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Resilience and robustness of IPM in protected horticulture in the face of potential invasive pests

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A B S T R A C T

Recently, various approaches for the biological control of major pests in protected crops have successfully been adopted. These successes have primarily occurred via the selection, release and/or conservation of generalist native predators that naturally colonize Mediterranean crops that are highly adapted to local environmental conditions. These generalist predators have resulted very effective in controlling key pests; as a result, pesticide use has been reduced considerably. In addition, because these predators are typically highly polyphagous, horticultural crops have become more resilient to newly emerging pests, which are preyed upon by these predators. Possibilities to further strengthen pest management in horticultural crops have recently arisen, such as the use of beneficial microbes (BM) to induce plant resilience. In this review, we used a tomato crop as an example to present two new, highly interrelated plant defense induction strategies: the use of Miridae zoophytophagous predators and the use of *Trichoderma* spp. microbial biological control agents. Both the mirid predators and *Trichoderma* symbiotic fungi can activate direct and indirect plant defense responses, which may increase the robustness of pest management against invading organisms. The practical use of these new approaches is discussed.

1. Introduction

Crop pests may reduce crop yields, this being the main reason for their management. Apart of this primary reason, in horticulture, farmers have aimed to exclude pests from their crops for other two important reasons. First, horticultural crops are subject to many serious diseases that are transmitted by insect vectors (Ali et al., 2006; German et al., 1992; Jones, 2003), so avoidance of the presence of insect vectors in the crops is preferred. Second, the sale of many vegetables depends on their visual appeal, which implies that the pest economic threshold is often based on fruit cosmetics (aesthetic appearance) rather than production costs (Lamichhane et al., 2015a). In particular, fruit cosmetics are an important consideration for horticultural products that are destined for export to other countries (e.g., from southern to northern Europe) (van der Velden et al., 2012). These considerations have led to the application of many chemical treatments for horticultural crops, sometimes without technical basis, to limit the presence of pests as much as possible (van Lenteren, 2001; Stansly et al., 2004). The mandatory adoption of Integrated Pest Management (IPM) principles, which went into force since January 1, 2014, markedly helped to reduce pest pressure in most fruit, vegetable and arable crops throughout Europe (Barzman et al., 2015). Today, the application of a chemical treatment must be justified not only economically but also with respect to other issues, such as respect for the environment and selectivity for non-target wildlife.

Several recent IPM programs based on the augmentation and conservation of polyphagous predators, have been successfully developed. Two well-known examples are those developed for sweet pepper and tomato greenhouse crops. In sweet pepper, the

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release of *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) and *Orius laevigatus* Fieber (Hemiptera: Anthocoridae) has provided effective control of two key pests, Western flower thrips (*Frankliniella occidentalis* Pergande [Thysanoptera: Thripidae]) and the whitefly (*Bemisia tabaci* Gennadius [Hemiptera: Aleyrodidae]) (Calvo et al., 2009a; van der Blom, 2008). In tomato, inoculation with predatory mirid bugs (Hemiptera: Miridae) [*Nesidiocoris tenuis* Reuter in Southern Europe and *Macrolophus pygmaeus* (Rambur) in Northern Europe] and conservation of their natural populations have been very effective for controlling key tomato pests, including *B. tabaci* and *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) (Arnó et al., 2010; Calvo et al., 2012b; Gabarra et al., 2008; Gerling et al., 2001; Urbaneja et al., 2012).

Horticultural crops provide many examples of the unintentional introduction and subsequent invasion of exotic pests (Desneux et al., 2010; Kirk and Terry, 2003; Stansly, 2010), and it has been difficult to limit the expansion of these pests and develop control methods. Because generalist predators have broad prey ranges, there is a strong possibility that a generalist species may select an invasive exotic pest as prey. Such selection of an invasive pest has recently occurred with *T. absoluta*. The impact of *T. absoluta* on greenhouse tomato production has been very low in areas where IPM programs based on the augmentation and conservation of predatory mirids have been implemented (Urbaneja et al., 2012; Zappalà et al., 2013). In addition, because pesticide use has been reduced in areas where mirids have been applied, other natural enemies that have become adapted to *T. absoluta* have made its management much more rapid and effective than that in areas where *T. absoluta* is still chemically controlled, and its management remains complicated (Gabarra et al., 2014; Urbaneja et al., 2009; Zappalà et al., 2013).

The examples provided by mirids in managing *T. absoluta* clearly demonstrate how the use of generalist predators can strengthen a crop against exotic pests. Recently, new possibilities for further strengthening the pest management of horticultural crops have arisen. In the present study, using the tomato crop in Europe as an example, we presented two new and highly interrelated plant defense induction strategies in the framework of the European project PURE: the use of Miridae as a zoophytophagous predator and the use of *Trichoderma* spp. as microbial biological control agents. To better describe how greenhouse tomato pest management can currently be applied, we present a brief review of its history.

2. The progress of IPM in tomatoes

2.1. Pest status in protected tomatoes

Approximately 150 phytophagous arthropods are associated with tomato. However, this crop is typically attacked by a relatively low number of key pest species, and the number of secondary pests is also typically low. The number of arthropod species reported on a tomato crop varies with geographical area (Lange and Bronson, 1981). For example, in four important tomato production areas in Europe (Spain, France, Italy and the Netherlands), which represent 65% of the total production destined for fresh consumption (FAOSTAT, 2016), the number of phytophagous species cited as problematic was 19 (Table 1).

Although all of the phytophagous species listed in Table 1 have been reported in these four production areas, their relative importance as pests has varied considerably in each country depending on several biotic and abiotic factors. Two of these factors are particularly influential - temperature and the applied pest management strategy. Whiteflies are an example of pests that are influenced by temperature. The sweet potato whitefly, *B. tabaci*, is adapted to high temperatures and, does not withstand cold winters (Bosco and Caciagli, 1998; Cui et al., 2008). It is a key pest in France, Italy and Spain but is considered to be an occasional pest in The Netherlands (Table 1). Conversely, the greenhouse whitefly, *Trialeurodes vaporariorum* Westwood (Hemiptera: Aleyrodidae), is better adapted to a temperate climate (Xie et al., 2011); it is a key pest in almost all tomato areas that do not experience extremely high temperatures. In Spain, the southernmost and, consequently, warmest of the four countries mentioned above, *T. vaporariorum* is considered to be an occasional pest. It has almost no importance in the tomato area located in the southeastern part (Almería region) (Stansly et al., 2004), but can cause severe damage in the north of Spain (El Maresme, Barcelona), where the climate is milder (Arnó et al., 2009).

The other factor that plays a crucial role in determining the importance of a particular pest is the type of pest management applied, especially the level of biological control that has been established. Except for the tomato russet mite *Aculops lycopersici* (Masse) (Acari: Eriophyidae), for which no effective natural enemies are reported (Table 1), all of the phytophagous species listed in Table 1 have several natural enemies that are commercially available for augmentation biocontrol (Table 1) as well as wild natural enemies (some also used in augmentation) that can be used effectively in conservation strategies (Aviron et al., 2016; Giorgini and Viggiani, 2000; Messelink et al., 2014). In areas where the use and conservation of natural enemies have been promoted, mainly mirid predators, the status of some important pests has significantly changed recently, and a hierarchy can be established for them according to the action of their natural enemies (Table 1).

2.2. Progress towards biological control-based IPM in greenhouse tomato

Marked differences in the use of natural enemies exist among the different tomato-producing areas in Europe and in the integration of biocontrol agents in IPM programs (Lamichhane et al., 2016). However, a shift from purely chemical control to an IPM strategy based on the biological control of pests has been observed almost everywhere. To explain this development, we describe here an example of protected tomato crops in southern Spain, where conventional pesticides are rarely used (Fig. 1). This shift began at the end of the 1990s when bumblebees were used for pollination. The use of bumblebees accustomed farmers to choosing pesticides that are selective for these pollinators (van der Blom et al., 2009). Consequently, the use of broad-spectrum pesticides significantly decreased as the use of bumblebees was adopted for most tomato crops. The use of selective pesticides allowed for the release of some natural enemies in this crop, although chemical control was still the main control measure for pests.

However, protected tomato crops were also challenged with new diseases from countries with warmer climates at that time, especially *the tomato yellow leaf* curl *virus* (TYLCV). Much of the work done to implement IPM based on the biological control of pests was disrupted, which led to a return to the use of broad spectrum pesticides to control vectors, especially *B. tabaci* (Stansly et al., 2004). During the first decade of this century, the development of disease-tolerant tomato cultivars and the advent of a new generation of more selective and environmentally friendly insecticides allowed the development of sustainable IPM programs, but pest control remained almost entirely dependent on pesticides (van der Blom, 2010). The appearance of the invasive pest *T. absoluta* in 2006 in Europe prompted the development of strategies based on mirid predators to control this threatening tomato pest (Urbaneja et al., 2012). The use of predatory mirids *N. tenuis* and *M. pygmaeus* resulted in the very effective management of key tomato pests: the whiteflies *B. tabaci* and *T. vaporariorum*, and

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