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Sustainable alternatives to chemicals for weed control in the orchard – a Review

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Abstract: This review is designed to address various alternative weed-control practices and their possibilities in the fruit orchard in terms of sustainability. Correct weed management and maintenance of adequate orchard biodiversity are crucial for sustainable orchard soil management. The key is to practice an alternative weed-management approach (single or integrated) rather than to use possibly harmful chemicals only. Integration of modern equipment with a shallow tillage system can provide effective weed control in tree rows, including optimised tree performance and soil biodiversity. Living mulch suppresses weeds and enhances orchard biodiversity, while selection of less competitive and less pest-attracting species is crucial. Plastic covers offer long-term weed control, but additional nutrient amendments are required to maintain the balanced fertility of the soil. Wood chip mulch is suggested where the materials are available on or near the farm, and where there is lower incidence of perennial weeds. High pressure water and robotic systems are still in their infancy for fruit orchards, and required more research to confirm their efficiency.

Keywords: biodiversity; soil quality; integrated mowing; mulching; precision weed control

Chemical herbicides have dominated traditional weed-management approaches in most perennial fruit orchards. The use of various chemicals such as herbicides and pesticides in fruit orchards might improve fruit yield, but this has been achieved at enormous costs to orchard biodiversity and soil and human health. Some herbicides have been shown to be detrimental to ecosystem health and sustainability (Shorette 2012; Meng et al. 2016). Further problems have followed too, such as soil acidification (Kibblewhite et al. 2008), soil infertility and contamination of other natural resources, particularly the underground water table (Meng et al. 2016). Some studies have reported that chemical herbicides can substantially decrease the number of microbial communities (Grossbard, Davies 1976) and the earthworm population (Gaupp-Berghausen et al. 2015), while the persistent effects of weed suppression can lead to reduction of nutrient availability and soil biodiversity (Gangatharan, Neri 2012). Soil biodiversity has an important role in efficient root functioning, as has been demonstrated for monocultures, where monospecific organic residues can disrupt root behaviour for several species (Endeshaw et al. 2015a, b; Polverigiani et al. 2018a, b). Thus, the persistent use of chemical herbicides and soil tillage can result in an impoverished soil quality, as well as decreased plant biodiversity (Yu et al. 2015; Robinson, Sutherland 2002; Meng et al. 2016). Moreover, another particular

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problem is that weeds are becoming more tolerant, and indeed resistant, to chemical herbicides due to their extensive application in farming systems (Pieterse 2010). Taking the above into account, there is an urgent need to reduce and gradually overcome this reliance on chemical herbicides to sustain optimum soil health and orchard biodiversity.

Weed management in the fruit orchard is crucial to diminish competition for water and nutrients during the early critical period of tree growth, and to increase productivity of the fruit trees (Granatstein, Sánchez 2009). Additionally, correct weed management in the orchard can have an important role towards operation of orchard machinery, reduction of pest habitats (e.g., for voles), and contributions to satisfactory economic benefit through the production of quality fruit (Hammermeister 2016), as required by the market. In a fruit orchard, the trees are grown in rows where the soil can be categorised into four distinct zones: (i) the planting row; (ii) the zone immediately adjacent to the planting row; (iii) the area between the planting rows, known as the alleyway, where there is a clear area compacted by the tractor wheels; and (iv) the free intermediate zone (i.e., the area between the two wheel tracks of the tractor). Usually, cover crops are maintained in the alleyway, with frequent mowing to provide physical protection to the soil through stabilising and reducing soil erosion, as well as to support the wheel traffic, minimise compaction, increase the habitat available for beneficial insects, and suppress weed growth. However, it is a serious challenge for fruit growers to manage weeds in the tree row area, where the weeds can strongly compete with the fruit trees for water and nutrients, because of the low root density of the trees compared to the weeds (Merwin 2003). Therefore, it is crucial to manage weeds in the tree row such that they do not have any adverse effects on tree performance.

The standard system for managing weeds in the tree row is to maintain a 0.6-m- to 2.0-m-wide vegetation-free strip in the tree row, which is managed using chemical herbicides in most orchards (Lisek 2014). In this context, orchard biodiversity can be lost through complete eradication of the weeds from underneath the trees and between the tree row areas, which is not desirable for sustainable orchard-floor management systems. Maintenance of vegetated soil in the tree rows might have a vital role for reduction of soil erosion, and provision of food for natural predators and a habitat for beneficial soil microorganisms. Therefore, it is essential to maintain vegetal soil with beneficial and less competitive plants in the tree rows. This can be achieved through different alternative methods to chemicals in sustainable orchard-floor management systems, which when embraced appropriately, will not only protect from soil structure degradation and nutrient leaching, but also improve orchard biodiversity and root trophism.

Farmers have several alternative options available for weed control in the orchard, through which they can manage weeds in more sustainable ways. The selection of the correct weed-management method is crucial, as this can have significant effects on tree performance and fruit quality (Van Huyssteen, Weber 1980; Guerra, Steenwerth 2012), as well as on orchard biodiversity. The choice of the appropriate alternative strategy for sustainable weed management largely depends on type and age of the plants, the types of weeds present in the orchard, costs and availability of labour and materials, the kind of soil and its fertility, and the ideology of the farmers (Hammermeister 2016). Furthermore, the weed management will depend on the critical weed-free period required for the orchard, and the ecological footprint of the strategy itself.

A sustainable orchard-floor management system depends on the three pillars of economics, ecology and equity. These indicate that an orchard must be managed in such a manner as to be economically viable, environmentally sound and socially acceptable (Granatstein, Kupferman 2008). To keep these pillars firm and steady, the use of alternative management systems either alone or integrated with the more standard practices should be encouraged. The main purpose of this review is to address the different alternative weed-management strategies and their efficacy for management of weeds in fruit orchards in terms of sustainability, quality fruit yield, and satisfactory orchard biodiversity.

ALTERNATIVE OPTIONS TO CHEMICALS FOR WEED MANAGEMENT

There are several alternatives to chemicals that have been proposed for orchard-floor management over different periods. All orchard-floor options have both 'pros' and 'cons' (Granatstein et al. 2010). In this section, we discuss the key sustainable alternative weed-management strategies in

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fruit orchards. These include mechanical practices (e.g., tillage and integrated mowing, modern finger weeders), mulching (e.g., living mulch, organic mulch, plastic mulch), thermal weed control (e.g., flaming, steaming), high-pressure weed control (e.g., water jet blasting), and precision weed control (e.g., robotic systems).

Mechanical weed control

Adverse effects of chemical herbicides and the increasing popularity of organic farming have led to the need for further advances in mechanical weed control. These systems are mainly associated with different cultivation and tillage systems, integrated mowing (e.g., brush weeder plus mower), and modern finger weeders. Weed management with traditional mechanical systems can have a substantial number of negative effects on orchard soil health and biodiversity, but it is possible to minimise these problems by using advanced integrated mechanical systems.

Tillage

Tillage is one of the key primary alternative weed-control methods for perennial fruit trees in many countries (Jordan, Day 1970; Lange 1970; Giudice 1981; Suzuki 1981). This provides weed control in the tree row more effectively and conveniently compared to other approaches. However, different kinds of tillage operations need to be considered, including hand weeding, hand hoeing, harrowing, rotary hoeing, and the use of rototillers, cultivators, brushes and discs (Bond, Grundy 2001).

Hand weeding and hand hoeing are the most ancient forms of weed control, and these continue to be used in some countries, as specifically in developing countries where manual labour is more readily available at relatively low cost (Hammermeister 2016). The hoe is the simplest form of tillage implement, and it can be effectively used in the zone immediately around young trees, to avoid trunk injury during the operation of other mechanical equipment, and thus to increase the efficacy of the other tools used (Bradshaw 2017). Hoeing is more useful for the control of annual and biennial shallow-rooted weeds, especially in areas where the field and/or climate are not favourable for mechanised systems or where there is a lack of technical knowledge (Bond, Grundy 2001).

Cultivators and rototillers are the main mechanised tillage equipment used. These are easy to operate, but they only provide weed control in the areas adjacent to the tree rows, and cannot provide weed control between the trees in the rows as they are fixed to the tractor (Hammermeister 2016). However, modern tillage equipment, such as the 'Wonder Weeder' and the 'Hydraweeder', can access the areas between the trees using their hydraulic systems, and thus provide efficient weed control in this zone (Granatstein, Sánchez 2009), while also ensuring substantial reduction in the labour required (Granatstein et al. 2014). Similarly, other modern implements include the 'Weed Badger' (USA), the 'Rinieri Cultivator' (Italy), and the 'Weed Hoe' (Spain), which can cultivate the areas between the trees along the rows. Their operation can be maintained either automatically or manually, depending on the age of the trees and vines. For example, a hydraulic system can be used for established trees, and a manual system for small trees and bushes (Hammermeister 2016).

Tillage has several beneficial factors. According to Hammermeister (2016), "it is less labour intense and capable of decomposing soil organic matter through soil disturbance, soil aeration, improved soil moisture status, and improved accessibility of decomposers to organic residues". However, as well as these benefits, excessive use of tillage can have substantial harmful effects on the soil-quality parameters, including biological diversity, soil structure and water holding capacity (Merwin et al. 1994). Tillage reduces the supply of carbon and nitrogen nutrients to microbes (Sanchez et al. 2001; Hoagland et al. 2008). Granatstein and Sánchez (2009) also reported adverse effects of tillage for the soil cation exchange capacity and the available phosphorous nutrients, with the consequent reduction of 13% in the soil organic matter. The use of conventional tillage equipment close to the trees has also been associated with tree-growth reduction, lower fruit yields and smaller fruit sizes (Neilsen et al. 2003; Granatstein, Sánchez 2009; Granatstein et al. 2010). Furthermore, several studies have demonstrated detrimental effects of tillage on the soil microbial composition, enzyme activities and biological processes (Dick 1984, 1992; Deng, Tabatabai 1997; García-Ruiz et al. 2008), as well as on trunk size and pruning mass of the trees (Wooldridge, Harris 1989). Tillage also destroys the tree roots near the soil surface that are responsible for the absorption of moisture and nutrients (Hammermeister 2016), thus reducing root abundance

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by 52.9% in comparison with herbicide control, and by 77.8% in comparison with straw mulch (Van Huyssteen, Weber 1980). For this reason, one of the major topics to be studied in this field is the depth of tillage, to find out the minimum depth at which the implements can be use so as not to adversely affect tree performance (Granatstein, Sánchez 2009).

Some studies have shown that considering the overall pros and cons, tillage might represent the most economically sustainable method for weed control compared to other alternative approaches, such as steaming or use of organic herbicides (Shrestha et al. 2013). The key problem with tillage is the lack of environmental sustainability. In this regard, the practice of a shallow tillage system with advanced equipment might be the sustainable solution to the problems related to the more traditional tillage equipment. A blade weeder is such a kind of shallow tillage tool. This might provide an effective weed-control option for tap-root species, as it can be used horizontally at just 3 cm to 4 cm under the soil, and it causes little soil disturbance compared to other conventional tillage equipment. Therefore, studies are ongoing to investigate the integration of this practice with the other available options to provide an integrated tillage system for sustainable weed management in the fruit orchard.

Integrated mowing

Integrated mowing in terms of a brush weeder plus a mower can be an excellent sustainable alternative strategy for weed management in the tree rows. In this system, two advanced types of equipment are used simultaneously: a rotary brush weeder, and a mower. Brush weeders have a polypropylene brush mounted on a horizontal axis that is powered by the tractor power take-off. This can bend down the weeds even near to the tree trunk without any trunk damage, and at the same time the mower can cut and shred the weed plants just above the soil surface without disturbing the soil (ongoing research). Thus, the maintenance of the vegetal soil underneath and between the trees is possible, and this might also increase biomass production (Neri 2013). The shredded weed plants can also serve as mulching material, as well as improving the soil nutrient status through the decomposition of the chopped plant materials in the soil, which can subsequently provide efficient erosion control and enhance the organic matter, to provide better soil structure. Also, only one person is required to operate this technique, and while it is new to the fruit orchard, it has been found to be useful on vegetable farms for weed management (Tei et al. 2003; Tei, Pannacci 2005; Turner et al. 2007). In another comparative study, Vester and Rasmussen (1990) reported that a brush hoe is more efficient than a conventional hoe when compared to horticultural crops, and this might be due to the possibility to work very close to the plant row. In addition, the most important part of this integrated technique is that it can control weeds while also improving soil quality, biodiversity and tree productivity, which are the ultimate goals of sustainable orchard management.

Modern finger weeders

Finger weeders represent another advanced technology for weed management of perennial fruit trees, and their use is now achieving public acceptance due to their environmental sustainability and their high working efficiency. Finger weeders are available with two adjustable hydraulic widths, with the bearing frame equipped with two star-shaped discs mounted at the ends. The first special steel disc positioned at the front of the frame works vertically on the ground and parallel to the plants, to break the soil crust and accumulate the soil under the tree row. The second rubber disc is positioned behind the frame, horizontal to the ground, and this eliminates the weeds between the plants (Source: Berti Macchine Agricole). Due to the use of rubber, this provides gentle weed control around the plant, just above the soil surface. These finger hoes are available in various versions with different hardnesses. The hardness of finger hoes is indicated using multiple colours; e.g., red indicates hard; yellow for medium; and orange for soft. The choice of a finger hoe thus depends on the type of soil and the type of weeds. In horticultural crops, some studies recommend their use in areas with loose soil and during the early stages of weed growth (Pannacci, Covarelli 2005; Panacci et al. 2008; Pannacci, Tei 2014), because they perform poorly in heavily compacted soil, like clay, and the efficacy of this technique decreases with the age of the weed plants, and especially for grasses (Pannaci et al. 2017).

There have been recent advances in finger weeders for management of vineyard weeds, whereby different companies have developed various forms of finger hoes (e.g., Kress, Stekketi and Berti, in Germany, The Netherlands and Italy, respectively), through which farmers can control intra-row weeds

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in fruit orchards in the same way as in vineyards. It is expected that this advanced practice will provide excellent weed management in the tree rows with little soil disturbance, which will maintain orchard biodiversity with economic sustainability due to their efficiency, reasonable cost, and eco-friendliness.

Mulching

Mulching is one of the best alternatives to chemicals, as it minimises weed problems in the fruit orchard by suppressing weeds at an early growth stage. The main aim of mulching is to conserve the soil moisture and suppress weed growth. The additional advantage of mulching includes the management of temperature fluctuations, improved physical, chemical and biological characteristics of the soil, and the ultimate enhancement of orchard biodiversity (Polverigiani et al. 2013a, b). However, mulches are available in different forms, which include natural mulches, such as living mulch, straw, sawdust, weeds, paper, and plant residues, and synthetic mulches, like plastic. These mulching forms can be used either alone or with integration with other practices in a 'sandwich system' (Tahir et al. 2015), with various combined techniques suggested (Granatstein, Sánchez 2009) for effective weed management and maintenance of biological diversity in the orchard.

Living mulch. Living mulches might be one of the best sustainable practices for tree-row weed management. These are growing plants, and they have the potential to reduce nutrient leaching (especially of nitrates) along with the absorption of carbon and nitrogen (Żelazny, Licznar-Małańczuk 2018).

Moreover, as well as reduction of nitrate leaching, the use of living mulches provides efficient control of soil erosion, builds up the organic matter for better soil structure, and provides a habitat for beneficial insects (Tedders 1983; Liang, Huang 1994; Lacey et al. 2006). Living mulches also contribute to root exudates and labile residues, to thus improve nutrient cycling and retention through stimulation of the soil biota (Rovira et al. 1990; Wardle et al. 2001). However, the benefits of this practice can come with certain drawbacks, such as competition with the fruit trees for water and nutrients, and reduced plant growth and yield (Granatstein, Sánchez 2009; Tahir et al. 2015). One study reported that living mulches can prevent tree root development and distribution, by limiting their access to the soil surface moisture (Yao et al. 2009). Therefore, Hammermeister (2016) recommended this practice at areas with fertile soils, a sufficient water supply, and the absence of perennial weed species, conditions that will thus improve the efficiency of the living mulches. In addition, living mulches should be used only with established fruit trees, as the competition for water and nutrients is a lot greater at the early stages of tree growth.

The selection of the living mulch species has a significant effect on suppression of weeds and tree performance. Many plant species have been tested as living mulch, especially for vegetables, where more attention has been focussed on leguminous plants, and especially white clover (*Trifolium repens*), as these can supply nitrogen (Neilsen, Hogue 2000) and provide improved soil biology through root exudates (Granatstein, Mullinix 2008). One study indicated that yield losses for apple from 11% to 24% can occur depending on the living mulch species used (Hogue et al. 2010). Neilsen and Hogue (2000) tested white clover as the living mulch in an apple orchard, and they reported that while it supplied nutrients to the soil, it also reduced the fruit yield compared to a vegetation-free control. Freyman (1989) reported higher berry yields when mulching with white clover compared to perennial ryegrass (*Lolium perenne* L.). Competition between fruit trees and the vegetation underneath is the core problem for the use of live mulches (Granatstein, Sánchez 2009). Fruit trees can be affected more here, because of their low root density per unit area of soil surface when compared to the vegetiton underneath (Merwin 2003). For example, grassy vegetation can have a root density that is 100-fold that of apple trees (Neilsen, Neilsen 2003). However, this problem can be minimised by the selection of a less-competitive species (Meyer et al. 1992) and by frequent mowing (Neri 2004).

Many studies have suggested that living mulches represent an excellent practice for weed suppression in sustainable agricultural systems, and have recommended their use as an alternative method to the use of chemicals, particularly when integrated with other strategies (Bond, Grundy 2001; Teasdale et al. 2007; Kruidhof et al. 2008; Kitis et al. 2011). A sandwich system from Switzerland is a good example of integration of living mulch species with a tillage system. In this concept, the living mulch species are maintained as a 40 cm to 50 cm band within the tree line, with tilling on both sides of the tree rows to leave a competition-free zone for the tree roots (Weibel et al. 2007). The vegetation

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strip provides weed control around the tree trunk, and reduces the competition. Some studies have indicated that this method as the most cost-effective weed-control practice, with good results obtained in terms of tree performance and fruit yield, compared to flaming and living mulches (Stefanelli et al. 2009).

Organic mulch. Organic mulches refer to mulches that derive from organic materials, such as bark, wood chips, leaves, grass clippings, sawdust, plant hulls, crop residues and weeds removed from the field. Here, wood-chip mulches appear to be the best organic mulches for effective control of weeds in orchards (Granatstein, Mullinix 2008; Ingels et al. 2013). A single application of wood-chip mulch can provide weed control for 1 year to 3 years, while also saving on irrigation water by over 20% (Granatstein, Sánchez 2009). However, it can be an expensive method compared to other alternatives, as the wood chips need to be maintained as at least a depth of 10 cm for effective weed control, and their purchase costs can be unusually high (Lisek 2014; Tahir et al. 2015), particularly if the materials are not available on the farm or near the farm. In addition, they are limited in terms of the control of established weeds, and especially for perennial weeds (Larsson 1997). Granatstein et al. (2014) reported that the effectiveness of wood-chip mulch for suppressing perennial quackgrass (*Agropyron repens*) lasts only 1 year, as the weed competition increased after a couple of years. Thus, apart from the higher cost, the further main cons of this method are this limited efficiency in the control of perennial weeds, and the high carbon to nitrogen ratio, which reduces the availability of nutrients in the soil (Treder et al. 2004). This might be due to an immobilising effect of wood-chip mulch (Larsson 1997), although this is not always the case (Forge et al. 2008; Granatstein, Mullinix 2008). Therefore, Hammermeister (2016) suggested the use of wood-chip mulches only in areas with at least moderate soil fertility, and for smaller numbers of perennial rhizomatous weeds in the field.

However, wood-chip mulch has a significant effect on tree growth and fruit yield. Some studies have reported improved tree growth with wood chip mulch, when compared to tillage or cover cropping, but they did not find any significant differences in terms of fruit yield (Teravest et al. 2010). In another study with blackcurrant, it was shown that the plants had relatively lower fruit yield under wood chip mulch compared to black plastic or bare soil (Larsson 1997). Therefore, many studies have suggested additional soil amendments and or placing a green mulch on top of the wood chip, to minimise immobilisation problems and lower fruit yield (Neilsen et al. 2013). Granatstein et al. (2014) reported highest apple tree growth and economic return when wood-chip mulch was combined with flaming, compared to herbicide with flaming or tillage alone. However, the practice of wood-chip mulching can provide better tree growth compared to flaming or tillage, and compared to cover cropping alone (Hammermeister 2016).

Plastic mulch. Plastic also represents an alternative weed-control method to chemical herbicides for fruit trees, and it can be especially effective at the early stages of plant growth (Mage 1982; Camposeo, Vivaldi 2011). Weed-management costs in the fruit orchard can be minimised using plastic because of the low cost and long-term efficiency (Hammermeister 2016). As Schonbeck (2012) indicated, "The plastic fabric is an opaque film that reduces germination of light-responsive weed seeds by shading out and blocking the emergence of weeds physically". However, to prevent weeding issues, it is always critical to be sure of the correct placement of the plastic edge into the soil, to make sure that the weed roots remain under the plastic layer (Grieshop et al. 2012). This can also save on water use for irrigation by 75%, compared to non-mulch controls (Duncan et al. 1992) and thus reduce farm irrigation costs. Some studies have shown that plastic mulch influences soil nutrient status by stimulation of nutrient mineralisation from organic matter, although this does not supply nutrients to the soil (Schonbeck 2012). For this reason, Neilsen et al. (2013) suggested the additional of nutrient amendments, and especially nitrogen (N), to maintain the balanced fertility of the soil.

Plastic mulch can also affect fruit size and yield. For example, the yield of blackcurrants was 26% greater under plastic mulch when compared to a single application of chemical herbicide (Dale 2000). In another study, Neilsen et al. (2013) reported increased apple yield for black plastic compared to alfalfa mulch. However, Larsson (1997) indicated smaller berry size for blackcurrant with plastic mulch, compared to bare soil or wood-chip mulch.

Plastic has a large effect on the microclimate around the plant as its use results in changes to the above-ground and below-ground temperatures and water content (Tarara 2000). The extent of these microclimate modifications depends on the opacity

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and colour of the plastic (Lamont 2005), as well as the optical properties of the plastic and the connection between the plastic sheet and the soil (Hammermeister 2016). For example, black plastic has higher light absorption over white plastic, with this reversed in terms of light reflectivity. Some studies have investigated the combined practice of photodegradable black plastic over white plastic mulch in vegetable crops, to keep the soil warm in spring and cool in summer; however, this did not increase yields over typical plastic mulch (Graham et al. 1995). The further alternative might be white plastic mulch over black plastic mulch, where the black plastic can block the light and thus supress the weeds, while the white plastic can reflect the light into the plant canopy and protect the soil from excess heating. Thus, different combinations of plastic mulch might represent good options for the growers, with the choice made based on the environmental conditions.

Thermal weed control

Modern technology has significantly improved the effectiveness of propane burners as an alternative weed-control method in the fruit orchard. Generally, this system requires one or two metal flame orifices to direct the heat at the weed strip and the base of the trees. These are connected to propane tanks (with a safety switch), which are pulled through the orchard at a speed whereby the heat provided breaks down the leaf cuticle of the weeds before they gain greater size or vigour, which causes their desiccation. In this system, a temperature of 60 °C to 70 °C can be maintained by using a propane flame with specialised equipment to heat the weed plants (Wei et al. 2010). According to Bond and Grundy (2001), an angle of 22.5° to 45.0° should be maintained between the burner and the ground for effective weed control. This system might also require several passes, and weeds should be flamed before reaching 5 cm in height (Bond, Grundy 2001). Of note, the purpose of such flame weeding operations is not to burn off the weeds, but to apply enough heat to severely damage the plant cells, so that the plants will ultimately wither and die (Wei et al. 2010). Flaming is most effective in controlling erect and broad-leaved weeds in an early stage of growth, and it has been shown to be less effective in the control of grassy and prostrate weeds (Shrestha et al. 2012). As flame weeding is also a temporary weed-control practice, there is also the need for reapplication after 1 week to 3 weeks (Shrestha et al. 2013). The use of this method is not particularly widespread, however, due to its relative inefficiency in the control of some weeds and the limitations in the timing of the treatments for effective weed control (Guerra, Steenwerth 2012). A large drawback of this method is also the fire hazard, which can lead to damage to the tree branches and to the irrigation line (Stefanelli et al. 2009). In another study, this method was shown to have relatively lower cost than herbicides and mulches, and similar costs to those of a tillage system (Granatstein et al. 2014). As an alternative to herbicides, the efficiency of flaming can be enhanced by its integration with tillage or mulching strategies (Granatstein et al. 2014). Thus, flaming represents a potentially good alternative to the use of chemicals considering all of the sustainability aspects, especially if a if biogas is used instead of fossil fuel for the flame operation.

High-pressure water

High-pressure water blast systems represent a modern revolution in technology for alternative weed management to chemicals, especially for weeds under vines. In this system, a high-pressure water blast is used rather than chemical herbicides, to avoid environmental degradation. This high-pressure water can break the foliage of the weed plants and bury this in the soil up to a few centimetres, thus also destroying the root system of the weed plants. 'Grass Killer' uses this kind of technology, as developed by an Italian company (Caffini) to control weeds under vines and orchards. This is composed of a very high pressure pump (maximum pressure, 1 150 bar) that is managed using hydraulic devices, a tank for the water, and a rotating head that is positioned laterally with respect to the forward direction (Source: Caffini, Italy). The rotating head on a breakaway arm is equipped with nozzles that are powered by a very high pressure pump that works in the same way as shrouded spray systems. The rotation speed of the nozzle is 600 rpm, which is combined with a forward speed of 2.5 km/h. This system requires approximately 2 000 L of water per hectare for 2.5-m-wide vine rows. Weeds can be controlled for a year with only two applications (according to the manufacturer).

Although this represents an environmentally viable approach, there remain concerns in terms of the social and economic sustainability due to its high cost (over EUR 30,000). Therefore, increased working efficiency is crucial to provide a more reasonable balance in terms of this high purchasing cost.

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Precision weed control

Precision weed control represents another modern and effective weed-management approach in the fruit orchard, where weeds in the tree rows can be controlled without harming the environment. Over the last few decades, rapid advances in automation have occurred for weed control in farming, and especially for field crops. Precision weed-control methods, such as 'robotic systems' might be the best modern technological intervention here (Bajwa et al. 2015). Peruzzi et al. (2017) provided a good overview of such precision weed-control systems. In this case, the autonomous weed-control approach was designed considering four key aspects: guidance, weed detection and identification, precision in-row weeding control, and mapping (Slaughter et al. 2008). Four kinds of intra-row robotic weeders are now available for precision weed-management systems: 'Robovator'; 'Robocrop'; 'IC-cultivator'; and 'Remoweed' (Peruzzi et al. 2017). Among these, Robovator appears to be the most effective intra-row weed-management system for organic farming. It cuts the weeds at a shallow soil depth (1–2 cm) using a pair of tines, where each tine has a flat knife-like blade (Peruzzi et al. 2017). When the blades approach the crop plant, they move apart to avoid damaging the plant. As soon as the plant has been passed, the blades immediately close again to continue cultivating the area between the plants. The movement in and out of the crop row is operated by a hydraulic actuator connected to a front-mounted camera. The camera recognition system defines each of the crop plants based on the difference in size between the crop plants and the weeds. Then, images are further processed by a computer to calculate the points at which the actuator of the blades need to be activated, based on the driving speed and the area that is always left uncultivated near the crop plants (Melander et al. 2015).

Bakker et al. (2010) suggested that such precision weed-management systems might have a pivotal role in sustainable food production at lower cost. It would be a big challenge for the growers to use this kind of technique in sustainable fruit production. As an alternative to chemicals, studies carried out with these precision systems of weed management have indicated an optimistic future for their use not only for vegetables, but also in fruit orchards, to reduce weed-management costs and the protect orchard biodiversity and soil health. Therefore, these precision weed-management approaches represent another possibility for sustainable weed management for perennial fruit trees.

CONCLUSION

Enhanced biodiversity and improved weed management in fruit orchards are crucial to increased orchard sustainability. It remains probably true that the use of herbicides is the most effective weed-management practice in the fruit orchard, although many farmers are now seeking comprehensive alternative solutions (single or integrated) to protect soil health and orchard biodiversity, as well as to avoid other harmful effects of chemicals, as indicated above. Moving towards more sustainable orchard-management practices is the desirable alternative option to offer eco-friendly management systems for maintenance of the vegetal soil, satisfactory orchard biodiversity, and adequate weed management in the orchard.

Mechanical methods are now one of the leading 'traditional' weed-management approaches in both conventional and organic fruit orchards. Over the long-term, the typical tillage approach has adverse effects on soil quality and structure, as well as on the fruit trees. These problems can be minimised using more advanced mechanical equipment, such as finger weeders, and brush weeders, along with a mower, rather than practicing conventional tillage. In addition, the timing and frequency of the treatments and the prevalent types of weeds are crucial factors for consideration for effective mechanical operations.

Using mulch in the tree rows can provide satisfactory weed control and promote orchard biodiversity and good soil biology and nutrient cycling. Living mulches can be used in established fruit orchards, as younger trees are more prone to competition with living mulch plants for moisture and nutrients. Therefore, the selection of a less competitive living mulch species is crucial to better tree growth and quality fruit yield. The European Core Organic project Domino is addressed to study the efficiencies of different living mulches for enhancement of fruit orchard biodiversity (http://www.domino-coreorganic.eu/).

Organic mulches are more effective for management of annual and biennial weeds, and show low efficiency *versus* perennial vegetation. The use of some of these materials, such as wood chip and sawdust, greatly depends on the area to be cov-

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ered and the availability of the materials, because of their high purchasing and transport costs. While plastic mulch can provide long-term weed control, it also requires additional nutrient amendments to maintain the soil nutritional status. Although the effectiveness of the various mulch materials in weed management is not as great as for herbicides, mulches can promote soil fertility and orchard biodiversity, as well as provide better economic returns with satisfactory weed management.

High pressure water blast and robotic weed-control systems are still in their infancy in fruit orchards, although they have been shown to be particularly effective in the control of weeds in vegetable crops. In this context, it is expected that these techniques will provide good alternative weed-management options in terms of improved sustainability. Future research is required to determine their long-term efficiency in fruit orchards.

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