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Pesticide use in current and innovative apple orchard systems

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Abstract Recent European incentive policies clearly targeted decreasing pesticide use in all agricultural systems as a key option to reduce environmental hazards and health risks. To reduce pesticide use is challenging in orchards where pesticides are recurrently applied to control numerous pests and diseases, but crucial to improve fruit production sustainability. Agricultural research has provided alternatives to chemical control for the management of a single pest or disease, but has very seldom addressed the design of overall sustainable strategies aiming at reducing pesticide use. New insights permitted by system approaches are now developing. Here, we report the level of pesticide use and the agri-environmental performances of three protection systems of apple orchards surveyed from 2005 to 2008: (1) conventional, (2) low-input and (3) organic farming. To assess the significance of the cultivar in decreasing pesticide use, these protection systems were combined with three cultivars differing in scab susceptibility: ‘Ariane’ (*Vf*-resistant), ‘Melrose’ (low-susceptibility) and ‘Golden Delicious’ (susceptible). Thus, nine ‘management × cultivar’ apple orchard systems were assessed. The level of pesticide use was the highest in conventional ‘Golden Delicious’ and in ‘Golden Delicious’ plots whatever the protection system. A 43–56% decrease in pesticide use was observed in ‘Ariane’ and ‘Melrose’ in

both low-input and organic farming protection systems compared to conventional ‘Golden Delicious’ as reference. Only low-input ‘Melrose’ and low-input ‘Ariane’ systems achieved a level of yield and fruit damages similar to the corresponding conventional cultivars under reduced pesticide use, also permitting reduced environmental impacts. But even the low-input ‘Melrose’ least pesticide-dependant system was far from being pesticide-free, suggesting that current straight-designed mono-clone orchards are hardly appropriate to drastically reduce pesticide use and that the range of commercial apple cultivars should be renewed to offer more robust cultivars.

Keywords Orchard system · Pesticide use · Pest and disease management · Longitudinal survey · Decision rule · Agronomic evaluation · Environmental evaluation · Indicator

1 Introduction

Conventional agriculture relies on the use of a high level of chemical inputs such as fertilisers and pesticides. These inputs imply environmental hazards and health risks. There is an increasing concern among citizens and consumers about the attested presence of pesticide residues in the environment and food (Aubertot et al. 2005). Recent European and French incentive policies (e.g. European directives in 2009 on pesticide sales and use; French ‘Grenelle de l’Environnement’ and ‘Ecophyto 2018’ schedule) clearly targeted a reduction in pesticide use in all agricultural systems as a key option to reduce the contamination of the environment. Such a decrease in pesticide use is crucial for the implementation of sustainable agricultural systems (Aubertot et al. 2005). The challenge is especially high in orchards where pesticides

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are recurrently applied to control numerous pests and diseases (Codron et al. 2003). Recently, information on the pesticide residues in fruits has also changed consumers' demands, leading in several countries to the implementation of zero residue programmes (Berrie and Cross 2006). The case study of apple (*Malus × domestica* Borkh.) production has economical and ecological outcomes because it is one of the most treated fruit crops (Eurostat 2002; Sauphanor et al. 2009a) and is planted worldwide, covering approximately seven million hectares (O'Rourke, 2003). Whereas integrated pest management (IPM) has been developed since the 1970s in Europe (Baggiolini et al. 1973) and despite the more recent availability of alternative technologies or resistant cultivars for the management of a single pest or disease (i.e. mating disruption, microbiological insecticides and scab *Vf*-resistant cultivars; Cross and Dickler 1994; Jones et al. 2009), orchard protection still mainly relies on the recurrent use of pesticides along the growing season (up to 8 months per year). There is a need to investigate more global approaches to minimise such reliance on pesticides through the conception of innovative systems and/or orchard redesign (Brown and Mathews 2005; Zehnder et al. 2007).

To face this challenge, the system approach is one possible option to compare the performances of current and innovative production systems without disentangling the system elements. The system approach consists in: (1) prototyping relevant sets of technical options, (2) evaluating them through a longitudinal survey and (3) iteratively improving them (Debaeke et al. 2009). Systems are considered to be complex entities defined by selected options (e.g. the orchard design and its cultural practices) according to aims within a fixed framework and its constraints (Drinkwater 2002; Debaeke et al. 2009). The agronomic and environmental assessments of current and innovative orchard systems started in the late 1990s. The authors have generally used the comparison of organic, IPM and/or conventional systems to assess the performances and the environmental effects of orchard management regimes. Some of these studies are based on the analysis of paired commercial orchards (Suckling et al. 1999) or on commercial orchard networks (Ricci et al. 2009). Only two experimental designs and longitudinal surveys, one in the USA (Reganold et al. 2001; Peck et al. 2006) and the other in Switzerland (Zürcher et al. 2003; Bertschinger et al. 2004), were dedicated to a system approach in orchards. In contrast, experimental system approaches have been more developed for the study of annual crops such as cereals and industrial crops (Jordan et al. 1997; Aubry et al. 1998; Debaeke et al. 2006, 2009; Munier-Jolain et al. 2008) with a focus on crop sequences, cultivar choices, and the level of inputs and labour within fluctuating regulatory and climatic contexts. Both design and context are different in

orchard systems. Any agricultural system would require the succession or the combining of many technical actions to produce yield and ensure the sustainability of the system. As perennial systems, orchards also require to: (1) modulate the tree architecture and physiology through pruning, tree training and thinning to ensure regular bearing; (2) fulfil the water and nutrient requirements of the tree for growth and quantitative and qualitative fruit production, but also tree reserves; (3) manage within-row and between-row soils for weed management and machinery driving, respectively; and (4) control a generally high number of pests and diseases and manage the risk of increasing populations or inoculums throughout the years because many pests and diseases can complete their biological cycle within the orchard. Tree resistance to pests and/or diseases is one intrinsic trait of the orchard which has a considerable weight in the development of pests and diseases whatever the production and protection system. Orchard protection is thus highly constrained throughout its lifetime by the choice of the planted rootstock and cultivar and its susceptibility to pests and diseases.

The aim of our study was to assess throughout a longitudinal survey the decreasing of pesticide use via protection systems which combined the use of non-chemical methods and an accurate evaluation of the infection or infestation risks to manage apple pests, diseases and weeds. The experimental apple orchard systems planted in January 2005 combined pest and disease management regimes and levels of cultivar susceptibility, thus enabling a focus on the significance of the cultivar in the decreasing of pesticide use. Due to the combining of decisions related to each pest or disease management, a variable range of protection practices was possible under a given management regime, requiring the accurate description of the sets of decision rules to be evaluated. The first part of this paper presents the steps involved in the design and the management of tested apple orchard systems, from planting to the first 3 years of yield. Pesticide use in the various systems and the first agronomic and environmental evaluations show the consistency and the limits of the designed systems. Lastly, the contribution of our system approach to the decreasing of pesticide use in orchards is discussed.

2 Materials and methods

Experimental orchards were planted in January 2005 at the National Institute for Agricultural Research (INRA) Gotheron experimental unit (France, 44°58'33" N, 4°55'45" E). The soil of the planting area was homogeneous and the land use before planting was winter cereals and grasses. The rooting depth is approximately 40 cm in a stony shallow sandy-loam soil derived from old washed out sediments.

This middle Rhône Valley area has a continental climate with summer Mediterranean influences. Average yearly temperature is 12.3°C and the mean annual rainfall is 880 mm. A weather station (ENERCO 411, Cimel Electronique, Paris, France) located on the site monitors a wide range of climatic parameters, including wetness duration. The main apple pests and diseases requiring direct control in apple orchards of this area are: codling moth *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), aphids (mainly the rosy apple aphid *Dysaphis plantaginea* (Passerini) (Hemiptera: Aphididae)), scab *Venturia inaequalis* (Cooke) Winter and, occasionally, powdery mildew *Podosphaera leucotricha* (Ell. et Ev.) Salmon.

2.1 Orchard systems and experimental design

2.1.1 General outline

As plant protection is one of the main causes of negative environmental effects in fruit production, attention paid to pest and disease management was emphasised. Orchard systems were designed for a commercial production, i.e. the level of acceptable risk in the orchard management aimed to keep pests and diseases under control, and thus to minimise fruit loss. These systems were defined within the framework of an evolving context related to rules, energy and input costs, and market with possible changes in pesticide registration, organic standards, input prices or market standards for fruit sale along the survey period. Three protection systems were defined to manage pests, diseases and weeds (Table 1):

1. Conventional: The general tactic was a ‘no risk, no extra-costs, relevant use of most efficient inputs’ strategy in order to maximise the income and to minimise the risks of fruit loss in a system where efficiency and productivity

were the background. As for most French fruit growers, the standard was the national guideline for apple production (Codron et al. 2003), adapted to the regional context through Growers’ Organisations guidelines and bulletins of extension services. Chemical pesticides were mainly and sometimes exclusively used to control pests, diseases and weeds. The elaborated decision rules proposed a supervised use of the pesticides, generally to be applied when an infection or infestation risk was identified or forecast by extension services.

2. Low input: The general tactic was ‘preference to other methods than chemicals’ following the IOBC European guidelines (Cross 2002). This strategy mainly relied on the use of alternative methods, including mating disruption, microbiological control, sanitation practices and labour input. Additional pesticide applications were based on the evaluation of the local infection or infestation risks (i.e. at the orchard and not only at the regional level, Table 1).

3. Organic farming: The general tactic was the ‘no synthetic input rule’ (with the exception of compounds such as pheromones) defined by the European rules for organic production (EEC 91/2092). Organic compounds presenting documented negative effects (i.e. copper and rotenone) also had their use limited to two applications per year. Alternative methods were privileged. However, due to bottlenecks in the management of increasing levels of pests and diseases, tactics were mostly preventive with applications of organic compounds before any infection or infestation risk. Whereas both other systems were auto-controlled only, the organic farming orchard was organic-certified by an accredited society.

The level of accepted risk was the highest in the low-input system, which led us to choose the highest treatment threshold when more than one was available in literature,

Table 1 Main principles and tools used to manage pests, diseases and weeds in the tested protection systems

Protection management	Conventional	Low input	Organic farming
Specific tactics	Efficiency and productivity	Minimise pesticide use	Minimise pesticide use under organic standards
Alternative methods	Not used unless effectiveness and cost similar to chemical control	Always preferred	Always preferred
Sanitation and mechanical practices	Not used unless low cost or for the durability of apple scab resistance genes	Always used	Always used
Evaluation of the infection or infestation risk	Regional risk forecast by extension services	Orchard risk assessed by pest and disease monitoring, prediction models	Regional and/or orchard risk, prediction models if usable in organic strategies
Use of treatment threshold	If highly recommended	Always used if existing	Used unless prevention of any infection or infestation risk
Pesticide choice	Highly efficient compounds	Selective compounds	Organic registered compounds

technical supports or proposed by experts (see also Table 2). Two current pest management regimes were thus defined within the frameworks of conventional and organic production, whereas the low-input prototype was based on the use of scientific knowledge and the combining of alternative methods and/or methods giving partial control of pests and diseases.

2.1.2 Orchard design

Susceptibility to scab, the prevailing disease, was the first criterion of cultivar choice in both low-input and organic farming apple orchard systems, together with aphid susceptibility in organic farming orchards. Scab-resistant but also scab-tolerant cultivars were planted because of the breakdown of scab *Vf* resistance in Northern French regions (Guérin et al. 2007). A ‘Golden Delicious’ type cultivar

planted in 32% of French production apple orchards in 2006 (Sauphanor et al. 2009a) was used as the reference in the conventional orchard system. Because most of the European inclusive organic farming orchards are planted with susceptible cultivars (Trapman 2010) that constrain growers’ practices and market opportunities, we also aimed at assessing the significance of the cultivar in decreasing pesticide use and created variants of each system differing in the cultivar. The same three cultivars that differed in pest and disease susceptibility were thus planted and managed under each of the three protection systems, creating nine ‘management × cultivar’ cases (plots). Planted cultivars were:

- ‘CG 10 Yellow Delicious’ (INFEL® 2832, Smoothee®), a mutant of ‘Golden Delicious’, here referred to as ‘Golden Delicious’, is susceptible to scab and also to the rosy apple aphid.

Table 2 Decision rules for the management of the prevailing pests and diseases from 2005 (planting year) to 2008 in the three tested protection systems

Target pests and diseases	Conventional	Low-input	Organic
Scab: general strategy (see also Brun et al., 2010a)	Period and level of ascospore ejection estimated by Melchior® model (Lagarde 1988; Brun et al. 2010b); Mills’ infection risk computed from weather data by Vintage® software (Cimelogic Communications, Pessac, France) Chemical control: preventive fungicide application before any rainfall forecast likely to induce scab infection, curative if failed Threshold to stop protection at the end of ascospore ejection: 1% infected shoots No sanitation practices except ‘Ariane’ (see below)	Sanitation practices: leaf removal in the orchard alleys and within-row leaf ploughing in	Mineral fungicides: preventive strategy only Threshold to stop: 2% infected leaves
‘Ariane’ scab management	Prevention of <i>Vf</i> gene overcome: orchard protection for moderate and severe Mills’ infection risks (Mills and Laplante 1951) when the level of ascospore ejection is high Leaf shredding as simplified sanitation practices	See above	See above
‘Melrose’ scab management	See ‘Golden Delicious’ strategy	Orchard protection along the period of ascospore ejection for the level of risk estimated by Olivier (1986) model, namely the choice of a level of Mills’ infection risk as treatment threshold	
‘Golden Delicious’ scab management	Orchard protection along the period of ascospore ejection for any Mills’ and Angers infection risk (Olivier 1986)		
Powdery mildew	Chemical control: pre-bloom fungicide application then 2% infected leaves treatment threshold	Sanitation practices Chemical control at 5% infected leaves treatment threshold	Sanitation practices Mineral fungicides at 5% infected leaves treatment threshold
Rosy apple aphid	Chemical control: pre-bloom insecticide applications then 1% infested shoots treatment threshold	Chemical control: winter mineral oil then 1% infested shoots treatment threshold	Pre-bloom control only: winter mineral oil then rotenone at 1% infested shoots treatment threshold
Mites (Tetranychidae)	Chemical control at 50% (May) then 75% infested leaves treatment threshold	Chemical control at 65% (May) then 75% infested leaves treatment threshold	No treatment (organic guideline)
Codling moth (2006–2008)	Chemical control along both annual flights using regional and site information to start pesticide applications	- Mating disruption and additional insecticide applications (treatment threshold) at flight peaks corresponding to 20–80% egg hatching in the codling moth phenological model by Boivin et al. (2005) Sanitation: apple removal or shredding after harvest Additional treatment: Granulosis virus or chemical control (compound alternance between flights) at 0.5% fruit damage threshold	Additional treatment: Granulosis virus at 0.3% fruit damage treatment threshold

- ‘Ariane’ (INFEL[®] 6407) is a recent INRA scab-resistant cultivar whose resistance is based on the *Vf* gene, which is not overcome in 2009 in the study area. ‘Ariane’ is considered to be susceptible to the rosy apple aphid (Roche et al. 2004).
- ‘Melrose’ (INFEL[®] 2643) is a scab low-susceptibility cultivar and may be considered to be the most pest- and disease-tolerant cultivar.

The three planted cultivars were grafted on ‘PI 80’ quite strongly growing rootstock (INFEL[®] 6275, Supporter[®] 4), which was adapted to our shallow soils and climatic conditions. The low planting density of 1,000 trees per hectare aimed at favouring tree aeration and light penetration within the canopy and was partly compensated by the growth of branches between trees after a few years. *Malus floribunda* pollinator trees were one tree out of ten. Each of the nine ‘management × cultivar’ cases was a 0.4-ha plot of 368 trees in eight rows, and the three cultivars were planted side by side within each protection system (Fig. 1), thus without a classical randomisation of the treatments. The low-input and organic farming systems were contiguous in order to optimise the use of mating disruption against codling moth. Scab management was used for the assignment of the cultivars; the scab-resistant ‘Ariane’ cultivar separated susceptible cultivars and/or protection systems. Lastly, variations due to extraneous agricultural and environmental factors, such as soil type, water availability or the presence of ecological compensation areas, were minimised in this experimental design.

2.2 Decision making and functional procedures to manage orchards

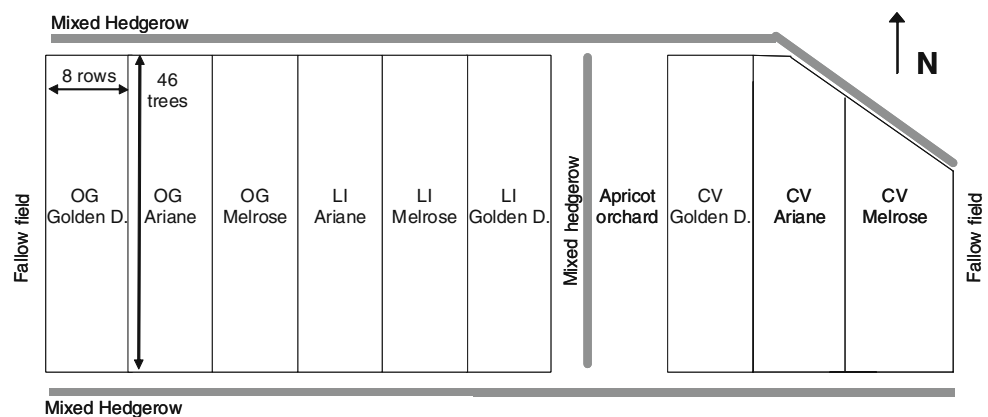
The decision rule describes the process involved to reach a technical decision. It takes into account technical constraints and environmental conditions, among which the infection and infestation risks and the plant stage. Most of the research bases

on elementary decision rules (e.g. treatment thresholds), which have been available for orchard pest and disease management in Europe since the 1970s (Baggiolini et al. 1973), were used as they were or were further developed and adapted. Scientific, technical and expert knowledge were used to select and/or adapt these elementary rules and to assemble them within a general set describing the processes used to manage each of the systems.

During the first 4 years after planting (i.e. in the 2005–2008 period), all systems had a similar management for: tree training (centrifugal training to favour light penetration within the tree canopy; Lauri et al. 2009); watering, delivered by microjets and managed according to water deficit and potential evapotranspiration; and alley management, with the sowing of grass in autumn 2005, which was then regularly mown. It was thus expected that the microclimate and therefore the habitat conditions of pests, diseases and natural enemies were similar in all plots at least in the first years after planting. With similar conservative design factors in each apple orchard system, most of the differences between systems were thus related to crop protection, including within-row weed management, and to thinning and fertilising:

- Fertilising: Fertilisers were applied according to tree requirements and soil storage capacity, with yearly soil analyses and tree vigour (estimated by trunk perimeter) as a check. The same schedule of mineral fertilisers was applied in both low-input and conventional systems. Compost in winter and organic fertilisers releasing easily available nitrogen in spring were yearly applied in the organic farming system. The mean total yearly available nitrogen was 45 kg ha⁻¹ and the mean K₂O supply was around 65 kg ha⁻¹ year⁻¹ in all plots. P₂O₅ supply was 30 kg ha⁻¹ year⁻¹ in organic farming plots and 50 kg ha⁻¹ in all other plots.
- Thinning: Thinning was carried out by hand only in the organic farming system (organic guideline), whereas

Fig. 1 Location of the nine ‘management × cultivar’ apple orchard systems in the experimental design. Planting distances are 5 m between rows and 2 m within rows. *CV* conventional, *LI* low input, *OG* organic farming, *Golden D.* ‘Golden Delicious’



chemical compounds were also used in other protection systems. The removal of spurs at the extinction procedure performed at bloom in the centrifugal training of trees (Lauri et al. 2009) first decreased the number of fruit spurs. Fruit load was then adjusted by chemical and/or manual thinning at six fruits per square centimetre trunk cross-sectional area, except in the organic system where it was four to five fruits per square centimetre only in the first years after planting.

- Weeding: Herbicide applications in conventional systems and mechanical or manual weeding in organic farming orchards were exclusively used. A mix of both strategies prioritising mechanical weeding was used for the low-input systems.
- Crop protection: Besides good agricultural practices, including the alternate use of compounds, the decision rules to manage pests and diseases were based on weather data, tree phenology, and regional and/or local risks of damages due to the development of pests and diseases (Table 2 and Fig. 2). In 2005, only foliar pests and diseases were considered (no fruit on the trees), then both foliar and fruit pests were managed from 2006 onwards. Due to a lower efficiency of mating disruption in young orchards with a low volume of canopy, codling moth treatment thresholds were only applied in 2008. Scab management (see Brun et al. 2010a) discriminated cultivars according to their susceptibility (Table 2).

This design step thus formalised for each protection system a corpus of decision rules and interactions between protection and other cultural practices (Fig. 3) to anticipate possible antagonisms between elementary rules. The highest numbers of interacting decision rules were formalised in both organic farming and low-input systems, which less relied on the use of plant protection products (Fig. 3).

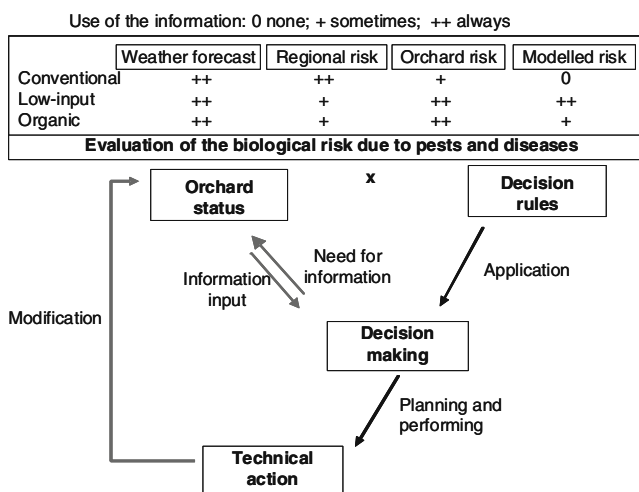


Fig. 2 Decision-making proceedings to manage the tested orchard systems

2.3 Orchard assessment

The level of pesticide use and the orchard performances for agri-environmental aspects were assessed using both field measures and indicators.

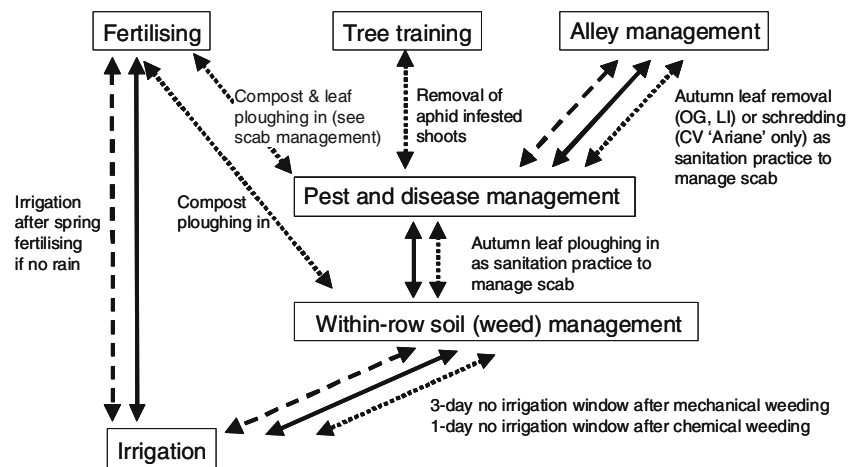
2.3.1 Assessment of pesticide use and practices to manage pests, diseases and weeds

The treatment frequency index (TFI) is classified as a simple indicator based on growers’ practices (Bockstaller et al. 2008) and is used at different scales to assess the intensity of pesticide use (Sattler et al. 2007; Brunet et al. 2008). In an orchard where n compounds are applied across the season, TFI is defined by:

$$TFI = \sum_{i=1}^n [(AD_i/RD_i) \times SA_i]$$

with AD_i the applied dose per hectare, RD_i the lowest registered dose for the crop and target pest, disease or weed, as indicated in official databases (<http://e-phy.www.agriculture.gouv.fr/>), and SA_i the treated surface area proportion ($0 \leq SA_i \leq 1$). TFI has an additive construction, i.e. TFI increases with pesticide applications, but does not consider compound toxicity. In orchards, most of the compounds are applied at full dose; one application of a single compound accounts for 1, with the exception of herbicides which were applied on a third of the orchard surface area in the present study (one application accounts for 0.33). The use of mating disruption was considered to account for 1. The plant protection compounds that were used were divided into five distinct categories to account for pesticide toxicity and/or category: PIRRP (French National Schedule for the Reduction of the Risks due to Pesticides) products (<http://www.ecologie.gouv.fr/Plan-interministeriel-de-reduction.html>) blacklisted for their detrimental effects on health and/or the environment; mineral fungicides such as copper, sulphur and lime sulphur mainly used against diseases in the organic orchards; microbiological products such as the *C. pomonella* granulosus virus (CpGV) and *Bacillus thuringiensis* mainly used against tortricids in both low-input and organic orchards; pheromones used for mating disruption against codling moth in these latter systems. All other products (e.g. other used fungicides, insecticides and herbicides) that were not included in one of the previous categories were regrouped under ‘Other products’. Special attention was paid in the discussion to the TFI related to the use of the highly specific CpGV because this compound had no known effects on other species nor on the environment (Lacey et al. 2008). Lastly, the number of mechanical or manual actions and visual controls required to control pests, diseases or weeds was also registered to account for all crop protection practices and observations carried out in the orchards.

Fig. 3 Interacting decision rules between plant protection and other cultural practices for the tested protection systems: conventional (CV, dashed line arrow), low input (LI, plain line), organic (OG, dotted line)



2.3.2 Agri-environmental performances

Usual agronomic parameters (yield), fruit damages due to pests and diseases, the level of wintering pest populations and disease inoculums, but also natural enemies of pests, were considered to assess agri-environmental performances together with the computation of an orchard-specific synthetic indicator:

- Orchard yield (2006–2008) was measured each year by the total weight of marketable fruits harvested within each plot (excluding both border rows) divided by the surface area. Market standards were the same in all production systems, as is the case for French growers.
- Harvest fruit damage was based on the visual inspection of 1,000 fruits per plot (20 fruits per 50 trees, both trees and fruits randomly selected in the four inner rows of each plot excluding edge trees of each row). As yield was very low in some plots in 2006, only 2007 and 2008 data are presented.
- Winter scab inoculums and codling moth wintering populations were recorded each autumn by a visual inspection of shoots for scab severity (Olivier 1986) and the count of codling moth diapausing larvae in corrugated cardboard traps circled around the tree trunks, respectively.
- I-phy Orchard is a fuzzy expert system indicator adapted for fruit production from the Indigo[®] methodology and I-pest indicator (Van der Werf and Zimmer 1998; Devillers et al. 2005). I-phy Orchard is designed to assess the environmental effects of pesticide programmes on air and water compartments and beneficial organisms (earthworms, bees and natural enemies of pests) in orchards (Sauphanor et al. 2010). I-phy Orchard scores from 0 (maximum negative environmental effect) to 10 (no environmental effect) and accounts for compound toxicity, application dose and conditions (e.g. soil or canopy application), and the number of treatments through an aggregation of elementary scores under a

fuzzy expert system stating that the impacts of repeated applications of a single compound are not additive.

- Beneficial arthropod abundance and richness were used as indicators of the functional diversity of the beneficial arthropod community. Beneficial arthropods preying on the rosy apple aphid were recorded in exact numbers in 40 marked infested apple shoots per system in 'Ariane' most susceptible cultivar at two dates during the infestation peak in spring. Only 2006 data are presented because no aphid infestation was recorded in early May 2007 and 2008 in both conventional and low-input systems. For statistical analysis, the numbers of the different observation dates were then pooled by system across the season. The abundance of the earwig, a generalist predator, was measured in 2008 in 'Melrose' plots by counting fortnightly the number of individuals in ten randomly distributed shelters per system. Shelters were made of plastic tubes filled with corrugated cardboard paper that were installed on the tree trunk.

2.4 Data analysis

Descriptive analyses are presented, which display tendencies to be validated or reoriented on the long term. Fisher's exact test was used to analyse the distribution of count data (fruit damages, natural enemies) into studied categories between paired plots and was computed using R statistical software package (R Development Core Team, 2009) when numbers allowed the calculations.

3 Results and discussion

In this study, the level of pesticide use was assessed in current and innovative orchard systems of an experimental design combining three protection systems (i.e. conventional, low-input and organic farming) with three cultivars differing in scab susceptibility. For each of the nine plots, the sets of

decision rules were applied from 2005 to 2008 following the functional management proceedings presented in Fig. 2 and Table 2 along the whole process of fruit production. All the decision rules were evaluated at the end of each season, but only minor adjustments were then needed. All the orchards were auto-controlled for the conformity of the practices to the rules and no discrepancies were identified. Two consultants of extension services were asked to analyse the cultural practices resulting from these strategies and to give their opinion about the orchard status (expert assessment).

3.1 Decreasing of pesticide use

3.1.1 Pesticide use and TFI index

The mean TFI index (Fig. 4) characterised the reliance of systems on categories of compounds:

- PIRRP blacklist products were mainly used in the conventional protection system, with organo-phosphate compounds applied against codling moth and the captan phthalimid compound against scab and post-harvest diseases.
- Mineral fungicides were associated with the organic system and powdery mildew control in other protection systems.
- Microbiological insecticides were mainly applied in organic farming and low-input systems, whereas their use in the conventional systems was only due to pre-harvest delay and approximately limited to the last 2 weeks before harvest.
- Other compounds were mostly used in the conventional systems.

The conventional plots and the organic ‘Golden Delicious’ plot were the most heavily treated (Fig. 4).

Considering the most and least treated plots, i.e. conventional ‘Golden Delicious’ and low-input ‘Melrose’, combining cultivar susceptibility, alternative protection methods, prediction models and orchard infection or infestation risk assessment in the low-input strategy permitted reducing the TFI by 56% along the 2006–2008 period. A 43–51% TFI decrease was also observed in organic ‘Melrose’ and organic and low-input ‘Ariane’ plots compared to conventional ‘Golden Delicious’ plot. Observed decreases in TFI were mainly due to the decreasing further to the management of the main target pest (the codling moth) and disease (the apple scab) which accounted for 50–90% of the global TFI (Table 3). Indeed, the decrease of insecticide TFI (mean of the three cultivars) was 48% and 28% compared to conventional in low-input and organic farming protection systems, respectively, and the decrease of fungicide use was 56% and 62% between conventional ‘Golden Delicious’ and low-input ‘Ariane’ and ‘Melrose’ plots, respectively. Lastly, the combining of mechanical and localised treatments in the low-input system enabled a 76% decreasing in herbicide TFI compared to the conventional protection system where herbicides were exclusively used.

The comparison of our results with data collected in French commercial orchards (Bouvier et al. 2005; Sauphanor et al. 2009a, 2009b) and expert knowledge (external expertise by extension consultants) indicated that our protection strategies were similar or very close to those of French growers for the standard conventional and organic systems. The mean annual number of treatments in a commercial orchard network in Southern France was around 30 in organic farming orchards and varied from 30 to 40 in conventional orchards (Bouvier et al. 2005; Sauphanor et al. 2009b). The recent national

Fig. 4 Level of pesticide use (treatment frequency index, TFI) in the tested ‘management × cultivar’ apple orchard systems according to categories of compounds. *CV* conventional, *LI* low input, *OG* organic farming, *Golden D.* ‘Golden Delicious’

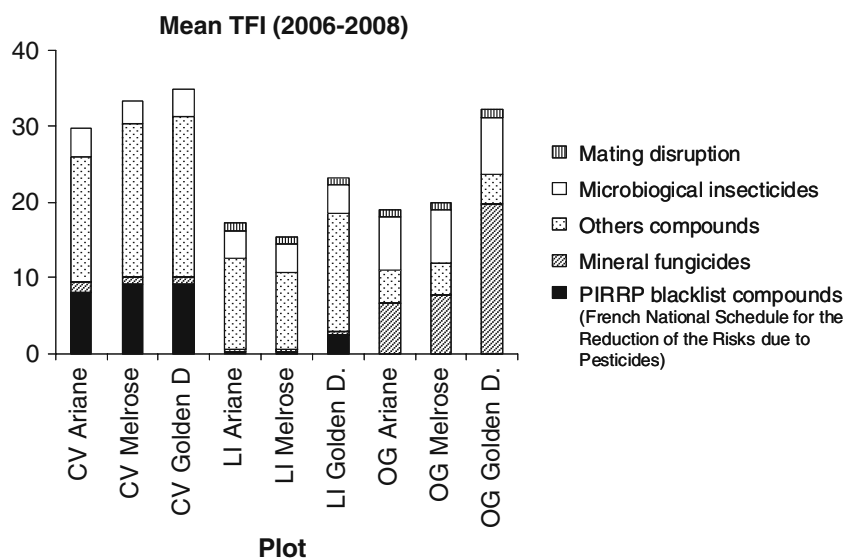


Table 3 From 2006 to 2008 mean annual number of field observations and cultural practices and mean TFI per target pests, diseases and weeds to manage systems according to the defined decision rules

Presumed target	Action or TFI	Conventional			Low-input			Organic farming		
		Ariane	Melrose	Golden D.	Ariane	Melrose	Golden D.	Ariane	Melrose	Golden D.
Aphids	Visual control	2.7	2.7	2.7	3.7	3.7	4.0	2.7	2.7	2.7
	TFI	5.0	4.7	4.8	3.3	3.3	3.3	3.3	3.3	3.0
Codling moth and Tortricids	Visual control	2.0	2.0	2.0	8.0	5.7	8.3	6.7	5.0	7.0
	Sanitation	0.3	0.3	0.3	0.7	0.7	0.7	0.7	0.7	0.7
	TFI	12.3	11.7	12.3	5.3	5.3	5.3	9.0	9.0	9.3
Mites	Visual control	2.3	2.3	3.0	3.0	2.7	3.0	0.0	0.0	0.0
	TFI	0.3	0.3	0.3	0.3	0.3	0.7	0.0	0.0	0.0
Powdery mildew	Visual control	4.0	3.0	3.0	4.7	5.3	3.7	3.3	5.3	1.7
	Sanitation	0.0	0.0	0.0	0.7	0.3	0.3	0.3	0.3	0.3
	TFI	2.3	1.7	1.7	2.7	0.7	0.0	1.3	0.7	0.0
Scab	Visual control	2.0	2.0	2.0	2.0	3.0	2.0	2.0	3.0	2.7
	Sanitation	0.7	0.0	0.0	2.0	2.0	2.0	2.0	2.0	2.3
	TFI	3.7	10.7	10.3	3.0	4.3	10.3	5.3	7.0	19.8
Decay diseases	TFI	1.0	1.3	1.3	0.0	0.0	1.3	0.0	0.0	0.0
Weeds	Mechanical weeding	0.0	0.0	0.0	6.7	6.7	6.7	7.3	7.3	7.3
	TFI	1.7	1.7	1.7	0.4	0.4	0.4	0.0	0.0	0.0
Thinning	TFI	3.3	1.3	2.3	2.2	1.0	1.8	0.0	0.0	0.0
Total	Visual control	13.0	12.0	12.7	21.3	20.3	21.0	14.7	16.0	14.0
	Mechanical action	1.0	0.3	0.3	10.0	9.7	9.7	10.3	10.3	10.7
	TFI	29.7	33.3	34.8	17.2	15.4	23.2	19.0	20.0	32.1

Golden D. ‘Golden Delicious’, *TFI* ‘Treatment Frequency Index’

expertise on protection practices in orchards (Sauphanor et al. 2009a) indicated a mean 35 TFI for conventional ‘Golden Delicious’ and a mean 26 TFI for scab-susceptible organic farming orchards in Southeastern France. Our practices in the conventional ‘Golden Delicious’ plot can thus be considered to be representative of current practices in French orchards, as are those in organic farming plots compared to organic farming commercial orchards.

3.1.2 Factors set in the decreasing of pesticide use

The highest TFI combined with fewer field observations were noted in the conventional protection system (Table 3). In contrast, mating disruption combined with visual controls enabled a strong TFI decreasing in low-input and, to some extent, organic farming systems. Monitoring of codling moth damages was costly, with up to 12 yearly visual controls (2008) in the low-input protection system and was on average threefold (organic) to fourfold (low input) higher than in the conventional protection system. Sanitation practices and models used for scab management in both low-input and organic farming protection systems could not alone enable to decrease the number of pesticide applications, as illustrated by

a similar scab TFI in ‘Golden Delicious’ conventional and low-input plots. The decrease in herbicide TFI was enabled by as many as six annual within-row tillages and additional manual or chemical (low input only) weeding in the first years after planting in young unshaded organic farming and low-input orchards (Table 3). The low-input and organic protection systems which displayed the highest integration of protection methods (Fig. 3) were also the least pesticide-dependant, with the exception of organic ‘Golden Delicious’ plot.

The organic farming protection system was the only one to be free of PIRPP products, and of course herbicides. However, and despite a technological and technical background (models, orchard risk assessments), orchard protection largely relied on pesticide applications. The use of treatment thresholds could be more risky in the organic farming system because no highly efficient compounds to control increasing levels of pests or showing a curative effect against diseases are authorised. This was illustrated by the management of scab which was based on a preventive strategy in the organic farming system: more frequent sulphur treatments were applied in organic farming ‘Melrose’ compared to low-input ‘Melrose’ plot (+63% scab TFI). The treatment threshold to manage codling moth in the organic farming protection

system was also lower than in the low-input protection system (Table 2). Some of the registered compounds for organic farming also require more frequent applications because of their low and only protective persistence. This is the case for CpGV, even though its high selectivity, and therefore its slight impact, is not expressed in the calculation of the total TFI index. But all protection inputs were included in the TFI calculations in our study to account for input reliance and related impacts due to manufacturing processes and orchard applications. Lastly, the use of copper fungicides and neurotoxic insecticides such as rotenone can hardly be avoided to prevent possible soil contamination and detrimental effects on beneficial arthropods. Under such constraints, the organic farming protection system exhibited the highest differences in TFI between ‘Golden Delicious’ and both other cultivars, highlighting the strong limits of planting susceptible cultivars in organic farming orchards despite the market demand.

Among cultivars, ‘Golden Delicious’ was the most treated as a result of its susceptibility to scab. Thus, the global decrease in TFI between the conventional and both other protection systems was the lowest for this cultivar. Under the preventive organic management of scab, ‘Golden Delicious’ fungicide TFI scored 19.8 and was the highest of all plots. In both low-input and organic farming protection systems, ‘Ariane’ and ‘Melrose’ cultivars showed similar fungicide TFI, although ‘Melrose’ is only tolerant and not resistant to scab as ‘Ariane’. The control of powdery mildew and the strategy used against scab to prevent or delay the breakdown of *Vf* resistance in ‘Ariane’ (Table 2) totalized a similar number of fungicide applications in ‘Ariane’ and ‘Melrose’ plots (Table 3). The low fungicide TFI observed in both cultivars was explained by the use of models (Olivier 1986) to estimate the risk of scab infection in ‘Melrose’ low-input and organic farming plots and by the fact that the ‘Ariane’ *Vf* gene is not overcome in the area. However, cultivar alone can hardly contribute to a drastic decrease of pesticide use. In the conventional protection system where scarce technology and time for visual controls were used, almost no difference in the TFI was noted between ‘Melrose’ and ‘Golden Delicious’ plots. Only the *Vf*-resistant ‘Ariane’ cultivar enabled a 15% decrease in the total TFI (Table 3).

The 50% decrease of pesticide use aimed within 10 years by the French Ministry of Environment following the ‘Grenelle de l’Environnement’ recommendations (Brunet et al. 2008) is reached (or almost) in low-input and organic farming ‘Melrose’ and ‘Ariane’ plots compared to the conventional ‘Golden Delicious’ plot (i.e. the reference plot). With an increasing efficacy of the mating disruption method in fully developed canopies, the average situation along next years should even present a higher decrease. For instance, the most favourable situation along the three study years (10.6 TFI in

2008 low-input ‘Melrose’ plot) represented a 73% TFI decrease compared to conventional ‘Golden Delicious’ plot (39.0 TFI in 2008). Our study highlights that a strong decrease of pesticide use could only be achieved through the combining of cultivar low susceptibility; alternative methods such as mating disruption, sanitation practices, mechanical weeding; and the use of computed models and orchard observations to assess the risk of orchard infection or infestation. From this analysis of the factors embedded in the decreasing of pesticide use, some directions to design innovative orchard systems can be recommended on the long term:

1. The first step to invest is the choice of the cultivar for the management not only of scab but also aphids and other diseases. As far as monogenic resistances to pests and diseases are not durable, polygenic resistances are to be preferred in order to minimise the selection pressure on pest and disease strains. We do not exclude that the range of available commercial cultivars do not satisfy the requisite criteria of robustness against pests and diseases. Research investments in breeding programmes are presently developing.
2. Orchard and site pest monitoring and computed models based on local weather data are powerful tools to assess the damage risk at the field and not the regional scale. However, access to training courses and computed prediction models, the cost of field observations and the required expert knowledge to build strategies based on orchard and regional information can be a high constraint for growers. As stated by Jones et al. (2009), this outlines the importance of the development of both research and extension services in plant protection.
3. The integration of alternative methods is to be continued and improved according to local conditions. Mating disruption and microbiological insecticides are validated alternative tools to control moths, provided they can be used (i.e. large-sized orchards with regular shape and/or low population level). However, reliance on a single compound to control pests is not durable, as exemplified by the recent selection of resistant codling moth strains to CpGV (Asser-Kaiser et al. 2007). Moreover, it is doubtful that the decrease of pesticide use can be far over that of the present low-input protection system in high-density mono-clone orchards. Other conservative design factors of the orchard such as tree training and habitat conservation for pest biocontrol also interfere with pest and disease management (Brown and Mathews 2005; Jones et al. 2009; Lauri et al. 2009; Simon et al. 2010). As a conservation biological control method, the introduction of plant diversity or companion plants can be an example of further possible implementation of our organic farming and low-input protection systems towards rede-

signed orchard systems maximising both bottom-up (through fruit trees) and top-down (through natural enemies of pests) processes.

3.2 Agronomic performances

3.2.1 Cumulative 2006–2008 yield

The agronomic performances of the systems measured by the yield of marketable fruits were still low because of the age of the orchards, the low tree density and adverse conditions (frost) after bloom in 2008 which were more severe in the conventional plots (Fig. 5). The cumulative marketable yield tended to be lowest in the organic farming plots and similar in conventional and low-input plots. The decrease in cumulative yield between the conventional and organic farming plots was 31%, 25% and 18% for ‘Golden Delicious’, ‘Melrose’ and ‘Ariane’, respectively. Such decreases were expected as that of productive French commercial orchards is estimated to be roughly 50% in orchards at full production (Sauphanor et al. 2009a). In this study, yield decrease was partly due to a slower fruit setting in the organic farming ‘Melrose’ plot, with lower or almost no yield in 2006. Besides reduced yield, frost in 2008 could also have altered on the long term the regular bearing of trees.

The proportion of first-class fruits in the total yield ranged 75–80% in organic, 80–85% in low-input and 85–90% in conventional plots. Both conventional and low-input protection systems thus presented an over 80% proportion of first-class apples, whereas smaller calibre

(data not shown) and higher fruit injuries (Table 4) were noted in the organic farming protection system.

3.2.2 Effectiveness of the strategies to control pests and diseases

The lowest fruit damages were always observed in the conventional risk-adverse system. Mechanical and physiological fruit damages prevailed (data not presented) followed by insect damages (Table 4). In 2008, a severe rosy apple aphid infestation affected the fruit development in the organic farming ‘Ariane’ plot. This aphid infestation was the cause of serious damages (21.4%). Main disease fruit damages at harvest were due to scab (Table 4). Powdery mildew was not observed on fruits, and other disease damages at harvest were due to decay. The analysis of fruit distribution within prevailing damage categories was focussed on pest damages using the ‘Lepidoptera (Tortricidae, Noctuidae) damages’ and ‘other pests damages’ (mainly due to aphids) categories. In 2007, no significant difference in pest damage distribution was observed between protection systems for ‘Ariane’ and ‘Melrose’ cultivars, whereas the conventional ‘Golden Delicious’ plot differed from the low-input and organic ‘Golden Delicious’ plots (Fisher’s exact test, $P < 0.05$) which both shared some aphid damages. In 2008, organic ‘Ariane’ and ‘Golden Delicious’ fruit damages (mainly due to aphids) differed from that of corresponding cultivars under other protection systems. In both years, a significant difference in fruit damages was displayed between cultivars within each of the low-input and organic farming protection systems (Fisher’s exact test, $P < 0.05$), with the exception of low-input ‘Ariane’ and ‘Golden Delicious’ plots which were not significantly different. In the conventional protection system, a significant difference was only displayed between ‘Ariane’ and ‘Golden Delicious’ plots in 2008. It is likely that cultivars differing in aphid susceptibility displayed scarce or no difference in fruit damages in the risk-adverse most treated conventional protection system. Observed differences in fruit damages thus seemed to be related to both cultivar and management.

In 2008, both ‘Melrose’ and ‘Golden Delicious’ cultivars showed a high level of winter scab inoculum whatever the protection system, with the exception of conventional ‘Melrose’ plot. Wintering populations of codling moth remained very low in any plot of the three protection systems (data not shown) certifying to pest control. The control of pests and diseases can be considered to be globally effective in the three protection systems, with the exception of aphids in organic farming ‘Ariane’ plot and scab in organic farming ‘Melrose’ and ‘Golden Delicious’ plots in 2008. The level of performance measured by yield and fruit damage needs to be

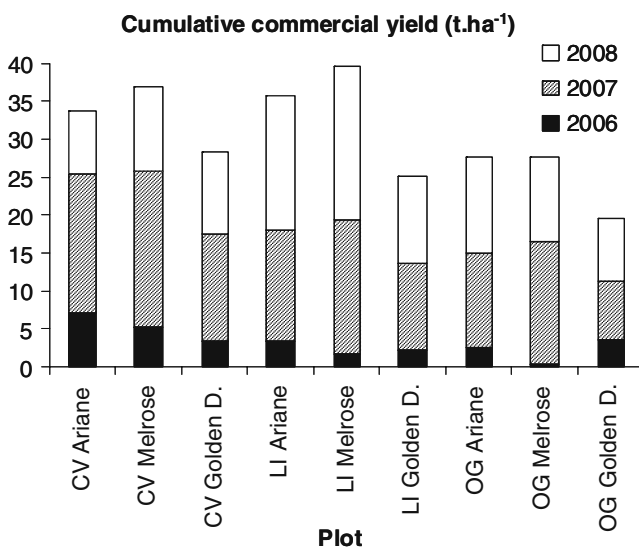


Fig. 5 Cumulative yield from 2006 to 2008 for the nine ‘management × cultivar’ apple orchard systems. CV conventional, LI low input, OG organic farming, Golden D. ‘Golden Delicious’

Table 4 Harvest fruit injuries due to pests and diseases (%) in the tested ‘management × cultivar’ apple orchard systems

Cause of damages	Conventional			Low-input			Organic farming		
	Ariane	Melrose	Golden D.	Ariane	Melrose	Golden D.	Ariane	Melrose	Golden D.
2007									
Total pests	0.3	2.2	2.1	1.7	2.3	1.9	4.5	6.3	4.9
Tortricidae	0.0	0.1	1.0	0.8	0.2	0.2	1.8	2.6	0.8
Total diseases	0.1	0.1	0.1	0.2	0.2	0.0	0.1	1.3	1.3
Scab	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
2008									
Total pests	1.8	1.0	0.5	5.6	8.4	3.4	23.7	9.9	5.0
Tortricidae	0.0	0.1	0.0	2.9	1.8	2.0	1.9	2.0	0.6
Total diseases	0.0	0.1	0.0	0.3	2.1	0.3	0.3	5.3	8.5
Scab	0.0	0.0	0.0	0.0	1.3	0.0	0.0	4.0	7.5

‘Tortricidae’ pests include codling moth and other Tortricids
Golden D. ‘Golden Delicious’

confirmed on the long term to validate the relevance of the recommended strategies.

These results are not similar to those of Reganold et al. (2001) who stated no differences between protection systems either in yield or in fruit damage 5 years after planting ‘Golden Delicious’ cultivar under organic, conventional and IPM management regimes in an experimental apple orchard. We may hypothesise that soil, climatic conditions and regulation context are not similar in the USA and Europe. The climate in Washington State is probably less favourable to scab than our climate (19–33 scab infection risks per year in the 2006–2008 period), and plots larger than ours certainly enabled a higher efficiency of the mating disruption method against codling moth. We either have no information on the prevalence of the rosy apple aphid and its management in these organic farming experimental orchards. Our within-row tillage practices instead of mulch in the experiment by Reganold et al. (2001) could also have been detrimental to tree nutrition in organic farming plots.

3.3 Environmental effects

3.3.1 Indicator assessments

I-phy Orchard indicator (Fig. 6) displayed the lowest scores, i.e. the highest environmental effects, in the conventional protection system but also in the organic farming ‘Golden Delicious’ plot due to the use of sulphur against scab. The low-input plots ranged the highest, i.e. the safest management regimes, followed by ‘Ariane’ and ‘Melrose’ under organic farming management. The best scores (5.9–6.0 out of 10) were performed in 2007 and 2008 in low-input ‘Ariane’ and ‘Melrose’ plots. When

computing I-phy Orchard without herbicides, the mean score of low-input ‘Ariane’ and ‘Melrose’ plots was increased by 10%, whereas a single herbicide was applied from 2006 to 2008 in these plots to recover from increasing weed development. This outpoints the negative effects of some current practices of orchards such as chemical weeding. Thus, the application of herbicides on the within-row bare soil largely decreases I-phy Orchard score in low-input ‘Ariane’ and ‘Melrose’ plots where most of other applied compounds were environment-friendly ones.

Reganold et al. (2001) assigned the lowest environmental impacts to their organic farming system planted with ‘Golden Delicious’. In our study, the organic ‘Golden Delicious’ plot displayed the highest negative effects according to I-phy Orchard. This discrepancy may be

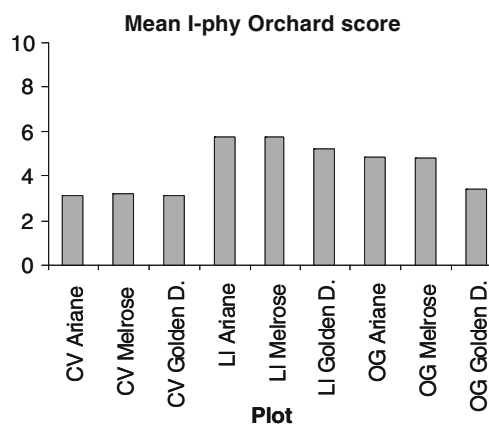


Fig. 6 Environmental assessment of the nine ‘management × cultivar’ apple orchard systems from 2006 to 2008. *CV* conventional, *LI* low input, *OG* organic farming, *Golden D.* ‘Golden Delicious’. No environmental effect scores 10

due not only to the already discussed orchard practices (see Section 2.2) but also to the structure and inputs of the models used to design indicators with additive algorithms in the implementation of the Environmental Index Quotient of Cornell University used in the U.S.A. vs. a fuzzy expert system with no additive aggregation of elementary effects in the present study (Sauphanor et al. 2010).

3.3.2 Beneficial arthropod abundance and biodiversity

The abundance and diversity of beneficial arthropods were the lowest in conventional ‘Ariane’ plot (Fig. 7a). Numbers were distributed within ‘syrphid’ (Syrphidae) and ‘other beneficial’ functional groups for analysis. Organic farming ‘Ariane’ plot exhibited significant differences with both other systems (Fisher’s exact test, $P < 0.05$) in the composition of its beneficial complex: a higher taxonomic richness and a lower proportion of syrphids were noted in this latter plot. The distribution of beneficial arthropods within the analysed functional groups did not show differences between low-input and conventional ‘Ariane’ plots. Earwigs were seldom observed in the conventional ‘Melrose’ plot, whereas both organic farming and low-input ‘Melrose’ plots showed high numbers from May onwards, with similar patterns for these latter plots (Fig. 7b). As natural enemy richness is reported to increase regulatory effects and pest control (Letourneau et al. 2009), such increase in richness is likely to favour a higher level of pest control in organic farming ‘Ariane’ system.

The decrease in TFI was concomitant of lower environmental effects as calculated by I-phy Orchard in any low-input plot. However, our survey displayed higher or similar arthropod richness and abundance in the organic farming protection system compared to the low-input system, whereas environmental scores were always lower in the organic farming system. Such discrepancies may be due to

the nature of the descriptors used to assess systems. As already stated (Suckling et al. 1999; Bouvier et al. 2005; Simon et al. 2007; Sauphanor et al. 2010), some negative externalities of orchard practices calculated by diversity or environmental indices are not always consistent with field observations of bird and arthropod communities. This suggests that global biological observations are needed, especially in the low-input protection system, to directly measure the effect of a decreasing of pesticide use on the orchard agrosystem and biological communities.

Orchard functional biodiversity as well as the pest arthropod community may also be constrained by the plot size, which was quite small in our survey. We may hypothesise that the presence of a similar plant environment in the experimental design induced similar edge effects. Besides space, the other key element is time. In perennial crops, the time step of the assessment stage is long because it has to be over the time needed to establish fruit setting at full production and to meet a wide range of climatic conditions to test the robustness of the recommended sets of decision rules. On the short term, there may even be contradictory aims between evaluating a strategy throughout a long period and integrating new practices in the strategy to improve the system. From our survey, we suggest that only long-term experiments can answer both aims of strategy assessment and orchard system improvement, with testing periods of at least 3–5 years under a given global management regime and phases of redesign using the conclusions drawn from the previous assessment period.

4 Conclusion

A system approach was developed during a 4-year period to assess the decrease of pesticide use and the agri-environmental performances of current and innovative

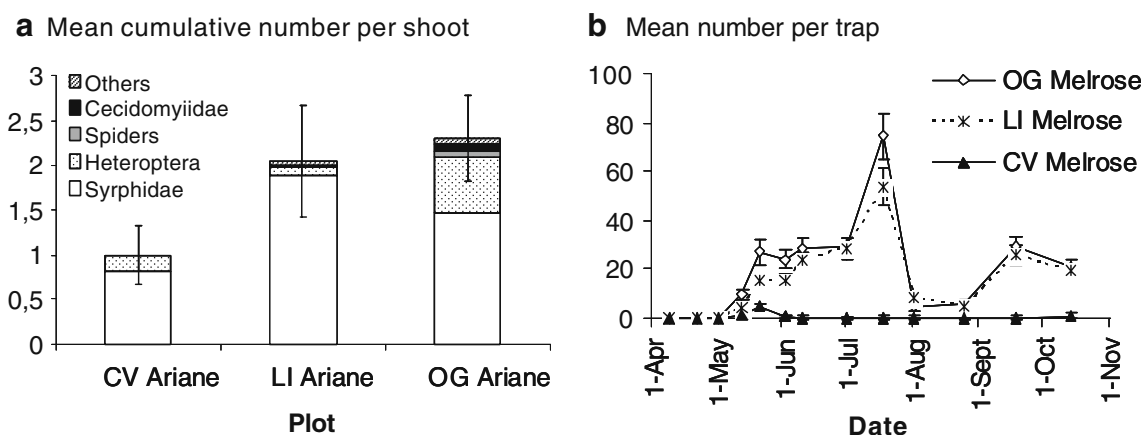


Fig. 7 Effect of the tested protection systems on the beneficial arthropod community. **a** Predators of the rosy apple aphid in 2006 (mean \pm SE). **b** Earwig abundance (mean \pm SE) in 2008. CV conventional, LI low input, OG organic farming

apple orchard systems. Systems were designed by cultivar susceptibility; reliance on alternative methods including mechanical weeding, sanitation practices, or methods giving partial control of pests and diseases; and use of different methods of damage risk assessment. To account for production and market standards, the conventional, low-input and organic farming tested systems included variants differing in the cultivar only in an original experimental design combining three pest management regimes and three apple cultivars of different scab susceptibilities.

In the first years of the study, a 43–56% decrease of pesticide use was observed in low-input and organic farming plots planted with scab-tolerant or scab-resistant cultivars ('Melrose' and 'Ariane', respectively) compared to conventional 'Golden Delicious' plot which was considered to be the reference. Moreover, the same low-input plots were the only ones in which yield and fruit damages were similar or very close to the reference plot under reduced pesticide use and at reduced environmental impacts. The 'Golden Delicious' scab-susceptible cultivar was always the most dependant on pesticide use whatever the protection system. Moreover, a low-susceptibility cultivar did not permit a decrease in pesticide use in the risk-adverse and low-technicality conventional protection system.

The present systemic approach was thus successful in evaluating the level of pesticide use reduction enabled by the integration of presently available tools to control pests and diseases within current straight-designed mono-clone orchards and for current fruit marketing standards. This study is still at its beginning and the present tendencies need further time to be validated. But the bases and results provided by this systemic experiment may be used from now onwards to orientate the redesign of orchards to decrease pesticide use and also to develop and calibrate assessment tools, as presently life cycle assessment, using the extensive registered datasets.

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