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REVIEW

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The use of *Telenomus remus* (Nixon, 1937) (Hymenoptera: Scelionidae) in the management of *Spodoptera* spp.: potential, challenges and major benefits

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Abstract

Spodoptera frugiperda (Smith, 1797) (Lepidoptera: Noctuidae), also known as fall armyworm (FAW) is a polyphagous pest which can cause significant losses and is considered a global threat to different crops and a risk to food security. Currently, in maize, the pest is predominantly controlled by pesticides or transgenic events. However, the use of biological control agents is considered the most sustainable and preferred method of control, providing high effectiveness. Among the various natural enemies reported for FAW, the egg parasitoid *Telenomus remus* has gained most interest, and has been mass released against FAW in the Americas for many years. In addition to FAW, other armyworms of the genus *Spodoptera* often cause high crop damage and may be controlled using *T. remus*. Among other important aspects, this paper presents a review on *T. remus* mass rearing techniques, estimated costs of mass production, and release strategies. Due to the recent invasion of FAW in Africa, Asia, and Australia *T. remus* provides good opportunities for the establishment of an augmentative biological control program, reinforcing sustainable production of major crops such as maize in affected countries.

Introduction

The genus *Spodoptera* Guenée (1852) comprises numerous lepidopteran moths, such as *Spodoptera frugiperda* (Smith, 1797), *Spodoptera eridania* (Stoll, 1782) and *Spodoptera cosmioides* (Walker, 1858) (Lepidoptera: Noctuidae) which are known for their economic importance as pests of several crops worldwide (Brown and Dewhurst 1975; Panizzi et al. 2012; Bortolotto et al. 2015). The fall armyworm (FAW), *S. frugiperda*, is one of the most devastating pests in the genus. It feeds on leaves, stem and reproductive parts of a wide range of host plants, including common beans, cotton, maize, rice, sorghum, soybean, and vegetables among others (Pogue 2002; Nagoshi 2009; Bueno et al. 2011; Silva et al. 2017; Sagar et al. 2020). Not only is FAW a global threat to different crops but also a risk to food security (Rwomushana et al. 2018; Sagar et al. 2020). Currently, growers frequently apply synthetic insecticides to control *Spodoptera* spp. However, the overuse of insecticides has triggered some negative side-effects (Song and Swinton 2009) such as the selection of resistant pest populations (Diez-Rodriguez and Omoto 2001; Carvalho et al. 2013), the reduction of biological control agents (Torres and Bueno 2018), or outbreaks of secondary pests (Bueno et al. 2021). Therefore, a more sustainable *Spodoptera* spp. management is of high interest for millions of farmers globally.

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Integrated Pest Management (IPM) is defined as the combination of different control methods, implemented jointly to keep insect pest populations below the level of economic damage, considering economic, ecological and social criteria (Norris et al. 2002). Along with cultural control measures, biological control plays an important role within the IPM approach as an environment-friendly and sustainable pest management strategy. In addition to classical biological control and conservation biological control, augmentative biological control has been increasingly accepted by growers and is currently being applied on more than 30 million ha worldwide (van Lenteren et al. 2018).

Egg parasitoids are one of the most important groups of biological control agents used in augmentative biological control due to their action on early pest stages before any damage occurs to the crop (Parra and Coelho Jr 2019). Therefore, augmentative biological control employing egg parasitoids has been increasingly used in Latin America to fight pests damaging a number of crops (van Lenteren and Bueno 2003; van Lenteren et al. 2018). The egg parasitoid *Telenomus remus* Nixon, 1937 (Hymenoptera: Scelionidae) is native to peninsular Malaysia and Papua New Guinea (Wengrat et al. 2021) and has been released against various pest species of the genus *Spodoptera* (Pomari et al. 2012; Bueno et al. 2008; 2010; Ferrer 2001; 2021). The biology and ecology of this egg parasitoid has been studied in the past and reviewed by Cave (2000). In addition to its high fecundity, *T. remus* is especially noteworthy for its effective action on eggs of *Spodoptera* spp. in superposed layers, even parasitizing eggs located in the inner layers of the egg mass (Figueiredo et al. 1999; Bueno et al. 2008) (Fig. 1). Furthermore, *T. remus* has high dispersal (Pomari-Fernandes et al. 2018) and host search capacities (Pomari et al. 2013a) underlining its potential for augmentative biological control programs. Noteworthy, *T. remus* has been released against FAW in maize on a large scale (several thousands of ha) during the 1990s in Venezuela as part of an IPM program and on slightly smaller scale until recently (Ferrer 2001; 2021). These releases have resulted in an overall reduction in insecticide use against FAW of between 49 and 80%. *Telenomus remus* has achieved up to 90% of FAW egg parasitism after releases (Ferrer 2021; Hernández et al. 1989).

However, a lot of information collected and experiences gained during the history of *T. remus* in biological control programs is neither published in peer reviewed journals and/or not available in English. This is of particular concern as recently there is increasing interest in this biological control agent also in the newly invaded regions, i.e. Africa, Asia and Australia (e.g. Kenis et al. 2019; Agboyi et al. 2021). We here thus review the available literature on *T. remus,* with a focus on the substantial practical experiences gained in Latin America on the management of FAW and other species of the genus *Spodoptera*, aiming to provide better guidance for improved and potentially global application of *T. remus* in integrated pest management programs against FAW. This includes important aspects such as mass production of *T. remus*, parasitoid release strategies, field use and its compatibility with chemical insecticides among others.

Telenomus remus mass rearing

Mass rearing of any augmentative biological control agent is a critical step to achieve success (Parra 2010). It has been studied for *T. remus* extensively for more than 40 years, reflecting not only the importance of this egg parasitoid in biocontrol attempts but also the major difficulties and challenges this species poses. Theoretically, there are three different ways in which *T. remus* could be reared: (i) on the natural host, (ii) on factitious hosts (both in vivo) and (iii) on an artificial diet (in vitro). To the best of our knowledge, only in vivo *T. remus* rearing has been used so far with both advantages and disadvantages comparing natural and factitious hosts.

Telenomus remus rearing started in India using eggs of the natural host *Spodoptera litura* (Fabricius, 1775) (Lepidoptera: Noctuidae) first (Joshi et al. 1976; Gupta and Pawar 1985), and then eggs of the factitious hosts *Agrotis biconica* Kollar (Lepidoptera: Noctuidae) (Gautum and Gupta 1994) and *Corcyra cephalonica* Stainton (Lepidoptera: Pyralidae) (Kumar et al. 1986).

Using FAW eggs (natural host) for *T. remus* rearing might pose a problem due to cannibalism among FAW larvae, which obviously is a major obstacle in any rearing. This might be overcome by switching artificial diet for FAW rearing. Ferrer (2021) reported on the mass production of *T. remus* on FAW eggs in which this host is reared with a diet based on spurge or castor leaves (*Ricinus communis*). The author considered this rearing method as a cost-effective one to be used on smaller mass production units, especially because low cannibalism is observed among FAW larvae, optimizing host production. According to Glober (2019), although larvae reared on castor oil plants are still cannibalistic, the extent of cannibalism is lower. The same author highlighted that this is probably due to the influence of castor leaves on the microbial midgut community structure and its composition making larvae emit chemical compounds that could repel conspecific larvae and in turn suppress cannibalistic behaviour. Alternatively, eggs of *S. litura* (natural, non-cannibalistic host) or a factitious host could be used. In addition, Gautum (1986) suggested the use of *Agrotis* spp. eggs as a factitious host for one generation to improve the biological efficacy of *T. remus*, because

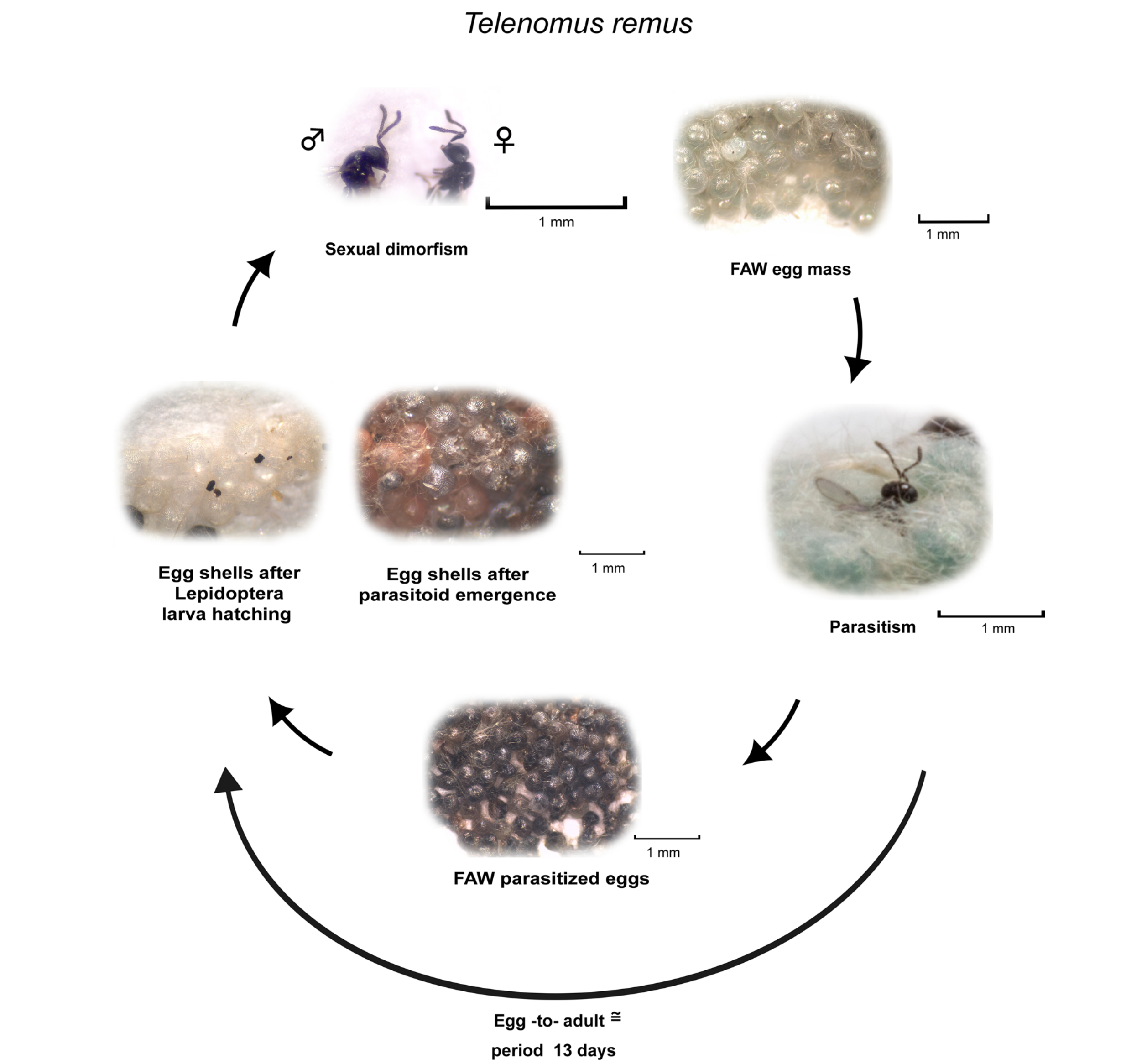

Fig. 1 *Telenomus remus* life cycle on FAW eggs

adults reared in *Agrotis* spp. eggs are bigger, live longer and are more fecund than adults reared in *Spodoptera* spp. eggs.

Another factitious host that can be used for *T. remus* rearing is *C. cephalonica*, which can be produced at low costs and has been already used for rearing other egg parasitoids such as *Trichogramma* spp. (Babendreier et al. 2020a). However, eggs of *C. cephalonica* are considerably smaller than *Spodoptera* spp. ones. Consequently, *T. remus* reared from these factious hosts are also smaller and live shorter than adults reared in FAW eggs (Kumar et al. 1986; Queiroz et al. 2017a). Moreover, lower lifetime parasitism on FAW eggs was recorded for *T. remus* reared on *C. cephalonica* eggs (Queiroz et al. 2017a) compared to *T. remus* reared on FAW eggs (Pomari et al. 2013b). Nevertheless, *T. remus* reared on *C. cephalonica* eggs does not lose its capacity of parasitizing eggs of *Spodoptera* spp. even in superposed layers and its flight abilities measured in laboratory trials (Pomari-Fernandes et al. 2016) or its dispersal capacities under field conditions (Pomari-Fernandes et al. 2018). The lower lifetime fecundity of course is still of concern but may be solved through the release of higher number of parasitoids. Another advantage of *C. cephalonica* eggs is that they can be stored for up to 21 days at 10 °C for subsequent parasitism by *T. remus* while *Spodoptera* spp. eggs can hardly be stored before being offered for parasitism (Queiroz et al. 2017b). Despite these promising findings, there are also cases of failures for *T. remus* rearing on *C. cephalonica* eggs (D. Babendreier, personal communication). Moreover, as far as we know, *C. cephalonica* has only been used for the production of *T. remus* for research purposes. So far, no mass rearing of *T. remus* using *C. cephalonica* has been established on a commercial scale, which raises concerns about the field effectiveness of *C. cephalonica*-reared wasps and overall cost-effectiveness. Therefore, underlying reasons regarding success vs failure of rearing *T. remus* on *C. cephalonica* and whether this may be due to different parasitoid strains or rearing protocols adopted, still deserves more research in near future.

Irrespective of the rearing host, control of environmental conditions is highly relevant. Overall, a moisture regime of 80% (Pomari-Fernandes et al. 2014) and a temperature range from 22 to 28 °C (Pomari et al. 2012) are reported as optimal rearing conditions. Adults should be fed preferably with honey offered as small droplets spread over adult cage walls. To establish the correct host-parasitoid ratio is also crucial since it directly impacts quality parameters, in particularly the sex ratio (van Welzen and Waage 1987). Considering that *T. remus* parasitism capacity ranges from 60 (Pomari et al. 2013b) to around 82 eggs (Morales et al. 2000) during the first 24 h of parasitism and then is reduced to less than 30 eggs on the second day and less than 20 eggs on the following days (Pomari et al. 2013b), it might be suggested that the ideal host-parasitoid ratio should be around 100 eggs/female on the first day of parasitism which later can be reduced to 36 and 24 eggs/female on the second and third day of parasitism, respectively. The proportion of around 20 eggs/parasitoid female should be kept until the fifth or sixth day of parasitism when the remaining adults alive may be discarded. The first day of parasitism is 48 h after the first adults had started to emerge because those first adults emerging are males (Cave 2000). These recommendations may need to be adapted to the specific conditions in a given rearing facility and still be tested in massive rearing conditions since they have been adopted so far only in laboratory rearing in small scales or research purposes.

As with all mass rearing facilities, it is very important to implement quality control measures to observe and potentially address any issues. One challenging aspect is the risk of parasitoid fitness losses in long-term production systems, as it is known that *T. remus* foraging and flying abilities can be reduced when reared for many generations (Naranjo-Guevara et al. 2020). As possible solutions to this problem, the establishment of varying rearing conditions (different regimes of light, temperature, and humidity, for example), and the introduction of wild individuals (periodically) into the laboratory rearing have been suggested. The refreshment of the insect colony with individuals collected from natural populations is likely the most effective measure but should be done with caution since taxonomic knowledge is required to avoid colony contamination with other parasitoid species (Wengrat et al. 2021) or fungal and bacterial pathogens from the field, among other possible negative issues.

Currently, *T. remus* is being reared in different countries mainly in Latin American and Africa, for commercial and research purposes at different scales. In Peru, mass production of *T. remus* has been conducted around the country by private companies facilitating the use of this natural enemy against *Spodoptera* spp. (Mujica and Whu 2020) on 37 ha of maize and vegetables. Another interesting example from Peru is the commercialization of *T. remus* by a government laboratory which produced *T. remus* on FAW eggs as part of the Chavimochic project implemented in the Libertad Department by the Agricultural Development Department. Farmers could buy the parasitoids at 20 PEN/1000 parasitoids, totalling 60–160 PEN/ha (around 15–41 USD/ha) (Gobierno de la Libertad 2012).

Since 2005, three laboratories run by the Venezuelan government have been rearing *T. remus* for inundative releases (Vásquez et al. 2020) offering *T. remus* to farmers for free or very much reduced prices. This differs from the previous work conducted by the private company named "Servicio Biologico" (ServBio) where parasitoids of *T. remus* were commercialized, establishing a sustainable business model in the 1990s (Ferrer 2001, 2021). It is considered that the success for the high production and adoption of *T. remus* in Venezuela against FAW in maize during more than 10 years (1989 to 1999) was not only due to the strong linkages between biological control producers and farmers associations (technology transfer services) but also to the low costs of *T. remus* (which varied from 7.5 to 17.5 US$/ha per release) and most importantly, due to the grower`s savings of 19.3 to 36.3 USD/ha when the egg parasitoid was used as part of the IPM package (Ferrer 2001). In addition to the use of *T. remus* in Venezuela, the adoption of the whole IPM practices allowed the reduction of 80% of the insecticide load commonly used in maize production with both financial and environmental benefits for growers (Ferrer 2001, 2021).

In addition, once Venezuelan farmers realized the importance of *T. remus* as biocontrol agent, they started their own mass rearing in a small scale, initiating the piloting process with a champion farmer who used *R. communis* for the mass production of FAW, having low costs for *T. remus* mass rearing. This champion farmer popularized the use of *T. remus* against FAW, as he used to promote its use and sell *T. remus* to local producers (Ferrer 2021). Thus, several field trials were carried out by SERVBIO (Servicios Biológicos C.A.) with the purpose of studying the dispersion, effectiveness and economic results in various states of Venezuela (Ferrer 2001; Fuentes et al. 2012), and in consequence implementations of biological control and IPM programs in 1960 ha in four Venezuelan states allowed to obtain 49% savings in insecticide use compared to the cost of a program without IPM application (Ferrer 2021).

Cost of mass production

Production costs of *T. remus* reported in the literature have a large range of variation, which is possibly related to differences found in insect colony size, host used, labour costs, level of mechanization, among several other issues that can dramatically impact final results. Certainly, one of the costly factors and often the limiting one in commercial production of *T. remus* is the labour costs (Román Suárez 1998), which can greatly vary among countries and even regions.

According to Santos-Erazo (1998) and Linares (1998), the rearing costs of producing 1000 individuals of *T. remus* using FAW eggs was 0.5 and 2.2 USD, respectively. Vieira et al. (2017) reported an even cheaper value in Brazil of 0.4 USD to produce 1000 *T. remus* using FAW eggs, considering as total cost only the effective operating expenses incurred based on diet, labour, energy consumed by existing equipment, expenses related to other materials, and costs related to depreciation of equipment and furniture (missing only the new equipment and building costs).

Generally, total costs for producing *T. remus* are highly influenced by the cost of producing FAW egg masses which can reach up to 84% of total costs (Santos-Erazo 1998). Thus, crucial attention should be given to FAW rearing diets due to its high cost and the cannibalistic habit of *S. frugiperda* larvae (Martínez-Martínez et al. 2015). As mentioned in the previous section, *R. communis* leaves have been used as food to rear *Spodoptera* spp. in order to reduce diet costs but also cannibalism among larvae and therefore overall FAW production costs (Cabezas et al. 2013). Martínez-Martínez et al. (2015) presented *R. communis* as an alternative to mass production of FAW, reporting similar survival of larvae and pupae when fed with corn leaves or *R. communis*. Despite promising results when using *R. communis* for FAW mass production in Venezuela (Ferrer 2021), further studies are necessary, also because several toxic substances have been reported in this plant species, especially when the extracts are coming from the seeds (Ramos-Lopez et al. 2010). Alternatively, an investigation carried out at CIMMYT, Mexico, showed that multicellular grids filled with diet are more effective to increase *T. remus* production, as it allows to increase the production of *S. frugiperda* compared to the traditional 1-oz cap system, which could help to reduce the costs of mass production (Mihn 1984).

More recently, the production costs of *T. remus* reared on FAW eggs were updated for a Venezuelan commercial setting based on the production of high-quality parasitoids sufficient for 4,000 ha of maize at 8,000 wasps/ha

Table 1 Operational costs (June 2021) for mass rearing of *T. remus* considering the need for construction of a facility (32 mio *T. remus* to be released which requires 35.2 mio parasitoids to be produced per crop season) in Yaracuy State, Venezuela

Item	Cost (USD)
Facilities construction (considering a 20-year depreciation) (f)	4500
Equipment (considering a 4-year depreciation)* (f)	6254
Direct inputs (Diet) (v)	9727
Direct material (plastic containers, consumables) (v)	5235
General supplies and materials (electricity, water, taxes)* (f, v)	9741
Labour (permanent staff = 6)* (f)	16,000
Labour (non-permanent staff, used only in production peaks = 3) (v)	3469
Services (maintenance, repair of equipment) * (f, v)	4163
Transportation* (f, v)	1500
Total costs	60,591
Unit cost (*T. remus* produced)	1.72
Unit cost (*T. remus* released)	1.89
Suggested selling price 30% of the cost	2.46
Cost per hectare (8000 parasitoids)	15.1

*Estimated costs. f = fixed; v = variable; fv = 50% for each type of cost (totalling 32 mio *T. remus* released as recently emerged adults) (F. Ferrer, personal communication, Table 1).

Following the experience in Venezuela with a successful mass production and release of *T. remus* for more than 40 years, the cost of production of *T. remus* per unit of 1000 wasps in June 2021 was 1.89 USD. The total cost per hectare was thus 15.1 USD, based on a release rate of 8000 parasitoids/ha.

Telenomus remus potential, use and field efficiency in different crops

Telenomus remus parasitism is highly influenced by both temperature (Bueno et al. 2010; 2014; Pomari et al. 2012, 2013b) and humidity (Pomari-Fernandes et al. 2014) under laboratory conditions, indicating that those climatic conditions are crucial for the success of an augmentative biological control program using this parasitoid species in the field. Despite climatic impact over parasitoid performance, it is important to point out that a single *T. remus* female can parasitize 140–220 FAW eggs during her lifetime in laboratory conditions, with similarly high numbers also on other hosts (Table 2) illustrating its high potential to control those lepidopteran pests in the field.

The differences seen in Table 2 might be due to host species as well as differences in relative humidity of the trials. A positive effect of increased humidity on *T. remus* parasitism has been reported from laboratory studies in *S. litura* (Gupta and Pawar 1985), *Agrotis spinifera* (Hubner, 1808) (Lepidoptera: Noctuidae) (Gautum 1986), and *C. cephalonica* eggs (Pomari-Fernandes et al. 2015). Similar effects of humidity were also reported for *Telenomus isis* (Polaszek, 1993) (Hymenoptera: Scelionidae) parasitizing coffee borer eggs (Bruce et al. 2009). Despite the clear effect of humidity, it is important to point out that this effect of environmental conditions can differ among host species (Pomari-Fernandes et al. 2014).

Table 2 Lifetime parasitism (number of parasitized eggs/parasitoid female during its lifetime) of *Telenomus remus* at 25 °C on different host eggs

Host species	Lifetime parasitism	Parental female longevity (days)	References
Spodoptera frugiperda	140.8	8.3	Pomari et al. (2013b)
	220.0	10.6	Bueno et al. (2014)
Spodoptera cosmioides	115.3	13.1	Pomari et al. (2013b)
Spodoptera eridania	139.5	8.0	Pomari et al. (2013b)
Anticarsia gemmatalis	200.5	12.4	Bueno et al. (2014)

Different biological features of *T. remus* highlight its high potential for field use in the management of FAW populations. When wasp females were kept fed but without access to host eggs for up to 10 days, there was no reduction in lifetime parasitism compared to females which had access to hosts since emergence (Queiroz et al. 2019). This is a positive characteristic of *T. remus* for augmentative biological control programs because adults can maintain their potential parasitism and efficiency during periods of low host availability unlike other species of egg parasitoids in which resorption of eggs occurs (Santolamazza-Carbone et al. 2008). It is also a beneficial characteristic for mass rearing as it increases flexibility to match production with the demand for releasing biological control agents in the field and might allow parasitoid storage on a small scale.

The potential to use *T. remus* for pest control in the field was explored first in India where the parasitoid was introduced for classical biological control of *Spodoptera* spp. in 1963 (Sankaran 1974). Subsequently, *T. remus* was used in inundative biological control programs against *S. litura* in potato. In this example, the parasitoid were combined with other natural enemies, reducing pest incidence in the crop by 60% (Ansari et al. 1992).

In the New World, the first introduction of *T. remus* to control caterpillars from the *Spodoptera* complex took place during 1971–1972 in Barbados (Caribbean), where levels of parasitism greater than 60% were recorded in different crops (Cave 2000). In Florida State (USA), more than 660,000 adults of *T. remus* were released for classical biological control of FAW in maize and sorghum from 1975 to 1977 with parasitism levels reaching 43% (Waddill and Whitcomb 1982).

Later the parasitoid was released and established in several countries of Central America and the Caribbean including Antigua, Dominica, Monserrat, St Kitts, St Vincent and Trinidad & Tobago. In El Salvador and Nicaragua, *T. remus* establishment was never detected (at least never reported), probably due to unfavourable environmental conditions at the release sites and/or low quantities released (Cave 2000). As part of an augmentative biological control program in Honduras, *T. remus* was experimentally released at different rates (from 35,000 to 50,000 wasps/ha/week to 75,000–105,000 wasps/ha/week) in maize and sorghum fields during 1991–1994 with observed parasitism rates varying from 20 to 92% between months, and a lack of clear correlation between parasitism and released rates (Cave 2000).

In South America, *T. remus* was introduced in 1979 in Venezuela to manage FAW (Ferrer 2001). Hernández et al. (1989) reported 60–83% FAW egg parasitism in maize after three weekly releases of 15,000 adults of *T. remus.* This parasitism level was observed at a distance of 2000 to 2200 m from the release point with even higher rates (78–100%) in eggs closer to the releasing point (from 30 to 1400 m).

Telenomus remus parasitism decreases with increasing distance to the release points regardless of crop studied. Dispersion capacity varies from 14.5 to 20.5 m in 4 days and was highly influenced by local wind speed and direction (Pomari-Fernandes et al. 2018). Thus, the parasitism (%) and *T. remus* dispersion observed by Hernández et al. (1989) is probably due to different generations of the parasitoid.

In some other countries of South America, inundative field releases of *T. remus* showed around 80% parasitism such as in Colombia (García-Roa et al. 2002), Guyana and Suriname, resulting in *T. remus* establishment in those countries (Cock 1985; Yaseen et al. 1981). In contrast to the mostly successful results reported in this section so far, a field trial established in Brazil during 2008 in maize recorded only a poor effect of *T. remus* on FAW outbreaks. Around 200,000 *T. remus* were released per hectare but did not increase FAW mortality compared to the control (Varella et al. 2015). Although *T. remus* was first introduced in Brazil over 35 years ago, its natural occurrences had not been reported until a recent collection of a *Telenomus* species alerted us to the presence of *T. remus* in the field in Brazilian agroecosystens (Wengrat et al. 2021).

Those contrasting results may be due to the strain used, and possibly a deterioration of parasitoid colony quality, coming from the Maize and Sorghum Research Center (Embrapa Maize and Sorghum—Sete Lagoas, Minas Gerais, Brazil) where *T. remus* colony had been kept using FAW eggs under laboratory conditions for more than 20 years. *Telenomus remus* from this colony had a lifetime fecundity of only 35.7 FAW eggs (Bueno et al. 2010), considerably less than found in other studies (Pomari et al. 2013b; Bueno et al. 2014, see Table 2) which used parasitoids originally collected in Ecuador in 1986 and grown at the parasitoid rearing facilities of ESALQ/USP (Luiz de Queiroz College of Agriculture/University of São Paulo). In addition, Varella et al. (2015) released *T. remus* in the pupal stage while the other previously mentioned successful field reports released *T. remus* adults already fed with honey.

Telenomus remus release strategies

As shown above, *T. remus* has potential as an augmentative biological control agent for the management of *Spodoptera* spp. However, challenges to be still addressed include: (i) the number (density) of parasitoids released; (ii) the best parasitoid release strategy considering dispersion, release frequency, predation, best timing of release, pest density and climatic conditions at the time of release, and (iii) interactions with other grower's management practices used in the field such as the use of chemical insecticides (King et al. 1985; Smith et al. 1986; Pinto and Parra 2002; Parra 2014).

(i) number of parasitoids released: Detailed information about the effect of numbers of *T. remus* released in the field is scarce in the literature. In Venezuela, the number of *T. remus* to be released has been estimated based on cost–benefit ratios. Based on field work conducted in various Venezuela States, the release of between approximately 4500 (Yaracuy State) to approximately 9000 (Lara State) parasitoids per hectare was considered most cost-effective (Ferrer 2001). This total number of parasitoids to be released in one hectare vary in different regions according to pest infestation rate, crop development stage, among other factors. Even in Venezuela other parasitoid numbers were used by different authors. Hernández et al. (1989) successfully released *T. remus* at early FAW infestation levels in maize fields in the country. Authors applied 5000 *T. remus* adults per ha of maize at vegetative stage during three consecutive weeks starting when the germination of the plants occur and resulting in parasitism levels of between 60 and 100% depending on distance from release points and days after release. Still in Venezuela, optimal FAW control levels were recorded after releasing 40,000–60,000 wasps in maize fields during the season (Linares 1998). Adults were released from 750 ml plastic containers with honey droplets on their walls and using 10,000–15,000 parasitoids per release point, which means four release points per ha.

Differently, Gutierrez-Martinez et al. (2012) reported that the release of 12,000 to 15,000 parasitoids per hectare triggered 36–100% of parasitism in FAW eggs in Mexico. Ivan et al. (2016) evaluated the necessary number of parasitoids to be released to reduce the damage caused by FAW to maize in Brazil and concluded that releasing 20,000 wasps per hectare for three consecutive weeks was sufficient to reduce the crop damage. Also in Brazil, Figueiredo et al. (2002) recommend the release of 9 to 12 females of *T. remus* per m^2 (90,000–120,000/ha), which resulted in 72.4 and 82.8% parasitism of FAW eggs, respectively. Rezende et al. (2016) reported that releasing 20,000 parasitoids of *T. remus* per ha was efficient to reduce the FAW damage to 3 using a damage score of 0–9.

The release of *T. remus* numbers divided in different consecutive weeks is usually recommended because adults of *T. remus* have a short longevity of between 4 to 7 days, when they carry 80% of their lifetime parasitism (Pomari et al. 2013b) and have the greatest parasitism capacity in FAW eggs from 24 to 48 h of embryonic development, with negligible parasitism in eggs of 72 h (Queiroz et al. 2019). Considering a field situation with the presence of FAW on different development stages, the release of the parasitoid numbers divided in 3 or 4 weeks in the field is a way to improve the matching of 4–7-day-old *T. remus* adults with host eggs of 1 or 2 days, which is essential for the successful management of FAW using *T. remus* (Fonseca et al. 2016).

As previously mentioned, the total number of parasitoids to be released per hectare differs from country to country and not always the studies present the percentage of parasitism obtained, or the criteria used for the best moment to initiate the parasitoids releases and the frequency applied. The most common numbers vary between 5000 and 50,000 parasitoids/ha and season. Table 3 presents the number of parasitoids released in different countries in Latin America, the frequency of parasitoids releases and the percentage of parasitism when reported. More recently, Wengrat et al. (2021) suggested that reintroductions of natural populations of *T. remus* from different geographical origins may be an efficient tactic for classical and augmentative biological control of *S. frugiperda* in different parts of the world, increasing the changes of parasitoid establishment in the environment as those authors observed in Brazil.

(ii) parasitoid release strategy: In general, *T. remus* can be released as pupae inside parasitized eggs or as adults. Most studies reviewed here released adults, already fed with honey and thereby increasing parasitoid chances to succeed. The methodology to release *T. remus* established in Venezuela in the 1990s consists of walking through the rows of maize with plastic cups containing newly emerged parasitoids and opening the containers at random near the corn plants. The initiation of parasitoid releases is recommended during the crop's germination stage (García-Roa 1999), followed by 3–4 consecutive applications every 7 days or up to 5 applications based on monitoring of FAW incidence (Hernández et al. 1989; García-Roa 1999). In terms of the number of releasing points of *T. remus*, some technical documents recommend the use of 12–14 points, by opening the containers with the parasitoids for a few seconds looking forward to ensure a good distribution of the parasitoids at the field level (Gobierno de la Libertad 2012). However, other studies reported the use of only three or four releasing points per ha (Figueiredo et al. 2002; F. Ferrer, personal communication) leaving the plastic containers in a centralized area of the field for 24 h to allow the exit of all parasitoids (Varella et al. 2015).

In Brazil, the pupa stage has been preferred by the biological control industry due to the ease of mechanization of the release process in the field, reducing labour and operating costs (Pinto and Parra 2002). Eggs of parasitized hosts, containing parasitoid pupae inside, can be easily and homogeneously sprayed onto the crop using drones. This kind of release has already been adopted in Brazil for other parasitoid species such as *Trichogramma* spp.

Differently from *Trichogramma* spp. where pupae can be released only a few hours before parasitoid emergence, the release of *T. remus* pupae is more complicated since males emerge 24 h before females. Then *T. remus* pupae exposed in the field one or two days before the emergence of adults may face high mortality due to the action of predators (ants, lacewings, ladybugs, among others) (Cave 2000; Parra 2014). Therefore, the use of adults already fed with honey should be considered as a good alternative option, despite its release mechanization process still need to be developed and tested on large scale.

Besides predation, the released parasitoids must also survive climate conditions (rainfall and temperature) to which they will be exposed. Adverse climate conditions

Table 3 Total Number of *Telenomus remus* per hectare released in maize in different countries in Latin America, frequency of releases and percentage of parasitism of FAW eggs

Country	Number/ha and season	Frequency of releases	Parasitism (%)	References
Venezuela	5000	3 at weekly intervals	60–100	Hernandez et al. (1989)
Venezuela	4433–9260	4 at weekly intervals	70–100	Ferrer (2001)
Venezuela	40,000–60,000	10 at weekly intervals	No information	Linares (1998)
Honduras	35,000–50,000	Weekly	65–92	Cave and Acosta (1999)
Brazil	60,000	No information	No information	Cruz (2007)
Brazil	90,000–120,000	One application	72.4–82.8	Figueiredo et al. (2002)
Brazil	20,000	3 at weekly intervals	No information	Rezende and Silva et al. (2016)
Brazil	20,000	3 at weekly intervals	No information	Ivan et al. (2016)
Brazil	100,000–200,000	One application	9–14	Salazar-Mendoza et al. (2020)
Brazil	200,000	One application	1.4–9	Varella et al. (2015)
Colombia	33,000	4–5 applications	80	García-Roa (1999)

can constitute an important mortality factor, in particular when egg parasitoids are released as immobile pupae in the field, unable to seek shelter to protect themselves.

Among climate conditions as abiotic factors of insect mortality, temperature is noteworthy (Frazer and Mcgregor 1992), as it directly affects parasitoid emergence (Braz et al. 2021). Based on that, Grande et al. (2021) suggested that adults of *T. remus* should be released early in the morning. This strategy may also allow adults to find shelter from high temperatures during warmer times of the day.

In addition, releasing *T. remus* adults late in the evening could be a mistake because the parasitoid is inactive during the night (Grande et al. 2021). The longer adult parasitoids are exposed in the field, the greater the chances they may be injured by pesticides (Carmo et al. 2010), climate (Bueno et al. 2008; Pomari et al. 2012) or other biotic or abiotic factors that can increase adult mortality and reduce their efficacy in controlling eggs of target pests (Cave 2000; Ferrer 2001).

(iii) interaction with pesticides: Despite the biological control potential of *T. remus* against FAW, chemical control might still be needed to control FAW outbreaks, or against other pests (Bueno et al. 2021). Thus, to understand the threats that pesticides pose for *T. remus* as well as the possible uses of selective pesticide is essential to allow both, chemical and biological control, to be used in combination within IPM programs (Torres and Bueno 2018). Recently conducted studies have demonstrated that numerous biopesticides are available for FAW control, some of which are showing good efficacy (Babendreier et al. 2020b; Guo et al. 2020; Bateman et al. 2021). These are generally harmless to parasitoids and some have been explicitly tested against *T. remus* (Amaro et al. 2018; Silva et al. 2016). However, even among the synthetic insecticides, active ingredients belonging to the group of Insect Growth Regulators (IGRs), such as diflubenzuron, flufenoxuron and methoxyfenozide, are relatively more selective and viable options to control lepidopteran pests in conjunction with *T. remus* whenever necessary. In contrast, pyrethroids such as bifenthrin, gamma-cyhalothrin or beta-cyfluthrin, organophosphates such as chlorpyrifos and acephate, and also spinosad were among the most harmful pesticides to the parasitoid, especially to adults, which is generally the most susceptible parasitoid stage (Hassan et al. 1985; Carmo et al. 2009, 2010). These broad-spectrum insecticides should be strongly avoided in fields around a couple of weeks before and after *T. remus* releases. Where stink bugs or chrysomelids need to be controlled, pyrethroids or organophosphates may be preferred by farmers, posing a challenge for *T. remus* preservation. Fungicides and herbicides are generally less harmful to *T. remus* when compared to insecticides (Stecca et al. 2016). However, they also should be only applied when necessary because products such as epoxyconazole or clomazone can still harm *T. remus* (Carmo et al. 2009, 2010).

Experience using *T. remus* in Africa and Asia

FAW was recorded for the first time in West Africa in early 2016 (Goergen et al. 2016; Cock et al. 2017) causing a significant loss on maize production soon after arrival on the continent (Day et al. 2017). In Africa, growers also responded by using lots of pesticides after arrival of FAW, threatening farmer's health as well as the sustainability of maize cropping systems, traditionally done with low inputs (Tambo et al. 2020). Targeting other armyworms, classical biological control involving *T. remus* has been initiated in Africa. It was released in the Cape Verde Islands in the early 1980s, but its establishment has not been confirmed. When the FAW invaded Africa in 2016, this option was discussed again but interestingly this egg parasitoid was found to be already present on the continent (Kenis et al. 2019). A recent survey found *T. remus* to be present in most regions of Benin and Ghana (Agboyi et al. 2020). Similarly, *T. remus* was found in Southern parts of Asia, with FAW egg mass parasitism rates of 30% already in the first season after pest arrival in China (Liao et al. 2019). Like for classical biological control, also augmentative approaches using *T. remus* have been put forward or already tested recently in Africa. Laminou et al. (2020) released 62,500 *T. remus* per ha in sorghum fields in Niger in relatively small plots of 200 m^2 and using sentinel eggs. Combined results for the two seasons, showed that 64% eggs were parasitized under these conditions while < 10% were observed in control fields. In field release studies in Ghana, three releases of 30,000 *T. remus* per ha were conducted in maize plots of 0.5 ha in the major and minor rainy season respectively (Agboyi et al. 2021). Egg mass parasitism reached 33% in the *T. remus* release plot in the major rainy season while 72–100% of egg masses were parasitized in the minor rainy season during which pest densities were much lower. However, no significant difference in egg mass parasitism was found between release and no-release plots, despite considerable distances of 150–400 m between them.

Conclusions and recommendations

In summary, no ready-to-use package is available to advise farmers in using *T. remus* against FAW and related pests. Further studies are urgently needed to precisely determine optimal release rates, release times and frequencies, number of release points, the best stage and device for releases and other aspects such as how large the fields should be to achieve efficient pest control. There is unfortunately surprisingly few data on the real effect mass releases of *T. remus* have on reducing plant damage and increasing yield, but often high egg parasitism rates together with long-term evidence from Venezuela suggest that *T. remus* has indeed high potential to successfully suppress FAW and related pests.

It needs to be stressed that most of the results reviewed here are based on *T. remus* reared from *Spodoptera* hosts. From these, relatively large and fecund wasps can be produced but also at relatively high costs, when compared to the rearing of *Trichogramma* spp. This points to the conclusion that, if biological control of FAW and related pests with *T. remus* should become a viable option, release rates may need to be more closely to rates used in the 1990s in Venezuela, i.e. rates of about 5000–10,000 wasps per ha and season, unless major breakthroughs with cheaper mass production of the parasitoid are achieved. This may be based on 3–4 releases of 2000–2500 wasps each, starting after FAW has shown up (usually around a week after maize emergence in the field).

A major point of concern is to what extent releases at one site can also have an effect on larger areas during the season. Recent findings from Ghana (Agboyi et al. 2021) are in line with studies from the Americas (Hernández et al. 1989) indicating that dispersal of *T. remus* throughout the season is high, and that a small number of release points per ha (<5) may be sufficient. These studies further suggest that releases for individual smallholder farmers owning little land may be inefficient, but on the other hand that regional approaches could work very well. Similar to probably all other biological control agents in field crops, the use of *T. remus* will best be done as a part of an IPM program, avoiding broadspectrum insecticides in release fields. Both quality control of the mass reared parasitoid and an optimized, cost-efficient release strategy is crucial to a successful pest management.

When considering the use of biological control agents, it is always necessary to include an assessment of possible risks for non-target effects, particularly for exotic species (De Clercq et al. 2011). In most of those countries where *T. remus* may be considered for release in the future, the parasitoid has been found to be present, e.g. China, India, Australia and several African countries, so cannot be considered exotic there. However, in regions where *T. remus* is not known from, its status should be carefully evaluated and appropriate risk assessment procedures followed. Altogether, *T. remus* releases may be having high prospects for contributing to FAW management in newly invaded areas though still challenges exist that would require further research.

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