Scientia Horticulturae 208 (2016) 13–27

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Going beyond sprays and killing agents: Exclusion, sterilization and disruption for insect pest control in pome and stone fruit orchards

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ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form 3 March 2016
Accepted 11 March 2016
Available online 21 March 2016

Keywords:
Exclusion
Mating disruption
Sterile insect technique
Cydia pomonella
Codling moth
Drosophila suzukii

ABSTRACT

Because of their perennial nature, orchards harbor one of the most complex ecosystems in agriculture. Nevertheless, crop protection programs still mainly focus on pesticides (synthetic or organic-approved) to prevent or limit the action of so-called noxious species in these systems. Killing agents represent the dominant paradigm and have been used in agriculture for decades. This paper synthesizes the available literature about the other approaches, more suited to organic farming, which recognize that the radicalness of killing is not necessary to prevent crop losses. Exclusion barriers represent one of the most readily available means of protecting the crop that way, but other behavior-based techniques have been developed, such as sterile insect technique and mating disruption. While there are many other possibilities, these are the three approaches that are currently getting the most interest in tree fruit production, due to ecological and agronomical characteristics, some of which will be detailed in this review.

1. Introduction

Modern agriculture relies heavily on pesticides to prevent crop losses by various organisms, from microbes to mammals that can develop in these agroecosystems. Because of their perennial nature, orchards harbor one of the most complex ecosystems in agriculture, but nevertheless, crop protection programs still mainly focus on synthetic (conventional farming) or natural (organic farming) pesticides to prevent or limit the action of so-called noxious species (FAO, 2009).

It is not our intention to review the pros and cons of pesticides in this article, these having been and still being strongly documented in various studies and reviews. However it is certainly worthwhile to note that two approaches exist to prevent pests from foraging on crops, and that "killing" is the one that has been mostly used in agriculture for decades. Killing agents – chemical, but also botanical, microbial, physical, predatory, parasitic – are present in both organic and conventional cropping systems and the use of these pesticides represent the dominant paradigm, whether they are considered safe or not.

The second approach to pest control will be the focus of this review. This approach recognizes that the radicalness of killing is not necessary to prevent crop losses, which is in closer accordance with the principles of organic farming. Exclusion barriers represent one of the most readily available means of protecting the crop that way, but other "behaviorally-based" techniques, such as sterile insect technique and mating disruption, have also been developed. Although there are many other possibilities, these are the three approaches that are currently getting the most interest in tree fruit production, due to ecological and agronomical characteristics that will be detailed for each one. Sprayable barriers such as kaolin clay (Glenn et al., 1999) will not be considered, due to their strong similarities (deleterious effects) with pesticides.

Efforts in those research fields have been quite variable, ranging from extensive (mating disruption), to limited (exclusion). Since orchards harbor numerous pests and are subjected to high levels of pest pressure (Kogan and Hilton, 2009), tree fruit pests have frequently been the subject of studies on those recent management strategies. In the following review, alternative control of the most important pome and stone fruit species or groups of insects will be discussed: a) the codling moth, *Cydia pomonella* (L.), the oriental fruit moth, *Grapholita molesta* (Busck) and other tortricids (Lepidoptera: Tortricidae); b) tephritid flies (Diptera: Tephritidae); and c) drosophila flies (Diptera: Drosophilidae). Complementary information regarding biology, damage and economic importance of those worldwide pests can be found in many review papers and textbooks, including those by Capinera (2008), Croft and Hoyt (1983) and Aluja et al. (2009).

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http://dx.doi.org/10.1016/j.scienta.2016.03.014

Table 1
Direct fruit pests of northeastern North American apple orchards, with average damage at harvest in a pesticide-free plot in Quebec, Canada 1977–2000 (updated from Vincent and Bostanian, 1998; Chouinard, unpublished data).

Plum curculio	*Conotrachelus nenuphar*	51%
Apple maggot	*Rhagoletis pomonella*	42%
Codling moth	*Cydia pomonella*	22%
Lesser appleworm	*Grapholita prunivora*	7.0%
Tarnished plant bug	*Lygus lineolaris*	6.3%
Eyespotted budmoth	*Spilonota ocellana*	6.1%
Obliquebanded leafroller	*Choristoneura rosaceana*	3.9%
Redbanded leafroller	*Argyrotaenia velutinana*	3.0%
European apple sawfly	*Hoplocampa testudinea*	2.3%

2. Exclusion (netting)

Exclusion nets have been used in agriculture since the middle of the 20th century (Scarascia-Mugnozza et al., 2012; Merrill, 1967), and more commonly since the 1990s, when they became widespread as a protection tool against whiteflies in greenhouses (Berlinger et al., 2002). As an exclusion device, the main mode of action of nets is to act as a barrier to deny access to the crop. Despite their high sustainability (Alaphilippe et al., 2016) and stable efficacy under variable conditions, they seldom have been considered economical to use. This has gradually changed over the last three decades in tree fruit production, as nets have been increasingly used in many parts of the world to prevent damage from hail (Iglesias and Allegre, 2006) and even mammal and insect pests (Tasin et al., 2008). Various types of net coverings are now widely used for a range of horticultural crops in various countries around the world to provide protection from birds, frugivorous bats, hail, wind, frost and sunburn damage (Lloyd et al., 2005). Net enclosures are more and more used in organically grown fruit to solve several production issues (Granatstein et al., 2015), and are currently investigated as a potential solution to the devastating problems caused by the brown marmorated stink bug, *Halyomorpha halys* in the United States and many other parts of the world (Marshall and Beers, 2016). These agricultural nets are almost exclusively made of clear high density polyethylene (HDPE) and have an average lifespan of six (Sauphanor et al., 2009) to ten (Rigden, 2008) years under field conditions.

The characteristics and effectiveness of exclusion systems adapted for tree fruit protection have been studied for many key pests of pome and stone fruits. The various systems used can be classified as either *complete* or *incomplete* exclusion (Fig. 1). In incomplete exclusion, the soil is not excluded from the system, thus allowing several key pest species (e.g. plum curculio, tephritid flies, European apple sawfly; Table 1) to complete their life cycle and remain inside the enclosed area. This type of exclusion is well represented by full block netting systems (Rigden, 2008) covering entire orchards. In complete exclusion however, the soil is excluded from the enclosed zone; this is the case for some row-by-row systems, or "tunnel" netting. Incomplete and complete exclusion systems have their advantages and disadvantages, which will be discussed below.

By adding a layer of complexity to their natural environment, netting also affects the behavior of both enclosed and excluded arthropods (Dib et al., 2010; Sauphanor et al., 2012); this in turn can affect the development of non-target species (pests and natural enemies). For example, anti-hail nets, even without side walls, have been found to reduce the density and damage of the codling moth in apple (*Malus domestica* Borkh.) orchards (Graf et al., 1999).

Marliac et al. (2015) defined four crop protection strategies used by organic apple farmers: pesticide-based, ecologically intensive, technologically-intensive and integrated. The technologically-intensive strategy, which mainly consists in the use of exclusion nets, had the lowest environmental impact of all four strategies, as based on the International Organization for Biological Control toxicity classes of the pesticides used (Sterk et al., 1999). However, despite a good environmental profile, exclusion systems are not totally free of sustainability issues. Siegwart et al. (2013) showed that behavioral adaptation of codling moth to exclusion systems is possible (see Section 2.1.1), in accordance with observations made in laboratory rearings of this species. Those systems also have the disadvantage of being costly. The use of netting, as presented by Stevenin (2011) for an organic high-density plot of 'Juliet' apples in France, represented 25% of planting costs over the first three years and 7% of annual production costs afterward. In this case, the netting was used solely to prevent codling moth damage, a common situation in Europe where this species is the key pest in terms of fruit damage (Blommers, 1994).

Table 2
Expansion of codling moth exclusion systems in France apple orchards.

Year	Stage	Coverage	Source
2005	Design	n/a	Romet et al., 2010
2006	Field validation	9 orchards	Romet et al., 2010
2007	Commercial introduction	30 ha	Romet et al., 2010
2008	Expansion—organic	150 ha	Sauphanor et al., 2009
2014	Expansion—organic and conventional orchards	2000 ha	Alaphilippe et al., 2016

2.1. Complete exclusion

2.1.1. Species-oriented systems: codling moth, tephritid flies and leafrollers

2.1.1.1. Codling moth. The codling moth is a severe pest of pome fruit worldwide (Grigg-McGuffin et al., 2015). Most exclusion studies on codling moth used Alt'Carpo nets (Filpack, Vitrolles, France). Alt'Carpo (a French designation meaning "codling moth arrest") is a noncopyrighted system that exists in two forms: a full block incomplete exclusion system (Fig. 1A), and a row-by-row complete exclusion system. Alt-Carpo nets have been designed by French extension services in 2005 (Sévérac and Romet, 2008) in an effort to reduce the number of insecticide applications specifically required to control codling moth-12 annually, on average in southeastern France (Sauphanor et al., 2009). This exclusion system is the first and one of the most widely used commercial exclusion systems for pome fruit in the world: estimated at about 2000 ha in Southern France (mainly on apples; Table 2) and 350 ha in Italy (mainly on pears) (Alaphilippe et al., 2016). Although both systems (complete and incomplete) are often presented as one single technique, their effectiveness and applicability differ considerably. For example, the row-by-row (complete) system creates much smaller enclosed environments and does not easily allow circulation. The full block (incomplete) system is presented in Section 2.2.1.

Complete exclusion systems aimed at controlling codling moth are usually put in place just after bloom, before the emergence of the first adults, and kept until harvest. Nets used are typically clear and have a mesh size of 2.2 × 5.4 or 5.5 mm. It is worth noting that the mesh orientation and size have not been strictly defined; larger mesh sizes and other adaptations are also used to better fit individual situations (e.g. size and age of trees, orchard density and exposure, cultivar, mode of production). Many of the reports and studies discussed in this review present overall properties of all variations, sometimes including full block systems.

Typical efficacy of complete exclusion systems for codling moth is high. In efficacy tests with nets performed in 2010 in 23 commercial apple orchards within the southeastern France Alt'Carpo network (Sauphanor et al., 2012), codling moth caused little fruit damage (0.2% infestation at harvest) as compared to the alternative program using 7–8 additional insecticide applications supple-