvae found within the leaf petioles and stem (Walters and Lane 1994). This method has been used to provide long term data on larval incidence (Nilsson, 2002; Crop Monitor 2020). However, this is technically demanding and time consuming, and to do accurately it needs to be done using a binocular microscope. The larval evacuation method (Conrad et al. 2016) whereby field-collected plants are left to dry in a container for 1-3 weeks stimulating larvae to

naturally exit the plant takes less effort but is less accurate, as not all larvae may exit the plant. Furthermore, the delay between the samples being taken and when the farmer obtains the results does not enable timely control decisions. A third method for monitoring larval numbers is to count the percentage of leaves with scars on the petioles (Fig 1.C-E; these characteristic marks are left as the larvae move between petioles for feeding), as there is a significant relationship between these and the number of larvae per plant during autumn (Walters et al. 2001). The number of larvae can be estimated from the number of adults in yellow water traps as these two factors are related (Green, 2008).

Principle 3. Decision for control based on action thresholds

Decision-making regarding pest control in crop protection mainly involves using economic thresholds to decide whether or not there is a need to apply insecticide. Economic thresholds are defined as the lowest pest population density (pest per unit area, per plant, or per part of plant) at which control measures are needed to prevent economic damage (Stern et al. 1959; Pedigo 1986; Ramsden et al. 2017). The use of thresholds is critical to IPM as it allows farmers and agronomists to ensure that insecticides are only applied when necessary, i.e. avoiding prophylactic use which may be unnecessary if the pest is not present at damaging levels. However, in most European countries (except for Switzerland (Ramseier et al. 2016)), thresholds are for guidance only. There are no legal stipulations that oblige use of thresholds, which seems at odds with the EU directive that member states should put in place IPM strategies.

Reliability of action thresholds for CSFB control

For thresholds to be valuable they must be based on scientific studies and consider the variation in crop damage, crop tolerance, control efficacy of the product as well as insecticide cost and crop value which are subject to varying market prices (Ellis and Berry 2012; Ramsden et al. 2017). However, reviewing the origin of current country-specific thresholds for CSFB on the European continent (Supplementary Material Table S1) indicates that peer-reviewed empirical studies on the relationships between pest injury and yield validating such recommendations are uncommon and several countries may be using the same thresholds as neighboring countries without validation. Godan (1950) first suggested the threshold of 5 CSFB larvae per plant as a threshold for treatment.

Data on the equivalence between larval number per plant and yield loss is scarce but the threshold is clearly based on the economics of insecticide use rather than a physiological threshold above which plants are unable to compensate. In the UK, a threshold of 5 larvae/plant for CSFB was established based on the economics of organophosphates (Purvis 1986). This was subsequently revised based on a lower return of £130/t (1991 World price), an average UK yield of 3t/ha for OSR and cost of pyrethroids of £8/ha (Lane & Walters 1993). This same threshold was revised again in 2007 as pyrethroids proved to be cost effective at 2 larvae/plant which provided an average yield response of 0.16t/ha (HGCA 2007) and reverted to 5 larvae/plant in 2013 to reflect lower efficacy due to pyrethroid resistance (AHDB-HGCA, 2013). However, none of these studies showed the relationship between the number of larvae per plant and yield losses. To our knowledge the amount of crop damage and/or yield loss caused per CSFB adult is still unknown. Mechanical damage in OSR (simulated injury) showed no effect on seed yield and percentage oil content but actual injury by *Phyllotreta* flea beetles led to significant reductions in both metrics (Antwi et al 2008). Similarly, patch defoliation (akin to slug injury) and shot hole injury (akin to CSFB) led to differing compensatory responses in OSR, with patch defoliation showing full recovery and shot hole injury reducing seed grain yield compared to controls (Susko & Superfisky 2009). In a recent study on the impact of simulated shot-holing injury and controlled CSFB larval infestation, it was shown that OSR can compensate for leaf area injury of up to 90% at the cotyledon stage however significant reductions in plant height, yield and quality occurred when artificially infested with more than 5 CSFB larvae/plant (Coston 2021). Further assessments are needed to quantify adult and larval damage, and their interaction in field conditions in order to develop confidence in the use of thresholds.

Furthermore, considering the presence and abundance of natural enemies is an important, yet absent, component of economic thresholds, and has great potential for rationalizing insecticide use as they may increase the pest abundance level that a plant can tolerate before economic loss occurs.

Decision support systems (DSS)

The influence of weather factors on population dynamics of OSR pests, including CSFB, were studied in Germany; phenological models were developed and incorporated into a computer-based DSS 'proPlant' (Johnen et al. 2000). This DSS allows the use of field observations (pest pressure, crop growth stage, growing conditions), combined with predicted local weather data to predict

potential pest infestation, control requirements and optimal treatment dates (Johnen et al. 2010). The system included phenological models for CSFB which predicted immigration start, peaks of adults in the crop, start of oviposition and larval development, allowing more precise timing of monitoring and applications of insecticides targeted against adults to prevent oviposition and against larvae. The proPlant system was commercially used for CSFB control in mainland Europe (Johnen et al. 2010). The system is now part of the Xarvio Field Manager® package but the CSFB model is not currently commercially available. Accurate models to predict adult CSFB migration (1-2 weeks in advance) could allow growers to better plan sowing dates to avoid peak migration or could be used to determine the need for seed treatment, as recently seen in the IPM strategy for sugar beet in UK (where emergency authorisation is subject to the predicted level of virus yellows infection based on the migration date of the aphid vectors (Abram 2021; Defra 2021). Understanding population cycles may also help to predict years when CSFB is a threat; long term monitoring data of larval populations in Sweden 1970-2000 suggest population peaks every 7-9 years (Nilsson, 2002), but such long-term data is rare and it is unknown if these patterns are consistent across Europe and if they persisted on neonicotinoid treated crops to date.

Principle 4. Non-synthetic (natural) control methods

If an intervention is needed, IPM strategies offer a sequence of control options to kill pests, giving preference to less environmentally damaging and sustainably produced ones. Barzman et al. (2015) terms these options ‘non-chemical’ but we prefer the term ‘non-synthetic’. These include biological, physical and a few other natural approaches.

Biological

Biological management of insect pests includes the use of live natural enemies in biocontrol and biopesticides. Understanding of the range of natural enemies of OSR pests and their impact has improved considerably over the last 20 years, mainly due to the completion of two EU-funded research programs investigating the potential for biocontrol in OSR (BORIS and MASTER) (Alford 2003; Williams 2010b).

(i) Generalist predators

Three carabid (Coleoptera: Carabidae) species have been reported to be active and abundant in OSR at the time CSFB are migrating into new crops and oviposition starts: *Trechus quadristriatus*

(Schränk) *Pterostichus madidus* (Fabricius), and *Nebria brevicollis* (Fabricius). Of these, *T. quadristriatus* and *P. madidus* showed significant spatial association with the larvae of CSFB during October but only *T. quadristriatus* fed on CSFB eggs in laboratory experiments (Warner et al. 2003). However, as there is no evidence that *T. quadristriatus* buries into the soil surface to feed, it is unclear whether CSFB eggs laid in the soil are accessible to them. Carabids could also feed on mature larvae leaving the plants to pupate in the soil (February - June). No information is available on which carabid species are most active in OSR during the early part of this period, but during May - June there are five species that could have biocontrol potential: *Amara similata* (Gyllenhal), *Anchomenus dorsalis* (Pontoppidan), *N. brevicollis*, *Asaphidion flavipes* (Linnaeus) and *Loricera pilicornis* (Fabricius) (Warner et al. 2008). Regarding spiders, money spiders (Linyphiidae) and wolf spiders (Lycosidae) are most abundant in OSR crops (Büchs and Alford 2003; Nyffeler and Sunderland 2003). However, there are no data on predation rates and effects on CSFB abundance by this group. There is therefore a need for more research to quantify the predation potential of generalist predators for conservation biocontrol of CSFB so that farmers can adopt appropriate habitat management measures to promote their populations.

(ii) Specialist parasitoids

Within Europe, eight species of parasitic wasps (Hymenoptera) have been reported to target CSFB: six attack the larvae and two attack the adults (Ulber et al. 2010a; Jordan et al. 2020). The exact number is confused due to potential misidentifications as it is suggested that *Tersilochus tripartitus* (Brischke) resulted from misidentification of *T. microgaster* (Ulber et al. 2010a). *Tersilochus microgaster* (Szépligeti) has been reported to be the most abundant and frequently occurring parasitoid of larval-stage CSFB in Europe (Klingenberg and Ulber 1994; Nitzsche and Ulber 1998; Ulber and Wedemeyer 2004; Barari et al. 2005; Ulber and Nitzsche 2006). The level of parasitism recorded for this species varies greatly, ranging from 40 - 50 % in Germany (Ulber and Wedemeyer 2004; Döring et al. 2013) to around 10% in UK (Barari et al. 2005; Ferguson et al. 2006). There is a close spatial association in OSR between larval stages of CSFB and *T. microgaster* (Ferguson et al. 2006); such associations are necessary for effective biocontrol and indicate that the parasitoid is very efficient at finding its host and has good biocontrol potential. All the other larval parasitoid species appear to be of minor importance (Ulber and Williams 2003). However, as larval parasitoids require full development of the larvae to complete their life

cycle they do not prevent economic damage, although they can help to reduce populations in the following year.

Microctonus melanopus (Ruthe) was long considered the only parasitoid attacking adult CSFB (Ulber and Williams 2003; Ulber et al. 2010b), but in the past few years an additional species, *Microctonus brassicae* (Haeselbarth), has been identified and studied in the UK. Recent work on *M. brassicae* has described its lifecycle, behavior and parasitism rate within captive colonies (Jordan et al. 2020; Ortega-Ramos 2021). Preliminary work indicates that parasitism rate in the field ranges from 0 - 36% in the UK (Ortega-Ramos, 2021) and this species could represent an effective biocontrol agent either via conservation biological control or as part of augmentative releases. Further investigation on the lifecycle of *M. brassicae* in the field, its geographical distribution and the impacts of landscape and management factors on its populations are required to develop strategies to use and improve its biocontrol potential.

Biopesticides

The term 'biopesticide' refers to a wide variety of pest management agents derived from natural (living) materials i.e. animals, plants and microorganisms (EPA 2021). Biopesticides fall into three main classes: (1) entomopathogenic microorganisms (2) botanical pesticides and (3) animal-derived pesticides.

Insect pathogens include entomopathogenic fungi (EPF), entomopathogenic nematodes (EPN), bacteria and protozoans; all occur naturally in most arable fields and play a vital role in insect population dynamics (Lacey et al. 2001). Entomopathogens already have a place in IPM programs for some pests (Lacey et al. 2015; Maina et al. 2018). The most thoroughly studied EPFs for potential control of OSR pests are *Metarhizium anisopliae* and *Beauveria bassiana* and are known to infect adult CSFB; certain isolates when applied topically were reported to cause up to 88% and 40% mortality, respectively (Butt et al. 1992, 1994) and are currently being further tested against CSFB (Claire Hoarau Pers.com; Pole 2021). Both have strains with the capacity to colonise and grow endophytically inside OSR (Batta 2013; Vidal and Jaber 2015). Inoculation of plants via seed treatments could be a solution against CSFB but research is still in an early phase (reviewed by Card et al. 2015; Hokkanen and Menzler-Hokkanen 2017).

Entomopathogenic nematodes, particularly species of *Steinernema* have been found to be highly effective against most of the important OSR pests under field conditions (Hokkanen et al. 2006). In field studies conducted in UK and Sweden, *S. feltiae* reduced CSFB numbers by 73% and 60%, respectively (Hokkanen et al. 2006). Three *Steinernema* species, including *S. feltiae*, were tested along with *Heterorhabditis bacteriophora* against CSFB adults, with *H. bacteriophora* being most effective (Claire Horarau pers. com.) – this species has already been approved for control of black vine weevil (*Otiorhynchus Sulcatus*) (Pole 2021).

Formulations derived from the bacteria *Bacillus thuringiensis* (Bt) are used widely as biopesticides against insect pests (Brar et al. 2006). Three formulations of Bt subspecies *tenebrionis* have been screened against CSFB but beetle mortality was low (Pole 2021). Bt formulations against CSFB larvae are not considered of potential value due its production costs and difficulty in reaching the larval stages that live inside plant tissues (Evans and Scarisbrick 1994). Regarding protozoans, none have been reported to attack CSFB.

Botanical insecticides are plant derivatives used to kill insects and can be applied as seed treatments or as sprays (Isman 2006). Essential oil sprays have shown potential against some OSR pests (but not CSFB) (Pavela et al. 2009; Pavela 2011; Jiang et al. 2018); Azadirachtin, derived from the neem tree, was effective against *Phyllotreta* flea beetles (Reddy et al. 2014) but efficacy on CSFB has not been reported. The effect of 12 un-named botanicals, seven biologicals and three promoters delivered as seed coatings was tested against adult CSFB; only one promoter significantly reduced feeding (by c. 50%) compared with the control (Lohaus et al. 2018); none were effective when applied topically onto the cotyledons.

FLiPPER® is a natural by-product of olive oil production and caused high mortality just one day after application in tests against CSFB (Pole 2021). Another fatty-acid based commercial product, M-Pede®, was effective in trials against *Phyllotreta* flea beetles (Reddy et al. 2014) and could show promise against CSFB. Fatty-acids can be derived from plants or animals and penetrate the insect cuticle to disrupt metabolic processes.

Physical and other non-synthetic controls

Physical and mechanical methods used in pest management include trapping, barriers and physical destruction. Mass trapping i.e. the placement of several traps in the field to capture beetles seems

impractical to manage CSFB in the absence of effective baits (sex/aggregation pheromones or attractive host plant volatiles). Various other non-synthetic options such as silicates/rock-dusts have been tested against OSR pests (Daniel et al. 2013; Faraone and Hillier 2020) but not CSFB as far as we are aware.

Principles 5-7. Synthetic insecticides, insecticide selection and resistance management

IPM approaches can include synthetic insecticides as a last resort for control; any insecticidal compounds should be “as specific as possible for the target and shall have the least side effects on human health, non-target organisms and the environment” (European Commission 2021).

Neonicotinoids

Neonicotinoid insecticides came onto the market in 1991 and seed treatment formulations provided effective control against CSFB adults and early-stage larvae for the first 6-8 weeks growth of the crop (Maienfisch et al. 2001, Sivcev et al. 2016). However, concerns over low levels found in nectar and consequent detrimental effects on honey bees (Blacquièrè et al. 2012; Palmquist et al. 2012) led the EU to restrict the use of clothianidin, thiamethoxam and imidacloprid neonicotinoids on seed and soil treatments on arable crops attractive to bees (including OSR) in December 2013 (European Commission 2013). The restriction was revised in 2018 and the EU extended the ban on the three main neonicotinoids for all outdoor purposes (European Commission 2018). After this, pyrethroids became the only method available for farmers to control CSFB.

Pyrethroids

Pyrethroid insecticides are synthetic forms of the botanical insecticide pyrethrin which is produced naturally by flowers of *Chrysanthemum cinerariifolium*. Developed in the mid-1970s synthetic pyrethroids offered good control of a wide range of insect pests including CSFB (Soderlund 2015). By 1990 pyrethroids replaced the more toxic and environmentally damaging

organochlorines and organophosphates as foliar sprays, and continued to be used along with neonicotinoids to reduce egg-laying by late-season adults and to target newly emerged larvae and early instar larvae as they move between petioles (Zhang et al. 2017). Since the ban on neonicotinoid seed treatments, pyrethoid usage in OSR has increased drastically (FAOSTAT 2021). Although farmers have been advised to use insecticides only when the pest exceeds the economic thresholds, pyrethroids are often applied several times in the same crop and sometimes prophylactically before the pest arrives (Williams 2010a; Defra 2020).

Alternative synthetic insecticides

In recent years, there have been several alternatives to pyrethroids trialled for CSFB management, with varying success. In 2013, Boravi WG (organophosphate) was evaluated against CSFB and showed potential in controlling adults and larvae (Westerloppe, 2017). Methiocarb (carbamate) was used with emergency approval in 2014 in the UK on 9% of the OSR crop, but only 4% of agronomists reported differences in crop protection between treated and untreated seeds (Alves et al. 2015). Seed treatment with cyantraniliprole (DuPont Lumiposa®), a broad-spectrum insecticide for use in OSR against CSFB and other autumn pests, is registered for use in OSR in Hungary, Poland and Romania with ongoing reviews in other Member States (Nieuwenhoven 2017; NFU 2018). Plots treated with Lumiposa had 65% less CSFB damage than untreated plots (Nieuwenhoven 2017) but Coston (2021) found no significant effects.

Insecticide selection from an IPM perspective

IPM relies upon the application of selective insecticides that minimise unwanted effects on human health, non-target organisms and the environment (Barzman et al. 2015). Although there are databases on pesticide selectivity that can be consulted (EPPO; Jansen 2013), there is no formal procedure or practical guidance for insecticide selection. Biopesticides are generally understood as more environmentally friendly and safer than synthetic insecticides (Lengai and Muthomi 2018; Lacey et al. 2015), but they are clearly not risk-free. A key topic in the assessment of side-effects is examining whether insecticides (synthetic or natural) affect beneficial or non-target organisms. Some biopesticides, including natural pyrethrins, soft soap and mineral oils permitted in organic agriculture, are broad spectrum - as are some strains of entomopathogens (Bathon 1996; Pavlyushin 1996).

From an IPM perspective, neonicotinoid insecticidal seed treatments had many advantages when compared with other application methods especially sprays. Their systemic properties meant they could be applied to the seed prior to sowing, offering plant protection throughout the growing season without the need for repeated spray applications (Bass and Field 2018). They only directly affect insects that feed on the plant, reducing contact and impact on non-target organisms (Elbert et al. 2008), delivered control at a reduced rates (Tansey et al. 2008), and generally have less surface runoff (Palmquist et al. 2012) and reduced environmental concentration (Nuyttens et al. 2013) than sprays. However, many counterarguments have arisen against neonicotinoid use (Pisa et al. 2014; Morrissey et al. 2015); primarily that their systematic translocation to nectar and pollen negatively affects non-target organisms, especially bees (reviewed by Blacquièrre et al. 2012; Lundin et al. 2015). It has also been argued that using insecticide-treated seed is not compatible with IPM as it involves prophylactic application, before any assessment of pest abundance or crop damage (Bell 2016). However, if the pest population can be forecasted, seed treatments could be used in specific cases when needed based on predictions (see DSS, Principle 3)).

Pyrethroid sprays, however, do not seem a good option from an IPM point of view. Pyrethroids are broad-spectrum insecticides exhibiting very high toxicity to nontarget invertebrates including pollinators (Sanchez-Bayo and Goka 2014; Charreton et al. 2015), natural enemies (Desneux et al. 2004; Devotto et al. 2007; Douglas and Tooker 2016), and aquatic invertebrates (e.g. Schulz et al. 2021). In OSR pyrethroids are applied throughout the year to control different pests. Spring applications for pollen beetle control (Thieme et al. 2010) may coincide with activity of the CSFB larval parasitoid *T. microgaster* in the crop, negatively affecting their populations and biocontrol potential (Ulber et al. 2010b).

Insecticide use and resistance management

Resistance of insect pests to insecticides has long been an issue and was a major initial driver for the development of IPM (Stern et al. 1959). The increase in use of pyrethroid insecticides after the neonicotinoid ban has increased selection pressure and resulted in escalations in resistance in CSFB populations (Højland et al. 2015; Willis et al. 2020). The first confirmation of pyrethroid resistance in CSFB was in Germany, 2008 (Heimbach and Müller 2012; Zimmer et al. 2014).

Resistance was thereafter confirmed in UK (Foster and Williamson 2015; Højland et al. 2015), Denmark (Højland and Kristensen 2018), France (Robert et al. 2017; Bothorel et al. 2018) and Czech Republic (Stará and Kocourek 2019). Three mechanisms conferring resistance have been discovered in CSFB: mutation in the voltage-gate sodium channel conferring target-site (knock-down) resistance (kdr) (Williamson et al. 1993); super-knock down resistance (skdr), due to the L925I/M918L mutation (Bothorel et al. 2018; Willis et al. 2020) and metabolic-based resistance (Foster and Williamson 2015; Højland et al. 2015). Given how common and widespread resistance to pyrethroids is, it is reasonable to think that applications of this insecticidal class could be doing more harm than good; with reduced efficacy on the pest and reduced levels of control provided by affected natural enemies.

Insecticide resistance management strategies developed by the “Expert Committee on Pesticide Resistance – Insecticides” (ECPR-I 2021) in Germany and the Insecticide Resistance Action Committee (IRAC 2021) are available. Guidelines for resistance management include (1) correctly timing the applications; (2) use of products at recommended rates; and (3) alternate different modes of actions. However, there are few other insecticides registered for CSFB that allow farmers to alternate products, making resistance management virtually impossible.

Reduced use

Reduced use of insecticides will, by the nature of resistance evolution, slow the development of insecticide resistance. Directive 2009/128/EC highlighted that ‘economic instruments can play a crucial role in the achievement of objectives relating to the sustainable use of pesticides’. Denmark has adopted a pesticide taxation linked to their environmental and health toxicity (Pedersen 2016; Ministry of environment and food of Denmark 2017). Norway, Sweden and France also have a pesticide tax (PAN 2021) but these strategies do not necessarily result in reduced use (Skevas et al, 2012; Böcker and Finger, 2016). There is a clear need to provide farmers with solid, evidence-based instructions and recommendations that they can follow to carry out IPM, perhaps supported by direct payments on ecological production (e.g., in Switzerland farmers receive payments based on agro-ecological crop management (ENDURE 2012).

Principle 8. Evaluation

Principle 8 encourages farmers to assess the soundness of the crop protection measures they adopt (Barzman et al. 2015) e.g. by leaving control areas in each field; however, there are no definitive guidelines or processes by which farmers should evaluate their IPM strategy. Two new decision support initiatives are underway that may help to address this lack of holistic evaluation approaches for IPM in OSR (Munier-Jolain and Paveley, 2021). Alternatively, evaluation strategies based on multicriteria analysis (Caffi et al. 2017) or long-term studies using randomized controlled trials could be explored (Rejesus and Jones 2020).

[Table 1 here]

Conclusions

European agriculture is entering a future where fewer synthetic insecticides will be available and their use less profitable (due to reduced efficacy as a result of increased resistance in pest populations); consequently, pest management will need to rely on a wider range of methods, and this is particularly true for CSFB control in OSR. IPM strategies will be vital to providing a framework for sustainable pest management. However, this review highlights that a full IPM strategy for CSFB barely exists. We have analysed the gaps where more research is needed (Table 1) and hope this review will help identify those research and dissemination efforts that will bring adoption of IPM in OSR to its full potential.

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Table 1. Summary of current measures available for use in Integrated Pest management strategies for cabbage stem flea beetle (CSFB) in oilseed rape (OSR), and main knowledge gaps for future research needed to improve measures.

Principle	Current measures	Knowledge gaps
1 Prevention	<p>Increased crop rotation, increased distance between previous years and current crop</p> <p>Sowing at the right time, with adequate moisture into a fine seed bed</p> <p>Use of minimum or zero tillage</p> <p>Companion cropping</p>	<p>Potential of synchronized regionalized zoning of OSR rotations</p> <p>Trade-offs between crop establishment and larval damage and the interaction with timing of adult migration and establishment conditions</p> <p>Effect of stubble length to reduce immigration</p> <p>Timing of mowing/sheep grazing to reduce larval infestation</p> <p>Rigorous assessment of the efficacy of different nurse crop species and understanding of the mechanisms of action, and optimisation of their agronomy</p> <p>Efficacy and spatial positioning of trap cropping; mechanisms of action</p> <p>Development of resistant or tolerant cultivars and understanding of mechanisms conferring protection.</p>
2 Monitoring	<p>Yellow water traps for monitoring adult CSFB</p> <p>Image-based automatic identification applications for adults in yellow water traps</p>	<p>Sensor-based automatic identification of adults in real time</p> <p>Identification, synthesis and formulation of attractant semiochemicals such as host plant volatiles or sex/aggregation pheromones</p>

	Protocols for monitoring CSFB larval abundance via plant dissections, larval evacuation and counting plant scaring.	
3 Decision-making	Economic thresholds for adults and larval stages of CSFB Phenological model for egg laying and larval development	Defining a physiological threshold and understanding the relationship between the number of larvae/adults per plant and yield losses Quantification of the effect of natural enemies on pest population Phenological model for adult migration and prediction of abundance
4 Non-synthetic (natural) control methods	Conservation biological control effected by natural enemies of CSFB	Quantification of the predation potential of generalist predators for conservation biocontrol of CSFB Data on geographical distribution of parasitoids and the impacts of landscape and agronomic management factors on their populations to develop strategies to use and improve their biocontrol potential. Identification of effective yet host specific strains of microorganisms, nematodes, protozoans and formulation as biopesticides Testing of botanical and other natural products for efficacy against CSFB Development of RNAi- based formulations for spray-induced gene

		silencing Identification of attractant baits (semiochemicals) for mass trapping
5 Synthetic Insecticides Insecticide selection	Pyrethroid insecticides (spray application) New seed treatments: cyantraniliprole (DuPont Lumiposa®) European Plant Protection Agency regulation process	Development of highly specific insecticides targeted to CSFB with low environmental impact Protocols for grading or ranking insecticidal products according to target selectivity, detrimental effects on the environment, non-target organisms and human health and production of clear guidance for farmers
6-7 Reduced use and Resistance management	Insecticide resistance management strategies developed by the “Expert Committee on Pesticide Resistance – Insecticides” (ECPR-I 2021) in Germany and by Insecticide Resistance Action Committee (IRAC 2021)	Updated strategies will be required once other insecticidal products are developed, registered and commercialised
8 Evaluation	Farmer evaluation method currently lacking. Other evaluation: European Parliamentary Research Service review of Directive 2009/128/EC (2018)	A framework/ process whereby farmers can evaluate IPM methods and strategy outcomes – possibly as part of a decision support system, using multicriteria analysis or using randomized control trials in farmer field schools/cluster groups

Figure legends

Figure 1. Lifecycle of cabbage stem flea beetle (*Psylliodes chrysocephala*) and damage symptoms caused to oilseed rape (OSR) host plant. A) adult migration to OSR crops and feeding on cotyledons causing ‘shot-holing’ symptoms; B) eggs laid in the soil; C) first instar larvae mining OSR petioles and petiole scars; D) second instar larvae mining OSR petioles and petiole scars; E) third and last instar larvae mining main stem and leaf scar; F) pupa buried in the soil; G) new generation adult feeding on OSR stems and pods; H) adult aestivation in sheltered areas such as hedgerows and woodlands.



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