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Review

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Special Collection: World-Scale Ecology and Management of Fall Armyworm (*Spodoptera frugiperda*)

# Potential Management Options for the Invasive Moth *Spodoptera frugiperda* in Europe

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## Abstract

We here review and discuss management options that growers in Europe could take in response to the expected invasion of the fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae). The focus is put on maize but the information provided is also relevant for other crops potentially affected. A sound forecasting system for fall armyworm both on a regional as well as at local scale should be established to alert growers as early as possible. Whilst a number of cultural control methods are adopted by maize growers in different regions globally to fight fall armyworm, many of them may either not be highly effective, too laborious, or otherwise unfeasible within the mechanized crop production systems used in Europe. Potential is seen in the stimulation of natural enemies through conservation biocontrol approaches, e.g., the planting of flower strips or intermediate cover crops, reducing tillage intensity, and avoiding broad-spectrum insecticides. To manage fall armyworm infestations, several effective biologically-based products are available globally, and some in Europe, e.g., based on specific baculoviruses, certain *Bacillus thuringiensis* strains, few entomopathogenic nematodes, and a number of botanicals. These should be given priority to avoid a major influx of insecticides into the maize agro-ecosystem once the fall armyworm arrives and in case growers are not prepared. Plant protection companies, particularly biocontrol companies should act proactively in starting registration of ingredients and products against fall armyworm in Europe. European maize growers should be made aware, in time, of key features of this new invasive pest and appropriate control options.

**Key words:** Spodoptera frugiperda, invasive species, Europe

The fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), is an insect pest native to tropical and subtropical regions of the Americas. *Spodoptera frugiperda* larvae can feed on more than 350 plant species, including maize, rice, sorghum, millet and sugarcane (Montezano et al. 2018). In the native region, *S. frugiperda* can be a severe pest requiring frequent insecticide applications (Young 1979) or the adoption of crops producing Bt proteins (Jabeur 2022). Thus, it was immediately of high concern when it was detected for the first time in Africa, i.e., in Nigeria, in early 2016 (Goergen et al. 2016). Since then, *S. frugiperda* has invaded nearly all countries in Africa and has recently further spread throughout most of South and South-East Asia and even to Australia (Maino et al. 2021). In response to the threat, the Global Action for *S. frugiperda* control was launched by FAO in 2019 to coordinate and strengthen prevention and sustainable pest control. This global action focuses on implementing IPM in countries with significant pest presence, and a prevention strategy in less affected areas (FAO 2021).

In its native area as well as in the newly invaded areas in Africa, Asia and Australia, *S. frugiperda* can cause significant yield losses if not well managed (Rwomushana et al. 2018, Njuguna et al. 2021, Prasanna et al. 2021a). Despite its polyphagous nature, most problems with *S. frugiperda* are seen on maize and occasionally sorghum although, in its native area, this pest may also cause damage on other major crops such as rice, soybean, cotton, or sugarcane. African growers who generally grew maize with limited amount of inputs now face a choice between high damage to their crop or taking severe actions to manage *S. frugiperda* (Hruska 2019). In the latter case, this has often meant applying laborious mechanical measures (e.g., hand-picking larvae) or the frequent use of broad spectrum and often rather toxic insecticides (Tambo et al. 2020).

*Spodoptera frugiperda* is a migratory pest that will continue to spread due to its biological characteristics and high volumes of international trade. In the US, infestations in most parts of the country are regularly occurring through annual migrations of populations that overwinter in Mexico, southern Texas, and Florida (Nagoshi et al. 2009). With the recent invasion of South and South-East Asia, the same scenario is happening from southern to eastern and north-eastern China, where maize is a major crop (Wan et al. 2021). The situation in Australia is similar where established *S. frugiperda* populations in the North are predicted to cause annual invasions to most maize growing regions across Australia (Maino et al. 2021). With regard to Europe, *S. frugiperda* may enter the continent via direct migration, e.g., from North Africa or the near East. The European and Mediterranean Plant Protection Organization (EPPO) is a regional plant protection organization responsible for cooperation in plant health within the Euro-Mediterranean region. Its 52 members include North African countries (Algeria, Morocco, and Tunisia) and the Middle Eastern countries Israel and Jordan. *Spodoptera frugiperda* is already present in Mediterranean countries such as in Egypt since 2019, Israel, Jordan, and Canary Islands (Spain) since 2020 (EPPO 2021) and *S. frugiperda* interceptions in traded goods, particularly on vegetables, are regularly reported from the Americas and sub-Saharan Africa (EFSA 2018). Whether the additional interceptions from the newly invaded areas increases the risk for establishment in mainland Europe is uncertain but seems manageable in light of the well established procedures in place.

Recent climatic models conclude that *S. frugiperda*, when introduced, will also likely permanently establish in some of the very southern parts of mainland Europe, i.e., Spain, Italy, and Greece (Du Plessis et al. 2018, Early et al. 2018, EFSA 2018, Paudel Timilsena et al. 2022). From there, and even from source populations in Northern Africa or the Near East, it should be expected that *S. frugiperda* regularly migrates to more temperate regions of Europe during the cropping season, as is known from the Americas (Westbrook et al. 2016), and China (Wan et al. 2021). Extrapolating from experience in the Americas, where this pest occasionally migrates as far north as Canada, we hypothesize that, in addition to all countries in Southern Europe and the Balkan region, most of Central Europe will be affected by seasonal migrations of *S. frugiperda*. This has been the case with another migrating moth, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) (EFSA 2014). In addition, as has been seen for *H. armigera*, *S. frugiperda* overwintering may occur in heated glasshouses, especially when a suitable soil or growth media for pupation is available (Lammers and MacLeod 2007). This scenario should be very carefully watched and avoided as much as possible as it would potentially increase the risk for producers in a larger area and over a longer part of the season.

In response to the above concerns, *S. frugiperda* has become one of the twenty priority pests on the EU quarantine list in October 2019 (European Commission 2019). In Europe, where many of the potential alternative hosts are not widely grown, problems are expected to occur mostly in maize. This is supported by a recent study from China, finding that maize accounted for 98% of the more than 1 million hectares of cropland attacked by *S. frugiperda* in 2019 (Yan et al. 2021). While silage maize dominates in northern Europe, maize grain production is common in southern Europe. Maize is the second most grown cereal in the EU and thus of high economic importance for the agricultural sector (EFSA 2018). It also means that arriving populations from the south will have favorable feeding conditions as maize is common throughout most of Europe. Maize growers in Europe have well-developed Integrated Pest Management strategies for maize, and as a consequence, they do not normally apply a large number of insecticide treatments and particularly avoid doing so in silage maize (Meissle et al. 2010). This is with the exception of areas where lepidopteran pests such as the European corn borer *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae) damage maize cobs and could lead to secondary fungal infections and aflatoxin problems, resulting in chemical treatments. In other European regions, the European corn borer is either left uncontrolled in field maize or controlled by applying *Trichogramma* wasps for biological control (e.g., in France, Germany, Czech Republic). Thus, *S. frugiperda*, as a pest having potential to destroy maize fields quickly, is a threat to the IPM approaches presently implemented in most of Europe and maize producers will need support to sustainably manage this new pest.

Taking a pro-active approach on *S. frugiperda* management in Europe, the present document focuses on reviewing and then recommending sustainable and IPM-compatible methods, with the aim to minimize the use of synthetic insecticides, in agreement with European agricultural policies (European Commission 2009, Meissle et al. 2010), in particular the recently announced 'European Green Deal' and the 'Farm to Fork Strategy' (European Commission 2020). Most nonchemical methods presently available for *S. frugiperda* control have been developed in tropical or sub-tropical regions against permanently established populations of the pest and this review evaluates their potential to be used in Europe. Information on management methods in temperate regions in the Americas, where the moth is a temporary migrant, is also considered. However, in these regions the pest is largely controlled by deploying GM crops, which at present are not available in most of Europe. Management options are explained and discussed in detail, also considering specific regulation in Europe and the context in which European growers are operating. While this document considers IPM-based growers as a baseline, most of the information is at the same time valid for organic production, obviously with the exception of that provided on synthetic pesticides.

## Identification and Life History

As there are few pests with which the *S. frugiperda* can be confused within European maize fields, we like to be brief here and refer to relevant general publications on the moth (e.g., FAO, 2018, McGrath et al. 2021). Adult *S. frugiperda* moths are greyish-brown with a wingspan of 32–40 mm. The species is sexually dimorphic, with males having distinct white spots on the forewings whereas in females these are uniform. Adults are nocturnal, and are most active during warm, humid evenings. After a preoviposition period of a few days, the female moth deposits most of her eggs during the first 4–5 d of her life. This pest is highly fecund, and, under warm conditions, a female moth can lay 6–10 egg masses of 100–300 eggs each. In contrast to most other lepidopteran pests, those eggs masses are usually covered with scales and hairs. *Spodoptera frugiperda* typically has six larval instars attaining lengths of about 1 mm (instar 1) to 45 mm in instar 6. Duration of larval development is between 2 and 4 wk, depending on temperature. After completion of larval development, *S. frugiperda* normally pupates in the soil at a depth of 2–8 cm but may web together leaf debris and other material to form a cocoon on the soil surface if the soil is too hard. Duration of the pupal stage is about 8–9 d during warm summer conditions. Thereafter, another generation might take place, until conditions are becoming inappropriate for *S. frugiperda* development due to decreasing temperatures and/or long dry periods (Prasanna et al. 2018).

## Fall Armyworm Management

### Cultural Control Methods

European maize producers are operating within the regulatory context of national legislation and also, for EU Member States, EU legislation. This means that growers may consider or even have to implement a number of cultural control approaches for maize production such as crop rotation, sound fertilization, and/or ecological compensation areas, which are often connected to subsidies. These measures are important to grow healthy crop plants which can tolerate a certain level of damage, especially in the vegetative stages (Harrison et al. 2019). However, heavy feeding damage by *S. frugiperda* can cause yield losses, which may become particularly severe when the growing tips of the plants are destroyed, cob formation is prevented, or when maize cobs are attacked. Unfortunately, there is no simple cultural control measure that would prevent crop damage altogether as known from other maize pests, such as crop rotation against the maize specific corn rootworm, *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae). It should also be stressed that *S. frugiperda* is a migratory pest with the potential to appear in large numbers within short time intervals, limiting the contribution of cultural control options for successful *S. frugiperda* management.

#### Host Plant Resistance

Traditionally-bred maize varieties with sufficient level of tolerance or resistance to *S. frugiperda* are currently not on the market in Europe. USDA-ARS has used tropical maize germplasm with a certain level of resistance developed by CIMMYT, as well as temperate maize germplasm, to develop and register inbred lines with *S. frugiperda* resistance (e.g., Mp704-Mp708, Mp713, Mp714, and Mp716) (Prasanna et al. 2021b). Screening for *S. frugiperda* resistance in maize in Africa is ongoing (e.g., Kasoma et al. 2021), so far with limited success (Chiriboga Morales et al. 2021). Efforts on conventional breeding for *S. frugiperda* resistance declined after the development of transgenic *B.t.* maize from the 1990s onwards. In light of a general lack of resistant varieties and the relatively long time needed for the development and registration of new lines, it seems relatively unlikely that any maize variety can provide high levels of resistance or tolerance to *S. frugiperda* in the short- or mid-term in Europe.

However, there are a number of transgenic maize varieties commercialized in the Americas. They express gut binding insecticidal proteins from *B. thuringiensis* providing maize resistance to fall armyworm (Dively 2018, Li et al. 2021a), whilst avoiding major impacts on natural enemies as known from insecticides (Romeis et al. 2019). To date, several *Bt* proteins are used in transgenic traits to control *S. frugiperda* including Cry1 proteins (Cry1F, Cry1Ac, Cry1Ab, Cry1A.105), Cry2 proteins (Cry2Ab2, Cry2Ae), and Vip proteins (Vip3A) (Jabeur 2022). In Europe, *B.t.*-maize based on Cry1Ab targeting lepidopteran stemborers are registered and commercially available in some European countries, mostly Spain. However, the evolution of insect resistance to transgenic crops containing single events is a threat to the sustainability of this technology (Huang et al. 2014) and growing an event showing only partial control will even increase risks. Therefore, GM maize with stacked events have and are being developed to control *S. frugiperda* in the Americas (Horikoshi et al. 2016). For instance, Vip3Aa20 is commercialized in a pyramid maize event against fall armyworm (Jabeur 2022). These may be expected to be of similar effectiveness against *S. frugiperda* in Europe, but currently are not approved in any European country. Recently, an EU-wide consultation process on legislation for plants produced by 'new genomic techniques' was initiated, but the outcome is uncertain and it will likely be years before such plants may become commercially available to growers in the EU.

#### Flower Strips and Vegetation Cover

Increasing and conserving key resources for natural enemies such as nectar via flower strips or shelter through undergrowth or intermediate cover crops can increase their abundance, which in turn reduces pest populations (e.g., Landis et al. 2000, Campbell et al. 2017, Harrison et al. 2019). In regions where *S. frugiperda* is native, particularly its eggs and larvae are attacked by numerous natural enemies, i.e., predatory insects, spiders, parasitoids, and pathogens (Hoballah et al. 2004). Shortly after the invasion of Africa, already a meaningful number of different natural enemies with considerable parasitism rates were found on *S. frugiperda* (Sisay et al. 2018). Similarly, surveys in India and China found numerous predators and parasitoids attacking all immature stages of *S. frugiperda* already in the first year of the invasion (Shylesha et al. 2018, Wan et al. 2021). This indicates that there is a high chance for natural enemies contributing to the natural biological control if and when their populations are supported through either the presence of natural habitats nearby the maize crops, or agronomic measures such as planting flower strips (Wyckhuys and O'Neil 2007, Niassy et al. 2021a), conservation tillage, and or cover crops to avoid bare soil between cropping cycles. Some of these measures are mandatory in many European countries already and will likely help the management of *S. frugiperda*. What plant mixtures would be best and how big the flower strips would have to be to maximize benefits is as yet unclear for particular locations and situations (but see Wäckers and van Rijn, 2012, Tschumi et al. 2016).

Overall, the contribution of the natural enemy complex in Europe is still uncertain and may differ from what is observed in Africa and Asia. Furthermore, if *S. frugiperda* is attacking maize fields, this will happen relatively rapidly with natural enemies not always being able to respond in time to suppress the pest sufficiently quickly. On the positive side it may be expected that, at least for those regions not having permanent populations, the attack will come a bit later in the season when natural enemy populations have already built up on other prey or hosts. For European growers it is important to note that, even though a contribution to *S. frugiperda* pest control should be expected (as stated above) from conserved or enhanced natural enemy populations, damage to the crop may not be avoided fully. This makes additional measures likely necessary, particularly at high pest levels.

#### Intercropping and Push–Pull Systems

Various crops are being used by growers, particularly in Africa and South America, to intercrop maize with a focus on beans or peas but also cassava, yam, and others. This helps to increase the numbers of natural enemies and improves pest control (Harrison et al. 2019). However, the exact benefits are often difficult to quantify, in particular on yield. A positive effect of intercropping maize with beans, soybean, or groundnut on *S. frugiperda* incidence and maize plant damage was found by Hailu et al. (2018) in Uganda. Babendreier et al. (unpublished) found only marginal effects of intercropping maize with common beans on maize damage, *S. frugiperda* incidence, or yield in Ghana. A survey among maize growers in Zimbabwe revealed mixed effects of the intercrop on the reduction of damage by *S. frugiperda* and increase of yield, with even negative effects when pumpkin is used as intercrop (Baudron et al. 2019). A special approach is 'push–pull', mainly implemented by African maize growers to control stemborers and striga weeds through a combination of planting Napier grass as a 'pull' factor around maize plots and *Desmodium* sp. as an intercrop and 'push' factor. This can effectively reduce *S. frugiperda* (e.g., Midega et al. 2018), however, achieving such benefits depends on the sound establishment and management of the companion plants and thus also on grower's capacity and availability of space. Altogether, the potential benefit of intercropping systems seems to heavily depend on specific local conditions. Niassy et al (2021b) found that intercropping and the push–pull technology accounted for only 10 and 1% of the surveyed area in six East- and South African countries, respectively. Since intercropping shows variable effects on *S. frugiperda* infestations and is making agronomic practices more difficult to implement, this measure appears to be rather unattractive or unsuitable for European maize growers.

#### Planting Date

Early planting maize is sometimes recommended for growers in Africa because *S. frugiperda* populations are expected to build up during the rainy season and, the earlier the crop matures, the less damage can be done by the pest (FAO 2018). However, in some cases, the opposite is observed, i.e., higher damage in early planted maize particularly in regions with overlapping *S. frugiperda* generations (M. Kenis, S. Toepfer, unpublished observations). A more promising approach would be to avoid staggered planting within an area so as to limit chances for *S. frugiperda* to always find the preferred growing stage. In any case, growers, in European or elsewhere, generally need to plant their maize as soon as agronomic conditions are favorable (mostly temperature and moisture), limiting the use of adjustment of plant times for the control of *S. frugiperda*.

#### Tillage

Maize growers, regardless of European or elsewhere, typically till their fields before seeding of maize, and often also after harvest. For some stubble—or soil—diapausing corn borers, intense tillage is known to reduce their pupal populations (Schaafsma et al. 1996). However, *S. frugiperda* does not stay dormant in maize residues, but in the soil, and effects of tillage practices on those pupae remain uncertain (Baudron et al. 2019, Harrision et al. 2019). On the other hand, there is evidence especially from the Americas that no-till maize supports a higher insect diversity, resulting in more natural enemies and overall improved pest control but specific evidence on the underlying reasons and how much no-till practices would help in reducing *S. frugiperda* numbers is scarce (Harrison et al. 2019). However, soil management techniques that increase soil health, such as no-tillage or conservation tillage, might have positive effects on the long term, e.g., by supporting soil-borne predators that prey on *S. frugiperda* (Rivers et al. 2016). How no- or conservation tillage approaches in maize can contribute to reducing *S. frugiperda* incidence would need to be tested for specific conditions under European settings.

## Monitoring and Decision Making

We anticipate that it will be challenging to avoid *S. frugiperda* getting established in mainland Europe (cf. EFSA 2018). Once arrived, eradication will unlikely succeed, due to the migratory behavior of *S. frugiperda*. Even containment zones may be difficult to establish as regular source populations of *S. frugiperda* may lay outside Europe. Nevertheless, efforts to delay the invasion and establishment as much as possible are relevant.

#### Early Detection

The EPPO/IPPC have identified five countries in Southern Europe (France, Italy, Spain, Greece, and Portugal) to help reducing the risk of *S. frugiperda* introduction and further spread by implementing phytosanitary standards. Probably, Turkey and northern African countries should be added (EFSA 2018). A formal surveillance program by National Plant Protection Organisations (NPPOs) with regional cooperation through EPPO may be implemented to serve several purposes: 1) early detection, i.e., determine if *S. frugiperda* is present or absent in an area, 2) defining containment and pest-free zones, i.e., establish the boundaries of an area considered infested by or free from a pest, and 3) monitoring to verify the spatio-temporal dynamics of a pest population. Defining pest free areas would also be relevant for trade. Detailed surveillance protocols are available (Kearns et al. 2020, IPPC Secretariat 2021, and references therein). As long as *S. frugiperda* is still absent from a country, a prevention and preparedness plan should be developed and implemented, followed by a response plan once an outbreak has been officially confirmed.

#### Forecasting and Monitoring

A specific action could be the establishment of monitoring networks similar to the national platform for prevention and control of *S. frugiperda* established in China (Yan et al. 2021) or the FAMEWS global platform (FAO 2020), or similar to approaches used for forecasting *H. armigera* migrations into some areas of Europe. Growers in areas likely to be affected should be trained and establish pheromone traps soon according to manufacturer recommendations in or near their maize fields and count *S. frugiperda* catches at least weekly (Guerrero et al. 2014). Where *S. frugiperda* incidence could potentially occur permanently, i.e., in the most southern parts of Europe, pheromone traps and/ or light traps should be established probably latest about a week after crop emergence. Where long distance immigration of *S. frugiperda* will be regularly happening every cropping season such as expected from most maize growing regions in southern and central Europe (EFSA 2018), pheromone traps should be established probably latest mid vegetative stage of maize. If *S. frugiperda* moths are detected, larvae feeding on the crop may be expected a few days later and their incidence should be checked. Despite a general positive relationship between trap catches and larval numbers, often crop infestation level for *S. frugiperda* is little related to the number of captures in traps (Kearns et al. 2020). Details on how to assess the larval incidence and plant damage can be found in the literature (e.g., McGrath et al. 2021). For growers or extension workers to properly plan direct pest control measures, trap captures can be helpful and have been shown to be still the most reliable proxy for decision making (Cruz et al. 2012), but damage monitoring as well as confirmation of *S. frugiperda* larvae on maize may be needed in addition.

#### Decision Making

There are currently no official action thresholds available for *S. frugiperda* in the EPPO region, although there are scientific studies published on thresholds from the Americas (reviewed by Overton et al. 2021). Those used on sweet maize in the US indicate that treatments for *S. frugiperda* may be needed when more than 15% of the plants in the early whorl stage are infested (Overton et al. 2021). During mid- to late-whorl stages, treatment for *S. frugiperda* may be necessary if more than 30% of the plants are infested. Monitoring may even be needed after treatments due to re-infestations during the cropping season. However, population dynamics of *S. frugiperda* vary considerably among regions depending on climate and cropping systems, making adoption of thresholds from scientific publications difficult. Therefore, action thresholds will need to be developed for the different agro-ecological zones of Europe once *S. frugiperda* regularly immigrates or has been established.

## Direct Control

In this section, we review biologically-based as well as chemical control options for their effectiveness and agricultural sustainability for the control of *S. frugiperda* in Europe. We here assume that *S. frugiperda* eventually establishes in some of the most southern European regions and migrates north to infest large parts of European maize fields during each cropping season. The leaf-feeding *S. frugiperda* larvae are the predominant targets for pest control whereas the pupae are hidden in the soil and difficult to reach with most control approaches. The eggs may be targeted, but their presence is difficult to predict and often egg masses are reached as well when treatments are done against early larval stages. Older larvae are usually found deep in the whorl feeding beneath a plug of frass, where they are to some extent protected from chemical control measures, particularly contact sprays, and even from biopesticides sprayed. Older larvae are also much more tolerant to chemical control measures (Prasanna et al. 2021a). Thus, fall armyworm can best be controlled while the larvae are small. Therefore, early detection, such as with pheromone traps or regular monitoring for early damage in field, is critical for proper timing of any direct control action.

Although older larvae in the whorl will feed on large amounts of plant material, maize plants often recover from whorl damage without reduction in yield (Hruska 2019), even though established thresholds should still be considered. However, they may bore into young maize cobs when plants begin to tassel and young ears become available. The ear/young cob, and even mature cobs, may be partly or totally destroyed and this damage tends to be much more important than leaf damage (Prasanna et al. 2021a). In addition, the attack of maize cobs raises concerns of secondary infection through aflatoxin-producing fungi.

## Biologically-Based Control Options

Unlike in greenhouses where large areas are already under biological control, this approach is rather challenging against agricultural pests in larger scale field crops, mostly due to aspects of cost efficiency and practicability. All the below listed options may be considered in maize fields, keeping costs in mind, but also if and when *S. frugiperda* would be found on crops grown under protected conditions in greenhouses or polytunnels (Table 1).

### Insecticidal Viruses

Baculoviruses are highly specific to the target host, and therefore nonpathogenic to beneficial insects and other nontarget organisms. Therefore, they are attractive candidates for the biological or integrated pest management of *S. frugiperda* in Europe. Two of such viruses are, to date, known to infect and kill *S. frugiperda*, this is the *S. frugiperda multi-nucleopolyhedrovirus* (SfMNPV), and the *S. littoralis nucleopolyhedrovirus* (SpliNPV) originally isolated from *S. littoralis*. For both, commercial products exist in some countries (Bateman et al. 2021, Popham et al. 2021, CABI 2022) while so far only SpliNPV is registered against *S. littoralis* in maize in the EU. Products based on SfMNPV, however, may be expected to be registered for the European market soon.

Baculoviruses need to be ingested by an insect to achieve infection. Therefore, only the feeding stages of insects can be controlled, in the case of fall armyworm the larvae, particularly the first and second instar (Guo et al. 2020). However, the egg stage can also be treated, because hatching larvae will feed through the egg shells and ingest the virus particles. As is the case for most other biological products, the larvae will not die instantly after application of a baculoviruses, but only a few days up to a week after ingestion. Nevertheless, compared to healthy larvae, infected larvae will eat only a small proportion during their remaining life span, thus causing only minimal damage (see Agboyi et al. 2019 for parasitized *S. frugiperda*). Given the good level of efficacy and the favorable environmental profile of NPVs, as well as the fact that no special equipment is needed (as long as the maize plants to be treated are not too tall), products based on NPVs have potential for sustainable *S. frugiperda* control by European maize growers.

### Insecticidal Bacteria

Products based on two subspecies of *Bacillus thuringiensis* (*B.t.*) have been widely used against lepidopteran pests, i.e., *B.t. aizawai* and *B.t. kurstaki*., both which are registered in the EU (CABI 2022). Several studies have shown that *B.t.* strains are variable in their control effects on fall armyworm (e.g., dos Santos et al. 2009, Liu et al. 2019). There is some evidence that some *B.t. aizawai* strains may be slightly more effective against fall armyworm than *B.t. kurstaki* strains (Bateman et al. 2021, Jepson et al. 2020) but further research would be needed. *B.t.*-based products need to be ingested by an insect to achieve infection, thus larvae need to be targeted. In conclusion, *B.t.*-products may become a viable option for *S. frugiperda* control in Europe, if a label extension of existing products based on *B.t. aizawai* or *B.t. kurstaki* strains are approved. This seems likely if (1) relatively low toxicity and low likelihood of nontarget effects are confirmed, and (2) research shows that strains of existing products in Europe would also work for fall armyworm control. If such label extension would not work out, it is relatively unlikely that new insecticidal bacteria will be searched for or existing ones used for the development of novel biopesticides against *S. frugiperda* in Europe, because of the strict and costly registration processes for such microbial agents.

### Entomopathogenic Fungi (EPF)

There are a number of strains of *Beauveria bassiana* (seven strains registered in the EU), *Metarhizium brunneum (*formerly *anisopliae*; one strain registered in the EU, five strains pending), *M. robertsii* (no strain registered in the EU), or *Metarhizium rileyi* (no strain registered in the EU), that have shown to inflict high mortality of fall armyworm, particularly the larvae, under laboratory conditions (Guo et al. 2020). However, to our knowledge, there is as yet no commercial use of EPF against above-ground lepidopteran pests in maize globally. This is likely because of high costs in case of application on larger field crops like maize, and the difficulty to achieve good spray coverage necessary to allow fungal spores getting into contact with the larvae. Before EPF would be considered a viable option for *S. frugiperda* control by European maize growers, sound application technologies, field data, and a less costly registration process would be required.

### Entomopathogenic Nematodes (EPN)

The larvae of fall armyworm are generally highly susceptible to entomopathogenic nematodes (Guo et al. 2020, Fallet et al. 2022a). Many entomopathogenic nematode species and strains can infect fall armyworm larvae, among others several strains of *Steinernema carpocapsae, S. abassi, S. riobrave, Heterorhabditis bacteriophora, H. zatatecana, H. ruandica, H. indica*, and *H. mexicana* (Guo et al. 2020, Fallet et al. 2022a). However, strains of the same species may differ considerably and need separate testing. Interestingly, EPN sourced from the area of origin or from the area of invasion of *S. frugiperda* can be as effective as commercial EPN (Fallet et al. 2022a). Application technologies are currently under development for maize

**Table 1.** Examples of biological-based plant protection products commercialized against *Spodoptera* pests in maize in selected European countries, with some potential to be studied for adoption to *Spodoptera frugiperda* control. Only a few selected countries, i.e., Germany (DE), France (FR), Spain (ES), Portugal (PT), and United Kingdom (UK) are shown (CABI 2022)

| Target *Spodoptera* | Agent or ingredient | Agent or ingredient group | Country |
|---|---|---|---|
| *S. exigua* | *Trichogramma brassicae* | Parasitoid | FR |
| | *Trichogramma achaea* | Parasitoid | FR |
| | *Habrobracon hebetor* | Parasitoid | FR |
| | *Heterorhabditis bacteriophora* | Entomopathogenic nematode | ES |
| | *Steinernema carpocapsae* | Entomopathogenic nematode | DE, PT, ES |
| | *Steinernema feltiae* | Entomopathogenic nematode | DE, PT, ES |
| | *Bacillus thuringiensis*(non specified strains) | Insecticidal bacterium | FR, ES |
| | *Bacillus thuringiensis* subsp *kurstaki* strain SA-12 | Insecticidal bacterium | FR |
| | *Bacillus thuringiensis* subsp *aizawai* strain ABTS-1857 | Insecticidal bacterium | DE |
| | *Bacillus thuringiensis* subsp *kurstaki*strain ABTS-351 (HD-1) | Insecticidal bacterium | DE |
| | *Helicoverpa armigera* nuclear polyhedrosis virus | Insecticidal virus | FR |
| | *Helicoverpa armigera* nucleopolyhedrovirus | Insecticidal virus | FR |
| | *Urtica sativa* extract | Botanical | FR |
| *S. littoralis* | *Trichogramma achaea* | Parasitoid | ES |
| | *Heterorhabditis bacteriophora* | Entomopathogenic nematode | ES |
| | *Steinernema carpocapsae* | Entomopathogenic nematode | DE, PT, ES |
| | *Steinernema feltiae* | Entomopathogenic nematode | DE, PT, ES |
| | *Bacillus thuringiensis*(non specified strains) | Insecticidal bacterium | ES |
| | *Bacillus thuringiensis* subsp *aizawai* strain ABTS-1857 | Insecticidal bacterium | DE |
| | *Bacillus thuringiensis* subsp *kurstaki*strain ABTS-351 (HD-1) | Insecticidal bacterium | DE |
| | *Spodoptera littoralis* nucleopolyhedrovirus | Insecticidal virus | PT |
| *Spodoptera* sp. | *Nesidiocoris tenuis* | Predator | ES |
| | *Trichogramma achaea* | Parasitoid | ES |
| | *Heterorhabditis bacteriophora* | Entomopathogenic nematode | ES |
| | *Steinernema carpocapsae* | Entomopathogenic nematode | DE, PT, ES, UK |
| | *Steinernema feltiae* | Entomopathogenic nematode | DE, PT, ES UK |
| | *Bacillus thuringiensis*(non specified strains) | Insecticidal bacterium | ES, UK |
| | *Bacillus thuringiensis* subsp *aizawai* strain ABTS-1857 | Insecticidal bacterium | DE |
| | *Bacillus thuringiensis* subsp *kurstaki*strain ABTS-351 (HD-1) | Insecticidal bacterium | DE |
| | *Spodoptera littoralis* nucleopolyhedrovirus | Insecticidal virus | PT |
| | *Urtica sativa* extract | Botanical | DE, PT |

(Fallet et al. 2022b), such as row or spot treatments targeting the maize whorls where larvae feed. Moreover, gel formulations have proven helpful in protecting the applied EPN and assuring treatment efficacies similar to insecticides (Fallet et al. 2022b). As EPNs are macrobials, the registration of native species is easy in most European countries, and in some even not needed. For example, some EPNs are already commercialized against other noctuid maize pests such as *S. exigua* in France and/or *S. littoralis* in Germany, Spain, or Portugal (CABI 2022).

### Parasitoids

A recent study from China showed that several *Trichogramma* species can parasitize and reduce egg survival of *S. frugiperda* in the field (Jin et al. 2021). As for Europe, *Trichogramma brassicae* Pint et Voeg. (Hymenoptera: Trichogrammatidae) is being available for the control of European Corn Borer and applied particularly by seed maize producers (Bzowska-Bakalarz et al. 2020). There are also parasitoid species registered in Europe against *S. exigua*, such as *T. brassicae*, *T. achaea*, or *Habrobracon hebetor* (Say) (Hymenoptera: Braconidae). Studies on efficacy of those European *Trichogramma species* on *S. frugiperda* are under way and indicate that they fully accept *S. frugiperda* as a host but are less successful to parasitize egg masses heavily covered with moth scales and hair and similarly eggs located beneath the top layer (Kenis et al. unpublished). Whether *T. brassicae* releases specifically against *S. frugiperda* in European maize fields would be cost effective still needs to be studied but releases against the European Corn Borer are expected to at least have a partial effect on *S. frugiperda* too. Another egg parasitoid, *Telenomus remus* Nixon, 1937 (Hymenoptera: Scelionidae), would be able to deal better with the covered multi-layer egg masses of *S. frugiperda* and to kill all eggs. This species has a long history as a biological control agent in South America, particularly Venezuela, and it also attacks *S. frugiperda* in Africa and Asia (Kenis et al. 2019, Colmenarez et al. 2022). However, so far, no commercial product based on this parasitoid species is available in Europe where it is also not native. A positive aspect of using egg parasitoids is that they can be applied by drones and thus also during later cropping stages of tall maize where applications of e.g., synthetical pesticides may be more challenging. Also, larval parasitoids are being studied currently and promising results have been found recently in India for *Bracon brevicornis* (Wesmael) (Hymenoptera: Braconidae) (Gosh et al. 2022).

Classical biological control, i.e., the introduction of parasitoids from the native range of the pest, is considered in several invaded regions (Allen et al. 2021). Should Europe be seriously invaded by *S. frugiperda* in the future, classical biological control could be envisaged, considering first the most cold-tolerant and most specific, thus safe, American parasitoids. It should be noted, however, that this approach can take years to implement due to the complex safety testing and strict regulatory procedures.

### Predators

In China, attempts are under way to test predatory insects as biological control agents of *S. frugiperda*, for example lacewings such as *Chrysoperla sinica* (Huang et al. 2020) or true bugs such as *Eocanthecona furcellata* (Wolff) (Hemiptera: Pentatomidae) (Li et al. 2020) and *Orius similis* Zheng (Heteteroptera: Anthocoridae) (Zeng et al. 2021). Mass rearing facilities are already existing for these insects. In Europe, few predatory insects are commercialized as biological control agents of lepidopteran pests, such as *Nesidiocoris tenuis* Reuter (Hemiptera: Miridae) against *Spodoptera* pests in maize in Spain (CABI 2022). However, other predators such as the lacewing *Chrysoperla carnea* or the true bug *Macrolophus caliginosus* Wagner (Heteroptera: Miridae) are known to attack *S. frugiperda* eggs and young larvae (e.g., Tavares et al. 2012) and commercially available in Europe for other crops. These species and other potentially promising ones may be studied in more detail to assess efficacy against *S. frugiperda* and cost effectiveness in open fields as well as for protected crops where these agents are already commonly used. An interesting effect to consider for any research done on predators is that older *S. frugiperda* larvae may act as predators themselves, for example feeding on their counterparts or on syrphid larvae (Li et al. 2021b).

#### Semiochemicals

Attract and kill as well as mating or orientation disruption techniques are based on the use of semiochemicals such as pheromones or kairomones. Also *S. frugiperda* females use a sex pheromone to attract males for mating. The pheromone consists of two key acetates; this is the (Z)-9-tetradecenyl acetate (Z9-14:Ac) as the major component, and (Z)-7-dodecenyl acetate (Z7-12:Ac) as a critical second component (Tumlinson et al. 1986). More components may play a role too and some companies have up to four components in their commercial fall armyworm lures (Russell IPM 2019). Although adult males of fall armyworm have been monitored for over 40 yr using commercial versions of female-produced sex pheromone mixes as lures in traps (Meagher et al. 2019), until recently mating disruption approaches were not much studied in maize. However, a pheromone-based product for mating disruption got regulatory approval in the US in 2018 and recently also in Kenya (CABI News 2021). Prospects for using mating disruption in Europe are unclear so far but the high mobility of moths, high longevity and the fact that they can mate several times are clearly indicating difficulties. In particular, the migratory behavior means that lots of *S. frugiperda* adults may be present that have previously mated elsewhere. Application technologies for maize would however exist in Europe, such as those used for the orientation disruption against the silk feeding beetles of *Diabrotica v. virgifera* in Austria (S. Toepfer CABI, unpublished).

#### Botanicals

Many botanicals are of broad-spectrum activity and therefore often also show some level of effectiveness against fall armyworm. Some botanicals that have been registered for use against *S. frugiperda* outside the EU (Bateman et al. 2021) are also approved for use in Europe such as azadirachtin (Sisay et al. 2019, Babendreier et al. 2020), rapeseed oil, garlic extract and pyrethrins (Jepson et al. 2020), or *Urtica sativa* extracts (CABI 2022). Azadirachtin, derived from the seeds of the neem tree seems to be particularly effective (Babendreier et al. 2020). Depending on the country, some of those would need national or regional registration specifically for *S. frugiperda*. Moreover, cost-effectiveness on field scale levels such as for maize needs to be understood.

#### Basic Substances

This group constitutes a new category of plant protection products under the EC Regulation No 1107/2009 (Marchand 2016) with currently 23 approved basic substances (European-Commission 2022). Though information is scarce, no evidence was yet found that any of these would have a good effectiveness against *S. frugiperda*. However, in Africa, South Asia, and Central America, several 'local' methods not based on pesticides are used for *S. frugiperda* management such as applying ash or soil to the maize whorl, or spraying solutions based on soap, fish soup, or sugars (Harrison et al. 2019, Hruska et al. 2019). For the latter two approaches, an indirect control effect may be expected through the attraction of natural enemies. Independent of the somewhat unclear efficacy (see Babendreier et al. 2020), significant research and development would be needed before considering any feasible and cost-effective large-scale use in Europe.

### Chemical Control

Within an IPM context such as taken in European agriculture, chemical control should be seen as a last resort. Notably, synthetic insecticides are not much used in maize in most growing regions of Europe, something that may change with the arrival of *S. frugiperda*. In addition to potential risks to human health and the environment, it has been demonstrated that *S. frugiperda* became resistant to many active ingredients (a.i.) of synthetic insecticides from most major classes in the Americas (Gutiérrez-Moreno et al. 2019). This includes also a.i. generally seen as viable options such as flubendiamide and calls for a careful approach when choosing a synthetic insecticide against *S. frugiperda*, considering sound resistance management procedures. As another obstacle, applications against larvae in maize usually require high clearance spraying machinery, particularly in areas where migratory *S. frugiperda* is expected to arrive later in the season.

A number of insecticides are currently registered in European countries for use in maize, and in some European countries, insecticides are specifically registered for the control of lepidopteran pests such as *O. nubilalis*, *H. armigera*, *S. littoralis*, and *Sesamia nonagrioides* (Lef.) (Lepidoptera: Noctuidae). For example, cypermethrin, etofenprox, and pyrethrin extracts from *Chrysanthemum cinerariaefolium* are all registered for use against Lepidoptera in Greece. In Spain, acetamiprid, cyantraniliprole, cypermethrin, deltamethrin, lambda-cyhalothrin, metaflumizone, methoxyfenozide, spinetoram, and tebufenozide are all registered against either *Helicoverpa spp.*, *Ostrinia spp.*, *Spodoptera spp.*, or Lepidoptera in general. Most of them are of broad-spectrum activity such as the diamides, pyrethroids, macrocyclic lactones, and even many of the insect growth regulators.

Promising a.i. for *S. frugiperda* control appear to be chlorantraniliprole, flubendiamide, methoxyfenozide and tebufenozide. These are registered for use against *S. frugiperda* in either Brazil or the USA, reported to be highly effective against *S. frugiperda* (Hardke et al. 2011, Jepson et al. 2020, Beuzelin et al. 2022), do not pose unacceptable risks to human health or the environment and the ingredients are already approved for use in the EU. Alpha-cypermethrin, cyantraniliprole, cypermethrin, deltamethrin, emamectin benzoate, etofenprox, indoxacarb, lambda-cyhalothrin, spinetoram, spinosad, and triflumuron are also all reported to be highly effective against *S. frugiperda* (Jepson et al. 2020), registered for use against *S. frugiperda* in either Brazil or the USA and are already approved for use in the EU, but would need label extension for *S. frugiperda*. However, a higher level of risks to human health or the environment is associated with this group of a.i., thus mitigation measures would have to be applied to ensure agronomic sustainability and worker safety as well as to prevent nontarget effects (Jepson et al. 2020) and finally effects on consumers. More information is found in the reviews of Bateman et al (2021) or Sisay et al (2019).

Considering all the above sections, we would like to provide the following conclusions and recommendations. The latter reach from politically ones to others more relating to promising management options of *S. frugiperda*. With these recommendations, we hope to contribute toward Europe preparing itself in time to prevent a sudden and major influence of insecticides into the maize agro-ecosystem once *S. frugiperda* would have arrived:

- There is a high risk of invasion of *S. frugiperda* into Europe due to its highly mobile behavior as seen from the quick invasion of Africa and Asia, and because permanent *S. frugiperda* populations have already been established in Northern Africa, the Near-East, and the Canary Islands. When *S. frugiperda* would be found in mainland Europe, eradication of this invasive species, and even containment measures, may be difficult. We expect that *S. frugiperda* likely will establish permanently in the most southern European regions, and regularly invade large parts of European maize growing areas on an annual basis.
- Sound management of permanent *S. frugiperda* populations in the source regions may be key for reducing damage EU continent-wise. In addition, early detection and control of hotspots occurring along the migration pathway during summer may reduce the moth's population over a larger area.
- Monitoring networks for fall armyworm based on pheromone traps will be needed to allow forecasting of seasonal pest arrival in the various European maize growing regions. They may be similar to approaches used for forecasting *H. armigera* migrations into some areas of Europe, and could be combined with them.
- Creating awareness among European maize growers on how to identify and monitor *S. frugiperda* and its damage symptoms in the field is critical for assessing pest populations on a local level timely and allowing for appropriate pest management decisions.
- A crucial question for the need and type of interventions will be the time of arrival in a given region. This also has implications for the likelihood of *S. frugiperda* attacking the young maize cobs, which is affecting yield and increasing problems with aflatoxin contamination caused by fungal infections.
- Many of the measures available for the control of lepidopteran maize pests in Europe can also be adapted for the control of fall armyworm and incorporated into maize IPM strategies. Good agricultural practices that promote the growth of healthy plants are important because healthy plants are generally less susceptible to *S. frugiperda* attack.
- Many natural enemies are able to attack and kill *S. frugiperda*, thus any measures to protect or enhance natural enemies by habitat management approaches, such as e.g., growing flower strips, reduced tillage, or intermediate cover crops are expected to contribute to the control of *S. frugiperda*.
- In case pest forecasting on regional level and local monitoring indicate the need for further action, a biological-based option should be preferred to avoid disruption of IPM systems in maize. Products based on baculoviruses, some *B.t. aizawai* strains, and several botanicals such as azadirachtin have been proven effective; also, macrobials like entomopathogenic nematodes or parasitoids may be used successfully in the near future. Otherwise, low toxicity pesticides with short environmental persistence are available and should be selected.
- More research on promising biological *S. frugiperda* management options would be relevant, e.g., on formulations, dosages, and application methods to make them more effective and economic.
- Genetically engineered maize varieties based on *B.t.* toxins would likely be effective tools to control *S. frugiperda* in Europe, particularly if stacked, but legislation in most European countries may be challenging. The potential of this approach might be evaluated first in Spain where *B.t.* events are already approved for lepidopteran pests in maize.
- Plant protection companies including biocontrol companies are advised to prepare for registration of products against fall armyworm, probably first targeting label extension of products existing for the control of other lepidopteran pests in maize in Europe, then adopting and registering products successful against *S. frugiperda* in other world regions, and finally developing new solutions suitable for Europe.
- Registration authorities may allow emergency registrations of plant protection products in case of a sudden arrival of fall armyworm. However, we advise that such emergency registration concentrates on biological options already existing for the control of this pest.

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