A review of alternative and novel weed control methods in blackcurrant (*Ribes nigrum* L.)

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Background

Weed control in blackcurrants is becoming progressively challenging due to increasingly limited number of safe herbicide options suitable for existing and establishing plantations. New approaches that provide an alternative to chemical weed control methods are required for production to be sustainable going forward, while also satisfying future consumer demand for high quality UK-grown fruit. Limited herbicide options are anticipated to affect the production of blackcurrants through reduced crop growth and yield. Additionally, competitive perennial weeds become established within the crop which interfere with and contaminate the product at harvest.

Several non-chemical approaches are being trialled in perennial and soft fruit crops around Europe (mulching, steam, electric etc.). However, these methods present several practical and financial challenges in commercial situations. There is, therefore, a need to increase the knowledge and assess a range of non-chemical forms of weed control in blackcurrant that may prove to be suitable as alternatives to current herbicide regimes for UK grown blackcurrants, and other similar crops in the future. This review is intended to summarise direct non-chemical weed control methods in blackcurrant with emphasis on existing methodologies.

The study was undertaken by performing literature searches of Web of Science and Google Scholar for existing peer reviewed literature with findings included in the main body of the text. Advisory, manufacturers and suppliers' websites were accessed for information on existing machinery and presented in Appendices 2-10. A grower survey (Appendix 1) and findings from respondents were followed up by manufacturer searches (Appendix 2-10) and personal conversations with growers and agronomists, which are included in 'Case Study' boxes. This information was complemented by searches of videos (YouTube), public interest websites, blogs, and agricultural websites (ADAS, AHDB, SARE, DEFRA) for recent research and field trials.

Disclaimer: The information contained in this review is accurate to the best of our knowledge. Authors are not responsible for outcomes of any actions taken based on this information. Although several machinery, products and companies will be mentioned in this review, it is not intended to promote and endorse them to the readers, likewise the companies did not prompt to achieve marketing exposure in the following document.

Summary of findings

- Several alternative weed control options exist or are under development.
- None of the approaches are sufficient for satisfactory weed control on their own.
- Higher cost, lower efficiency and lack of confidence are the main barriers to application of alternative weed control options.
- There is a need for more applied and fundamental research to design an alternative weed control toolkit for blackcurrant.
- There is a need to design a long-term decision-making protocol for selection of appropriate alternative weed control options depending on site specific circumstances.

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Main barriers to integrated weed management

Integrated weed management (IWM) includes diverse chemical, mechanical, cultural and biological weed control methods underpinned by strong emphasis on prevention as tools for sustainable weed management. So far growers, agronomists and literature indicate that the main barriers to successful IWM include lack of knowledge, research and grower confidence. In addition, preliminary studies have indicated lower effectiveness of alternative weed control options coupled with higher cost, need for specialised equipment, complexity and potential penalties on crop yield and quality which slow down the process of integrating methods in conventional perennial crops. Additionally, most technological developments are adapted to major crops and cannot be applied without further modification in crops such as blackcurrant (e.g., machinery successful in wider crop spacing). Moreover, technologies such as machinery developed specifically for minor crops like blackcurrant receive insufficient demand to sustain production. Weed control practices are critical during the establishment of perennial crops such as blackcurrant and are perhaps more crucial than later during the production phase of the crop, due to the limited competitiveness of the crop with weeds, and the spacing and vulnerability of the transplants.

In this report, the applicability of alternative methods for weed control during establishment and post-establishment, are indicated in summary tables at the end of each section as:

(+) positive – supported by literature and practical evidence,

(+/-) potential – show potential but several barriers exist,

(-) problematic – negative effects or lack of current evidence.

Additionally, main barriers and potential alternatives and recommendations are also summarised.

Current outlook

Herbicides are currently the main tool used for weed control in commercial blackcurrant plantations. They are effective for selected weeds targeted at the right stage of growth and provide affordable and ‘easy to apply’ management solutions. However, herbicide-only solutions are becoming less sustainable due to herbicide revocations, difficult registration processes for new active ingredients in minor crops, and poor herbicide penetration within the plantations, to name but a few.

Currently, blackcurrant bushes are planted in rows, with ca. 40cm between plants and rows approximately 3m apart. The majority of plantations are now maintained with a herbicide-treated strip down the row and grass alleyways in between. Weed control within the row is crucial for maintaining crop quality and yield and reducing the chance of contamination and machine damage at harvest. Control of weeds between rows is important to limit the spread of weed seed and pests and diseases, and to overcome access problems for mechanical harvesting. Perennial broad-leaved weeds such as creeping thistle, perennial nettle, docks and field bindweed are a persistent problem in blackcurrant crops. Perennial grass weeds such as couch grass and annual broad-leaved weeds such as mayweed and common chickweed also require control in blackcurrants. Alternative weed controls are becoming more widespread for weed control in blackcurrant.

Where bindweed becomes a problem in blackcurrants at harvest it is removed from the bushes by hand to stop it becoming tangled in the harvesting machinery. During the growing season, due to the limited herbicides available, weeds with large tap roots, such as thistles or docks must be removed manually in order to stop seed set.

Hand weeding and hoeing is effective in the zone immediately around plants especially during crop establishment. Mechanising this slow and costly operation could provide a cheaper alternative, however limitations in penetration ability between plants reduce effectiveness of mechanical equipment.

Currently the main methods assisting blackcurrant crop establishment include the use of synthetic plastic mulches and mechanical weed control. Each of those methods come with their own challenges as described below.

Mulches

Mulches supress weeds by forming a physical barrier at the soil surface. Covering the soil surface prevents weed seed germination and suppresses the growth of emerging seedlings by blocking the light (Schonbeck, 2012). Mulches take the form of sheeting, loose particles, or a living layer of vegetation (living mulch). Whether synthetic, organic or living, mulches alter the above and below ground environment, resulting in both desirable and undesirable effects that have an impact on crop yield and quality, such as change in plant canopy density and temperature, humidity, photosynthetic rate and root growth (Abouziena *et al.*, 2008; Jacometti *et al.*, 2007). Additionally, effects of altering soil nitrogen by some organic mulches should be carefully managed (Wang *et al.*, 2019). Different plant species and cultivars may respond differently to the same mulch (Robinson, 2008).

Types of mulches are described below, including synthetic plastic mulches and bioplastic, inert organic mulches and living mulch, cover cropping and companion cropping.

Synthetic mulch

Plastic and bio-degradable plastic represent a main alternative weed control method to chemical herbicides and tillage in blackcurrant and other fruit crops such as blueberry. Use of plastics, however, is not sustainable and poses environmental concerns linked not only to the use of non-renewable resources and the creation of non-degradable waste, but also through the negative impact on soil and epigeal fauna by modifying the undercover microclimate and increasing the need for irrigation (Bandopadhyay *et al.*, 2018; Cook *et al.*, 2019). Synthetic mulches include polypropylene plastic, nonwoven polyacrylic fabric and woven black polypropylene fabric ‘mypex’ (Lisek, 2014); the latter is more expensive than the others but is also longer lasting (up to 12 years, as opposed to 6-8 years). Weeds can still establish in the planting holes containing the cuttings or if the plastic is torn accidentally. This is addressed with sawdust in blueberry (Strik *et al.*, 2008). Other novel media addressing this issue include hydrophobic kaolin clay mixed with soil and applied in a 4-cm layer around the base of blackberry cuttings after planting, which can be effective in weed control with no significant impact on yields in the mature crop (Takeda *et al.*, 2005). Even with undamaged plastic, vigorous weed growth can occur on the mulch surface especially if soil and other debris accumulates. Some growers clean the polypropylene surface of debris and soil, to prevent residue build up (Hammermeister, 2016). Mypex is often recommended due to its greater durability and better water penetration, although this mulch is more expensive and in the long term, may be detrimental to soil quality due to soil heating effects (Neilsen et al., 2003). Using woven fabric can provide better and more cost-effective weed control than using sawdust or sawdust with compost in blueberry, but this method increases planting costs (Julian et al., 2012). Some plastic mulches have reflective properties that increase light penetration into the crop and can improve crop productivity (Comeau *et al.*, 2012; Petridis *et al.*, 2018). Additionally, new emerging data suggests that plastic mulch may provide a barrier for pests such as *Drosophila suzukii* (spotted wing drosophila) to pupate. Field trials and greenhouse experiments showed that larvae burrowed to pupate underneath sawdust mulch, but were unable to pupate underneath a plastic weed mat mulch (Rendon *et al.*, 2020).

When installed correctly, usually in autumn, plastic mulch will aid establishment of the blackcurrant crop and provide good weed suppression. The synthetic mulch is laid tight to the ground forming beds to keep moisture and heat in the soil. This also provides flexibility for planting cuttings at a convenient time after mulch-laying, as the beds are already prepared. Problems arise when mulch is laid poorly or too late or if plastic contact around the base of cuttings is too loose or too tight. Further disadvantages include the possibility of creating too wet an environment, often associated with addition of organic manure, that can encourage cuttings to rot after planting. Disposal of waste plastic is a problem and mulches are expensive to purchase, so alternatives should be used whenever possible.

The main advantages of plastic cover in blackcurrant are during the establishment phase, as covering the soil surface prevents weed seed germination and suppresses the growth of emerging seedlings giving competitive advantage to cuttings. Other mulches such as dead organic materials (inert mulches) and plastic alternatives such as bioplastic covers are under evaluation to assess their usefulness in mimicking this physical property.

Several scientific reports presented in this study show contradictory results when demonstrating impact of plastic mulches as compared to organic alternatives on blackcurrant growth and yield. This may be the result of differences in the range of genotypes tested, having very different vigour profiles and root characteristics (Lindhart Pedersen, 2001). Regional differences will also have an impact in terms of background variation in environmental conditions, particularly soil properties which will influence nutrient uptake, water availability and complex dynamics in soil processes (Larsson, 1997). This emphasises the need for long-term, regional trials across a range of environmental conditions using common genotypes and comparable data collection protocols.

Larsson (1997) indicated that blackcurrants grown with plastic mulch had a smaller berry size compared to bare soil and wood-chip mulch; by contrast, plastic mulch in irrigated blackcurrants has been shown to increase yields by 26% when compared to weed control using chemical herbicides (Dale, 2000). Several reports also suggest that organic mulches can increase vegetative growth (Paunović *et al.*, 2016), fruit vitamin C content (Paunović *et al.*, 2017), and yield (Paunović *et al.*, 2020) when compared to plastic mulch. Larsson (1997) has shown that both plastic and sawdust increased shoot and bush growth.

Summary Plastic Mulch			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+) Aids establishment when laid correctly, good weed control	(+/-) Poor weed control when damage occurs or in planting hole, need for removal and disposal, environmental impact	Impact on environment, cost of removal and disposal	Alternative environmentally friendly mulches (organic, bio-based, bio-degradable)

Bioplastic

Bioplastics can be divided into three groups:

1. Bio-based or partly bio-based, non-biodegradable plastics such as bio-based PE, PP, or PET, and bio-based technical performance polymers such as PTT or TPC-ET
2. Plastics that are both bio-based and biodegradable, such as PLA and PHA or PBS
3. Plastics that are based on fossil resources and are biodegradable, such as PBAT (reviewed by European Bioplastics (EuBp Fact Sheet)

Although biodegradable, some mulch products may contain fossil fuel-derived stabilisers. On the other hand, non-petroleum-derived films may still take several months to biodegrade and residues can be dangerous to fauna (Kasirajan et al., 2012). Not all plastics made from plant biomass are biodegradable - the level of biodegradability depends on its chemical structure. Ghimire et al. (2018) suggests a ‘focus on the biodegradation of mulch in field environments and the fate of the resulting molecules, rather than on the source of the carbon in a biodegradable polymer’. The topic is complex, and ideally the sought-after mulch will be bio-based and (rapidly) biodegradable (PLA, PHA or PBS), so not containing petroleum-derived compounds but providing sufficient weed control during crop establishment phase. This could offer a sustainable alternative to plastic mulch thereby reducing waste and contributing towards agricultural productivity by preserving soil health and overall environmental quality. Ongoing research contributes to the improved quality of biodegradable plastics, their durability and biodegradability, although those are opposing requirements (Chapman, 2020). A wide range of biodegradable plastics are available as mulch film.

Blackcurrant Case Study: **Starch based biofilm**

One UK grower is using starch based 50 microns black OPL biofilm from Gromax Industries Ltd, with anticipation to include this as a system with living mulch and organic mulch derived from alleyways for topping up starch-based mulch film for better weed suppression and other benefits. In this trial, the cost of corn starch mulch was comparable to that of plastic mulch and the water retention and weed control were satisfactory in the system with drip lines (Berry, pers. comm).

Starch based, PBS and Mater-Bi mulch products offer similar mechanical properties to conventional PE, and do not have any adverse long-term effects on the environment, but the cost involved in making these biodegradable mulch films is still high (Chapman, 2020; Marí *et al.*, 2019). Mater-Bi is an innovative bio-based plastic mulch based on starch and biodegradable polyesters derived from vegetable oils developed as a part of the EU-funded project 'Development of enhanced biodegradable films for agricultural activities' (AGROBIOFILM, 2013).

Blackcurrant Case Study: **'Alternatives to Plastic Film Mulch'**

An ongoing field lab 'Alternatives to Plastic Film Mulch' is taking place through an innovative farmers incentive in the UK. In blackcurrant, two sizes of willow wood chip and biofilm are compared to bare soil (www.innovativefarmers.org). In the first year of the trial, wood chip appeared to outperform biofilm (Mater-Bi), especially where there were tears in the biofilm. There was a higher rate of dwarfism and deaths in the cuttings under biofilm compared to woodchip. The mulches were equally effective at suppressing weed cover, resulting in slightly taller plants compared with the un-mulched plot. The un-mulched plot experienced full weed coverage.

The blackcurrant grower would prefer to use woodchip as a mulch and has access to willow and spruce on farm. However, there were possible indications of mineral deficiencies (yellow tinge on leaf), which may affect the plant in the long term, so choosing the right type of wood and further research into mulching effects on crop is crucial. Drip lines were laid under the woodchip to maintain moisture https://innovativefarmers.org/case-studies/alternatives-to-plastic-free-mulch/

Novamont (Italy) are producers of Mater-Bi mulch, used in a range of crops including vines (Gastaldi *et al.*, 2018). In open field raspberry, blueberry and vine trials in Europe, Mater-Bi had durability of up to 18 months (Novamont). Degradation of Mater-Bi based film is possible to control by changing the thickness. Smaller manufacturers such as 'Samco.ie' develop customised options for vegetable crops and provide customised material to suit growers depending on soil type and local weather conditions (Shine, pers. comm.)

Summary Bioplastic			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+/-) Poor durability, tears more easily than synthetic plastic. Better establishment using organic mulches	(+/-) Poor durability, variable biodegradability depending on thickness and composition.	High cost, poor durability	Use in combination with alternative mulches (organic), reformulation

Inert organic mulches

Organic mulches are derived from plant materials such as wood, grass and crop residues. They increase soil organic matter content, improve soil characteristics, and maintain good water holding capacity (Sinkevičienė *et al.*, 2009). However, on low lying, poorly drained sites or soils, excessive moisture under mulches during wet springs may result in root suffocation or increased frost injury (Robinson, 2008). Natural materials can be less effective than plastic mulches and different organic materials have variable influence on soil properties (Forge *et al.*, 2003) and weed suppression capacity (Jodaugienė *et al.*, 2006). However, they provide more sustainable weed control options, can be very effective if applied in the optimum way and provide added benefits to soil and crop health. The implementation cost of organic mulches is higher than that of synthetic herbicides (Merwin *et al.*, 1995) or plastic covers and could be prohibitive unless the material is produced on the farm or is made of cheap waste (Lisek, 2014). Additionally, installation of some organic mulches can be difficult and requires specialistic equipment (Pedersen, Coode-Adams pers. comm). To growers, however, other advantages may outweigh the incurred costs, especially considering long term benefits to soil health and minimising environmental impact. Decomposition of natural mulches can affect the establishment of the crop, as a result of short term mineral nitrogen reduction, particularly for mulches rich in cellulose (bark, sawdust, straw, wood chips) with a high C:N ratio (> 30:1) (Bond *et al.*, 2001; Treder *et al.*, 2004). Fresh sawdust (C:N ratio 500:1) and wheat and barley straw (C:N ratio 100:1) will require additional applications of nitrogen to compensate for this imbalance. However mulches of young grass clippings (C:N ratio 12:1), average grass clippings (C:N ratio 19:1) or seaweed (C:N ratio 19:1) will not (Robinson, 2008). Additionally, phytotoxins released during decomposition of organic materials can have allelopathic effects on weeds and crops (Bond *et al.*, 2001).

Mulching has been shown to be effective against annual weeds, although it can be less effective against established perennial weeds which regenerate from deep root stocks (Bond *et al.*, 2001; Hammermeister, 2016; Larsson, 1997; Rowley *et al.*, 2011; Stefanelli *et al.*, 2009). Additionally, mulches restrict nutrient and water management on infertile sites (Hammermeister, 2016) so may require installation of drip irrigation. The most common non-living organic mulches in fruit crops include rape and buckwheat straw, sawdust, wood chips, manure, shredded paper, compost, hay, aggregated lignite, composted poultry litter, fruit pomace, textile (linen, jute, wool) and peat moss (Lisek, 2014). A few of the most commonly inert organic mulches used in fruit and perennial crops are reviewed below.

Wood chip and Sawdust

Wood chip is one of the most common organic mulching materials and is widely used in other perennial crops such as blueberry (Strik *et al.*, 2019) and in orchards (Ingels *et al.*, 2012). A single application of a minimum of 10 cm wood chip can provide weed control for up to 3 years. However, large amounts are required for commercial production, it can be difficult to obtain, has variable quality and can be expensive (Lisek, 2014). Choice of wood type will also be important as some sources may cause phytotoxicity and in some cases, immobilisation of nitrogen with a potential knock-on effect on yield (Larsson, 1997; TerAvest *et al.*, 2011). Other drawbacks of wood chip include limited efficacy in controlling perennial weeds and increased rodent infestation (Granatstein *et al.*, 2014; Larsson, 1997).

Blackcurrant Case Study: **'Alternatives to Plastic Film Mulch'**

Ongoing UK blackcurrant trials (Innovative Farmers, 2020) showed that willow wood chip based treatment resulted in leaf chlorosis. However, plant establishment in this treatment outperformed biofilm and there was higher rate of deaths and dwarfism in the cuttings under biofilm compared to wood chip. In this trial two different sizes of farm produced wood chip were used: 1) large 30mm and dry (less than 30% moisture) and 2) smaller, Timberwolf type chipper mulch, chipped wet and composted for a year. The smaller wood chip was more prone to weeds and visibly rotted during the trial but provided more organic matter to the soil. The trial has also highlighted practical considerations for wood chip application: wood chip was applied by hand with cardboard tubes placed around the blackcurrant cuttings to prevent contact, as cuttings died when removed by the activity of crows or rabbits. In the same trial, drip lines were laid under the chip for additional irrigation. The grower highlighted that in the future they will aim to electronically link the monitoring of the moisture under the wood chip to the drip line to automate the watering. After a one-year trial, the grower concluded that wood chip can be an excellent solution especially as they can source their own willow material but further trials over a longer period are required to increase knowledge and refine the system (Code-Adams, pers. comm.)

Several studies suggest using soil amendments or green mulch on top of wood chip for nitrogen supplementation (Neilsen *et al.*, 2013). In a study of woodchip mulch in blackcurrant in Latvia, a higher N rate (9.5g N per plant) applied to 10 cm wood chip mulch treatment was found to show no significant effect on phenological development, yield and fruit size compared to herbicide control. Additionally wood chip treatment significantly reduced weed growth and leaf spot severity (Laugale *et al.*, 2016).

Blackcurrant stems contain hardwood lignin (Stewart et al., 1996) and have been found to be effective in eradicating liverwort (*Hepaticae*) when used as pot dressing (Särkkä *et al.*, 2020). In Elder (*Sambucus* spp.), a combination of landscape fabric and layers of softwood or fresh ramial wood chip is used for weed control at the base of the trees (Jones, 2020). Chipped ramial wood has also been shown to increase soil organic matter content, stimulate soil biological activity, improve medium-term nutrient availability and preserve moisture (Barthes et al., 2010).

Sawdust has potential to improve physical, chemical and biological properties of the soil leading to an increase in plant growth and yield of blackcurrants (Larsson, 1997; Paunović *et al.*, 2020; Paunović *et al.*, 2016). Sawdust and wood chip mulch have a favourable effect due to lower variations in soil temperature (lower during the day and slightly higher at night) and reduced soil evaporation when compared to plastic mulch treatment (Robinson, 2008). As a result, phenological development can be delayed. However, in raspberry, a yield benefit has been detected (Pantsyreva *et al.*, 2020). Old or rotted sawdust will form humus more rapidly and is less likely to cause nitrogen deficiency. However, it can provide a good germination medium for wind-blown weeds and can become matted causing soil to become wet and airless. In a 3 year study conducted on a blackcurrant plantation, it was found that sawdust mulch led to an increase in fine sand content (7.7%), and a decrease in clay (6.4%) and silt (1.3%) content (Paunović *et al.*, 2020). The soil was classified as sandy clay loam at the beginning of the experiment, and at the end was classified as sandy loam. In the experiment, the lowest decrease in soil pH was found in sawdust mulched soil and it also had a stimulating effect on nutrient content (humus, N, P and K) and microbial count (colony forming units) in the soil. In other trials, sawdust mulch treatment increased berry content of vitamins C, A and B3 (Paunović *et al.*, 2017), and was effective in increasing shoot and bush growth (Larsson, 1997).

In blueberry, organic soil amendments such as compost are used with sawdust to aid the building of organic matter and N supply and increase yield (Strik *et al.*, 2012). However, this doesn't increase yield long term (Strik *et al.*, 2019).

In blackcurrant and apple, colonisation of roots by arbuscular mycorrhizal fungi was studied following mycorrhization and the use or organic mulches; the study showed that all of the organic mulches used in the experiments (peat, bark, sawdust, manure, compost, mycorrhizal substrate, straw) increased the degree of mycorrhizal association of the roots of the apple and blackcurrant plants (Derkowska *et al.*, 2013). Additionally, roots of blackcurrant bushes were more frequently colonised by mycorrhizal fungi than the roots of apple trees. Mycorrhizal fungi present an opportunity to promote the growth of juvenile plants through multiple mechanisms (Orrell, pers.comm). As the root systems of juvenile plants are less developed than adult plants, dependence on mycorrhizal fungi for nutrient acquisition is increased (Aldrich-Wolfe, 2007; Van Der Heijden, 2004). The proper development of the root system and the activity of the processes taking place in the rhizosphere, including the activity of symbiotic mycorrhizal fungi and rhizosphere bacteria, are of great importance for the proper development of plants in all natural communities as well as in orchards and berry fruit plantations (Sas Paszt *et al.*, 2002; Sas Paszt *et al.*, 2003). Similarly, mycorrhizal fungi can improve the ability to mitigate abiotic stresses such as drought, improving resilience and in turn biomass accumulation in seedlings (Birhane *et al.*, 2012). Benefits realised from mycorrhizal fungi are dependent on the specific combination of mycorrhizal community/species/strain and plant species, and as such it is key to select the most appropriate mycorrhizal fungi for the intended application (Orrell, pers.comm). For example, mycorrhizal fungi can influence specific traits, such as plant-pollinator interactions, but the direction and degree of influence can depend on the specific pairing of mycorrhizal fungi and plant species (Barber *et al.*, 2013; Gange *et al.*, 2005; Orrell, 2018).

Summary Wood chip and Sawdust			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+) Satisfactory weed control, can improve establishment of a young crop	(+/-) Phytotoxicity and reduced mobilisation of nutrients has negative impact on crop	Large quantities required, specialised equipment required for application, need for drip irrigation, lack of knowledge of management of nutritional imbalance and phytotoxicity	Explore mulch effects on root system, soil biota and crop, and link the interactions to improved crop performance. Increase knowledge on prevention of nutritional imbalance and phytotoxicity. Explore sources of in-house mulching materials. Trial in combination with other approaches such as companion cropping and residue retrieval, soil amendments (incl. mycorrhizae). Review nutritional requirements of blackcurrants.

Straw

Straw has been widely used in strawberry crops for many years, and it is also successfully used in other fruit crops such as raspberry (Lisek, 2014). It can originate from grain, rape, buckwheat and other sources. Straw also contains high carbon content so may reduce the availability of nutrients. However, straw has the highest water penetration properties and can increase potassium levels in the soil (Hammermeister, 2016) when compared to wood chip and sawdust.

Yield benefit has been reported in: apple when compared to tillage (e.g. Andersen *et al.*, 2013, where an additional benefit to earthworm communities was also demonstrated); rose hip when compared to black plastic and wood based treatments if supplemental hand weeding was included; and grape when compared with cultivation or green cover (Hammermeister, 2016). Straw in its natural form may require anchoring and there is a risk of interference with mechanical harvesting if disturbed or lifted. In addition, it provides a perfect environment for rodents and presents a potential fire hazard. It is essential when using straw as a mulch not to introduce more problems by ensuring the straw is free of weed seeds (AHDB, 2018) and cereal grains, and contains no herbicide or growth regulator residues. Some growers solarize the bales by sealing them in clear plastic then leaving them in full sun for at least 2 weeks to kill off the weed seeds. Similar to wood chip, supply of straw may be temporarily limited in some regions and material could be inconsistent so in house production would be favourable.

Blackcurrant Case Study: **Field trials in Denmark**

Thick layers of stiff rape straw lasted for more than 2 years in blackcurrant plantations (Lindhard Pedersen, pers. comm), where the yield of 'Ben Hope' was significantly higher in non-watered straw plots as compared with shallow mechanical cultivation using Tournesol (Pellenc) or black 'mypex' mulch. Lowest yields were recorded in hand weeding and grass cover treatments. In watered plots there was no significant difference in yield between treatments except in grass cover plots which had significantly lower yields.

Photo 1 Rape straw treatment in Danish blackcurrant trials. Courtesy: H Lindhard Pedersen

In Danish trials rape straw applied at planting (25-30cm) got compressed by the time of harvest to 5cm, did not interfere with mechanical operation and, in this case, rodents were not a problem (Lindhard Pedersen pers. comm.). This trial identified the need for development of machinery for efficient cutting and spreading of the straw.

Straw is the most under-utilised, abundant, renewable and low cost agricultural residue and has extremely high potential to be utilised in green composites such as reinforcement/filler in bioplastics (Zhao, 2013). Proprietary mulches have been developed in the past e.g., straw dust consisting of resin impregnated granules of wheat straw. This material was believed to be long lasting, sterile and contained a slow release nitrogen fertiliser (Robinson, 2008).

Summary Straw			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+) Satisfactory weed control, can improve establishment of a young crop	(+/-) Shown to increase yield. Re-application required, may interfere at harvest	Large quantities required, specialised equipment required for application, fire risk, rodent issues, contamination risk	Potential for straw-based formulations or proprietary mulches. In house production favourable

Paper

Paper mulches are approved by the UK Soil Association as suitable for use in organic farming. The main advantage of paper mulches is that they do not create the disposal problems that plastic and partially biodegradable materials do. Paper mulch breaks down naturally and can be incorporated into the soil where it biodegrades rapidly (within six months) of soil-incorporation (Haapala *et al.*, 2014). Paper mulches are beneficial in the fact that they are porous, allowing rainwater to penetrate and air to circulate which improves root growth. Paper can be effective at weed control and increase yield and quality of the crop (Haapala *et al.*, 2014). However, laying and using paper mulch in commercial farming is not practical as it tears very easily. Crepe paper has been shown to have better pliability, flexibility, and stretch for best moulding to the contours of soil (Moore *et al.*, 2019). When tested in different trials, crepe paper did not tear compared with the non-creped paper and both gave good weed control, comparing favourably with black polyethylene (Bond *et al.*, 2003). Shredded newspaper at 2-3.4 tons/acre was also found to be as effective, if not superior to, wheat straw in suppressing most annual and some perennial weeds (Haapala *et al.*, 2014). In apple orchards, wetted, shredded office paper has been found to provide good weed control and yields comparable to plastic and alfalfa mulches (Granatstein *et al.*, 2008; Neilsen *et al.*, 2003; Neilsen *et al.*, 2002). Paper sheeting comes in a choice of weights, widths, and lengths, creped and un-creped and also containing fertiliser enrichment such calcium or humic acid.

Successful use of paper mulch to aid crop establishment will depend on rapid crop growth, paper reformulation or further advances in coating and managing paper mulches (Haapala *et al.*, 2014).

Summary Paper			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(-) Not practical as it tears very easily	(-) Only applicable on small scale	No robust options for commercial scale	Reformulation required to overcome poor durability on commercial scale

Waste and by-products

Waste by-products used as a mulch include de-oiled olive pomace (DOP) in vines, which provided reasonable weed control, improved vine physiology and soil fertility (Camposeo *et al.*, 2011; Ferrara *et al.*, 2012), cranberry fruit and leaves in blueberry which controlled weeds but reduced yield (Krogmann *et al.*, 2008) Krogman et al., 2013) and grape marc – pomace residue containing grape skin and pulp (Bekkers, 2011). Phenols and tannins in coniferous bark and sawdust improve the degree of weed control (Robinson, 2008). Blackcurrant pomace contains high levels of phenolics (Sójka *et al.*, 2009). Extracts of blackcurrant fruit (Ochmian *et al.*, 2014) and leaves (Nour *et al.*, 2014; Vagiri *et al.*, 2015) contain antioxidant-active compounds such as phenolics that inhibit the growth of certain microorganisms (Werlein *et al.*, 2005). There is no information regarding blackcurrant pomace use as mulches, and it is likely that the amount of material required will not be obtainable on a commercial scale. For example, one hectare of super high-density orchard, with a 3 cm layer of mulch, needs 40 tonne of de-oiled olive pomace for soil mulching (Camposeo *et al.*, 2011). Waste can also be incorporated with other materials for bulking up and added benefits. Hydramulch is a biodegradable paper-like material that consists of a slurry of cotton waste, newsprint, gypsum and adhesive and provides an alternative to plastic mulch with a tougher layer to prevent penetration of more difficult to control weeds like grasses (Hammermeister, 2016; Warnick *et al.*, 2006). Where available, blackcurrant growers used spent mushroom compost as a mulch in organic plantations although continuation of supply was an issue (Baryła, pers. comm). Spent mushroom compost also provides a rich source of nutrients to plants - an application of 20 tons per acre will provide 36 kg nitrogen, 34 kg phosphorus and 158 kg potassium per acre (Maher, 1990).

Summary Waste and by-products			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(-) Lack of research	(-) Lack of research	Not enough knowledge, not enough waste available for even and timely distribution	Waste as additive to organic mulches for potential in creating closed economy.

Living mulch, cover cropping, companion cropping

Living mulches are cover crops planted between rows of the main crop as a living ground cover throughout or for part of the growing season. The term living mulch can be also be referred to as companion cropping or intercropping (Cook *et al.*, 2019). In addition to suppression of weeds by physical means of intercepting light, cover crops shade the soil and reduce soil surface temperatures, and have allelopathic properties (Bond et al., 2003). Several sources (Bond *et al.*, 2003; Cook *et al.*, 2019; Granatstein *et al.*, 2009; Hammermeister, 2016; Hogue *et al.*, 2010; Mia *et al.*, 2020; Tzortzi *et al.*, 2015) indicate that as well as suppressing weeds, cover crops influence overall soil health: they increase organic matter content which improves soil structure and water holding capacity, reduce soil erosion and enhance biodiversity of soil organisms. When mown and blown under the crop, cover crop residue can provide a source of organic matter to the soil (Granatstein *et al.*, 2009). Cover crops also improve nutrient cycling and nitrogen fixation (particularly if legume species are included). Nitrogen (N) supplied by legume crops can be held in the soil for extended periods and be available for plant uptake, unlike highly soluble N fertilizers, which have a significant potential to leach out of the plant root zone. The increase in plant biodiversity through cover cropping also aids pest control, by providing habitat and alternative food resources for beneficial predators, and could benefit fruit set by providing floral resources for pollinators (Beizhou *et al.*, 2012).

Blackcurrant Case Study: **Austrian residue retrieval**

In Austria blackcurrant growers use mown grass mixes from alleyways as green mulch under the blackcurrant plants (Lampl, pers. comm). For this purpose, mowers are used rather than mulchers so the grass is longer and less prone to be blown away.

Kivijärvi *et al.* (2005) indicated that green mulch is effective in suppression of weeds in blackcurrant, although it had to be reapplied due to fast decomposition. In blackcurrant, Lindhart Pedersen (2001) found that annual and perennial cover crops provided sufficient nitrogen supply in organic production for crop establishment and there were no significant differences in yield between several treatment combinations including mulching, mechanical weeding, cover cropping and N addition. The main disadvantage of cover crops is competition with the crop for water and nutrients. Tall cover crops used as living mulches can also shade the crop and increase risk of Botrytis disease (Granatstein *et al.*, 2009). Cover crops have been shown to create habitat for rodents, provide variable ability to compete with weeds, show variable persistence and can need re-sowing (Granatstein *et al.*, 2009). Subterranean clover, which can thrive in poor quality soil, is self-seeding (underground) which is an advantage when used as an on-going mulch in perennial crops. Volunteer cover crops can also re-seed in the alleyways and planting holes, so there is a need for management of the cover crop prior to crop establishment (Attwood 2017). The most important attributes of plant species suitable as living mulches are quick emergence and soil covering, short height and low water and nutrient demands, perennial habit, frost tolerance and physical separation from the crop at harvest. Living mulches such as white clover (*Trifolium repens*), black medic (*Medicago lupulina*), creeping red fescue (*Festuca rubra*), birdsfoot trefoil (*Lotus corniculatus*) and a combination of creeping red fescue and birdsfoot trefoil can significantly supress the weed population in apple orchards as compared to untreated control and herbicide treatment (Tzortzi *et al.*, 2015). However, negative impact on apple yield is common and can reduce the likelihood of uptake by growers (Atwood *et al.*, 2016; Hogue *et al.*, 2010;

Neilsen *et al.*, 2000). Low root density of fruit trees compared to the understory vegetation may be the main reason for such competition which can be mitigated by selection of less competitive species and by frequent mowing (Bond *et al.*, 2003; Mia *et al.*, 2020). Significant reduction in blackcurrant yields and competition for water was previously demonstrated when cover crops such as red fescue (*Festuca rubra*), alfalfa (*Medicago sativa* subsp. *glomerata*) and red clover (*Trifolium pratense*) were grown in blackcurrant alleyways (Dale, 2000; Larsson, 1997). Red fescue (*Festuca rubra*) and black medic (*Medicago lupulina*) cover crops sown prior to planting blackcurrant cuttings were found to supress noxious weeds with no effect on blackcurrant establishment, although the effects on yield were not evaluated (Atwood *et al.*, 2016). This experiment also highlighted the need for selective eradication of weeds depending on treatment, emphasizing the need for specific cover crop species or species mixture trials. In vineyards cover crops are often a mix of grasses, legumes and forbs to achieve several benefits simultaneously. For a comprehensive review of cover crop species recommended for vineyards at various locations and cover crop properties and suitability, see Guerra *et al.* (2012). Timing and rate of sowing living mulch also affects the success of weed control and crop competition (Mohammadi, 2013).

In addition to species mentioned in the literature in the body of the text, popular orchard cover crops (as listed by Lisek (2014) include:

Common name	Latin name
blue grass (smooth meadow-grass)	*Poa pratensis*
perennial ryegrass	*Lolium perenne*
white clover	*Trifolium repens*
persian clover	*Trifolium resupinatum*
berseem clover	*T. alexandrinum*
pea	*Pisum sativum*
white lupine	*Lupinus albus*
crown vetch	*Coronilla varia*
common serradella	*Ornithopus sativus*
blue (sheep's) fescue	*Festuca ovina*
hard fescue	*F. longifolia*
tall fescue	*F. arundinacea*
annual ryegrass	*Lolium multiflorum*
colonial bent grass	*Agrostis vulgaris*
timothy grass	*Phleum pretense*
orchard grass	*Dactylis glome rata*
wheat	*Triticum aestivum*
rye	*Secale cereale*
barley	*Hordeum vulgare*
oat	*Avena sativa*
harlequin marigold	*Tagetes patula nana*
white mustard	*Sinapis alba*
tansy phacelia	*Phacelia tanacetifolia*

Living mulches are best used in established crops, when competition for water and nutrients is less significant than during establishment (Hammermeister, 2016). Competition from living mulches can be managed mechanically. Crimper Rollers have been developed for cover crop termination (IWMPRAISE, 2020a), but could offer a solution for living mulch management – e.g. to 'knock back' green understories to manage crop-mulch competition during establishment or at key developmental stages (Sayre, 2010) (Appendix 2). Resident crops, i.e. those previously cultivated in the field where plantations are to be established and synanthropic flora, can also be used as living mulch when maintained beyond the sowing year. The presence of winter annuals and living mulches helps control escaped weeds and may prevent or slow the invasion of new weeds. Monteiro et al. (2007) concluded that the resident crop performed similarly to a sown mixture of grasses and legumes in vineyards and was a preferred option as a living mulch as it does not need to be sown. Synanthropic flora can be beneficial and has influence on living organisms and can improve chemical and physical properties of the soil (Lisek, 2014)

Use of cover crops is possibly most successful in a managed system. The Swiss Sandwich System developed by the Research Institute of Organic Agriculture uses living mulches directly under the crop in combination with a strip of shallow tillage running parallel on either side of the crop and grass alleyway in between rows to reduce root competitiveness and avoid cultivation damage to crop roots just below the soil surface. This also allows compost and manure to be applied to the bare, cultivated area (Stefanelli *et al.*, 2009). This method has been found to be the most optimal for yield, weed control and cost, outperforming flaming and living mulches in several orchard trials (Lisek, 2014; Mia *et al.*, 2020). In an organic apple trial in Argentina, legume cover crops were planted in the alleyway, while resident vegetation was left in the weed strip and mowed twice a year (Sánchez *et al.*, 2007). The cover crops were mowed in place, and the resident crop was disturbed by disking twice in late winter for passive frost control and then allowed to re-grow. The legumes led to increased trunk size and fruit yield compared to the control, but leaf N still declined over time (Sánchez *et al.*, 2007). It was suggested that this negative effect could have been mitigated by delivering cover crop clippings directly to the tree row where most tree roots are located. It should be recognised that cover cropping benefits are often not a quick fix and can take several cycles to accrue and become apparent (AHDB, 2015).

Blackcurrant Case Study: **Integrated system in Kent, UK**

Currently, a grower in Kent, UK is evaluating use of radish (*Raphanus sativus*), common vetch (*Vicia sativa*) and phacelia (*Phacelia tanacetifolia*) in combination with corn starch bio-degradable mulch with the intention of mowing the living mulch onto the crop rows for additional crop benefits. Some machinery had to be adapted for sowing and mowing of the living mulch.

Photo 2 Living mulch used in combination with corn starch-based mulch. Courtesy J. Berry

The choice of the living mulch will depend on the grower's goal, natural resources (water, nutrient, soil conditions) and cover crop trait characteristics to reduce competitiveness with the crop and enhance provision of regulating ecosystem services (pest control, nutrient availability etc.). Cover cropping is likely to be a part of the overall farm management system.

Summary Living mulch, companion cropping, cover crop			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+/-) Cover crops pre-planting reduce weed pressure. Companion plants compete for water and nutrients during crop establishment. More suitable for established crop	(+/-) Require maintenance (mowing, grazing, rolling), require re-sowing, competition with the crop, potential yield penalty	Variable persistence, variable ability to compete with weeds, potential yield reduction, lack of knowledge of most suitable species/species mixes	Comparative studies of soil biology under different species and understory management approaches stimulating mycorrhizal colonisation of crop roots, stimulating nitrogen fixing, introduce and sustain nitrogen fixing organisms. Identify (review/trial) best crop mixes and management practices also in combination with other approaches (mow and blow) and rotation practices for weed suppression but also soil enrichment (legumes). Use cover crops pre-planting.

Mechanical weeding

Mechanical weeding is the most common physical method complementing herbicide use for weed control in several perennial crops including blackcurrant (Andersen *et al.*, 2013; Cook *et al.*, 2019; Lisek, 2014; Mia *et al.*, 2020). Mechanical weeding can significantly reduce the number of herbicide applications required for weed control and is widely used by organic farmers. Manual weed removal by hoeing especially during plantation establishment is practiced and although it provides a very good complementary control it is logistically challenging on a commercial scale and an expensive option due to labour cost. Research and commercial efforts have aimed at replacing laborious hand-weeding with mechanisation (Melander *et al.*, 2005), mainly based on tillage which controls weeds by burying in soil, uprooting and tearing plants into pieces (Mohler *et al.*, 2001). Plant spacing is critical for successful mechanical weeding and crops need to be planted in rows or other regular patterns to avoid being damaged. In row crops, intra-row weeds growing between plants along the row pose a major challenge (Pannacci *et al.*, 2017). Several machinery types have been developed and adopted for orchards where spacing between plants is much greater than in blackcurrant plantations. Tree fruit and vines with single trunks are also easier to manage compared to soft-fruit bushes which are branched at the base and form a dense canopy above. The effectiveness of mechanical weeding is dependent upon soil type and moisture levels, weather conditions, weed size, species and their resistance to uprooting and the type of equipment including adjustment of angle and position and speed (aggressiveness) (Chicouene, 2007; Simoncic *et al.*, 2005).

High UK rainfall may pose a barrier to regular machinery usage as it can encourage uprooted weed seedlings to root again or to stay attached to soil aggregates during weeding, allowing subsequent re-growth. Additionally, machine entry to the field may not be possible. Higher soil moisture may also encourage weed growth more than in other European countries where several machinery types are developed and used in drier conditions in which machinery is more efficient and will require fewer passes during the growing season. Some of the other drawbacks of using machinery include: the need for skilled and knowledgeable operators; low work pace caused by delays due to wet conditions leading to the risk of weed control failure as weeds become larger (Van Der Weide *et al.*, 2008); high costs due to fuel use and high initial purchase price; damage to soil structure by cultivation, resulting in soil erosion; soil disruption triggering further germination of weed seeds (AHDB, 2017); and, as germination of weeds can occur over two to six weeks or longer, multiple passes may be needed to provide good weed control. As reviewed by Mia *et al.* (2020) excessive tillage can have harmful effects on the soil-quality parameters such as biological diversity, soil structure and water holding capacity. It also reduces the supply of carbon and nitrogen nutrients to soil microbes, soil microbial composition, enzyme activities and biological processes. Tillage affects the soil cation exchange capacity and nutrient availability, with a consequent reduction 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.

Reduced tillage, however, offers many economic and environmental benefits (Alskaf *et al.*, 2020) and several modern machines have been developed to overcome some barriers to adoption such as poor weed control. For example, modern finger weeders are recommended for shallow tillage for crops with abundant shallow roots. Below we describe a few of the mechanical weed control options used in orchards, vineyards, blackcurrants, and other fruit crops. Those include finger weeders and rotary star tillers, rotary hoes, side weeders and tillers, brush weeders, mowers, strimmers and mulchers.

Finger weeders and Rotary star tillers

Swing arm weeders with feelers allow machinery to operate within and in some degree around the crop such as fruit trees, recessing into intra-row space while avoiding contact with tree trunk. The main drawbacks of this mechanism are slow operation and the need for sufficient clearance between plants. Finger weeders are designed to weed close to the base of the plant and within the row and are suitably adapted to work in orchards, vineyards, vegetables and berry fields (Mia *et al.*, 2020; Pannacci *et al.*, 2017). Finger weeders are also used around single stem plantings in raspberry plantations and orchard nurseries as little as 10 days after planting according to the manufacturer (K.U.L.T). They have been designed to replace swing arm weeders with feelers to reduce cost of operation and increase precision near the plant base. The fingers are made of rubber which provides weed control around the plant base to a depth of 2-3cm, with less limitations due to planting space within the row as the fingers reach round the plant base to some degree. They are available in various sizes and levels of hardness which is indicated by colours e.g., red indicating hard, yellow-medium and orange indicating soft. The choice will depend on plant spacing and weeding aggressiveness required. Examples of finger weeders with company, website and brochure links are provided in Appendix 3. Finger weeders pull out and remove the above ground parts of the weed only and are best used when weeds are small (<2nd true leaf), especially grasses (Pannacci *et al.*, 2017), so timing of use is critical. In vegetable crops, the amount of hand weeding can be reduced by 40-70% using finger weeders (Van Der Weide *et al.*, 2008). The finger weeder technique relies on a loose surface tilth and is not suitable where soil is consolidated or too wet. Moreover, clay soils may stick to fingers decreasing effectiveness of the operation (Pannacci *et al.*, 2017). Some machine models have discs placed in front of the cultivating finger head, to loosen the soil before the finger weeder cultivates, which increases the effectiveness of the head's operation (Pannacci *et al.*, 2014).

Blackcurrant Case Study: **Finger weeder in the UK**

In the UK, the Bahr finger weeder is used in organic blackcurrant plantations combined with rotary star tiller Rollhacke by Braun (Snell, pers. comm). Finger weeder provides good control but is not as effective as herbicide control. It is not possible to deploy it during plant establishment only after two years of establishment. Finger weeder programme requires 5-6 passes in the field so more than in the herbicide programme and more fuel usage is required. Another problem may be caused by the machinery flicking the soil to the middle of the bush leaving residues on fruit. Additionally, because control of weeds is not as effective with mechanical weeding there is a higher level of slugs and snails in the field that may contaminate fruit at harvest.

Rotary star tillers such as Rollhacke are similar to a disc plough, where a star element replaces the hollow wheel. The tines of the stars are curved - they roll in and tear small furrows in the ground surface loosening the soil, breaking down clods and disturbing and lifting weeds from previously turned over root mat. Star elements rotate during contact with the ground forming a wavy line which helps to reduce soil erosion and allows better water penetration. They have adjustable depth, pitch and angle. Accurate steering is required to minimise crop damage, and slow driving speeds are important (4-5km/h) (Van Der Weide *et al.*, 2008). Star tillers work best when combined with a finger weeder attachment to allow access in and around the plants that cannot be reached by the tiller. The finger weeder will also flatten mounds created by the tiller. Perennial weeds may still be present within the rows after finger weeder and rollhacke treatment and some hand weeding may still be required. Additionally, a minimum of four treatments during the growing season is required (Lampl, pers. comm).

Case Study: **IWMPRAISE**

IWMPRAISE EU Horizon 2020 project initial trial results using finger weeder with rollhacke indicated increased number of inflorescences per vine compared to herbicide or control treatment indicating potential for higher yields, although these are preliminary results and the experiments are still ongoing (IWMPRAISE, 2020b). http://www.iwm-uk.co.uk/

Generally tillage can reduce shallow root abundance in fruit trees by ca. 50% in comparison with herbicide control (Mia *et al.*, 2020). Further research is needed to determine whether these cultivation techniques will have an impact on blackcurrant shallow root integrity. This is especially important as surface roots play an important role in the uptake of nutrients and moisture from the soil surface (Hammermeister, 2016). Several reports, however, indicate that modern finger weeders are a more advanced technology compared to conventional tillage, with little soil disturbance which can maintain orchard biodiversity at reasonable economic cost (Mia *et al.*, 2020; Van Der Weide *et al.*, 2008).

Summary Finger weeders and Rotary star tillers			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+/-) May provide good control if regular treatment possible, more efficacy trials required early during establishment	(+/-) More efficacy trials required in blackcurrant, may need to be combined with other alternatives	Upfront cost of specialised equipment, frequent and regular passes required, weather / soil condition dependent	Trials into optimal depth, timing, aggressiveness, examination of potential root pruning and regrowth, organic matter compensation, potential use as complementary (i.e., with other alternative control systems) rather than singular approach.

Rotary hoes, Side weeders, Tillers

Hoes can be fixed with a single bar to under-cut weeds or have rotating tines, knife heads or discs. The rotating heads can have pairs of spring claw and/or vertical knives that break the soil surface crust helping to reduce soil erosion and allow water penetration while destroying weeds. Some hoes weed with a high level of precision while others require accurate steering to minimize crop damage. Most are hydraulically powered for adjustment of width, speed of the head and height and can be controlled by an electric console located in the tractor cab or else manually (Appendix 4). Desiccation on the soil surface is a critical factor in preventing weed regrowth, and wet conditions after hoeing can decrease the level of control. Cultivation is particularly effective against mature weeds. However, the efficacy, optimal depth and number of passes of this method needs to be assessed, in particular with respect to the type of perennial weeds present. In addition, as tillage will break roots, rhizomes and stolons, it can aid the spread of rhizomatous weeds to other areas of the field (Cook *et al.*, 2019).

Machines can be equipped with several tool options, for example extra nutrients can be incorporated into the soil with a ‘hilling up’ tool on some models, which cuts the weeds and directs the soil back under the bush to cover smaller weeds growing there. Regular use of hoes may cause soil erosion, soil structure damage and compaction, affecting biological processes within the soil, adversely affecting nutrient availability (Granatstein *et al.*, 2008; Merwin *et al.*, 1994; Sanchez *et al.*, 2001), and its use is dependent on favourable weather conditions. Side weeders and hoes are popular machines for orchard and blackcurrant understory management in eastern European countries such as Poland, Serbia, Latvia and Ukraine (Lisiecka, Yereshenko, Lisek pers. comm). Some of the more popular orchard hoes include twin side hoe hydraulic weeders (Appendix 4). The manual machines are controlled by an operator sitting on the device controlling the operation of rotating heads via a mobile arm. There are options for using these in establishing crops as well as in mature plantations.

Blackcurrant Case Study: **Danish Tournesol trials**

Surface cultivators, such as Tournesol by company Pallenc (Appendix 4), comprise two retractable blades which roll around the vine or the tree trunk on the soil surface. In trials in Denmark, yields in rainfed blackcurrant plantations of cultivar ‘Ben Hope’ were at similar levels using Tournesol and mypex and weed control was satisfactory (Lindhard Pedersen, pers. comm). This machine is also valued for a very shallow cultivation and has been found suitable for shallow-rooted blackcurrants. Several weeders such as Tournesol have been developed but discontinued from manufacture due to lack of demand. As a prototype it could be developed as part of an R&D project that might help with the issues of cultivation in terms of soil structure and root damage.

Other examples of weeders, including blade, disc, bladed hub rotary hoes, are described in

Blackcurrant Case Study: **French Disc trials**

In 2020, Disc plough 'Valmatic' by company Boisselet has been trialled with promising results in France. Disc placed horizontally provides shallow cultivation near plant base (Dulor, pers. comm, Appendix 4)

Potential advantages and disadvantages of using several of those machines are not documented in blackcurrant so there is a need for trials and development of knowledge in this area.

Summary Rotary hoes, Side weeders, Tillers			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+/-) Some equipment is designed for use during establishment however efficacy and impact on crop and soil are not fully understood	(+/-) More efficacy trials required in blackcurrant, may need to be combined with other alternatives	Upfront cost of specialised equipment, weather / soil condition dependent, potential adverse effects on soil, lack of knowledge	Trials into optimal depth, timing, examination of root pruning and regrowth, organic matter compensation potential, use as complementary (i.e., with other alternative control systems such as living mulch) rather than a singular approach.

Brush weeders

Brush weeders are primarily intended for inter-row weeding. Horizontal rotation brush weeders work in inter-row spaces while vertical rotation brush weeders eliminate weeds in intra-row spaces in which cropping plants are protected by shields (Pannacci *et al.*, 2017); the latter are used as strimmers (see; Mowers, strimmers and mulchers). In the horizontal rotation, weeding action comes from strong nylon, fiberglass, plastic, metal or flexible tine brushes that rotate, uproot the weeds and brush the weeds onto the soil surface. Very shallow cultivation avoids the emergence of new flushes of weeds and provides a shallow tillage option (Pannacci *et al.*, 2017). Horizontal brushes can be angled, and the direction of rotation altered to move soil away from plants or to earth up the crop row and bury any weeds that the brushes cannot reach. In tests with the brush hoe on a horizontal axis, it was found that working depth was the most important factor in ensuring good weed control (Melander *et al.*, 2005; Weber, 1994). Tractor speed, brush velocity and soil conditions interact to determine the working depth. Nylon brushes can produce a lot of dust, especially under dry soil conditions, but flexible tines can be used instead to prevent this problem. Brush weeders are most effective at early weed growth stages (2-4 true leaf), deteriorate over time and have low effectiveness on mature and perennial weeds (Pannacci *et al.*, 2017). However, both finger and brush weeders are more effective than the traditional torsion weeders used in vegetable crops against weeds with true leaves (Van Der Weide *et al.*, 2008). Brush weeders are generally used where surfaces are level and can be operated under moister soil conditions than a tractor steerage hoe (Bond *et al.*, 2003). However, it has been noted that fine soil created by the brushing effect, combined with moist weather conditions, could result in additional weed plant emergence after the weeding operation.

Blackcurrant Case Study: **Brush trials in France**

Horizontal brushes are used in vineyards and have been trialled in blackcurrant plantations in France using NaturaGriff and Boisselet metal brush (Dubois, Dulor, pers. comm, Appendix 5). They gain increased interest especially for control of bindweed for which 'Brosmatic' metal brush by Boisselet is advised to give very good results (Dulor, pers.comm). It is also speculated whether brush weeders can be used in combination with electric or hot water treatment (survey, Appendix 1).

While horizontal rotation brushes can provide some weed control in intra-row spaces when combined with feelers in wider spaced crops such as tree fruit and vines, vertical rotation brush strimmers described below have been used in blackcurrant for intra-row weed control.

Summary Brush weeders			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(-) Not documented	(-) Mostly inter-row due to blackcurrant spacing. Early weed growth only. No data available	Lack of knowledge and trials, requirement for specialised equipment, fast flush of weeds post operation in moist conditions, only effective on early stages of weeds	Need for trials in blackcurrant, potentially in a combination with other approaches (thermal control), interesting due to potential bindweed control

Mowers, strimmers and mulchers

Mowing is used to prevent weeds from flowering and to decrease seed set. It is mostly used to supress rather than eradicate weeds. Mowers tend to be slow to operate but double-sided options cover the ground at a speed faster than cultivation yet slower than herbicide application. Mowers may be a good option in warm areas with limited summer weed growth but may be a less feasible option where summer rainfall or irrigation encourages regrowth, requiring multiple passes (Bekkers, 2011). Mowers allow a degree of crop-weed competition however they also encourage plant diversity, with potential benefits in terms of soil and moisture retention, and pollination and pest control by natural enemies. The cutting residues can provide green mulch for the 'mow and blow' approach where biomass growing in the alleyway is spread to the crop row for additional nutrient addition and weed suppression benefits. However care should be taken as this can increase the risk of fruit infection by saprophytic fungi and Botrytis leading to poor post-harvest fruit quality in some cases (Granatstein *et al.*, 2009).

Flail, rotary and reciprocating knife and string mowers (strimmers) are becoming more popular in understory management in vineyards, orchards and in organic blackcurrant plantations. One of the main advantages is avoiding soil structural damage associated with cultivation. The most commonly used machinery can be separated into two main types. First are the vertical rotation strimmers that remove young seedlings, cut down vegetation and established weeds along the row with a horizontal axis floating cylinder of spinning polypropylene brush / strings. Second are the knife disc hood mowers used for topping vegetation and keeping growth to a minimum. The latter are designed to go under the tree trunks leaving cut biomass as an additional source of potential nitrogen (Granatstein *et al.* (2009), Appendix 6). Placed at an angle, vertical rotation strimmers allow good penetration between the orchard plants without disturbing the soil surface (Bond *et al.*, 2003), and such cutting treatment has been shown to be capable of reducing perennial weed pressure (Aquilina *et al.*, 1994). Currently strimming is mostly used in organic blackcurrant plantations in Austria, Switzerland and Denmark but is becoming more popular in orchards and blueberry plantations in Poland (Holme, pers. comm).

Blackcurrant Case Study: **Greenmaster in Denmark**

In Denmark, an Italian machine 'Greenmaster' has been used for weed control in organic blackcurrant plantation in combination with the white clover variety 'Rivendel' sown in alleyways (Holme, pers. comm). 'Rivendel' is a small-leaved and very persistent clover with short rhizomes which makes it suitable for close mowing and grazing (www.dlf.com). The 'Greenmaster' strimmer requires regular mowing (up to 7 times a year). Some weeds may persist within the rows and are manually removed.

Other companies offering similar strimmers include Arrizza, Ladurner and Salf, which vary in size and are mostly adapted to orchards, so their efficacy in blackcurrant crops is unknown (Appendix 6).

Integrated mowing (vertical rotation brush weeder and mower) is recognised as an excellent and sustainable weed management system in orchards (Mia *et al.*, 2020). Brush weeders are often used simultaneously with mowers and mulchers, providing mulching material leading to improvement of the soil nutrient status through the decomposition of mower clippings, enhancing organic matter and improving soil structure, biodiversity and crop productivity. Tatnell *et al.* (2020) recognised mowing as essential to ensure the weeds are at more manageable height and density before an electrical treatment is applied, especially when grasses are present. Mulchers such as Clemens mulcher or KS-220R, SAVA or DRAGONE are mostly used for alleyways but can also reach under the bushes (Appendix 6). Under vine knife mowers can cut and shred weed plants just above the soil surface and some instead have adopted a round disc hood with a three leaved clover shape to rotate better under the vine trunks (Viticulture Solutions, clover leaf, Appendix 6). Although trialled autonomous mowers still require further improvements in their mechanical drive systems, they show promise as one of the simplest, smart prospects in agriculture (Magni *et al.*, 2020; Sportelli *et al.*, 2020), especially when coupled with understory management using living mulch.

Summary Mowers, strimmers and mulchers			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+/-) Can be used to suppress vegetation in combination with living mulches and to mow and blow to provide mulch. Allow degree of competition with crop	(+) Can be used to supress vegetation in combination with living mulches and to mow and blow to provide mulch. Pose a degree of competition with crop, but this is less significant post establishment	Regular and frequent passes required, need for specialised equipment, remaining competition with crop can have negative impact on yield	Potential to use in combination with other approaches (living mulch, mow and blow, electric weeding). Need for more systems trials.

Thermal

Flaming machinery has developed in recent years from a very basic and potentially dangerous system to become the most popular method of direct weed control after mechanical weeding in organic farming (Bond *et al.*, 2001). Thermal weed control works using heat to suppress weeds. Several techniques have been developed including flaming, radiant heat, hot foam, hot water, saturated steam and electricity (Ascard *et al.*, 2007; Astatkie *et al.*, 2007). However, most of these methods may only cause foliar damage and not penetrate into the crown or roots of the plants effectively enough for complete kill, meaning that perennial weeds will re-grow rapidly following treatment, and often require more frequent interventions before complete control is achieved. Some of the drawbacks to thermal weeding include potentially higher cost and energy consumption, slow application speeds, and in some cases fire risks and applicator safety concerns. Nevertheless, thermal weeding is useful for inter-row weed management as it can get close to the base of crop plants without undue damage to the stems. The portable mobile nature of this type of equipment can also be of benefit for spot treatments and as there is also no soil disturbance or chemical residues there are some benefits to soil biophysical quality. In recent years there has been a renewed interest in development of thermal apparatus for weed control. The most commonly used or trialled apparatus is described below, including electrical weeding, flaming, foam and hot water and steam.

Electrical weeding

This technology works by transferring a strong electric current through target plants; the energy is converted into heat, boiling the plant tissues. As demonstrated by ADAS PS2143 (2014), Cook *et al.* (2019) and Tatnell *et al.* (2020), the main advantages of electrical weeding include less dependence on weather than with herbicide application, no need for chemicals, flames or water, no disturbance of the soil through tillage, no toxicity to the soil micro-organisms, and it is cheaper than hand weeding. As with most methods there are drawbacks which include slow application speeds, operator safety concerns, need for development of customised machinery and variable effectiveness as it works better on weeds with higher water content. Three specific scenarios have been identified for the use of electric weed control (ADAS PS2143, 2014): control of perennial weeds in the alleyways, under, in and around the plants, and spot treatment of specific weeds. The most economically viable alternatives included:

1. Integrating the electrical weeding with herbicides. (March - residual herbicides, replace the three applications of glyphosate with two passes of the electrical weeder, April/May and September), no hand weeding.
2. Using the electrical weeder only (three passes of the electrical weeder March, May and September), no hand weeding needed but poorer overall weed control is likely.
3. Polythene mulched raised beds, retain the alleyway treatments but the black polythene will suppress weed growth between plants, especially in establishing plantations. Hand weeding, or herbicide spot treatments may be required (seeds blow in and polythene mulch degrades).

ADAS PS2143 (2014) showed that using a handheld device controlled common nettle, broad-leaved dock and creeping thistle, although there was regrowth on nettle and dock and also some phytotoxicity on the crop.

Blackcurrant Case Study: **Electrical weeding in the UK**

Using Ubiqutek RootWave™ technology, electrical weeding for bush and cane fruit has been trialled through an innovative farmers initiative and has been found to be an effective method for weed control and an ideal tool for integrated weed management approach (Tatnell *et al.*, 2020). The study concluded that multiple treatments were more effective, slower travelling speeds (possibly through increased contact with plant) improved efficacy of treatment, control of creeping thistles was extremely effective (one year of data) - mowing is essential before an electrical treatment is applied and fuel consumption is no higher than a conventional tractor used for mowing, spraying or treating weeds. (www.innovativefarmers.org/electricweeding)

In 2021, a UK grower will deploy electric weeding in organic and conventional blackcurrant commercial plantations for long term commercial use for the first time (Snell, pers. comm)

Although recent trials are promising and machinery is already deployed on blackcurrant farms in the UK, there is a need for further developments and adaptation of machinery to blackcurrant plantations considering the design, speed, efficacy and timing of treatments. With the advent of robotics it may also be possible to use electric weeding in combination with vision recognition for selective treatment (Reed, 2009). RootWave and Zasso are leading companies in developments in this field (Appendix 7), although very little modern peer-reviewed literature is available. Zasso equipment uses an intercept arm in vineyards to optimise the weeding area. The Small Robot Company is automating weeding in agriculture using robotics and RootWave technology to precisely zap weeds in arable crops (Appendix 7).

Summary Electrical weeding			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(+/-) In combination with polythene or inert mulches	(+/-) In combination with mowing and mulch, more efficacy trials required	Further developments and adaptation of machinery required for blackcurrant plantations considering the design, speed, efficacy and timing of treatments, need for specialised equipment.	Further engineering progression and trials into efficacy (speed, timing, weed type). Introduction of smart technology

Flaming

Flamers work by scorching above ground weed tissues, damaging cellular structure and disrupting water and nutrient flow which kills the leaves and prevents photosynthesis. As reviewed by Peerzada *et al.* (2018), when flaming is compared to herbicide application, advantages include no residual impact on crop, soil, air or water and no chemical carry over. Additionally, when compared with hand weeding it reduces cost, weed transfer and erosion due to limited soil disturbance. On the other hand, disadvantages as compared to herbicide application include higher potential for regeneration post treatment and slower application. The energy requirement and use of gas, coupled with CO_2 emissions (combustion), can also be highly disadvantageous (Peerzada *et al.*, 2018). The main limitation, however, is low efficacy of weed control (Hammermeister, 2016). Flaming can be used for all weed stages but not always with success. Some good effects were seen pre-emergence in blueberry (White *et al.*, 2016), but the growth stage at which the treatment is applied is crucial as it determines the location of the plant's growing points, the degree of protection of shoot apices, and the level of lignification (Guerra *et al.*, 2012). For a review, see Bolat *et al.* (2017) on flaming use in several crops including vineyards and blueberry. Generally, the control of annual weeds is more effective than that of perennials due to regeneration from roots and lignification of the latter. The effectiveness is particularly poor on grasses (Bond *et al.*, 2001) and weed regrowth is rapid when there is insufficient control of perennial weeds, with regrowth leading to more weed biomass than untreated plants due to reduced competition from neighbouring flame-susceptible weed species. For adequate control, perennials should be treated before the 2nd leaf stage (Peerzada *et al.*, 2018), so regular treatment is required at around 2-3 week intervals (Hammermeister, 2016). Annual weeds such as chickweed, fat-hen, field bindweed and annual nettle were found to be relatively susceptible to flaming (Bond *et al.*, 2001). Efficiency of flaming is greatly reduced in windy conditions or where moisture is present on the plants. In these circumstances, exposure time will need to be increased. Flaming can be used when the soil is wet, and the threat that flaming poses to micro-organisms is small. However, as with shallow cultivation techniques, this method is not suitable for crops with shallow or sensitive root systems (Bond *et al.*, 2001).

Overall, flaming is currently not widely used due to the limited efficacy in controlling some weeds and limitations in timing of treatment for effective control (Guerra *et al.*, 2012). Flaming can also be damaging to the crop and irrigation lines and creates a fire risk (Stefanelli *et al.*, 2009). Flaming works best when used alongside other weed control methods or as a spot treatment. An interesting example of spot treatment has been developed in Denmark (Robovator, F.Poulsen engineering, Appendix 8) with vision activated flames using cameras for weed recognition in vegetable crops. Further examples of flamers are presented in Appendix 8.

Summary Flaming

Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(-) Potential injury to crop	(-) Fire risk, limited efficacy, potential damage to the crop	Fire risk, limited efficacy, potential damage to the crop	Other thermal technologies are more advantageous (Electrical, Hot water/steam), precision flaming is an interesting development

Foam

This thermal method of weed control is based on hot foam made from natural plant oils and sugars. The heat is insulated by a biodegradable foam blanket preventing it from escaping to the atmosphere, keeping the heat on the plant for longer. Foam also sterilises surrounding seeds and spores in the ground and helps to reduce weed regrowth. In the UK, Weedingtech™ technology called Foamstream was used in trials (ADAS AHDB CP 86, 2013) and showed good efficacy towards a broad range of weeds including perennial types in hardy ornamental nursery stock, strawberries and organic field vegetables with multiple applications (Cook *et al.*, 2019). Some phytotoxicity was seen when foam came into contact with strawberry plants. Overall, further improvements were required such as treatment speed, application timing and design of tractor mounted equipment for open field crops. In other trials, Martelloni *et al.* (2019) demonstrated that different doses of foam were required for successful treatment of different species of weeds using Foamstream. In this trial, foam treatment of *Festuca arundinacea* (Schreb.), *Taraxacum officinale* (Weber) and *Plantago lanceolata* L led to 100% weed devitalisation, slower regrowth, and lower weed dry biomass. Hot foam was better at damaging the meristems of weeds as compared to flame, glyphosate and nonanoic acid. Weed regrowth using this technique was delayed by up to 30 days with foam which is more than achieved with flame (Martelloni *et al.*, 2020). Not much equipment exists that could be used on a commercial scale. Contacted in 2020, Foamstream were not supplying machinery to the agricultural sector. The only foam machine currently in a phase of engineering and improvement for the agricultural sector is Schiumone (Spezia Tecnovict, IT, Appendix 9).

Summary Foam			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(-) Potential injury to crop	(-) No equipment available for commercial scale trials	No equipment available for commercial scale trials, potential phytotoxicity, lack of research	Interesting due to potential residual effects. Other thermal technologies (electrical / steam and water) are more advantageous.

Hot water and Steam

Heat can also be delivered as hot water or a mixture of saturated steam and hot water. The steam uses less water and may provide better leaf canopy penetration (Ascard *et al.*, 2007), but it also evaporates faster than water. Through gas technology, steam heat intensity increases 1000-2000 times when compared with flaming (Peerzada *et al.*, 2018). Hot water treatments can be used under varying weather conditions, including wind or rain, with no concern for drift, run off or loss of efficacy and has no fire risk. It also recycles the nutrients from the weeds back into the soil, as in the mulching options. Steaming is an effective way of reducing soil-borne diseases, although it would therefore also disrupt beneficial micro-organisms so this is not a benefit longer-term. Steam sterilises most species of weed seeds on the soil surface (except clover and other hard seeded legumes) and if soil is undisturbed it can be more effective at delaying weed emergence compared to flaming (Ascard *et al.*, 2007; Bond *et al.*, 2003). As reviewed by Peerzada *et al.* (2018) and similarly to other thermal applications, single applications of steam can eliminate most annual weeds and early stages of perennial weeds, but mature perennials will need at least two applications and control of upright grasses can be challenging. Consequently, successful steam weed control depends on the weed species, growth stage, steam temperature, exposure duration, soil type and soil moisture (Melander *et al.*, 2011; Peerzada *et al.*, 2018). Steam can also be activated by using exothermic compounds such as CaO and KOH for increasing soil temperature (Barberi *et al.*, 2009; Peruzzi *et al.*, 2012). Reports of the effectiveness of steam as compared with other weed control methods in vineyards and orchards are mixed (Rifai *et al.*, 2003; Rifai *et al.*, 1999; Shrestha *et al.*, 2012). Generating and maintaining the high temperatures required for effective control was difficult to achieve on a commercial scale with some currently available equipment. Additionally, fuel and water consumption can be a barrier to using this method. Examples of available equipment are summarised in Appendix 10.

Summary Hot water and Steam			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(-) Not enough evidence of efficacy and phytotoxicity, may require mulch	(-) Not enough evidence of efficacy and phytotoxicity, may require mulch	Not enough evidence of efficacy and phytotoxicity, equipment not robust and scaled up enough for commercial use, may prove difficult to control established perennials	Requires engagement with companies to develop / adapt existing technology. Potential to use with organic mulches, mowers

High-pressure water

High-pressure blast systems represent a modern innovation in alternative weed control in vines and orchards (Mia *et al.*, 2020). The system works by blasting high-pressure water (up to 1,150 bar) through a spinning hood (600 rpm) breaking the foliage of the weed plants and burying them in the soil by penetrating a few centimetres deep, which also damages the roots to some degree. Developed by the Italian company Caffini, the 'Grass killer' machine achieves forward speeds of 2.5 km/h and requires 2,000 L of water per ha for approx. 2.5m wide vine rows. According to the manufacturer, € 30,000 equipment will control weeds for a year with only two applications but cost and lack of research might be the main barrier in using this system.

Summary High-pressure water			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(-) Not enough evidence of efficacy	(-) Not enough evidence of efficacy	Not enough evidence of efficacy, cost	Efficacy trials in blackcurrant

Grazing

Grazing sheep or cattle in vineyards and other crops is not a new concept and economic pressures in recent years have made this technique even more popular especially in the USA and New Zealand (Dastgheib *et al.*, 2000; Nóbrega *et al.*, 2017). When employed well, running stock in a vineyard can produce excellent results in terms of weed control and has the effect of changing the weed/pasture population composition (Bekkers, 2011). Improved soil health and structure and other benefits including control of difficult weeds such as blackgrass are highlighted by the National Sheep Association in 'The Benefits of Sheep in Arable Rotations' publication (NSA, 2018). Intensive grazing can be disadvantageous and cause soil compaction and overgrazing, both of which need to be managed. Strip or cell grazing as well as some digital technologies for geospatial stock management may have application in vineyards in the future in aiding a more targeted approach (Nóbrega *et al.*, 2017). In Cumbria, 19 cows on the RSPB reserve of Geltsdale have successfully trialled the £300-per-collar technology as part of a North Pennines AONB Partnership project funded by the National Lottery Heritage Fund (The Guardian, Fenceless grazing widens possibilities for cows and wildlife). Where stock is available, minimal or no cost is incurred, although grazing can only be done outside of the growing season, requires physical or digital fencing and animals may damage irrigation infrastructure. Growers should also give consideration to the risk of stock bringing in weed seeds contaminating plantations (Cook *et al.*, 2019).

Blackcurrant Case Study: **Sheep grazing in New Zealand**

Sheep are used extensively as one of the methods for weed control for blackcurrant plantations in New Zealand (Photo 3). Sheep are usually used for about 3 months out of season (May, June, July (November, December, January equivalent in Europe) to clean up weeds and this helps overcome any issues with resistance from glyphosate which is the main material used in early spring (Langford, pers. comm)

Photo 3 Sheep in New Zealand Blackcurrant. Curtesy: www.rediscover.co.nz

Summary Grazing			
Establishment	Post-establishment	Main barrier	Alternatives / Recommendations
(-) Not enough evidence of efficacy	(+/-) Can be part of integrated approach where stock available	Can only be done outside of growing season, access to stock, requires fencing or digital management, potential weed seed contamination	Integrate where possible, may require fencing or other geospatial management

Other approaches further from commercial field application

Several other tools exist or are under development that may provide small scale, spot treatment or commercial opportunities for weed control once scaled up and when more advanced, safer or efficient options are developed. Bio-controls such as biological control agents, bioherbicides and allelopathy require further research to design practical weed management plans for effective and consistent weed control including reduction of costs, application rates, and adaptation to climate conditions (Cook *et al.*, 2019; Ghosheh, 2005; SCEPTRE CP77, 2011-2014). A range of abrasive methods are under development and may provide opportunities in the future, especially where visual recognition is applied with decision making software and driven spot treatment will be undertaken (Forcella *et al.*, 2020; Perez-Ruiz *et al.*, 2018; Wortman, 2015; Wortman *et al.*, 2018). Equipment such as the Pnaumat that uses compressed air to control weeds by blowing them out of the crop row may be developed to work on commercial scale (Lütkemeyer, 2000; Van Der Weide *et al.*, 2008). Further thermal options such as freezing, microwave radiation, radiant heat, ultraviolet radiation and lasers have potential for safer, more energy efficient and potentially targeted application when coupled with smart technologies, but these are still in their infancy (Ascard *et al.*, 2007; Cook *et al.*, 2019; Peruzzi *et al.*, 2017). Amenity sector machinery companies who are currently leading in brush and steam developments are those developing equipment based on combined technologies such as weedsteam by the Belgian company Anrob using hot air, infrared radiation and steam in one tool (www.anrob.be).

Precision and prediction technology

Precision weed control systems such as robotic machines provide notable technologies assisting the use of weeding tools through guidance, weed detection and identification, precision control and mapping (Slaughter *et al.*, 2008). Driven by rapid advances in field crops some of the more widely recognised precision systems include Robovator, Robocrop, IC-cultivator and Removeed (Mia *et al.*, 2020). Image recognition systems and traditional weeding tools can be used to help define crop plants from the weeds, offering great opportunities but also challenges for some crops (Melander *et al.*, 2015). Some models (e.g., Garford Robocrop technology) have sensors attached to enable the heads to move automatically around the plant base, avoiding any risk of plant damage. This technology, however, needs access from above the crop and around plants which is more suited for vegetable and low growing crops. The Garford imaging system is based on the mixture of position prediction and contrast between the crop and weed and soil. In addition to side weeders and hoes, MCMS Warka developed a prototype of an intelligent row hoe (IPR-3), which is controlled by means of 3D cameras. The three-dimensional detection and decision system (TSDD) enables automatic recognition of weeds by species in the field. The efficiency of the hoe is about 96%. Work is still underway to improve the machine in cooperation with, amongst others, the Warsaw University of Technology (MCMS, 2020). Further innovations include fully autonomous robots such as precision spraying Avo (Ecorobotics), BoniRob (Amazone), precision hoe Anatis (Carre), and adapted to vineyards straddle hoe BAKUS (Vitibot), finger weeder or hoe blade TED (Naio Technologies), other propotypes (Reiser *et al.*, 2019) and robots combining selective weed and pest control such as Australian RIPPA . These systems are still too expensive to be used in minor crops such as blackcurrant so further research into practical and efficient use and weed control adaptation is required. Automation has enormous potential when combined with some of the tools described in this review for integrated weed management, making farming more efficient, profitable and sustainable through intelligent machines that have the ability to collect and process information for a selected outcome (Fennimore *et al.*, 2019; Melander *et al.*, 2015; Peruzzi *et al.*, 2017). This may mean that in the future, apart from enabling novel machinery to operate on a farm, a major shift in mindset and realigning or roles may be required, including the way our farms are designed in terms of spatial and operational character (Atkinson, 2018; Christensen *et al.*, 2009). For further reviews on automated weed control see Cook *et al.* (2019), Fennimore *et al.* (2019), Slaughter *et al.* (2008), Van Der Weide *et al.* (2008), Atkinson (2018).

To assist decision making and gathering data on weed population and densities aligning this to on farm or robotic decision making, several digital tools allowing prediction of weed occurrence are under development. As reviewed by Cook *et al.* (2019), these include prediction modelling, decision support systems and a range of internet tools and apps. These could be collaboratively adapted and should always be considered as a part of future research into improved weed control, particularly with the need for a more systems approach to weed management. Developing weed control technologies needs to be studied in the context of agroecological interactions as the science of weed management slowly refocuses on the foundations of weed biology and ecology to enable an ecological systems approach to promote agricultural sustainability (Gage *et al.*, 2019).

Cost

Cost of alternative weed control options can be one of the major barriers for introducing them in a timely manner into minor crops such as blackcurrant. With tight growers' margins and many uncertainties in crop performance caused by a range of environmental and economic factors, very little margin exists for introduction of costly innovations. There is no doubt that herbicide weed control is still the most economically viable option at the moment. Additionally, yield or plant vigour penalties induced by inefficient weed control can lead to further economic losses as experienced by organic growers. In an organic or high value crop setting, however, cost can often be recouped with premium pricing. This is less likely to be a viable solution for minor processing crops such as blackcurrant, although there are some long-term gains in general security in the face of herbicide withdrawals, sustainability and positive impacts on fauna, flora and a fundamental natural resource to growers – the soil.

Apart from the operational cost of alternative weed control, there is a need to purchase materials or specialised, often single purpose, machinery. Some of the cost information is included in Appendices 2-6 as provided through direct quotes from manufacturers or distributors. Price of the required mechanical equipment will depend on existing fleet and crop spacing and special frames and arms may have to be additionally purchased to suit. Estimates of costs are presented in Table 1 (below) based on growers' feedback and other studies as a full economic costing was out of the scope of this review. In the literature, mowing was shown to be cheaper as compared with herbicide application (Ingels *et al.*, 2012). Single cultivation can be cheaper than herbicide application but requires more passes in the field (higher fuel and operator costs) and purchase/hire of specialised equipment so will depend on the intensity of the operation (Shrestha *et al.*, 2013). Electric weeding can be comparable to cultivation cost (ADAS PS2143, 2014), steam treatment was shown to be variable and cost similarly or up to double of cultivation (Fahey, 2019; Shrestha *et al.*, 2013). Mulching with organic, plastic or bioplastic is the most expensive option as compared with herbicides (Lisek, 2014). Mechanical weeding was found to be the most affordable alternative option and cost quoted by growers in Poland is at a range of €200-400/ha. A full assessment of the economic benefits needs to reflect the longevity of the effect on weed populations, repeated applications depending on environmental circumstances and any effect on crop yield. Hand weeding is the most expensive means of weed control.

Table 1. Weed control cost references

Weed control	Purchase of equipment/materials	Operational cost	Total	Reference, Year
Polythene (oil based) mulching	£450/ha	Ploughing £54/ha, Cultivations £34/ha, GPS tractor Hire £70/ha, Poly laying (16-man hrs/ha) £240, Plastic lifting £800, Plastic disposal £250 (£1200 per ton - 300 kgs per ha)	£ 1,898 /ha incl. materials	Grower communication, UK 2020
Bio-Polythene mulching	£1480 /ha (ca. 8 rolls/ha 1.2m x 500m @50mu, £185/roll black OPL biofilm from Gromax Industries Ltd.)	Ploughing £54/ha, Cultivations £34/ha, GPS tractor Hire £70/ha, Poly laying (16man hrs/ha) £240	£ 1,878 /ha incl. materials	Grower communication, UK 2020
Mater-Bi mulch	£ 2,382 / ha (ca.8 rolls/ha 1m x 500m @ 50mu, £298/roll Capatex)	as above	£ 2,780 /ha incl. materials	Capatex / Hutchinsons

Weed control	Purchase of equipment/materials	Operational cost	Total	Reference, Year
Inert mulch (wood chip)	Depending on sources, may be more practical to buy in wood in the round and chip it on site to have control over the type of wood. 333,000m x 0.8m on the 0.15 depth 40,000 cubic metres for a hectare. Weight and volume depend on type of wood. Not viable to deliver such volume. Boiler type hard wood is 40cu m for £1500 inc VAT at 5% but not for use in a field as calorific value is too high. Willow and poplar may be better as high volume and low calorific value. To make the system work would require land to plant coppicing willow/poplar on site so there is the cost of that.	Application will require specialised equipment hire (cost not determined on commercial scale)	Needs evaluation	Grower communication, UK 2020
Mechanical	For cost and operation speed Appendix 2-3	Tractor travels at 3kph – work rate 1.6 hrs/ha, Labour cost for a skilled operator £8.34/hr , total labour £13.90/ha, tractor cost – four-wheel drive, 110hp, diesel & oil £8.37/hr, total tractor £13.95	£28/ha at 3km/h per pass, + equipment +depreciation	ADAS PS2143, 2014
Electric weeding - tractor mounted	~£20,000	Tractor travels at 3kph – work rate 1.6 hrs/ha, Labour cost for a skilled operator £8.34/hr , total labour £13.90/ha, tractor cost – four-wheel drive, 110hp, diesel & oil £8.37/hr, total tractor £13.95	£28/ha at 3km/h per pass + equipment +depreciation	ADAS PS2143, 2014
Steam	£23,000	Weedtechnics, SatusteamTM, SW2800 in vineyard, water set at 120 °C and 20 psi pressure, travelling at 1 km/h with a 30 L/min water output rate using 17 L/h of diesel in Australia	£15/ha + equipment +depreciation	Fahey, 2019

Weed control	Purchase of equipment/materials	Operational cost	Total	Reference, Year
Electric weeding - hand held	£10,000 - £15,000	Walking speed 3kph – work rate 1.6 hrs/ha, Labour cost for a skilled operator £8.34/hr , total labour £13.90/ha, Fuel consumption was assumed to be similar to that used in running a tractor pulling a mechanical weeder for the same period of time	£28/ha per pass + equipment +depreciation	ADAS PS2143, 2014
Hand weeding	-	Removal of thistles and nettles and docks within rows on 1 occasion. Very variable dependant on weed pressure	£300-£900 /ha	ADAS PS2143, 2014
Herbicide		March application directed spray through base of bush. Residual and contact. Hooded spray (Unda Vina) – 1-2 applications of glyphosate in April and May, and an additional one in September. Average speed 1 hectare an hour	£310/ha	ADAS PS2143, 2014
Companion crops / intercropping	species dependent	white clover 2.8g/m2 £380, black medic 3.2g/m2 £440, creeping red fescue 15g/m2 £480, birdsfoot trefoil 2.8g/m2 £400	£380-480 /ha + some equipment required	CP086, 2013
Drip irrigation		additional cost when considering mulching	£ 2,500 /ha	Grower communication UK, 2020

Discussion

Several methods of alternative weed control exist or are under development. None of the approaches are sufficient for satisfactory weed control on their own. Furthermore, continual use of one method may bring long term disadvantages (e.g., soil erosion), therefore combining several solutions and adopting integrated weed management strategies will be beneficial. Each system has barriers to application such as cultivation system, weed flora, soil fertility and other socio-economic issues linked to the need for expensive materials, specialised machinery, and technical knowhow.

Weed control options

Currently **synthetic** (plastic) mulches provide excellent weed suppression during crop establishment and long-term weed control, although the environmental impact of the material and potentially negative impact on fauna creates the need for using alternatives providing similar physical properties especially during establishment. Fully degradable and compostable **bio-based** materials such as Mater-Bi provide environmentally friendly alternatives but at much higher cost and their durability is not fully satisfactory. The raw material manufacturer (Novamont) does not envisage this technology cost to be in line with synthetic plastic in the future although there might be opportunities to collaborate with product manufacturers to reformulate, bulk or find optimal thickness for affordable cost while maintaining good effectiveness (Samco.ie). Use of bio-based and biodegradable materials can be complemented with organic mulches.

Inert **organic mulches** such as wood chip and sawdust can provide satisfactory weed control especially during establishment but are more effective against annual and biennial than perennial weeds. Use of materials such as wood chip and sawdust will depend on their availability and it is recommended to produce them in-house to reduce cost. Straw is especially valued for its permeability but there might be practical and accessibility limitations. Further research is required into mitigating locked nitrogen effects on crop and phytotoxicity, exploring mulch effects on root systems, soil biota and the crop, and linking the interactions to improved crop performance. Root growth of blackcurrant in non-irrigated conditions was ranked from highest to lowest growth as spun polypropylene + wood chips, black plastic, degradable plastic and wood chips followed in decreasing order by paper, silage, spun polypropylene only and bare soil (Larsson, 1997). Similar ranking for shoot growth was black plastic, spun polypropylene + wood chips, wood chips, degradable plastic, paper, silage, spun polypropylene and bare soil. It was concluded that shoot and root growth were greatly influenced by soil moisture and nutrient benefits or toxicity associated with the treatments, and treatment effects on soil temperature had less influence on root growth. Moisture conserving mulches in blackcurrants promote root growth near the soil surface without reducing deep rooting, thus the mulches improve total root biomass (Larsson, 1997). So, in addition to knowledge of nutritional requirements of blackcurrant and potential promotion of soil/root health through long term management (prevention and cultural control), other approaches should be explored in combination, such as cover crops, companion cropping and residue retrieval (mow and blow), and also use of beneficial soil microbes (mycorrhizae). Other in-house waste materials can also be recycled to provide potential for closed economy.

Living mulches are recommended for established plantations as younger plants may be more prone to suffer from competition for nutrients and moisture. More research is required to identify less competitive living mulch species or species mixes and their use in rotation. Comparative studies of soil biology under different mulch species could identify those stimulating mycorrhizal colonisation of crop roots, and nitrogen fixing organisms. There is a need to identify the best approach for managing living mulches, making use of devices such as crimper rollers and in combination with frequent mowing (mow and blow), rotation practices and spatial arrangements such as the 'sandwich system' for weed suppression but also soil nutrient enrichment (legumes). Use of cover crops pre-planting also provides advantages in blackcurrant.

Mechanical methods are currently leading traditional ways of controlling weeds in conventional and organic orchards and fruit plantations. Those methods are also the most affordable to growers. Long-term repeated tillage has adverse effects on soil health and crop performance so alternative more modern equipment such as finger weeders and brushes could be used to provide weed control at shallow cultivation depths. Additionally, mechanical methods can be combined with mowing or living mulches for a multi-level approach such as the swiss sandwich system where strip tillage is used. Further knowledge is required to understand interaction of those systems with the blackcurrant crop (especially potential root pruning effects and impact on soil health). Further research into mechanical weed control should identify optimal depth, timing, type of tillage, examination of root pruning and regrowth in tilled systems, organic matter compensation, contribution of the topsoil to the nutrient supply of the plants, and potential use as complementary (i.e., with electric weeding) and not singular approach. Further innovation in mechanical weeding is required to develop and adopt the precision farming technologies for mechanical weed control which long term, will fully replace hand weeding. Mowers and strimmers can provide complementary options for suppression of weeds (e.g., with electrical weeding) or management of living mulches and also improve biodiversity. Further research should study the impact of living ground competition on the crop and optimal timing and species for use in those systems. Autonomous options are available and should reduce time and increase efficiency in the future.

Thermal methods are becoming more sophisticated and are gaining a lot of attention from growers and manufacturers especially as their cost is comparable to cultivation but without soil disturbance. Although significant innovation has been achieved to date, further developments are required. Electric weed control can provide a great alternative as compared to other thermal (flame) and non-thermal (cultivation) control options due to the potential for controlling perennial weeds, especially if weed root destruction can be achieved. Further research is required to establish a systems approach in combination with mowing and to establish optimal treatment speed, frequency and additionally the potential for more selective application using precision technologies. Hot water/steam/foam systems are interesting for their potential for residual weed control, although equipment is not yet scaled sufficiently for commercial use in Europe. This requires engagement with manufacturers and engineers to adapt, develop and trial the technology more broadly. Once technology and application methods have advanced, thermal methods could be used in combination with guided weed control systems or robots.

Innovative **physical** methods such as high-pressure water systems should be trialled to assess efficacy as the reduced need for application may provide a cost-effective option despite high purchase price. Other novel physical methods such as abrasion, freezing, microwave radiation, radiant heat, ultraviolet radiation and lasers may provide good precision tools in the future so progress of this research should be followed.

Where available, potential of **grazing** could be explored further and incorporated into a systems approach complementing out of season weed control.

Overcoming the barriers

With the major transition to incorporating alternative weed control options into soft fruit production, promoting environmentally friendly and systems-based approaches to weed control is equally if not more important than eradication. An Integrated Weed Management (IWM) System is accomplished by management of the weed community including crop and weed community actions linked to variety choice, density of cropping, in-row and intra-row distances, irrigation method, fertilisation, the use of cover crops, etc. These actions are important for improving crop competitiveness against weeds. Management of the weed community is required to maintain a balanced weed flora and to reduce soil seedbank size. Good site preparation is a critical part of an establishment plan. Control of problem weeds, especially rhizomatous perennial weeds, prior to planting, reduces the weed management challenges and, coupled with addressing soil fertility issues before planting, can increase the options available to growers. There is a need to establish key decision-making plans for weed control depending on on-farm circumstances (e.g., soil health, type of prevailing weeds) as not every approach will fit all.

Knowledge, research, and confidence

In order to assist selection of the most environmentally suitable approaches, taking into account effectiveness, cost and influence on yield, there is a need to develop a weed control toolkit and gain confidence in different technologies by trialling and adapting them for blackcurrant and then providing further options depending on site specific circumstances and a long-term IWM system approach. It is possible that future weed control will be field specific and less of a blanket approach. Pannacci *et al.* (2017) presented three scenarios of weed control in vegetable crops, depending on infestation, through integrated use of cultivation, flaming, brush weeder, sprit hoe, manual weeding and finger weeder; this approach could be utilised for weed control decision making based on potential yield and cost balance. Hammermeister (2016) concluded that weed management in organic orchards is dependent on the prevailing type of weeds and soil fertility status with all type of mulches (manufactured, organic and living), restricting nutrients and tillage being the most appropriate options for those sites. Living mulches were only suitable on fertile sites with intensive mowing and organic inert mulches were not adequate for sites dominated by rhizomatous weeds. Further applied and fundamental (interdisciplinary and agroecological) research as well as engineering advances are crucial to improve knowledge, develop IWM systems approaches and gain confidence in different practices of alternative weed control. Additionally, working agronomy groups such as International Blackcurrant Association can play an important role in international collaboration and sharing practices amongst growers and researchers.

Crop establishment and integrated approach

Crop establishment is critical during blackcurrant development, and there is a need to develop more environmentally robust IWM systems, replacing the use of synthetic plastics and non-renewable resources. Although several methods of weed control were described in this review, only a few were deemed suitable. Additionally, not all methods are readily available. Below is a figure presenting potential suitability of the methods of weed control during crop establishment and post establishment, and their readiness-for-use.

Figure 1. Alternative methods of weed control during crop establishment and post establishment as (+) positive – supported by literature and practical evidence, (+/-) potential – show potential but several barriers exist, and (-) problematic – negative effects or lack of current evidence, and their readiness-for-use qualified as 1) available – product and machinery readily available (green), 2) accessible – specialistic machinery required (blue), 3) attainable – theoretically available but further adaptation is required (orange), additionally potential of integration of the practices together is outlined as √ - recommended, ● – compatible, ○ – compatible but less likely to be integrated together.

	CONTROL OPTION	ESTABLISMENT	POST-ESTABLISHMENT	MULCH							MECHANICAL				THERMAL				ABRASION	LIVESTOCK
				SYNTHETIC	BIOPLASTIC	WOOD CHIP SAWDUST	STRAW	PAPER	WASTE	LIVING MULCH	FINGER WEEDER STAR TILLER	HOES SIDE WEEDERS TILLERS	BRUSH WEEDERS	MOWERS STRIMMERS MULCHERS	ELECTRIC WEEDING	FLAMING	FOAM	HOT WATER STEAM	HIGH PRESSURE WATER	GRAZING
MULCH	SYNTHETIC	(+)	(+/-)			○	○			●	●	●	○	●	●					
	BIOPLASTIC	(+/-)	(+/-)			○	○		○	√	●	●	○	√	●					
	WOOD CHIP SAWDUST	(+)	(+/-)	○	○		○	●	●	√	●	●	○	√	●	●	●	●	●	
	STRAW	(+)	(+/-)	○	○	○		●	●	√	●	●	○	√			●	●	●	
	PAPER	(-)	(-)			●	●		●	√	●	●	○	√						
	WASTE	(-)	(-)		○	●	●	●		√	●	●	○	√	●	●	●	●	●	
	LIVING MULCH	(+/-)	(+/-)	●	√	√	√	√	√		●	●		√	●	●	●	●	●	
MECHANICAL	FINGER WEEDER STAR TILLER	(+/-)	(+/-)	●	●	●	●	●	●	●		●	○	●	●	●	●	●	●	
	HOES SIDE WEEDERS TILLERS	(+/-)	(+/-)	●	●	●	●	●	●	●	●		○	●	●	●	●	●	●	
	BRUSH WEEDERS	(-)	(-)	○	○	○	○	○	○		○	○		√	●	●	●	●	●	
	MOWERS STRIMMERS MULCHERS	(+/-)	(+)	●	√	√	√	√	√	√	●	●	√		√	●	●	●	●	
THERMAL	ELECTRIC WEEDING	(+/-)	(+/-)	●	●	●			●	●	●	●	●	√		○	○	○		
	FLAMING	(-)	(-)			●			●	●	●	●	●	●	○		○	○	●	
	FOAM	(-)	(-)			●	●		●	●	●	●	●	●	○	○		○	●	
	HOT WATER STEAM	(-)	(-)			●	●		●	●	●	●	●	●	○	○	○		●	
ABRASION	HIGH PRESSURE WATER	(-)	(-)			●	●		●	●	●	●	●	●		●	●	●		
LIVESTOCK	GRAZING	(-)	(+/-)																	

Cost

Several of the alternative control methods are more cost effective than hand weeding, but undoubtedly most of those methods are more expensive than herbicide control. Additionally, the potential prospect of integrating several methods and their lower effectiveness of weed control coupled with further need for hand weeding may be the major barrier to deploying Integrated Weed Management Systems. Lack of evidence of immediate success and view of the return on investments of time and money only strengthen those economic barriers. Costs of some of the IWM systems could potentially be reduced by sharing equipment through cooperatives and production of own materials such as mulch. To unlock farmers potential to transition to new and more sustainable farming practices while facing an uncertain future, innovative funding support might be needed, as outlined by The RSA Food, Farming and Countryside Commission (2019). This report makes several recommendations, including 'need for investors and lenders to share the risk, universally accessible baseline payments that engage the whole sector in gathering data, building skills and strengthening assurance, clear priorities for public investment and future payments, which incentivise farmers to follow agroecological principles while accepting that payment and investment schemes will evolve, realigning fiscal incentives to help deliver net zero carbon emissions from agriculture, and a timetable for more stringent controls on the use of pesticides (herbicides), anticipating that the scientific case for this will continue to grow' (TheRSA, 2019).

Crop Competitiveness

Vigorous crop varieties have more opportunities to establish and tolerate some weed burden at establishment. Scottish varieties 'Ben Gairn' and 'Ben Dorain' are slow to establish and weeds are very competitive in those plantations. Currently varieties with 'get up and go' vigour at establishment provide more opportunities for mitigating weed problems. In a herbicide-free management system, there will be an increased need to emphasise the importance of crop traits such as early season vigour, rapid canopy expansion and nutrient efficiency in breeding programmes that will have to accommodate potential trade-offs of agronomic traits with quality and yield. Increased knowledge of cultivar performance under different weed control systems may improve decision making processes and improve effectiveness of weed control including density and orientation of crop also to suit modern precision tools. As most precision tools are developed to suit major crops, the challenge for using them in minor crops will in some degree involve adapting the cropping systems to the available technologies. Long term planning, management, cultural control and prevention are of great importance to reduce weed burden and increase crop competitiveness.

Environmental impact

Major shifts in perception may be required in the transition to integrated systems around whether a weed free landscape is desirable. While there are many benefits of 'clean' fields that are perceived as a sign of good management, getting the best out of our agricultural landscapes in the future may require a shift in expectations to leverage the benefits of a biodiverse crop system with improved ecological functioning and 'ecosystem services' to produce high quality product. The importance of weed diversity in mitigating yield losses has been identified as one of the top five research priorities in weed science (Adeux *et al.*, 2019). There is evidence to support hypotheses that not all weed communities generate yield losses and more diverse weed communities can mitigate yield losses. In tune with functionality in a natural system, then diversity and an acceptance of some level of natural deviation when managed correctly should be seen as a positive for agroecosystem functioning rather than a negative. Again, biodiversity and agroecology should go hand in hand with weed control.

Several dynamic agroecological programmes are undergoing at time of writing, and amongst others these include IWMPRAISE (Integrated Weed Management: Practical Implementation and Solutions for Europe), Domino (Dynamic sod mulching and use of recycled amendments to increase biodiversity, resilience and sustainability of intensive organic fruit orchards and vineyards) and DIVERSify (Designing Innovative plant teams for Ecosystem Resilience and agricultural Sustainability). Collaborative research is particularly important for scaling up and adopting existing technologies, and engagement with engineering companies in collaboration with interdisciplinary scientists is becoming paramount.

Currently a combination of chemical, mechanical, physical and cultural practices might be most effective in promoting in the long-term crop health and weed control, especially as growers transition towards gaining knowledge and experience in the use of alternative weed control options. Early adopters will develop on farm IWM systems, although structures, funding and long-term planning are required to support development, research and knowledge transfer in this area.

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Appendix 1 - The survey

The Survey has been kindly distributed on the 4th of October 2020 by IBA (International Blackcurrant Association, https://www.blackcurrant-iba.com) in a newsletter received by 1263 contacts from 64 different countries. The survey has been opened by 50 persons (16%) of the total clicks in the newsletter from 14 countries. The survey had responses from Canada, Denmark, Estonia, France, Germany, Latvia, Lithuania, The Netherlands, New Zealand, Norway, Poland and United Kingdom, mostly from growers (60%) but also advisers (13.33%), researchers (13.33%), manufacturers (6.67%) and breeders (6.67).

Questions	Summarised answers
1. Which alternative (non-chemical) weed control technologies are you aware of (please list eg. hot foam, flame).	• mechanical tools, • mulching, • straw mulch, • herbicide with clover in alleyway, • hoeing, • electric weeding, • planting through recyclable polythene
2. Which companies do you know that are bringing innovation in this sector? - please list	• Kress, • A lot of companies but machinery not adapted, • Anrob – Belgium (weed steam, brush weeding, hot water) • Zasso, • Boisselet, • Clemens, • Braun, • Heatweed Technologies, • As Adigo AS, • Krogzeme SIA, • CNH Industrial Deutschland Gmbh, • electric
3. Which technologies/machinery do you implement - please add make of the equipment	• Kress finger weeder, • testing several, • cultivator, • mower, • hoeing in first year establishment, • Boisselet's Plough, • hydraulic weeder machine ZUZA (one sided), • finger weeder Klaudia, • mechanical weeder, • BCS walk-behind tractor for small research plot, • none, • built special machine to bring straw under red currants, • green master mulcher

Questions	Summarised answers
4. What alternative weed control technology do you find useful during plantation establishment - right after planting!	• small finger weeders, • plastic mulch – but it’s not compatible with mechanical weeding, • weeding by hand, • hoeing, • will test hot water against weeds ad runners in newly planted strawberries from next year, • Zuza, • weed barrier, • black folia, • Finger hacke, • best answer is planting through black polythene, because it is good for weed control, retaining soil moisture, and warming soil.
5. What type of mulches have you trialled or are using in your production? (please list)	• short growing grass/clover mix, • plastic mulch, • grass, • wood bark, • mypex, • hay mulch, • straw, • small pieces of wood or miscantus giganteus (Germany)
6. Have you used any other approaches into alternative weed control such as bioherbicides, companion plantings, cover crops, alleopathy.. what are they? (please list)	• no • cover crops with clover, • cover crops before planting
7. If you have an alternative weed control programme, what is the order of the treatments, can you give an overall cost/year.	• no programme, • 4/5 hoeing per year@2hours per hectare 50-55 Euro/hour • mechanical weed control 3-4 times a season, the price of one is 250 Euro / ha

Questions	Summarised answers
	• In organic growing you need strong growing cultivars. Best weed control is a green currant umbrella to reduce light for weeds. Use mechanical tools but do not disturb BC roots. Still Orchards won't last as long as the chemical treated ones.
	• It is very difficult, expensive, with disappointing results and use of human work
8. Last one! Have your say, where do you think opportunities for alternative weed control lie for blackcurrant crop. Do you have any suggestions, experiences - thank you for all your answers.	• Weeding for 2 years after planting. • We have rows at 3 meter 80% are white clover • The best way for me is to test and develop Zasso's system. (Electric weed control) - France • In development of machinery, robot technology etc. in combination with spraying (precision agriculture) • Climate action requires organic approach. • Very interesting topic: main weeds are perennial grasses (e.g. *Dactylis glomerata*, *Elymus repens*) and horsetail (*Equisetum arvense*). I have no suggestions but commend the research • Bi degradable weed mat applied from establishment, New Zealand • mulch with straw or black folia • Nothing alternative weed control can stand on there own- hand work also had to be done.

Appendix 2 - Crimper rollers

Type	Company	Machine	Main crop	Brochure/video	Website	Price	Photo
Crimper roller	Clemens	Eco-roll	vineyards, orchards			€ 665 (attachment only)	
	Boisselet	Facamatic	vineyards, orchards			€ 1,094 (attachment only)	

Appendix 3 - Finger weeders and Rotary star tillers

Type	Company	Information	Machine	Main crop	Adjustments	Brochure	Website	Price	Photo
Finger weeder	K.U.L.T	Woldwide patent EP1127481B1 on finger weeder attachment.	Maxi Finger weeder	vine, tree nursery, rose, lavender, perennial shrubs, **blackcurrant**	4 types (500mm disk recommended for blackcurrant)			€ 1,500 – 2,500 per unit	
Rotary Star Tiller + Finger weeder	Jagoda JPS	Machine using finger weeder technology	Klaudia	hascap, vine, orchards, berry fields, **blackcurrant**	700 mm 3 degrees of hardiness + 2-4 disc cultivators single/double sided			€ 2,450 (single-sided attachment with 2 discs cultivator and cylinder)	
	Braun +Bahr	Front mounted Braun Rollhacke and Bahr finger weeder	Rollahacke	vine, Tree nursery, rose, lavender, perennial shrubs, **blackcurrant**	Speed 3-12km/h, angle/tilt for optimal depth			£11,250.00 + VAT (complete kit)	

Type	Company	Information	Machine	Main crop	Adjustments	Brochure	Website	Price	Photo
	Clemens	Finger hoe, Finger roller (roll hacke), rotary cultivators, mowers	Finger hoe + Finger roller	vine, aronia, blueberry, **blackcurrant**	Ø 370 mm, Ø 540 mm, Ø 700 mm			€ 1,495 (attachment only)	

In Europe popular finger weeders are made by K.U.L.T, a Germany based company which has a patent on the finger weeder attachment (EP1127481B1), also known as a Kressweeder. K.U.L.T supply several other companies using this technology in Europe, those include Berti Macchine Agricole (Italy), Boisselet (France), Braun Maschinenbau GmbH (Germany), Clemens GmbH & CoKG (Germany), Fisher SRL (Italy), Grenier Franco (France), Jutek (Denmark), Orizzonti SRL (Italy), Solemat (France), Rinieri SRL (Italy), Zannon SRL (Italy). Simple finger weeder arm such as MAXI finger weeder from K.U.L.T will cost in a range of €1500-2500 and can be incorporated into existing tractor equipment on site (K.U.L.T). Several of the above companies develop more comprehensive machines using other attachments incorporated with finger weeders and various arm frames. The cost will depend on the design, adaptation and existing machinery on site.

Appendix 4 - Rotary hoes, side weeders, tillers

Company	Type	Machine	Main crop	Speed [a)]	Brochure	Website	Price*	Photo
Jagoda JPS	Side weeder, rotating hoe	Lucy	orchard, vineyard, **blackcurrant**	1 - 3 km/h			€ 3,600	
		Zuza	young establishing plantation	1-3 km/h operator required			€ 2,320	
		Zofia	orchard, vineyard, **blackcurrant**	up to 3km/h operator required			€1900 (one sided), € 2,430 (two-sided)	
		Zana	orchard	1 - 3 km/h			on request	
Weremczuk	Inter-row tiller	part of SAVA	berry crops, **blackcurrant**	1 - 3 km/h			€ 1,800	

Company	Type	Machine	Main crop	Speed [a)]	Brochure	Website	Price*	Photo
Pellenc	Blade cultivator with star shaped dome	Tournesol	vineyard, trialled in **blackcurrant**	2-4 km/h			on request	
Boisselet	Disc hoe	Valmatic	vineyard, **blackcurrant**	3-6 km/h			€ 838	
	Disc hoe	Petalmatic	vineyard	2-3.5 km/h			€ 396 (one side attachment)	
	Rotary hoe	Starmatic	vineyard	2-3.5 km/h			€ 396 (one side attachment)	
Greensort	Side weeder, rotating hoe	Side weeder	berry crops	4 km/h			€ 1,560	

Company	Type	Machine	Main crop	Speed a)	Brochure	Website	Price*	Photo
Ladurner	Blade cultivtor	Ladurner cultivator	orchard	up to 5 km/h			£ 20,000 + VAT one sided, £25,000 +VAT double sided	
Rinieri	Blade tiller with disc	Turbo	vineyard	up to 10 km/h			On request	

* individual arm attachments may be required for attaching equipment to existing tractor at additional cost

a) speed dependent on weather and ground conditions, age of plantation and other site conditions

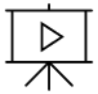
Appendix 5 - Brush weeders

Type	Company	Machine	Brochure	Website	Price	Photo
Horizontlal Brush	Naturagriff	Brush			€ 60-150 (attachment only)	
Horizontal Brush	Boisselet	Brosmatic			€ 2,295	

Appendix 6 - Mowers, strimmers, mulchers

Type	Company	Information	Machine	Main crop	Brochure/video	Website	Price[*2]	Photo
Strimmer	Greenmaster	mower/strimmer (rotary brush)	Greenmaster	vineyard and **blackcurrant**			€ 18,000 (complete machine)	
	Arrizza	mower/strimmer (rotary brush)	Trinciaerba singolo/doppio series	orchard			upon request	
	SALF	mower/strimmer (rotary brush)	Bio agri	orchard			upon request	

Type	Company	Information	Machine	Main crop	Brochure/video	Website	Price[*2]	Photo
Mulcher	Weremczuk	flail mower and shredder with hammer	Dragone	orchard, bush crop			temporarily unavailable	
	Clemens	mulcher	mulcher	vineyard			€ 7,400	
	Weremczuk	inter-row mower	part of SAVA	**blackcurrant**			€ 1,660	

Type	Company	Information	Machine	Main crop	Brochure/video	Website	Price*2	Photo
Mower and slasher		Mower and slasher	KS-220R	bush crop			temporarily unavailable	
Mower	MGV SARL	Under vine mower (clover leaf)	Tondeuse intercep	vineyard		You Tube	unknown	

* 2) arms and frame attachments may be required to attach equipment to existing tractor at additional cost

Appendix 7 - Electrical weeding

Company	Machine	Main crop	Website	Photo
Ubiqutek	SFM Technology RootWave™	Fruit crops, blackcurrant		
	RootWave™ Pro - Handheld	Amenity, agriculture, spot treatment, invasive species		
Small Robot Company + Rootwave™ technology	Dick	Arable		
Zasso	XPowerxPS	Orchard, Vineyard, Coffee, Amenity, Forestry		

Appendix 8 - Flame weeders

Company	Machine	Main crop	Website	Photo
F Poulsen Engineering	Robovator	Vegetable		
Constructions Humeau	Thermal weeder	Viticulture		
Officine Migozzi	Pirodiserbo	Viticulture		

Appendix 9 - Foam weeding

Company	Machine	Description	Website	Photo
Spezia Tecnovict (Italy)	Schiumone	Awarded at the International Agricultural Machinery Exhibition in Bologna in 2016 in recent tests run in the vineyard prototype gave very promising results. The foam, during its deposition on the ground above 70°C, causes the denaturation of the proteins in blades of grass, with subsequent drying within a few days. The goal for machine speed is 4 km/h for full row of vineyard but the manufacturer is hoping to raise these limits in the future. A reduced quantity of water is required, equal to 0.30 litres per square meter treated (Spezia Tecnovict). The potential phytotoxicity of hot foam on blackcurrant is unknown.		

Appendix 10 - Hot water and Steam

Company	Machine	Description	Website	Photo
Weedtechnics (AU)	Satusteam™	Super-saturated high temperature steam technology for weed control in several crops including bush fruit. Models range from small portable machines to tractor mounted, hydraulically operated hydra-booms. The most preferred solution for horticulture is the SW900 horticulture trailer equipped with Rowtech head for band steaming. Singular and dual arms can be operated with left and right mountings, a vertical and horizontal pivoting system tracks the terrain and the unique break away system allows the domes to roll around the plant. This apparatus using SW2800 unit was trialled in vineyards with water set at 120 °C and 20 psi pressure, travelling at 1 km/h with a 30 L/min water output rate using 17 L/h of diesel in Australia (Fahey, 2019). It provided satisfactory weed control however wood chip mulch with compost (80/20) provided superior weed control. A good residual effect using this technology has been seen in blueberry and aloe vera, allowing the speed to be increased to 3-4km/hour in subsequent applications due to its residual effect in depleting seed banks (Weedtechnics). Import from Australia to the UK can be difficult as the product carries no CE (health, safety, and environmental protection standards for products sold within the European Economic Area (EEA)) mark.		
Multevo (UK)	Weedmaster	Small self-powered, hand-held lance or large trailer mounted hot water units with outputs of between 8-30 litres of water per minute, and depending on the unit, covering an area of between 1,250-7,500 m2 per day. Those units are mainly set up for hand lance application, but when contacted company is open to adaptation for other requirements (Christie, pers. comm).		

Company	Machine	Description	Website	Photo
Heatweed Technologies AS (NO)	Mini, Mid, Multi, XL, Sensor 2.0	Offer several machinery options (portable hand lance – tractor mount arms) with heat stability technology (98-99.6ºC), low energy consumption and emissions. The company are in discussions with researchers to develop technology suitable for agricultural and horticultural crops in Norway (Sonseby, pers.comm).		
Mantis ULV (GB)	Biomant Aqua	Treats weeds at 99.5ºC. Tractor mount equipment is used in organic orchards and vineyards and is gaining popularity in Europe especially as equipped with adjustable spray boom with flexible spray hood for protection of cultivated plants.		
Irsara (IT)	Eco GP	Tractor mount hooded attachments for steam treatment in orchards and vineyards. Using a patented system (patent no. MO2012A00143). There is interest in Poland in this system.		

Company	Machine	Description	Website	Photo
Oeliatec (FR)	Hoedic	Also called burning water drop weed control. The water is heated up to 115°/120°C then spayed on weeds. Several models are available.		

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