EIP-AGRI Focus Group

Sustainable ways to reduce pesticides in pome and stone fruit production

Mini Paper 3

Towards a comprehensive approach to achieve pesticide reduction in fruit production systems

From the combination of alternative methods to orchard redesign

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funded by European Commission

Introduction

Orchards rely on a heavy use of pesticides to control pests and diseases, and, to a lesser extent, weeds as well as to adjust fruit load (e.g., chemical thinning in apple) and quality (e.g., bioregulators). This may be related to several aspects:

-Perennial crops allow the permanent presence of some pests and diseases such as some moths and fungal diseases that may complete their lifecycle in the orchard, therefore inducing the building up of pest populations or inoculum across years;

-Specialized orchards require a high amount of investment and labour; the consequences of taking risk in pest control can be economically dramatic whereas pesticide cost is low compared to other expenses;

-Fresh fruits are marketed, and the 'zero defect' fruit is the standard, with a payment system that rewards the visual quality of the fruits;

-Chemical pesticides assure cultivation of high producing, standardized and international cultivars even in non-ideal production areas creating a vicious circle fostering the increase of input use;

-There is a lack of breeding programs focusing on the development of I) locally adapted cultivars, II) cultivars specifically selected for low-input cultivation and/or III) cultivars suitable for mixed cropping to increase plant diversity within the orchards, including mixtures of crop and non-crop species;

-Production systems are dominated by a few cultivars selected for high production and for fruit easy to transport and to store, neglecting the importance of biodiversity both at the crop and agroecosystem sides. This leads to high input demanding intensive monocropping systems.

All the fruit production chain, from breeders to retailers (through protection against post-harvest diseases), relies on an extensive use of chemical inputs which are economically effective and easy to use, and highly efficient (with some exceptions) to maximize production and minimize, at the same time, losses caused by pests and diseases. Such dependency generates lock-in effects hindering changes in the mainstream model of fruit production despite initiatives such as Integrated Pest Management (Cowan and Gunby, 1996; Deguine et al., 2021). Therefore, to reduce pesticide use and maintain a high productivity and high economic returns requires a paradigm shift based on a holistic approach to consider not merely the orchard management, but the orchard design and the ecosystem services provided by the ecological communities within and outside the orchard, as well as innovation throughout the production chain. We here propose to consider the orchard agroecosystem from its design to the management using both agronomy and functional ecology perspectives, with some general references to the fruit sector. This comprehensive view of the agroecosystem 'orchard' may integrate, without detailing them, the knowledge and experiences brought by other mini-papers of this Focus Group focused on specific dimensions or practices used in orchards to decrease pesticide use.

The use of chemical pesticides as main measure to control pests in current orchards entailed single approaches of pest control using a 'silver bullet', with poor consideration of methods giving partial control of pests, their possible combination, and the potential of biodiversity to provide us with ecosystem services, namely benefits for the orchard (see the recent concept of 'Agroecological Crop Protection' with biodiversity at the heart of crop protection proposed by Deguine et al. (2016)). Pest control is far more complex than a 'one pest-one pesticide' approach: Even chemicals alone can hardly control pests on the long term since the selective pressure posed by long-term use of pesticides promotes resistance development in pests and pathogens.

The development of pests and diseases and subsequent damage is generally related to abiotic conditions in the orchard and within the tree canopy (rainfall, humidity, temperature, wind etc.), the crop status (cultivar, phenology and growth), cultural practices (direct or preventative measures towards pests and diseases) and/or the presence of natural enemies or antagonistic organisms which can suppress pests and diseases, this latter process being affected by all previous points as well as landscape (Fig. 1). This creates a complex ecological network within the orchard. Deciphering the chemical signaling and interactions regulating it will allow us a precise tailoring of human inputs to exploit beneficial services without detrimental impact on non-target beneficial organisms and functions.

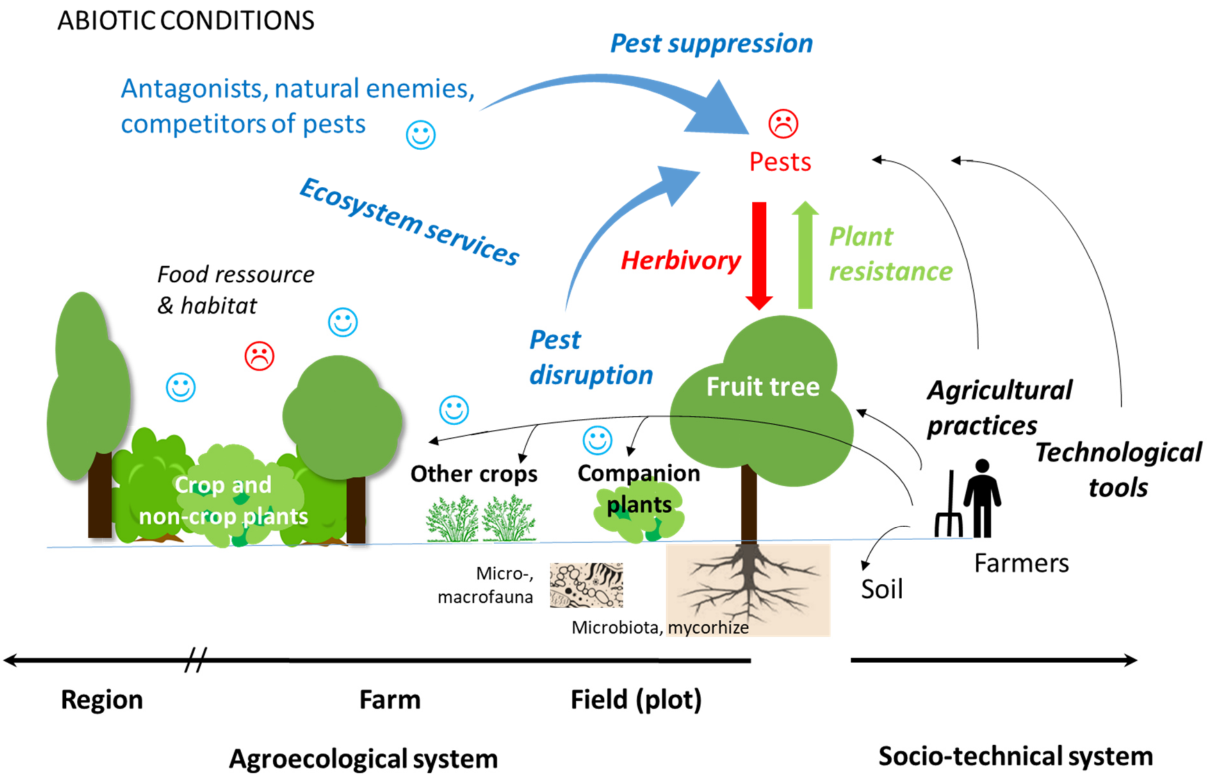


Figure 1 - Comprehensive representation of the orchard agroecosystem with regards to pest control that includes plant-mediated and natural enemy-mediated processes, and agricultural practices.

Targeted processes occur at various scales from plot to landscape. '*Pests*' refer to animal pests, pathogens and weeds, and affect the main crop through herbivory, infection and competition. '*Pest suppression*' includes predation, parasitism and competition. '*Plant resistance*' considers genetic resistance but also conditions unfavorable to pests and diseases through plant architecture (microclimate, branching density), growth pattern and phenology (avoidance) or emission of disruptive Volatile Organic Compounds. '*Pest disruption*' considers Push-pull (using repellent and/or trap plants), barrier and dilution effects*.* Some approaches used to disrupt pests and diseases may have other benefits for the orchard, e.g., companion plants used to promote natural enemies of pests can serve as ground cover or can be nitrogen-fixing plants.

Thus, as ***system approach***, we here consider the whole cropping system with its components and interactions, and the way to design and manage all those components in a consistent way according to specific aims, namely multi-pest control in a sustainable way. Alternative methods to pesticides such as biocontrol are developing and are more and more used, making such comprehensive approach relevant because they rely on complex biological processes whose effect may vary depending on conditions of use. Besides, since some methods give partial control of pests or diseases only, combining plenty of them is of the utmost importance. Many questions may arise: Is knowledge about the implementation of given alternative methods locally available? What are the costs and the efficacy? Are they compatible with each other and with other orchard practices? Does their implementation entail changes in the orchard design and/or work organization? Are there additional benefits? Or possible detrimental effects in the long term? etc. Such approach is complex and knowledge intensive, and it is rather tailored than generic depending on soil and weather conditions, type of orchard, marketing channels, farm and landscape. In a context of pesticide use reduction and ban of some active ingredients for environmental and health reasons, a 'multi-lateral' approach of pest control is at the core of the transition towards more sustainable orchards (Fig. 1).

➔ This mini-paper proposes to highlight and analyze current experiences to decrease pesticide use through a system approach that combines a range of methods and actions to design pest suppressive and resilient orchards, in existing as well as completely redesigned orchards. It first considers the case of current existing orchards where the conservative design (i.e., cultivar monocrop, tree training, planting distances) may constrain the use of some alternatives to pesticides, then innovative designs as prospective avenues for future orchards.

CONSIDERING THE WHOLE SYSTEM

Taking advantage of interactions between practices

A management of an orchard with less use or free of pesticides requires different methods and measures. Nevertheless, all these methods and measures cannot be efficient alone and require to examine precisely the complementarity and the overlap between them. Besides, transition to a pesticide free orchard is only part of the challenge towards sustainability. The orchard must also be productive, climate resilient and at the same time efficient to enhance biodiversity, soil and water quality in the long term. The case study of the UNISECO project in Greece highlights such multi-purpose and tradeoff approach [1][1].

Firstly, an orchard should create, as much as possible, a microclimate that makes fruit trees less affected by climate change and extreme weather conditions. Better air circulation and light distribution through the canopies are also vital preventive measures for pest and disease management. High relative humidity and increased temperatures favor the development of diseases and impede circulation of natural enemies and other beneficial insects. In our peach orchards, narrow and shorter canopies of the trees were an important orchard key trait to ensure a better integrated pest management. To achieve narrow canopies, we managed the tree vigor with green pruning (Fig. 2a) and a precise choice of the rootstock genotype.

At the same time, green pruning reduced aphids' infestation since a percentage of young leaf area was trimmed (aphids mainly infest growing shoots). The trimmed foliage was also used as fresh organic matter which is easily decomposed by the soil microorganisms compared to the wood residues from winter pruning. As a result, we had better soil quality when green pruning of peach trees is used as green mulch. Green mulch could also reduce the use of herbicides in the tree row (Fig. 2a). Of course, depending on the phytosanitary context, such practice may not be convenient if there is a risk of pest or pathogen multiplication or dissemination.

Figure 2 - Peach orchard in the UNISECO project [1] (Greece), in summer after green pruning (a) and in winter showing 2-D canopy and cover crop (b). Photo credits: Ioannis Iordanidis, AGRO Q.

The narrow canopies lead to moderate light reduction to the ground, to the benefit of clover cover crops grown in the orchard alleys (Fig. 2b). The benefits of cover crops were mani-fold: to enhance biodiversity since many beneficial insects can shelter and feed in it, to increase soil organic matter through mulch, and to stabilize the trees' nutritional status since the nutrient requirements of the fruit trees are more easily covered (Fig. 3). The selection of plant species or assemblages in the cover crops were adapted to the local context and objectives, with possible prioritization of them.

[1]All numbers between brackets refer to web references organized per theme at the end of this mini-paper.

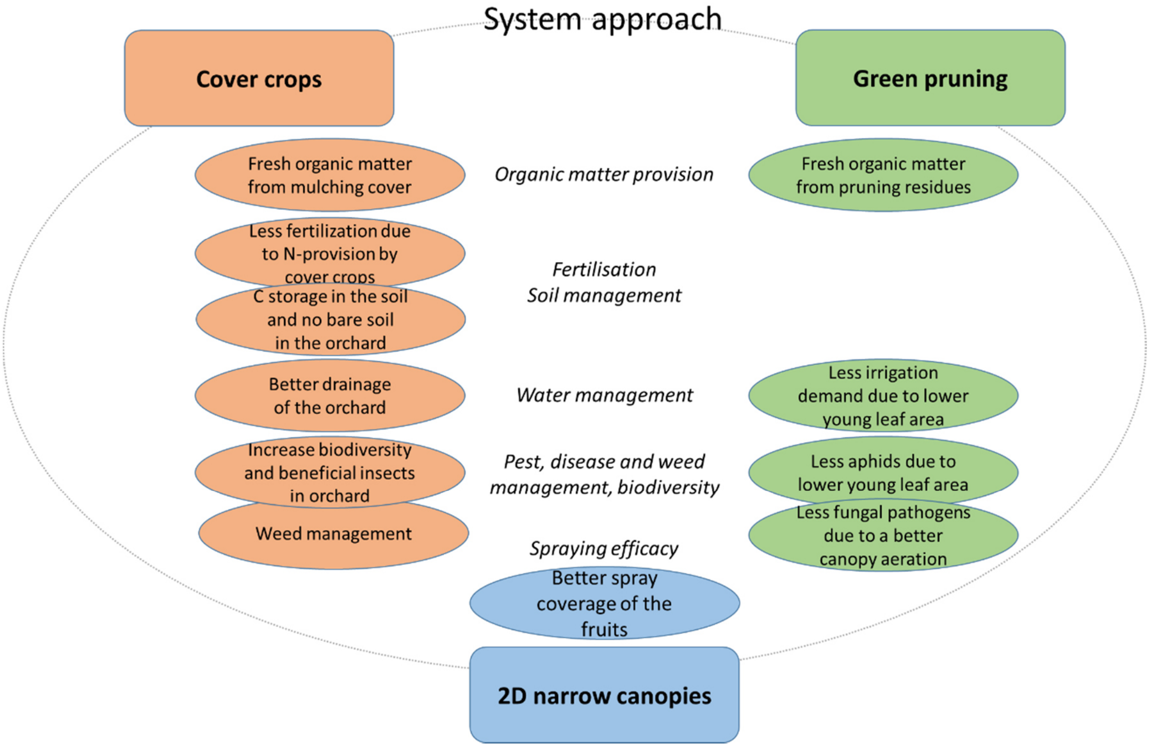


Figure 3 - Multi-purpose agroecological practices in orchards towards a comprehensive approach of orchard management to face the current challenges of reduction in pesticide use, conservation of soil fertility, adaptation to climate change and biodiversity support. After UNISECO project EU HORIZON [1].

A tree with a good nutritional status has the ability to be more tolerant to diseases. Narrow canopies have less water requirements through their reduced leaf area. Less water needs also means a tree with less water shoots and a lower young leaf surface area which are highly susceptible to aphids' infestations. Finally, plantation of different fruit trees at the orchard edges could enhance the biodiversity. Different insects and some of the beneficials could manage pest infestations of the main cultivar.

This case study highlighted the importance to consider a range of practices (e.g., soil cover, green pruning, narrow canopies) as interrelated and synergistic measures to control pests, diseases and weeds, but also as actions benefiting soil fertility, fruit quality, water use and quality (Fig. 3). The idea is I) **to consider fruit tree health globally**, taking advantage of pest and disease suppressive conditions (microclimate), plant status (nutrients and water uptake, growth, vigour) and beneficial arthropods (conservation biological control), and II) **to use multi-purpose practices** that will also benefit the soil, the fruit tree nutrition, the fruit quality, natural enemies of pests, and possibly work organization… In other words, agroecological practices such as cover crops support diverse functions and services of which pest control as additional (and partial effect) benefit; possible extra-costs or labour related to such practices are supported and counterbalanced by a range of benefits.

Taking advantage of interactions between orchard communities

Knowledge on ecological interactions occurring between crop plants and other organisms is crucial to develop a sustainable management of the orchards. Indeed, the elucidation of the complex ecological network surrounding the plant leads to the development of a system approach considering the plant as a continuum encompassing both beneficial/functional interactions and the negative ones. For example, this knowledge promoted the development of biological control agents, mating disruption, microbe- and/or plant-mediated resistance induction, push and pull strategies, biostimulants and biofertilizers. To precisely manipulate these interactions to increase the beneficial over negative ones, we need to decipher the vast chemical signaling governing them. However, despite the recent groundbreaking advances in chemical ecology, our comprehension of these languages is at its infancy. To improve knowledge and to overcome this limitation, possible strategies are to develop laboratory and field experiments, to collect empirical knowledge about plant association, as well as to integrate ecological and precision agriculture tools and automation in the orchards. A precise monitoring of plant performances, needs and health allows for targeting specific ecological functions at the exact time they may express their maximum potentialities.

Promising approaches are currently under study or yet available to control pests and diseases from this knowledge about interactions whether it concerns the localization of the host plant by the pest; the capacity of the pest or the pathogen to infest or to infect the plant, respectively; the capacity of the plant to induce defences against pests or pathogens or to recruit natural enemies of pests; predator-prey interactions; the pest or pathogen development and dispersion (see also Mini-papers 2 and 6).

HOW TO COMBINE ALTERNATIVE METHODS TO CONTROL PESTS AND DISEASES and/or TO REDESIGN THE ORCHARD TOWARDS LESS PESTICIDE USE?

Alternative methods used alone often display a partial effect on pests and diseases which is not sufficient regarding the critical damage thresholds used by farmers or the quality expected from consumers or market chains. However, the combination of alternative methods in a consistent way may trigger a synergy that increases the global efficacy on pests and diseases –and even provide the farmer with additional benefits for the orchard. Such combining to achieve diverse objectives is less documented than the evaluation of single methods. '***System experiments'*** are a way to investigate the benefits and the limits of various combinations of practices. In short, system experiments aim to assess through multi-criteria evaluation the performances of combined practices to achieve a given general objective (Lechenet et al., 2017). They are generally carried out in 'full scale' systems to permit the occurrence of some large scale processes (e.g., pest predation) and socio-technical evaluation (e.g., work time). Several system experiments aiming at decreasing pesticide use were supported within the frame of the French national program Ecophyto [5]. A range of possible available methods alternative to pesticides can be identified in orchards (Fig. 4).

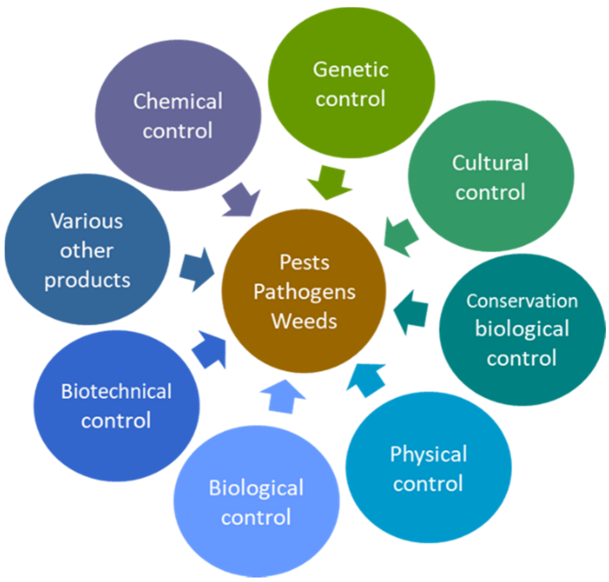
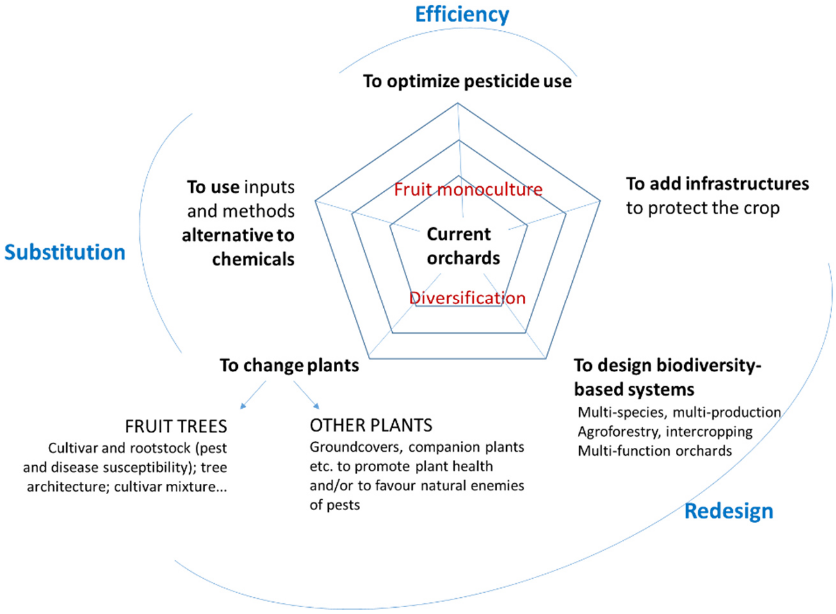


Figure 4 - Possible measures or actions to be combined to control pests and diseases in current orchards. After Laget et al. (2015), Guide méthodologique Ecophyto Fruits [12].

Control of bioaggressors can be realized through genetic control, cultural control, biological control, biotechnical methods (e.g., mating disruption), conservation biological control, physical control (mechanical, barriers), chemical control and the use of other products (e.g., kaolin, plant extracts) and their combinations.

Some of those methods, either preventative or curative, directly target pests and diseases, e.g. physical barriers, classical biological control, mating disruption etc. Others such as genetic control, cultural control or conservation biological control have a more general and indirect effect. Many combinations can be considered, for more or less important changes in the orchard management and design, from changes to improve the efficiency of current practices and substitution of chemical methods by alternative ones, to deeper changes including orchard redesign (Hill and MacRae, 1995; Fig. 5).

Figure 5 - Different approaches to reduce pesticide use in orchards, which are not mutually exclusive. Depending on the relative importance of each approach, the design of orchards can be altered from monoculture to a very diversified fruit production area.



Combination of methods entailing very minor changes in orchard management and design

The timely combination of biocontrol products with complementary modes of action, or targeting various stages of the pest, is a possibility.

In the 'BioREco' system experiment [6] (South-East France, 6 year-survey), the control of the codling moth *Cydia pomonella*, a major apple pest, was achieved using biocontrol alone through the combination of 3 methods: mating disruption; applications of codling moth granulosis virus (CmGv), a microbiological compound used along the periods at high fruit damage risks; and the application of entomopathogenic nematodes in autumn to lower wintering populations. This strategy also included sanitation practices (i.e., removal of all fruit from the orchard) and scouting to get an accurate information about infestation and to assess the efficacy of the strategy (Simon et al., 2018). Although the effect of conservation biological control could not be measured, bats and birds likely to predate codling moth adults and larvae were also observed on the site.

The outcome of the survey indicates that this strategy resulted in moderate extra-costs (inputs, time to monitor) for slightly higher fruit damage (0.5-1.4% in the alternative systems vs. 0.2-0.4% in the conventional one where chemical pesticides were mainly used) whereas no increase in codling moth populations was observed across years. As constraint, weather conditions were important to consider since they could impair the efficacy of the (micro)biological control. Conversely, a better monitoring of the orchard with the early detection of any problem, a higher abundance of natural enemies of pests, less exposition of workers to pesticides, less pesticide residues on fruits and less environmental impact (toxicity, ecotoxicity) were observed. Finally, those practices could bring additional income as a strategy under eco-label or organic farming certification.

Combination of methods including cultivar & rootstock choice and their management

Part of the reduction in pest infestation and disease infection in the orchard is mediated by the fruit-tree itself through cultivar and rootstock choice that first aims at fruit production and quality, and the way the fruit-tree is managed, namely cultural practices:

- Reduction of fertilization and irrigation to limit aphids' population through resource availability for pests is under study in the French project RegPuc [3].

- As highlighted in the UNISECO project [1], tree architecture and tree training can affect the spraying efficacy but also modulate pest infestation and disease infection through the canopy microclimate, as well as growth and branching patterns (Simon et al., 2006).

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- Legume plants can be used in the orchard alleys (see UNISECO project) but also within the tree row. In Southern France peach orchards, white clover *Trifolium repens* seeded within the row increased fruit tree root density, water infiltration rate, nitrogen content and water availability compared to bare soil (Parveaud et al., 2012). Besides, such ground cover limited susceptibility to post-harvest brown rot due to *Monilinia* spp. after heavy rainfall, most probably because water retention in the cover crop mitigated excessive water absorption by the fruit trees and therefore reduced fruit cracking (Bussi et al., 2016; PLACOHB project [2]).

-Since most biological methods and products display a higher efficacy under pest and disease low-pressure conditions, planting of resistant or low-susceptible cultivars is a way to reduce pest and disease pressure in the orchard and to optimize the efficacy of biological products.

-In apricot, a high grafting (1.2 m) is a way to limit the bacterial disease due to *Pseudomonas* spp. without any copper use. Moreover, high grafting produces fruit trees with a tall trunk which facilitates the use of glue applied around the tree trunk against earwigs (Cap Red project [7]); the benefit is therefore two-fold (Brun et al., 2019).

When a range of direct and indirect measures are combined in a consistent and locally-adapted way to achieve pest and disease control, pesticide use reduction can be high. In the BioREco experiment [6], an overall decrease in pesticide use of ca. 45% was observed in systems combining a range of measures compared to conventional ones in a 6-year survey (Fig. 6).

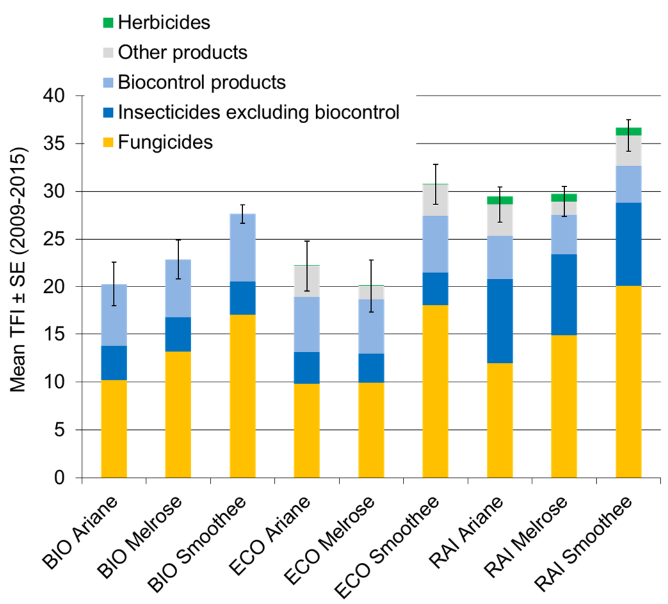

Figure 6 - Potential of reduction of pesticide use in apple orchards using more or less measures to control pests and diseases. After BioReco experiment [6], INRAE Gotheron (Simon et al., 2018).

Pesticide use was measured by the Treatment Frequency Index (TFI) which totalizes the number of registered full doses of pesticides applied in the orchard across the season (i.e., one compound applied at full dose on all the orchard accounts for 1 TFI).

BIO: Organic; ECO: low-input; RAI: conventional; The 3 planted cultivars differed in disease susceptibility with Smoothee, a Golden Delicious apple type as susceptible cultivar; Ariane, a *Vf* scab-resistant cv; and Melrose, a low-susceptible cv to most apple diseases.

In this experiment (Fig. 6), the cultivar alone permitted around 20% decrease in pesticide use in the conventional system. But, when combined with other alternative methods and sanitation, the decrease was reinforced up to 38-45% (see organic and low-input Melrose). Planting a disease susceptible cultivar limits the possibility to decrease pesticide use. Conversely, cultivar choice cannot be considered as a stand-alone solution regarding I) the lack of multi-pest resistance cultivars and II) the risk of gene resistance overcoming in monogenetic resistance cultivars, as was the case in this experiment for Ariane cv in the last years of the survey. In other words, considering together cultivar choice and a range of practices that reinforce each other is more efficient over time than relying on single actions.

The multicriteria evaluation of those systems indicated moderate extra-costs (inputs and/or monitoring time) for both organic and low-input systems, and similar yields in low-input and conventional systems. Differences in yield between organic and conventional were compensated by higher organic prices. Less common cultivars such as Melrose were not rewarded in long sales channels despite very low-input management, supporting the interest to market under a quality label or in direct sales. Finally, management in the low-input systems required responsiveness (e.g., to apply a fungicide at the very last moment if the infection risk is confirmed) which questions work organization and the size and structure of farms.

Systems achieving the highest decrease in pesticide use integrated an accurate evaluation of the risk of damage (efficiency) with orchard monitoring and the use of decision support systems; the combination of a range of alternative methods to chemicals (substitution) such as mechanical weeding, (micro)biological control and mating disruption; sanitation practices against scab and codling moth; and disease low-susceptible cultivars trained to have an aerated canopy.

A similar approach was developed in a French network called EXPE Ecophyto Pomme [9] (Zavagli et al., 2018). On 19 apple systems different methods and strategies were tested to reduce the use of 'chemical' pesticides compared to 8 references representing the regional protection management. The project was carried out for 5 years. The use of a resistant apple scab cultivar brought a reduction of pesticide use measured by the treatment frequency index (TFI) of 35%. Combined with the use of biocontrol fungicides such as Sulphur and potassium bicarbonate against apple scab (at projection peak) and powdery mildew, a Alt'Carpo exclusion netting[2] or mating disruption against codling moth combined with biocontrol insecticides (Cmgv granulosis virus, *Bacillus thuringiensis*), achieved between 55% and 65% reduction. The most important (> 75%) reduction was obtained in organic production systems, or in systems where the treatment volume and doses were adapted to the vegetation volume during the whole season. With apple scab susceptible cultivars, the reduction was 10 to 15% less important than with the resistant cultivars. However, a system covered with a rain protection combined with an Alt'Carpo net or mating disruption brought more than 58% reduction. From an economic point of view, only the organic orchards gave satisfaction due to the possibility to sell the fruits at a higher price, but the turnover remained low (between 15,000 and 20,000 euros/ha).

Cultivar and rootstock are therefore key elements in the orchard to adapt the fruit trees to the biotic and abiotic conditions, to be combined with a range of cultural and alternative methods to strongly decrease pesticide use over time. Cultivar choice therefore implies the consideration of orchard practices, work organization on the farm (periods of peak of activity) and the marketing strategy. The genetic diversity of fruit tree species related to the susceptibility to pests and diseases is to be mobilized through breeding programs (upstream the production food chain). Knowledge about cultivar susceptibility to pests and diseases under diverse conditions is a key information for farmers that local guidelines and knowledge may provide (e.g., GRAB-INRA leaflet on fruit tree cv susceptibility, France [14]; TransBioFruits guidebook, Belgium [13]). Finally, as highlighted above, it is the combination of low-susceptible or resistant cultivars with relevant tree training and management, and alternative methods to pesticides which permits a significant decrease in pesticide use in current orchards.

Combination of methods including technology and/or infrastructures

Netting (e.g., AltCarpo nets against codling moth, AltMouche against *Drosophila suzukii* in cherries) and rain-proof protections (experimented in apple against scab, used in cherries against fruit cracking) are infrastructures targeting pesticide use reduction through pest exclusion and the management of the orchard microclimate, respectively.

As other infrastructure, underground irrigation in the Ecopeche project in peach orchards [8], was a means to modulate the orchard microclimate and to limit grass within the tree row. A less humid microclimate is a way to limit the incidence of the brown rot post-harvest disease and also to decrease or even remove herbicide use.

More prospectively, a possible strategy is to integrate ecological and precision agriculture tools and automation in the orchards. Among the several examples currently available on the synergic integration between precision sensing of plant disease and ecological strategies to control them, one system is currently under investigation by the University of Bologna. An over canopy fixed spray system (FSS) has been deployed over an apple orchard grown under rain-proof nets. This prototype, although presently not authorized as spraying system in commercial farms in many countries, allows for a rapid low volume application of plant protection products regardless of the weather conditions. In the same orchard, based on next generation sequencing and direct isolation has been also isolated and characterized a biological control agent (BCA), *Clonostachys rosea*, which is active against the scab pathogen, *Venturia inaequalis*. The fixed spray system is now under implementation to spray BCA and GRAS (generally recognized as safe) compounds (e.g., ammonium bicarbonate, thyme essential oil) only when they are needed on the basis of a disease risk model.

Furthermore, similarly to what has been achieved for fire blight, where specific biomarkers (e.g., Volatile Organic Compounds) have been identified as indicators of plant health status, also for scab the identification of specific

[2] https://www.alt-carpo.com/

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biomarkers will allow us to tailor control input based on a precise monitoring of plant health. Since biological control may fail in conditions unsuitable for the growth of the introduced agents or when the pathogen population has already exceeded the infection threshold, precision agriculture may also help to I) overcome the current limitations related with the erratic results of biological control; II) minimize competitive effects over synergistic ones by avoiding excess of resource supply; III) monitor pathogen population to target plant protection inputs; and IV) monitor beneficial functions.

Most of the presented measures to control pests in those combinations are available for farmers and most of them are compatible between each other except some associations, e.g. exclusion netting on the tree row and flower strips to promote natural enemies of pests in the orchard alleys. Starting from an analysis of the context and the objectives of the farmers, frames and tool boxes can help adopt more or less measures to control pests and diseases in existing orchards (e.g., Laget et al., 2015; [12]). All those measures to control pests and diseases and their combining are of course constantly enriched by research results and may evolve rapidly.

From fruit tree and plant diversification to other types of orchards

Current orchards are monocrops mostly based on monoclonal high density tree assemblages thereby favouring pest and disease development with poor benefits provided by biodiversity. The development of such intensified orchards also induced a loss of vision of the complexity of interactions, but also of the potential of the perennial multi-layer agroecosystem that is an orchard to produce ecosystem services and/or to support multi-production. How can cultivated and associated biodiversity help manage pests and diseases at various scales?

First of all, cultivar and rootstock choice and relevant associated practices are a powerful way to manage pests and diseases over time in current orchards; the cultivar and therefore the level of susceptibility to pests and diseases of the fruit tree will affect the effort to manage pests and diseases throughout the orchard life span (see above).

At the plot scale, within-row apple mixtures are less scab infected than pure stands attesting the added value of genotype diversity to lower pathogen (auto)infection (Didelot et al., 2007). At the farm scale, diversifying cultivated fruit trees species and cultivars limits pests and diseases towards more economically resilient systems (i.e., put your eggs in different baskets). A diversity of species and cultivars at the farm and regional scales will also prevent homogeneous resource and practices in the landscape likely to induce the overcoming of plant resistance and the resistance of pests and diseases to pesticides. Diversity entails diverse types of interactions between pest and host, thus limiting the possibility for the pest to adapt to one single type of mechanism, and slowing down the possibility of overcoming resistance mechanisms.

Finally, non-crop diversity, adjacent crops and habitats are likely to enhance conservation biological control and to disrupt pests (Fig. 1). Companion plants are important to provide natural enemies of pests with food resource and shelter (see also Mini-paper 2) within or around the orchard. They can also act as barriers to prevent pests locating their host plant, or have a disruptive effect towards pests (e.g., aromatic plants as aphid repellent plants; API-tree C-IPM European project leaflets [4]). Such increase in plant diversity in the agroecosystem that aims at fostering natural enemies of pests is to be supervised to limit I) competition with the fruit trees and II) possible detrimental effects since associated plants may also host some pests and diseases of the crop (Box 1).

We now propose to analyze innovative orchards designed to reinforce ecosystem services, especially pest regulation, to go beyond the conservative design (i.e., cultivar, monocrop, infrastructures) and the constraints of the market channels that may limit the field of possibilities in current orchards. Most of these case studies, either in experimental stations or as farmers' initiatives are very innovative and have to be considered as prototypes currently under study to inspire redesign of orchards. All those systems are very low-input or even pesticide-free systems, not only to favour biodiversity: in intercropped and mixed systems, pest management is constrained by regulations since a pesticide needs to be registered for all the crops of the system to be applied.

Box 1 - How to implement and welcome biodiversity in the orchard and on the farm to promote pest control?

A few generic principles can be identified:

1. **Do not harm**, i.e. do not use disruptive practices such as recurrent chemical applications, but also frequent grass mowing which suppresses resource for many predatory arthropods. Conversely, do not plant species hosting quarantine or major pests or diseases of crops. This is a key point regarding polyphagous pest species that can develop on many host plants.

2. **Provision natural enemies with food** resource (nectar, pollen, alternative prey) **and habitat** through supervised plant assemblages that provide **a succession of resource** across the season.

3. Consider **orchard spatial organization**, to redesign it, but also to use the alleys mainly devoted to machinery traffic in current orchards, within-row area and any interstitial space to associate companion plants that will provide specific benefit for the fruit tree and fruit production.

This can be done step by step: installing nest boxes, then adopting more environmentally-friendly practices and developing a range of agroecological infrastructures following orchard and fauna observations; installing companion plants for multi-purpose objectives (e.g., windbreak hedgerows or cover crops), then adding other species in or around the orchard (Penvern et al., 2019).
Interstitial spaces (orchard corners, alleys, headlands) can be used in current orchards, and diversifying the soil cover within and between fruit tree rows is a powerful practice that provides multiple benefits: weed management, prevention of erosion and water evaporation, organic matter provision and increase in water storage capacity, nitrogen provision for legume species, food resource for alternative prey and/or natural enemies etc.

Fruit agroforestry systems encompass various types of multi-production systems:

I) A **biodiversity-based fruit system** to impair pest and pathogen arrival, development and dispersion is under study at INRAE Gotheron (France) [15]. In this 'pest-suppressive' circular orchard, the design relies on barriers with hedgerows and crop mixtures (fruit species alternate between circles, and cultivars alternate within circles); companion plants and shelters to favor natural enemies of pests; low-susceptible and trap cultivars to impair and divert pests; and sanitation (Fig. 7). Tradeoff between three overlapping dimensions were considered in the design: pest suppression through plant diversity; resource sharing among associated plants; and work organization and distribution along the season in the redesigned system (Penvern et al., 2018).

II) **Mixed vegetable-orchards** aim to optimize the use of space above and below ground, to enhance synergies and mutual services among crops, and to maximize production and income on a given plot. Such systems are complex and change over time according to fruit tree ageing and the rotation of vegetables. Their design needs to consider plants' requirements (light, water, nutrients) over time to associate them, work organization and ergonomics in the spatial design, available skills to manage a diversity of crops and their interactions, and marketing. From a survey of French mixed vegetable-orchards in the SMART project [16], guidelines are available to support the design and management of such systems (Warlop et al., 2017).

III) Other fruit agroforestry systems may **intercrop fruit trees with rotational crops, wood trees, aromatic plants etc**. The association may be transitional in current orchards, with cash crops cultivated in the orchard alleys in the young stages of the orchard, as was traditionally the case in some regions (e.g., maize, squash and various crops intercropped with young peach or walnut trees). Current experiments [10, 11] aim to evaluate the benefits and sustainability of fruit agroforestry systems associating peach and rotational crops. In another experiment (case study on apple at Restinclières, Southern France), shade of forest trees limits apple sunburn during hot summers; the spatial design and planting distances need to consider light reduction due to the upper layer of forest trees on the fruit tree to achieve the tradeoff between the decrease in return bloom due to light reduction and the decrease in fruit damage due to shade (Lauri et al., 2020). Aromatic plants can be used as intercrop as well as companion plants that compete weeds, feed natural enemies and/or repel pests (API-tree leaflet [4]). Finally, food forests including fruit species are also an option to be considered, with a long step for designing and managing the whole system before reaching an equilibrium and harvest period with very limited time investment. These food forests have to be thought on the long-term, and are not economically sustainable in the first period.

IV) **Animals** such as chickens, hens, ducks, geese in dwarf orchards, but also sheep, pigs… may be associated to the fruit trees to weed, keep some pests and diseases under control through direct predation (insects, voles), disruption due to trampling and/or sanitation (consumption of infested and infected fruits and leaves), to fertilize, and even to get additional production. The association may be punctual (i.e., a shepherd brings his/her animals for a period in the orchard), or permanent on the farm with rotational grazing using portable or permanent fencing. Depending of the type of association (e.g., animal species, animal density, grazing of all the orchard or alleyways only), adaptation of fruit tree training and orchard infrastructures may be necessary to avoid damage on the trees. Sanitary regulations require to remove animals from the orchard to other fields at some periods to avoid the exposition of animals to pesticides, and also fruit contamination by some pathogens. Such reconnection between animal husbandry and orchards or vineyards is recent but developing due to more frequent hot and dry summers entailing shortage in fodder, and to farm diversification [17].

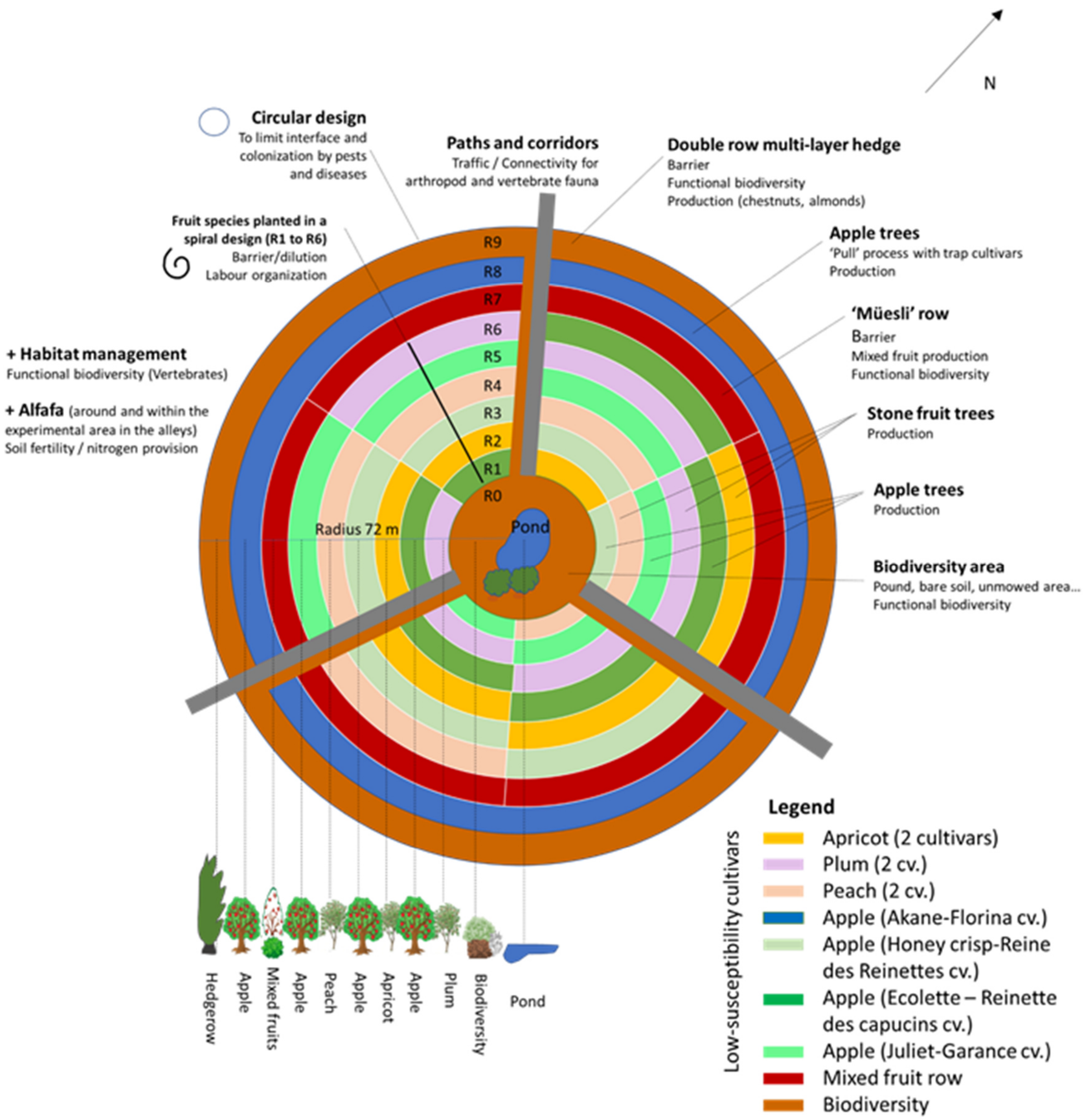

Figure 7 - An experimental pest suppressive fruit production area, INRAE Gotheron, France. The objective of this exploratory project [16] is to design and experiment a pesticide-free fruit production agroecosystem by reinforcing ecosystem services. The orchard was planted in 2018 on a surface area of 1.7 ha.

funded by European Commission

If the focus of this overview of multi-production orchards was on the agricultural system, all corresponding farms also innovate in the way they market fruits and other productions: direct sales, 'Do it yourself' harvest, processing, health and cosmetic products etc. They are of course more complex to manage, and require diversified skills and knowledge, with sometimes specific farm organization such as association of farmers with complementary expertise to manage the diversity of productions. Conversely, such diversified systems are less monotonous to manage and are more self-regulating and resilient due to a diversity in production and valorization, whatever the hazard.

Final considerations

Many types of orchards that meet the challenge of reducing pesticide use will co-exist. There are presently different innovations under study on farms and experimental stations. Depending on the farm context, the farmer's objectives and the considered stage (planting or transitioning), diverse adapted methods and approaches will be selected and combined in a 'tailored' orchard system, with no more 'one-size-fits-all' solutions. Direct and indirect measures are to be considered to promote fruit tree health and pest suppression, from the use of multi-purpose agroecological practices such as cover crops and combining of alternative methods to intercropping and agroforestry. Plant diversification is a powerful means to promote ecosystem services (pest suppression, pollination, services related to soil fertility) and benefits to the orchard, provided the introduction of plant diversity is supervised to limit the risk to favor some pests and diseases.

High tech or low tech? They are maybe not that opposed in the sense that both require observation and/or monitoring and constant adjustments in the crop to optimize production. One challenge for research and practice may rely in harmonizing ecological and precision agricultural tools to get further knowledge on processes likely to impair pest and disease abundance and damage.

More generally in the fruit production sector, we identified other challenges related to innovation in orchards:

-Upstream: There is a new paradigm for plant breeding programs to include more traits to be selected such as multi-pest resistance mechanisms, capability to grow with other plants, adaptation to new types of orchards: less water, less soil nutrient availability, new types of plant architecture, intra- and inter-specific mixtures etc.

-Downstream: Coupled innovation are needed to change together the orchard and the marketing system (Meynard et al., 2017) because of lock-in effects of the mainstream marketing system but also the need to optimize the valorization of diversified fruit production with smaller quantities of each fruit, and possible irregular and heterogeneous quality (see also Mini-paper 4).

Finally, such changes also question knowledge and support necessary to farmers to transition towards new practices and orchards. Co-development and collective actions are a powerful way to embed farmers in such transition. The role of advisors and researchers is also fully questioned to produce, share and integrate knowledge to change practices and design: What is relevant? Does knowledge on it exist? Where is the information? How can it be shared and applied? etc. Beside meetings, technical days and workshops, social networks and internet devoted to agroecology (e.g., https://osez-agroecologie.org) are important source of knowledge and experience sharing to inspire innovative approaches, as is basic knowledge on chemical ecology and ecological interactions among communities within the agroecosystem. The challenge may rely on identifying, gathering and hybridizing a lot of scattered academic and empirical knowledge, on developing on-farm and on-station experiments to identify generic principles and locally adapted methods, and on building networks to share it all.

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