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Review

Towards sustainable insect pest management: A conceptual review using the example of pollen beetles in rapeseed

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ABSTRACT

Agricultural intensification is a major driver of global biodiversity loss, jeopardising the health of ecosystems and people. As the demand for agricultural products continues to grow, a major challenge is to increase production without harming the environment. This will require rethinking insect pest management and, in many cases, a shift in focus from individual fields to agroecosystems.

We review advances in insect pest management using the example of the pollen beetle (*Brassicogethes aeneus*) in oilseed rape (*Brassica napus*). Where possible, we also provide relevant pest and crop characteristics to facilitate knowledge transfer to other systems. We integrate control measures from different scientific disciplines into three scenarios: "reduced harm" - "no harm" - "biodiversity positive". All scenarios are expected to ultimately facilitate successful pest management, but with varying outcomes for biodiversity.

Environmentally sustainable pollen beetle management is in our opinion possible, but only if pest population management is facilitated by collective action (e.g. joint action of farmers). This is because immediate damage prevention requires rapid mortality of adult pollen beetles during the vulnerable bud stage of oilseed rape, which is often not achieved by either chemical pesticide substitutes or natural pest control. The latter has the potential to facilitate the control of not only pollen beetles, even under future climate projections, but will require major efforts to restore or create biodiverse and functional agroecosystems. To halt biodiversity loss, it is essential to envision a pest management strategy that facilitates this and to set the political and scientific course accordingly.

1. Introduction

Key challenges to humanity are to increase or maintain agricultural production and to reverse the trends on biodiversity loss. Meeting these challenges is urgent as the human population is projected to increase from 8.1 billion in 2023 to 9.7 billion in 2050 (United Nations, 2024), whereas biodiversity continues to decline (Díaz et al., 2019; Mühlethaler et al., 2024). Drivers of biodiversity decline include the expansion of agricultural production area to the detriment of (semi-)natural habitat as well as intensive chemical pesticide use (Díaz et al., 2019; Wagner, 2020). This is because the chemical pesticides frequently used to control insect pests that damage crops can also have detrimental impacts on non-target organisms and the environment (Aktar et al., 2009; Pretty et al., 2001; Rehman et al., 2014). This raises the question of how insect pests can be successfully managed without chemical insecticides to reduce such undesirable impacts. In this conceptual review, we describe three alternative scenarios for chemical-pesticide free insect pest management: "reduced harm", "no harm" and "biodiversity positive". The scenarios require different measures, approaches (individual/local vs. collective/large-scale) and mindsets (short-term treatment vs. long-term prevention) - and thus different degrees of agricultural transformation. They also differ in their potential for biodiversity (see 4). We illustrate the scenarios using the example of oilseed rape, a globally important oil crop (Zając et al., 2016), and one of its major pests in Europe, the pollen beetle (Williams, 2010; Zheng et al., 2020). Conventionally grown oilseed rape relies heavily on chemical insecticides (Zheng et al., 2020), whereas the organic, and therefore chemical-insecticide free, oilseed rape is restricted to areas where insect pest pressure is low (FiBL, 2023). At the same time, there is a gap between the wealth of scientific literature on alternative measures of insect pest management in oilseed rape

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(CABI, 2017; Skellern & Cook, 2018a, 2018b; Williams, 2010) and current farming practices (Zheng et al., 2020). Our objectives are 1) to provide an overview of current insect pest management measures and advances across scientific disciplines (e.g. chemical ecology, crop breeding, landscape ecology) - but organised by the underlying mechanisms (i.e. increasing pest mortality, reducing pest density, increasing crop resistance and tolerance) - by synthesising and complementing existing books, research and review articles on pollen beetle management in oilseed rape; 2) to present three scenarios - “reduced harm”, “no harm” and “biodiversity positive” - of how described measures can be integrated to successfully manage insect pests without chemical insecticides; 3) to raise awareness that measures aimed at reducing chemical pesticides will not automatically contribute to reversing biodiversity loss. Where possible, we identify insect pest and crop characteristics that are relevant to the effectiveness of a measure to facilitate transfer from pollen beetles in oilseed rape to other pests and crops.

2. Challenging insect pests – pollen beetles in oilseed rape as an example

Five to six insect pests have been identified as the main biotic threats of oilseed rape in Europe (Williams, 2010; Zheng et al., 2020). One of the most important in Europe is the pollen beetle - mainly *Brassicogethes aeneus*, but also to a lesser extent *Brassicogethes viridescence* (Gagic et al., 2016; Williams, 2010; Zheng et al., 2020). Adult pollen beetles overwinter in grassy or woody vegetation, from where they set out to find oilseed rape fields the following spring (Rusch et al., 2012, 2013). Pollen beetles cause most damage in the bud stage of the crop, when the adults feed on small buds (mostly <3 mm), resulting in a podless stalk later in the season (Seimandi-Corda et al., 2021; Williams, 2010). Excess flower buds or regrowth can compensate for this kind of crop damage, unless adult pollen beetle numbers are too high during the bud stage (Williams, 2010). Once the crop is flowering, adult pollen beetles prefer foraging on open flowers and cause little further damage (reviewed by Williams and Cook, 2010). Female pollen beetles also oviposit in flower buds, but the larvae that develop inside the buds are thought to cause little damage (Williams and Free, 1978). Eventually, larvae drop to the ground to pupate in the soil and the new generation emerges in summer (Williams, 2010). Yield losses to pollen beetles can be substantial (Zheng et al., 2020). Pollen beetle infestation on oilseed rape is commonly controlled solely by applying chemical pesticides with low specificity, which harm biodiversity (e.g. bees, soil biota, aquatic organisms and others), the environment (e.g. water pollution) and human health (Aktar et al., 2009; Pretty et al., 2001; Rehman et al., 2014).

3. Diverse perspectives for insect pest management

Although using chemical pesticides for insect pest control is the most prominent approach, there is a wealth of other measures that have been studied to manage insect pests, and particularly the pollen beetle in oilseed rape. Typically, management measures can be divided into those implemented at field scale (reviewed by Skellern and Cook, 2018b) and those mainly outside crop fields, such as landscape management

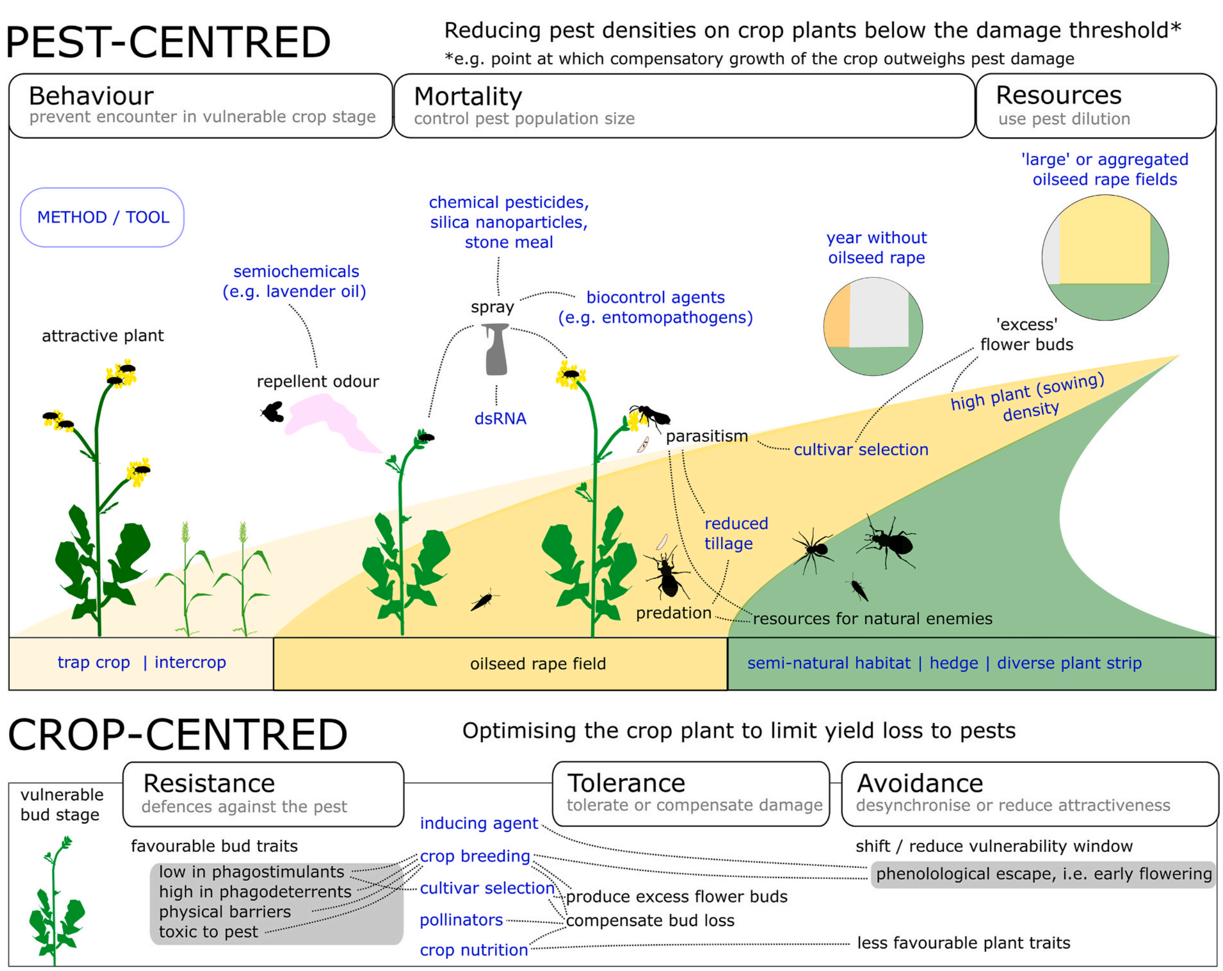

Fig. 1. Representation of the diverse pest management actions against the pollen beetle from the pest and the crop perspective. Blue font highlights tools or methods. Dotted lines link methods to mode of action or application. Adapted from (Fricke, 2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(reviewed by Skellern and Cook, 2018a), while crop breeding for crop plant optimisation is considered separately (reviewed by Hervé, 2018; Hervé and Cortesero, 2016). These measures feed into two fundamentally different perspectives on insect pest management, pest-centred and crop-centred (Fig. 1). From the pest-centred perspective, the aim is primarily to reduce the number of pests per plant below the damage threshold. This can be achieved by either directly increasing pest mortality or by reducing pest density on the crop (e.g. by interfering with pest “behaviour” or “resources”; Fig. 1). From a crop-centred perspective, management often focuses on improving the crop plant to make it (partially) resistant or tolerant to pests, for example, by making it less appealing (e.g. low in phagostimulants) or its consumption harmful (e.g. toxicity), or by enabling the crop plant to withstand or compensate for the damage (Kogan and Ortman, 1978). Yet, management may also aim to reduce pest densities through phenological escape (e.g. breeding crops able to pass through vulnerable growth stages before the pest infests the crop). Pest management approaches typically focus on one of these two perspectives (Fig. 1). However, when both perspectives are considered jointly, synergies can emerge, for example, if more pest-sensitive organs are produced than needed for optimal performance (“tolerance”, Fig. 1) and this reduces pest densities per sensitive organ (Skellern and Cook, 2018b), or if crops are bred to delay pest development and this gives more time to natural enemies to attack the pest (Hervé and Cortesero, 2016). Nevertheless, little is known about the advantages or disadvantages of integrating a given set of measures (Stenberg, 2017). Here, we bring together measures from different scientific disciplines (e.g. crop breeding, behavioural ecology, landscape ecology) that provide complementary and, when considered jointly, new perspectives on agricultural systems that are often separated by disciplinary boundaries. In the following sections of the manuscript, we present the measures largely independent of disciplines and according to three underlying mechanisms: 1) increasing pest mortality, 2) reducing pest density, and 3) increasing crop resistance and tolerance. This provides a basis for selecting from a variety of options those that are most likely to be complementary and feasible in a given context and suitable for a given scenario (see 4).

3.1. Increasing pest mortality

An essential mechanism in any pest management strategy is to increase pest mortality in order to prevent pest damage by reducing the number of pests on the crop plant during the vulnerable growth stage(s). For oilseed rape and the pollen beetle, the most vulnerable growth stage is the early bud stage (Seimandi-Corda et al., 2021; Williams, 2010). This can be achieved in the short term through direct interventions at a specific (vulnerable) crop growth stage, or in the medium or long term through various interventions to prevent high pest pressure in the subsequent years. Pest mortality is commonly increased directly by using chemical pesticides. To reduce negative impacts on the environment, a logical alternative to chemical pesticides is the use of non-chemical substitutes (3.1.1). Pest mortality can also be increased by removing pest resources; in this case, the oilseed rape crop (3.1.2). Lastly, natural pest control can be an efficient, yet long-term strategy for indirectly increasing pest mortality by manipulating natural enemy communities at field or landscape scale (3.1.3). All three pest mortality approaches can be combined in the broader concept of long-term pest population management (3.1.4).

3.1.1. Substitution of chemical pesticides for direct control

Substitutes for chemical pesticides offer a promising alternative for the immediate and direct control of pests (Fig. 1). To reduce crop damage by treating pest-infested crops, chemical pesticides are designed to kill 100 % of the insect pest within 24 h, and even if a pest is classified as pesticide-resistant, $<$90 % to $\geq$50 % of the pest will still die within 24 h (Slater et al., 2011). Limited or delayed lethality is likely to strongly limit the success of preventing crop damage, particularly when treating pest-infested crops at the vulnerable crop stage. This is the case for some substitutes such as applications of stone meal (e.g. suffocation, desiccation, abrasion of the exoskeleton), dsRNA (i.e. RNA interference silencing genes) and entomopathogens (e.g. infection) against pollen beetles (Table 1, Fig. 1). If a pest is particularly damaging when the population size builds up on the crop plant (e.g. aphids), measures with limited or delayed lethality, such as dsRNA, limit pest population growth (Zhang et al., 2023) and potentially also crop losses. Essential oils were only effective against pollen beetles in the laboratory but not in the field, and effective doses were also lethal for parasitoids (Table 1). Application of silica nanoparticles quickly achieves high pest mortality, but has not yet been tested against pollen beetles, and there are reports of negative side effects (Table 1, Fig. 1). Quick and strong lethality of an agent seems to be associated with the risk of greater negative side-effects, while agents with limited or delayed lethality may be a more environmentally-friendly alternatives for the direct control of some pests, but may require an additional pest population management strategy for pests that cause crop damage on arrival in the crop, such as pollen beetles.

3.1.2. Depletion of pest resources

Apart from substitutes for chemical pesticides, completely removing the resources required by pests (year without oilseed rape, see Fig. 1) may help to break pest cycles, increase pest mortality, and thus reduce pest pressure in subsequent years (Schneider et al., 2015; Zheng et al., 2020). However, if the scale of such actions is not large enough, pollen beetles may concentrate on the small areas of oilseed rape that do exist (Fricke et al., 2023). In addition, specialised natural enemies may be negatively affected depending on the scale of resource depletion. Therefore, careful planning is required for years without oilseed rape.

3.1.3. Harnessing natural pest control as a strategy

In the case of pollen beetles, natural pest control facilitates pest population management rather than direct damage prevention, as most natural enemies (e.g. parasitoids, entomopathogens, ground-dwelling predators) kill pollen beetles at life stages or times other than those associated with crop damage. Parasitoids such as *Tersilochus heterocerus* and ground-dwelling predators are known to reduce the number of next-generation pollen beetles emerging from crop fields, with complementary effects of parasitism and predation being known (Dainese et al., 2017), while entomopathogens reduce the fecundity, longevity and overwintering survival of pollen beetles and can be transmitted between beetles (Hokkanen and Menzler-Hokkanen, 2017). In a study in Germany, ground-dwelling predators and parasitoids (i.e. *Tersilochus heterocerus*) were observed to reduce the emergence of the new generation of pollen beetles by an average of 44 % and a maximum of 50 %, and in combination by an average of 60 % to $>$90 % (Dainese et al., 2017), while in France total parasitism rates (i.e. *Tersilochus heterocerus*, *Phradis morionellus* and *P. interstitialis*) of 0–98 % were observed (Rusch et al., 2011). Natural infection rates of pollen beetles with entomopathogens tend to be low, with an average of 4 % *Nosema meligethi* infections in Europe, most in Finland, single observations from Austria and Denmark, and none in the UK, Germany and Switzerland (Hokkanen and Menzler-Hokkanen, 2017), and 1.8 % *Beauveria* spp. infections in Switzerland (Meyling et al., 2012). A number of measures can be taken to promote natural enemies, with potentially positive consequences for natural pest control (Dainese et al., 2019).

Measures promoting natural enemies include adjustments in crop management (e.g. reduced pesticide use, constant soil cover, intercropping) and changes in field size and the surrounding landscape (e.g. increasing non-crop habitats). Reduced pesticide use likely benefits entomopathogens (Hokkanen and Menzler-Hokkanen, 2017), parasitoids (Ulber et al., 2010a), and ground-dwelling predators such as carabids (Williams et al., 2010). Constant soil cover and avoidance of long periods without a host are critical in promoting entomopathogens (Hokkanen and Menzler-Hokkanen, 2017). Reduced tillage benefits

Table 1
Substitutes (agents) for chemical pesticides that increase insect pest mortality when applied to a crop - using the example of the pollen beetle - are presented, together with their mode of action, approval status (A.s.) in the EU ("?": unclear/°pending, C: conventional, O: organic), pollen beetle mortality rate, success factors and potential side effects.

Agent [Mechanism]	A. s.	Pollen beetle mortality rate	Success factors	Side-effects
Silica nanoparticles [physical]	? C	Unknown, but other pests: 25–90 % in 1 day,80–100 % in 5–7 days (Thabet et al., 2021)	Dose, time - e.g. effect increases with time lag -, formulation - e.g. solution, dust - and particle size (compare: Shoaib et al., 2018; Thabet et al., 2021)	Dose-dependent negative effects on natural enemies (Thabet et al., 2021), pollinators (Mommaerts et al., 2012), plants and soil microbes (Saw et al., 2023); low doses possibly attract natural enemies to crops (Thabet et al., 2021)
Natural product: stone meal (e.g. containing silica oxide) [physical]	O	0–100 % in 1 day, 11–100 % in 5 days; 3.6-fold and 2.8-fold fewer beetles after 1 and 4 days compared to control fields (Dorn et al., 2014)	Formulation - e.g. combination of product and wetting agent or dust - and weather - e.g. absence of rain for effectiveness of dusts (Daniel et al., 2013; Dorn et al., 2014)	Sorptive dusts may harm parasitoids more than insect pests (Ebeling, 1971)
Natural product: essential oils	? O	0–100 % in 1 day (Dorn et al., 2014; Willow et al., 2020); no effect in the field (Dorn et al., 2014)	Identity of the essential oil and dose (Dorn et al., 2014; Pavela, 2011; Willow et al., 2020); formulation, e.g. nanoencapsulation (reviewed by Devrnja et al., 2022)	Dose-dependent negative effects on parasitoids, with parasitoids being more sensitive than pests (Sulg et al., 2023)
dsRNA [biochemical]	? C	12–43 % in 10 days, 16–66 % in 15 days, 54–92 % in 17 days (Willow et al., 2021b)	Dose, time, identity of dsRNA-treated item - e.g. anthers more effective than buds -, life stage of the pest - e.g. larval mortality only marginally increased (Willow et al., 2021a, 2021b); 1st spray induced gene silencing trials failed to increase pollen beetle mortality (Willow et al., 2023)	Parasitoids, pollinators and predators appear to be unaffected (Willow et al., 2025); Sequence length and number, starting ("seed") sequence, dose and delivery system modulate off-target effects (Zarrabian and Sherif, 2024)
Entomopathogen: e.g. *Beauveria bassiana* [biological]	? O	<10 % in 1 day, <20 % in 3 days, 21–70 % in 20 days (Kaiser et al., 2020)	Formulation - e.g. synergistic effect of rapeseed oil (Kaiser et al., 2020); Time to first disease symptoms depends on pest species, life stage, temperature and fungal strain (Zimmermann, 2007)	Infections are highly strain-specific, but occasional infections of non-target organisms as pollinators and predators; risk of allergic reactions in humans and mammals (Zimmermann, 2007)

those parasitoids (Ulber et al., 2010b) and carabid species (Williams et al., 2010) overwintering in former oilseed rape fields. Growing more than one crop in the same field often suppresses pests and generally benefits the diversity and density of arthropod predators and parasitoids (Rakotomalala et al., 2023). However, there are also examples where this seems not to be the case. For instance, intercropping oilseed rape with wheat did not affect pollen beetle parasitism (Alarcón-Segura et al., 2022) and intercropping turnip rape (a close relative of oilseed rape) with faba bean did not significantly affect carabid abundance and species assemblages (Järvinen et al., 2023). Semi-natural and non-crop habitats (e.g. hedges, woody areas, diverse plant strips) in vicinity, small field size, beetle banks, organic matter (e.g. manure, crop residues) and other local and landscape-scale factors are associated with higher activity density, richness and/or fitness of predators and parasitoids - e.g. carabids (Williams et al., 2010), spiders (Frank et al., 2010), and *Tersilochus heterocerus* and *Phradis* spp. (Rusch et al., 2011; Vilumets et al., 2023). However, more biodiversity is not automatically associated with more natural pest control (Birkhofer et al., 2018). In the case of a specific pest, the (functional) identity or composition of natural enemies may be more important than species richness (Alhadidi et al., 2018; Gagic et al., 2015; Griffin et al., 2013), but more generally, high natural enemy richness is often associated with high provisioning of natural pest control services (Dainese et al., 2019). In addition, biodiversity is critical to the resilience of ecosystem functions or services under climate change (Oliver et al., 2015), although natural enemies of the pollen beetle, such as certain carabid species (e.g. *Poecilus cupreus*) and especially lycosid spiders, are likely to cope well with the warmer temperatures expected under climate change (Feit et al., 2021; Laubmeier et al., 2023). Thus, while it is important to aim for high biodiversity in the long term, it seems important to promote specific natural enemies in the short or medium term in order to achieve satisfactory natural pest control services within reasonable time frames. Crop breeding could support such a natural pest control strategy, for example by making plants more attractive to natural enemies (Hervé and Cortesero, 2016, Fig. 1).

Although many factors are known that influence the abundance and diversity of natural enemies, it is still difficult to predict - and therefore manage - natural pest control services (Alexandridis et al., 2021). Essential for successful pest population management by natural pest control will be to select measures carefully to meet the needs of the natural enemies relevant to the focal pest (Alexandridis et al., 2022; Martin et al., 2019), to establish measures at a scale large enough to facilitate migration of natural enemies (Metzger et al., 2021), and to allow for sufficient time before judging the success of a (set of) measure (s), as ecosystem restoration can take years, decades or even longer (Moreno-Mateos et al., 2020). This requires collective action and a long-term mindset for natural pest management.

Natural pest management of pollen beetles could benefit the control of more than just this pest. For example, generalist predators such as the carabids, *Anchomenus dorsalis* and *Poecilus cupreus*, co-occur spatiotemporally with several oilseed rape pests (Williams et al., 2010) and both carabids and lycosid spiders occur in a wide range of crop fields in

Europe (Frank et al., 2010; Kromp, 1999). In addition, ground-active predators were observed to reduce not only the emergence of the new generation of pollen beetles by an average of 44 %, but also that of cabbage stem flea beetles (*Psylliodes chrysocephala*) by 38 % (Dainese et al., 2017). Measures that target the promotion of natural pest control through increasing the number and species richness of natural enemies are in themselves promoting biodiversity, but are likely to also have positive side-effects on further organisms. For example, landscape elements like hedges provide food resources and shelter to predators (Williams et al., 2010) but also benefit wild bees (Kremen and M'Gonigle, 2015). However, more natural pest control is not automatically associated with more biodiversity (Gagic et al., 2015). Thus, optimising natural pest control may need to be accompanied by a perspective of promoting endangered species and optimising pollination, soil formation and other ecosystem services to achieve multifunctional and biodiverse agricultural landscapes.

3.1.4. *Long-term pest population management*

Even if a measure does not directly prevent crop damage, it can reduce the growth rate of the pest population by increasing mortality during or before the reproductive phase of a pest. For pollen beetles and oilseed rape, this is the case for a reduction in pollen beetle numbers at life stages other than adult or after the bud stage, such as predators or parasitoids that kill pollen beetle larvae (Dainese et al., 2017), plant genetics that reduce pest oviposition and larval survival (Hervé et al., 2015, 2016), entomopathogens that reduce overwintering survival (Hokkanen and Menzler-Hokkanen, 2017), and many more (Table 1). This shifts the focus from the vulnerable crop stage or growing season to the life cycle of the pest when it comes to containing pest populations.

The effectiveness of a measure for containing a pest population depends on the scale of implementation and the dispersal of the pest. If a measure is implemented on a small field, it will have little effect on the population size of a mobile pest, whereas the effectiveness is expected to increase as the scale of the measure increases, especially if the area exceeds the dispersal range of the pest. Pollen beetles are known to disperse over more than 13 km (Williams and Cook, 2010), but the average dispersal range appears to be much lower, just a few kilometres from overwintering sites (Juhel et al., 2017). Thus, increasing pest mortality in areas stretching a few kilometres in each direction could help to contain pollen beetle pressure, while interventions over areas of more than 13 km are likely to do so more reliably, as they also reduce immigration from a greater distance. Harnessing pest population management will require large-scale (collective) action and a change of mindset from treating pest-infested crops to containing pest pressure in the coming years.

3.2. *Reducing pest density*

Apart from increasing pest mortality, pest density (e.g. the number of pests per vulnerable organ or plant) could also be reduced by interfering with pest distribution or the availability of resources. This can be achieved using a push-pull strategy (reviewed by Mauchline et al., 2018; Skellern and Cook, 2018a) or intercropping (Alarcón-Segura et al., 2022) to misguide or distract the pest, while alternatively, early flowering oilseed rape may allow temporal escape from pollen beetles (Fricke et al., 2023; Williams, 2010). In addition, the number of buds or plants ("resources") can be increased in at least four ways, which can result in pest dilution (reviewed by Skellern and Cook, 2018b, 2018a).

3.2.1. *Push-pull systems and intercropping*

Trap crops and repellent semiochemicals have been tested against pollen beetles in oilseed rape (Fig. 1), providing potential elements for a push-pull system. Several trap crops have been proposed for oilseed rape, such as *Brassica nigra* and *Raphanus sativus* (Kaasik et al., 2014; Skellern and Cook, 2018a), but *Brassica rapa* has been the most extensively studied. *Brassica rapa* is more attractive to pollen beetles than oilseed rape *(B. napus)* when both plants are in the bud stage, and tends to flower earlier, making it even more attractive (Cook et al., 2007; reviewed by Skellern and Cook, 2018a). However, despite the high attractiveness of pollen beetles to *B. rapa*, bud loss and yield of the adjacent oilseed rape crop were unaffected in a three-year field study (Kühne et al., 2013), making *B. rapa* unsuitable at least under the conditions tested (i.e. 6 m wide strips on opposite sides of 2–7 ha fields). Semiochemicals such as lavender oil (Mauchline et al., 2005), but also less expensive essential oils such as corn mint oil (Daniel, 2014), have been shown to repel pollen beetles. In a pilot field study, lavender scent released from sachets attached to canes at crop height successfully reduced pollen beetle numbers in treated units of an oilseed rape crop compared to control units when established prior to pollen beetle infestation (Mauchline et al., 2013), but a simple method for continuous scent release in non-permanent crops does not yet exist (Mauchline et al., 2018). Thus, although elements of push-pull systems exist, there is no ready-made system. If a push-pull system can be found that reliably reduces the number of pollen beetles in an oilseed rape crop during the vulnerable bud stage, the trap crop may also reduce the reproductive success of the pest or increase parasitism rates (Hopkins and Ekbom, 1999; Kaasik et al., 2014), thus reducing pest pressure in the subsequent years, especially if push-pull systems are used on a large scale.

In a strip intercrop of oilseed rape with wheat, the number of pollen beetles in the strip intercrop was similar to that in a conventionally managed monoculture of oilseed rape when the intercrop was grown without pesticides, and was reduced by 20 % in the same intercrop under conventional management (Alarcón-Segura et al., 2022), suggesting that pollen beetles are less attracted to a strip intercrop with wheat than to an oilseed rape monoculture. Legumes (e.g. faba bean) grown in between rows of winter oilseed rape also reduced the number of pollen beetles per inflorescence of oilseed rape compared to a monoculture (Breitenmoser et al., 2022; Magnin et al., 2025). The positive effect was stronger for frost-sensitive than frost-resistant faba beans, and intermediate for an artificial faba bean made from polyethylene, suggesting visual and physical disruption as mechanism (Magnin et al., 2025). Intercropping oilseed rape seems to be a promising avenue for reducing the number of pollen beetles per crop plant.

3.2.2. *Early flowering*

An alternative strategy to early flowering trap crops (Cook et al., 2007; Kühne et al., 2013), is early flowering of the oilseed rape itself. As oilseed rape is susceptible to pollen beetle damage at the bud stage and the onset of flowering is plastic (Pak et al., 2009; Srikanth and Schmid, 2011), early flowering can help escape pollen beetle damage (Fricke et al., 2023; Williams, 2010). Genetic variability in flowering time of oilseed rape could be used for this purpose (Wang et al., 2011). Early flowering has also been observed in response to treatment with methyl jasmonic acid (Pak et al., 2009) and to certain herbivore attacks (Hoffmeister et al., 2016). If an affordable flowering inducing agent can be found, flowering onset could potentially be accelerated when pollen beetle infestation is forecasted to fall within the vulnerability window of the crop (Johnen et al., 2010). However, temperature affects both flowering time (Srikanth and Schmid, 2011) and pollen beetle migration, with pollen beetles being predicted to migrate earlier under climate warming (Junk et al., 2015). Furthermore, it is known that crop plants need time to reach the optimal size for seed production (Anten and Vermeulen, 2016). This sets a limit for escaping pollen beetle damage by early flowering, depending on the given climatic conditions, but still early flowering oilseed rape can be a powerful strategy depending on the given conditions (Fricke et al., 2023).

3.2.3. *Increased plant (organ) number*

Pest densities per bud or plant can be reduced from the plant side by: i) cultivars with more buds, ii) higher plant (sowing) density, iii) large crop fields or growing oilseed rape on adjacent fields (aggregation), and iv) increasing the proportion of oilseed rape cover in the area (Fig. 1).

Oilseed rape typically produces more buds than required for optimal pod number, with cultivar-specific differences in the "excess" produced (Skellern and Cook, 2018b) and the ability to compensate for bud loss (Pinet et al., 2015). In addition, high plant densities tend to reduce pollen beetle damage (Valantin-Morison et al., 2007), although not consistently (Rusch et al., 2013; Skellern and Cook, 2018b). The choice of plant density may need to be cultivar-specific, as high plant densities can reduce the branching potential of individual plants (Leach et al., 1999) and therefore may fail to increase the number of "excess" buds. For a given plant density, a larger field size means more locally available host plants for the pest, which may also be associated with pest dilution (Schneider et al., 2015). However, this option should be carefully weighed up against potentially reduced parasitism rates, a potential increase of pollen beetles over time (Hokkanen, 2000) and lower plant and animal diversity associated with large field size (Clough et al., 2020). Dilution effects are favoured by pest characteristics such as low in-season reproduction rate and low dispersal range (Segoli and Rosenheim, 2012). However, while pollen beetles produce only one generation per season (univoltine), they are relatively good dispersers with dispersal ranges exceeding 13 km (Williams and Cook, 2010). Univoltism facilitates the dilution effects of larger oilseed rape patches, but dispersal capacity and changes in oilseed rape area between years may limit local dilution effects. For example, if oilseed rape is grown on a much-reduced area compared to the previous year, pollen beetles from the larger surrounding may concentrate on the few oilseed rape fields (Fricke et al., 2023; Schneider et al., 2015). Therefore, to successfully reduce pollen beetle density by increasing the number of buds or plants, care must be taken with cultivar selection, plant or sowing density, spatial planning and their combination.

Table 2

Pest control measures (sorted by mechanism; R&T: Crop resistance and tolerance) and their fit into three different scenarios for future agriculture - "reduced harm", "no harm" and "biodiversity positive" - with respect to the pollen beetle ([pollen beetle]) and more generally insect pests ([insect pests]). For pollen beetle management, core measures per scenario are highlighted (dark blue) as well as measures that fit all scenarios (light blue). We indicate measures that may be of limited suitability (±) or unsuitable (–) for a given scenario and those that require collective action in general ("collective") or when used for pollen beetle management ("(collective)").

	Measure	reduced harm	no harm	biodiversity positive
Pest mortality	**Silica nanoparticles**	[pollen beetle] [insect pests] (dark blue)	± may negatively affect other arthropods and microorganisms	± may negatively affect other arthropods and microorganisms
Pest mortality	**Natural products** such as stone meal and essential oils	[insect pests]	± negatively affect parasitoids	- negatively affect parasitoids
Pest mortality	**dsRNA**	[insect pests]	[pollen beetle] (collective) [insect pests] (dark blue)	± may negatively affect closely related species
Pest mortality	**Biocontrol agents** such as entomopathogens (application)	[insect pests]	[pollen beetle] (collective) [insect pests] (dark blue)	± may negatively affect closely related species
Pest mortality	**Year without focal crop**, e.g. without oilseed rape	± too complex	[pollen beetle] [insect pests] collective (dark blue)	± only if extra measures are taken to support natural enemies
Pest mortality	**Natural pest control**, e.g. conservation and promotion of natural enemies through a ***range of measures***	± too complex	± other measures less laborious	[pollen beetle] [insect pests] collective (dark blue)
Pest density	**Push-pull system**, e.g. combination of semiochemicals and a trap crop	± too pest-specific/ too complex	[pollen beetle] [insect pests]	[pollen beetle] [insect pests]
Pest density	**Intercropping**, e.g. oilseed rape with wheat	± too complex	[pollen beetle] [insect pests]	[pollen beetle] [insect pests]
Pest density	**Early flowering** (cultivars, induction)	[pollen beetle] (light blue)	[pollen beetle] (light blue)	[pollen beetle] (light blue)
Pest density	**Excess buds** (cultivars)	[pollen beetle] (light blue)	[pollen beetle] (light blue)	[pollen beetle] (light blue)
Pest density	**(High) plant density** that fits the cultivar	[pollen beetle] [insect pests] (light blue)	[pollen beetle] [insect pests] (light blue)	[pollen beetle] [insect pests] (light blue)
Pest density	**Large crop fields**	[pollen beetle] [insect pests]	[pollen beetle] [insect pests]	- limits immigration of natural enemies
Pest density	**Aggregation of crop fields**, e.g. oilseed rape fields on adjacent fields with a field margin in between	± too complex	[pollen beetle] [insect pests] collective	[pollen beetle] [insect pests] collective
R&T	**(Partially) resistant cultivars**	[pollen beetle] [insect pests] (light blue)	[pollen beetle] [insect pests] (light blue)	[pollen beetle] [insect pests] (light blue)
R&T	**Nutrient management**	[pollen beetle] [insect pests] (light blue)	[pollen beetle] [insect pests] (light blue)	[pollen beetle] [insect pests] (light blue)

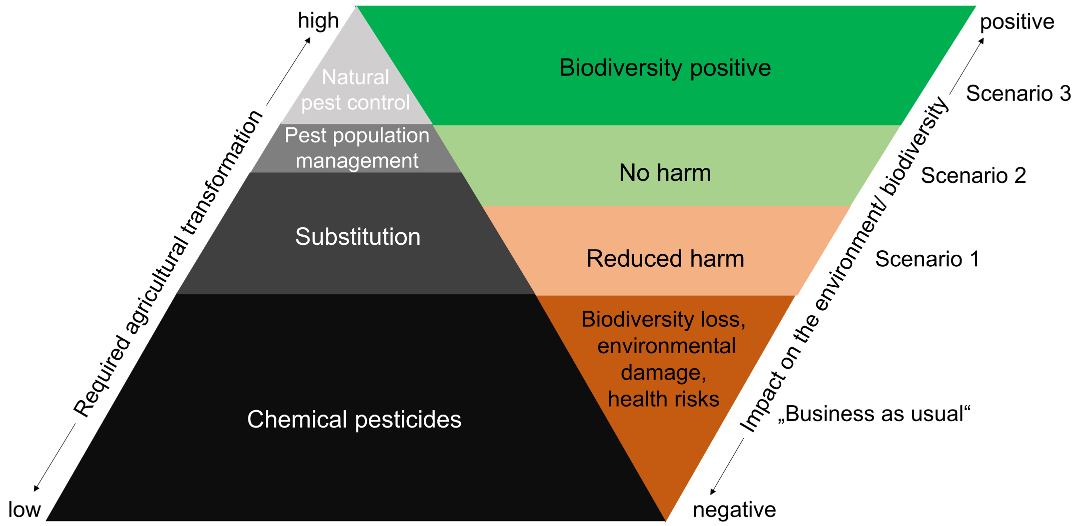

Fig. 2. Insect pest management strategies (left triangle: in order of commonness from bottom to top) are presented as core strategies of the current situation and potential scenarios for insect pest management (right triangle) with their impacts on the environment and biodiversity and the degree of agricultural transformation required for their implementation.

3.3. Increasing crop resistance and tolerance

There is variability in the susceptibility of cultivars to pests (e.g. depending on their phagostimulant or phagodeterrent effects on the pest), but there is no oilseed rape cultivar with satisfactory resistance against the pollen beetle (Hervé and Cortesero, 2016). One reason may be that pollen beetles have little contact with the plant defence system of oilseed rape, due to preferably foraging on pollen from open flowers (Cook et al., 2007). This also leaves little room for defence induction or priming, which may prove helpful for other pests that are more exposed to plant defences (reviewed by Dicke and Hilker, 2003; Martinez-Medina et al., 2016). An alternative could be transgenically expressed toxins (Hervé and Cortesero, 2016) or physical barriers (Fig. 1) such as dense coverage with trichomes (Gruber et al., 2006). If it is possible to obtain oilseed rape with "hairy" buds, this may confer some resistance to pollen beetle damage.

Optimised nutrient management can also help to limit pollen beetle damage (Fig. 1). Crop nutrition is known to affect several bud and flower characteristics of oilseed rape, with consequences for the number of pollen beetles per plant and the capacity of oilseed rape to regrow (Pinet et al., 2015; Skellern and Cook, 2018b). Good nitrogen status has been shown to reduce damage from pollen beetles (Rusch et al., 2013; Valantin-Morison et al., 2007), but plant responses to fertilisation regimes are variable (Pinet et al., 2015; reviewed by Skellern and Cook, 2018b). Further research is needed to provide practical advice on optimal fertilisation in relation to crop damage prevention and compensation.

Looking beyond crop damage to crop yield, the presence of pollinators can compensate for yield losses due to pollen beetle damage, although the highest crop yields are expected when pollen beetle numbers are low and pollinators are present (Sutter and Albrecht, 2016).

4. Scenarios and pathways into a (more) sustainable future

A pest management strategy should always include a component of pest mortality to prevent a build-up of the pest population over a number of years, as was observed for the pollen beetle over a 16-year increase in oilseed rape area in Finland (Hokkanen, 2000). However, there are many options other than chemical pesticides to reduce pests, and additional mechanisms can be used and may be needed as a complement to pest mortality (Fig. 1, Table 2). The wealth of measures available or being researched to control insect pests can be assigned to different scenarios with some overlap (Fig. 2, Table 2). It is important to note that the different scenarios depend on different measures at their core and therefore different degrees of agricultural transformation, while the outcomes for the environment and biodiversity are also likely to differ. Pathways into a (more) sustainable future are outlined in order of increasing need for change - from a scenario requiring minimal change from the current agricultural system to a scenario requiring substantial change - which is also the order of increasing expected benefits for biodiversity (Fig. 2, Table 2). The only measures that are currently likely to kill pollen beetles quickly enough to directly prevent damage, and thus feed into a "reduced damage" scenario (minimal change scenario), are chemical pesticides or perhaps silica nanoparticles, which are currently being researched and require sound risk assessment to minimise environmental impacts (Saw et al., 2023). With respect to a "no harm" scenario, the use of species-specific dsRNA and biocontrol agents - carefully selected to avoid off-target effects - may work to directly prevent pest damage, but likely not for pollen beetles (Table 1). The limited or delayed lethality of this pest in response to these measures may allow population management, when used collectively (see 3.1.4). Thus, depending on the pest and crop, collective action and long-term strategies may be necessary when pursuing the "no harm" scenario. In the "biodiversity positive" scenario, collective action is an asset, as efforts are needed at the landscape scale to achieve diverse natural enemy communities capable of regulating pest populations (Bommarco, 2024; Metzger et al., 2021).

4.1. From single pests to agricultural systems

When dealing with a single pest and a single crop, it may be relatively easy to achieve pest control at reduced or zero environmental harm, but with an increasing number of pests, whose biology may be very different, it becomes increasingly complicated. Different strategies and sets of measures may be needed for different pests and crops (Alexandridis et al., 2022; Martin et al., 2019). Thus, if whole agricultural systems are considered as the sum of insect pests across all crops, the "biodiversity positive" scenario can play to its strengths if a diverse natural enemy community provides natural control of a wide range of pests (see 3.1.3).

4.2. Realising scenarios

The "reduced harm" scenario is probably the most likely future if no other scenario is specifically targeted, as it is associated with the least need for transformation and is in line with interim policy considerations such as a 50 % reduction in the use of chemical pesticides in the EU by 2030 (Commission, 2022, 2024). Both the “reduced harm” and “no harm” scenario could feed into a land-sparing strategy (highly specialised land use including separate production and conservation areas), with the risk that “reduced harm” is still too much harm to reverse biodiversity loss, as negative impacts of agricultural practices can spill over into adjacent habitats (Mühlethaler et al., 2024).

The “no harm” scenario can also fit into a land-sharing strategy (less specialised land use integrating production and conservation) if additional measures are taken to promote on-farm biodiversity. This modified “no harm” scenario may come close to the “biodiversity positive” scenario in terms of high biodiversity on farmland – this needs to be evaluated with biodiversity monitoring -, but probably with less beneficial returns in terms of natural pest control (Birkhofer et al., 2018). This modified “no harm” scenario could be the best-case outcome if (policy) efforts to reduce pesticide use and increase biodiversity remain separate. However, it is important to remember that collective action is needed to achieve this scenario in all crops, e.g. for pollen beetle control in oilseed rape (Table 2).

The “biodiversity positive” scenario is only likely to be achieved if a policy target of zero environmental damage is set (see “reduced harm” scenario above), a framework for collective action is established (Joffre et al., 2019; Lang et al., 2012; Zollet & Maharjan, 2021) and sufficient resources are allocated to develop and implement strategies in order to actively promote natural pest control in agricultural landscapes (Birkhofer et al., 2018; Bommarco, 2024). Measures to promote natural pest control through biodiversity restoration may take several years, decades or even longer, depending on the initial conditions and the measures taken (Moreno-Mateos et al., 2020). To achieve the “biodiversity positive” scenario without major yield losses along the way, but also when pest outbreaks are caused by dispersal of pests over tens or hundreds of kilometres, strategies are needed that complement natural pest control without hindering biodiversity restoration, e.g. strategies to reduce pest densities per plant (Table 2). In addition, biodiversity and natural pest control services (pests, natural enemies and their interactions) need to be monitored in order to assess the success of the measures taken and to be able to readjust along the way.

Measures to pursue each of these scenarios are available, or at least in the pipeline, and are summarised in this review (Fig. 1, Tables 1 and 2), but putting these ideas into practice is much more complicated. Measures that have been scientifically evaluated are not necessarily feasible without technical innovations (e.g. continuous scent release of lavender oil) or coordination infrastructure (e.g. years without oilseed rape). In addition, knowledge transfer requires trust - and thus a long-term partnership between scientists and practitioners - (Lundmark et al., 2023) and alternative (partial) solutions may have been found in practice without being reported in the scientific literature (e.g. Thompson and Jex (2024)). This calls for more transdisciplinary research to bridge this gap (Lang et al., 2012). In addition, collective action of practitioners to facilitate pest population management, biodiversity restoration, or both has costs (e.g. time investment) and returns may not be economic or may be delayed. For example, biodiversity restoration - and ultimately increased (Dainese et al., 2019) and more climate-resilient natural pest control (Feit et al., 2021) - may take years, decades or even longer (Moreno-Mateos et al., 2020). Therefore, incentives, such as subsidies for collective action, may be needed to change to (more) sustainable practices, as in the case of companies or brands moving towards sustainability (Chen et al., 2025). Scientists, practitioners and policymakers are needed to accelerate (collective) experimentation and implementation at large spatial scales to facilitate pest population management and biodiversity restoration, and ultimately environmentally sustainable insect pest management in the foreseeable future.

5. Conclusion

Given the wealth of measures for insect pest management and different possible scenarios, what will insect pest management and agroecosystems look like in the future? Probably this will depend on the (political) course that is set: Will no environmental harm from pest control, including no use of chemical pesticides, be a goal? Will structures be put in place to facilitate or support collective action? Will efforts to promote biodiversity in agricultural landscapes be combined with efforts to promote natural pest control? At EU level, the current answer to these questions seems to be “maybe”, with the risk that biodiversity loss will not be halted. If the answers to the first or the first two questions (necessary in certain crops such as oilseed rape) are “yes”, simplified agricultural landscapes may not necessarily change much, but environmental toxins will be reduced and biodiversity will ideally be maintained at current levels. If additional measures - not tailored to pest control - are taken to promote biodiversity (land-sharing framework), the agricultural landscapes of the future are likely to include more landscape features such as semi-natural habitats (e.g. woodlands, grasslands and hedges), and to consist of smaller fields with greater plant diversity (e.g. intercropping). This has the potential to reverse biodiversity trends from decline to increase. However, only if all three questions are answered in the affirmative will the agroecosystems of the future be more functional (already in the medium term), allowing agricultural inputs to be minimised through increased natural pest control. In conclusion, if the health of ecosystems and people is to play a major role in the agriculture of the future, it is important to go beyond the reduction and substitution of chemical pesticides and set the course accordingly.

CRediT authorship contribution statement

Ute Fricke: Writing – original draft, Conceptualization, Visualization, Writing – review & editing. **Sarah Redlich:** Writing – review & editing, Conceptualization. **Dani Lucas-Barbosa:** Writing – review & editing, Conceptualization. **Ingolf Steffan-Dewenter:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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