University of Southampton

Faculty of Natural and Environmental Sciences

Biological Sciences

Perimeter Land Management for Pollination and Pest Control Services in Apple Orchards

by

Emma Joslin

Thesis for the degree of Doctor of Philosophy

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Abstract

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Dessert apple orchards in the UK have successfully intensified their growing systems to enable a higher yield output per unit area. This agricultural intensification has allowed for more efficient crop management. However, this intensification has come at the detriment to space for non-crop vegetation in the orchards, attributed to sustaining invertebrate populations of pollinators and natural pest enemies with alternative resources and refuge. Therefore, the remaining populations of beneficial invertebrates in these systems might not be able to deliver sufficient or stable regulating ecosystem services such as pollination and pest control to the crop system.

To address this concern, I firstly carried out a survey with a select group of top-fruit growers in my study region to understand the practices and perceptions surrounding existing non-crop vegetation in orchards. Non-crop trees were already in place on farms as hedgerow or windbreak structures; however, these had rarely been designed to support beneficial invertebrates. Furthermore, various blockers for annual wildflower adoption were identified. Therefore, this knowledge contributed to the design of a novel ecological experiment to enhance apple orchard edges with perennial lavender and thyme plants. The aim was for these plants to provide successional floral resources in close vicinity to the crops to sustain pollinator populations after the mass apple bloom, whilst not deterring natural enemy populations to thrive on-site during the apple-growing season.

Orchard edges with either a mixed lavender and thyme treatment, or a lavender treatment, successfully sustained wild pollinators, such as bumblebees, in the orchards over the late summer months. The wild bee visitation rate to apple flowers in the spring also increased in orchards with a mixed orchard edge treatment. Although no repellent effects of lavender and thymes on natural enemies were found; the effects on ground or tree dwelling natural enemy populations remain uncertain due to sampling methods and agrochemical use. Aerial hoverfly abundances were higher in the orchards with a mixed lavender and thyme edge however, it would need to be

confirmed that these were aphidophagous species before concluding that natural enemies with an aerial life stage, which relies on floral nectar or pollen provision, could benefit from this orchard edge enhancement. Apple yield and quality were both unaffected by orchard edge treatments in the first two years after establishment. However, pollinator exclusion experiments confirmed the necessity of pollinators to the apples to achieve good yields and quality. Therefore, any increase to wild bee abundances from the orchard edge treatments could potentially contribute stability to the pollination service delivery by buffering the natural fluctuations in pollinator populations and the potentially inconsistent pollination services from managed honeybees.

This research shows how collaborating with the select group of growers that are responsible for non-crop habitat provision and management on farms in the study region can enable the development of novel alternatives to ensure that floral resource provision is available on-site for beneficial invertebrate populations.

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Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

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2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
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Definitions and Abbreviations

AES	Agri-Environment Schemes
DEFRA	Department for Environment, Food and Rural Affairs
EU	European Union
FAP	Farming with Alternative Pollinators
IPM	Integrated Pest Management
NGO	Non-Governmental Organisation
MRL	Maximum Recommended Limit (of pesticide residue)

Chapter 1 Literature Review

1.1 Intensive Agriculture and Biodiversity Loss

Modern agriculture has intensified further since the initial 'Green Revolution' when crop yields were vastly improved via new technologies such as chemical inputs (e.g. pesticides and fertilisers), machinery and new crop varieties (Tilman *et al.*, 2001). Although this continued agricultural intensification has been successful at increasing food production, it comes with the consequence of a major decline in biodiversity, such as for farmland birds and some small mammal populations (Krebs *et al.*, 1999; Chamberlain *et al.*, 2000; Donald *et al.*, 2001; Mathews *et al.*, 2018). This is due to the simplification of natural ecosystems where space made for large crop monocultures has reduced the abundance and diversity of habitat available for natural organisms (Tscharntke *et al.*, 2005). In addition, the chemical inputs that have been beneficial for yield improvements can be detrimental for the wider landscape via nutrient runoff, pesticide or insecticide damage to non-target species, health risks to humans of high insecticide use, and greenhouse gas emissions from farming practices and machinery (Zhang *et al.*, 2007; Power, 2010).

The current human population of 7.6 billion is predicted to rise to 9.8 billion by 2050 (United Nations, 2017). In the meantime, biodiversity is still declining (Butchart *et al.*, 2010); therefore, a need exists to increase production from the agricultural land that is currently in use in a more sustainable way. Scientific researchers and those involved in the implementation of policy need to incorporate an ecological approach that balances the agricultural productivity demand whilst ensuring that existing biodiversity is not diminished (Tilman *et al.*, 2002; Tscharntke *et al.*, 2012; Bommarco *et al.*, 2013; Armstrong McKay *et al.*, 2018).

1.2 Ecosystem Services

1.2.1 What are 'ecosystem services'?

To combat the loss of biodiversity, and to safeguard the earth's natural resources that underpin human society whilst ensuring sustainable development, the framework of 'ecosystem services' services is often used to link society to ecology. The Millennium Ecosystem Assessment defined ecosystem services as the 'benefits that humans obtain from ecosystems' (MEA, 2005). There are three main categories of ecosystem services, provisioning services (products that we obtain directly from the ecosystems); regulating services (regulate and affect the quality of other ecosystem services) and cultural services (non-material benefits from ecosystems) (Haines-Young and Potschin, 2010). In view of the variety of ecosystem services and ways in which they can benefit us, the original definition of ecosystem services was enhanced by Fisher *et al.* (2009) into 'aspects of ecosystems that actively or passively, produce human welling-being'.

1.2.2 Biodiversity and ecosystem services

The relationship between biodiversity and ecosystem services is complex (Mace *et al.*, 2012). The ecosystem services approach not only aims to protect biodiversity but biodiversity itself positively underpins the delivery of ecosystem services (Balvanera *et al.*, 2006; Mace *et al.*, 2012). This can come about via different mechanisms. It could be that the way in which increased species richness improves the benefit to crop production is through a 'sampling/selection effect'. For example, if there were a higher bee species richness in agro-ecosystems it means that it is more likely for an efficient pollinator species to be present (Klein *et al.*, 2003; Mallinger and Gratton, 2015). Alternatively, there may be a benefit to ecosystem service delivery if the extra species cover additional functional niches. Therefore, it could be that the presence of different functional groups is of higher importance to the efficiency of ecosystem service delivery than increased species richness alone (Balvanera *et al.*, 2006). However, others believe that instead of the innate preferences of each species, it is specifically "interactive complementarity effects" that are crucial (Cardinale *et al.*, 2002; Brittain *et al.*, 2013b; Fründ *et al.*, 2013). This means that an individual organism's ability to contribute to ecosystem service delivery is dependent on the wider community due to how the interactions with other species can affect the efficiency of their ecosystem service delivery. However, there may be species redundancy whereby after a certain number of species present in the system there is no further additional effect on the service delivery (Tscharntke *et al.*, 2005).

Communities with a higher biodiversity are also more resilient to environmental stress, therefore providing insurance against changing environmental conditions (Steudel *et al.*, 2012). However, the effects of biodiversity buffering disturbance are highly dependent on what the disturbance to the system is (Balvanera *et al.*, 2006) and the potential for higher species diversity to buffer the system may just depend on the presence of one species that has the ability to respond positively to a change (disturbance) (Cariveau *et al.*, 2013). Therefore, one stable, specific species may actually be better at buffering environmental changes than having more species that all react differently. However, as is the case regarding the sampling effect, studies on response diversity (Elmqvist *et al.*, 2003) differ greatly when considering their methodologies. For example, some studies possibly do not look at enough drivers of climate change, such as focusing solely on agricultural land cover, and also assume that each species is as efficient at multiple sites (Cariveau *et al.*, 2013).

Biodiversity may also benefit ecosystem service delivery and ecosystem function by ‘buffering’ the effects of species loss. If a species is lost, biodiversity may be able to provide understudy species that can act out another’s functional role in the event of extinction; i.e. ‘functional redundancy’. However, some argue that compensation for losses by surviving species is only possible when the extinction risk does not correspond to functional traits. If a species does not originally contribute much to the ecosystem service, then their loss may not be too detrimental (Hooper *et al.*, 2005).

1.2.3 Valuing ecosystem services for an ‘ecosystem services approach’

Considering ‘ecosystem services’ helps us to enable the realisation of goals such as the ecosystem approach from the Convention of Biological Diversity (CBD, 2010) which recognises that humans are integral to ecosystems. This ecosystem approach aims to integrate the management of terrestrial and aquatic resources in order to use them in a sustainable way with thought given to conservation and how to share the benefits obtained from them.

With the first analysis of the UK’s ecosystem services in 2011 (UKNEA, 2011), ecosystem services are fast becoming a way to integrate sustainability into the management of the Earth’s resources that we use. The consideration of ecosystem services is crucial in policy and management as the increasing cost of biodiversity loss and ecosystem degradation are made more apparent through various economic valuations (TEEB, 2010). These economic valuations can be used within policies to support conservation targets and allow payments in ecosystem service schemes. However, some warn against using ecosystem services alone to motivate biodiversity conservation. For example, in the case of bees, sometimes only the most common contribute the majority of pollination services to crops (Kleijn *et al.*, 2015).

1.3 Pollination and Pollination Services

1.3.1 Importance to agriculture

Pollination of plants or crops is achieved in different ways depending on the plant species; some rely on the wind whereas others require animal or insect mediated pollination. Approximately 65% of plants require animal pollination and importantly 75% global crop species rely on this method of pollination for productivity, mainly from insects (Klein *et al.*, 2007). A wide range of insects carry out invertebrate pollination such as bees, butterflies, hawkmoths and hoverflies. There is even variation within ‘bees’ alone as species richness naturally occurs due to the shape, size and nectar diversity of the native flowering plants (Potts *et al.*, 2003; Kremen *et al.*, 2007).

Insect mediated pollination is a regulating ecosystem service that is important to agricultural production, although the extent of pollination dependency will depend on the crop in question (Klein *et al.*, 2007). Pollination is fundamental for a healthy diet as insect pollination is necessary for many of our essential nutritional requirements; for example, pollination services are required for 90% of the crops that provide vitamin C (Eilers *et al.*, 2011).

Pollination services are also important financially; in Europe, insect pollination services are thought to account for around 12% of the annual agricultural production value which equates to 14.6 billion Euro (Leonhardt *et al.*, 2013). Gallai *et al.* (2009) estimated that the global contribution of insect mediated pollination is $153 billion per annum. However, this value should arguably be even higher because pollination services from insects could previously have been underestimated if their role in determining quality as well as yield was not adequately considered. For example, pollinators can increase the quality of fruits such as some apple varieties (Garratt *et al.*, 2014) and strawberries (Klatt *et al.*, 2013; Wietzke *et al.*, 2018).

1.3.2 Pollinator declines and suggested strategies

The concept of current 'pollinator declines' is often debated due to differing data sources and timescales used to draw conclusions (Aizen & Harder 2009). For example, despite suggestions that managed honeybees (*Apis mellifera*) are in decline (Potts *et al.*, 2010b), honeybee populations have actually been increasing in some areas for 50 years i.e. since the 1960's, despite specific time periods of losses (i.e. during 1990s) and declines in some countries (Aizen and Harder 2009). Therefore, when considering the data overall, managed honeybees are not in decline; globally, the number of hives has increased.

However, this does not guarantee that this key managed pollinator species is present in the necessary population abundances required to pollinate the dependent crops. Aizen and Harder (2009) found that the global rate of increase of managed honeybee hives is too slow for the increase of pollinator-dependent crops. Indeed, looking at data from 41 European countries, it was worryingly found that for over half of them there are not enough honeybees to supply the demands (Breeze *et al.*, 2014). In the UK alone, the importance of insect pollinated crops is rising and yet honeybee populations can only supply a third of the pollination requirements (Breeze *et al.*, 2011).

Unfortunately, it is not just as simple as embracing management plans that suggest a gradual phase out of honeybee reliance in order to allow native pollinators to take over (Tepedino *et al.*, 2007). This is because there have been reported declines of wild pollinators such as solitary bees, bumblebees and hoverflies in Europe since 1980 (Biesmeijer *et al.*, 2006) as well as declining species in North America and Asia (Williams and Osborne, 2009). This adds to the growing concern over whether countries can cope with wild pollinator losses if they do not have enough honeybees to rely on and vice versa (Breeze *et al.*, 2014).

The area of pollinator decline remains a controversial topic. Some think that pollinator decline has slowed down compared to before 1990 (Carvalheiro *et al.*, 2013). Additionally, the link between pollinator decline and pollinator-dependent crop productivity is also heavily questioned (Ghazoul and Koh, 2010). Aizen *et al.* (2008) found that on a global level there is not an explicit negative effect on insect pollinated crop productivity due to a pollinator deficiency. However, agriculture is becoming more pollinator dependant, due to increased planting of pollinator dependant crops; even if there is currently no impact on agricultural production, the dependence on pollination services will only increase over time. This will mean that in the future there is the potential for pollinator declines to greatly impact agricultural crop yields. The yield benefits of intensive agriculture are now being offset by the reliance of crops on pollination (which causes lower yield stability) (Deguines *et al.*, 2014).

There is still much debate around the specific drivers of pollinator decline. The multiple potential causes for pollinator population declines make mitigating current and future potential declines challenging. This is further complicated by interactions between factors that will differ between regions and species. For example, when considering the stability of managed honeybee populations: beekeeper numbers, the mite *Varroa destructor*, pathogens and 'colony collapse disorder' could all contribute (Potts *et al.*, 2010b; Ratnieks and Carreck, 2010). Causes for wild pollinator declines have been linked to reductions in plant species richness, through general habitat loss and the reduction of floral diversity and abundance (Biesmeijer *et al.*, 2006). Agrochemicals, such as neonicotinoid pesticides, also contribute to wild bee declines (Woodcock *et al.*, 2016) and pesticides contribute sublethal effects to bee learning and memory (Siviter *et al.*, 2018). Although some still deny that agricultural causes are responsible for pollinator species decline (Ghazoul, 2005), others recognise the effects of agricultural intensification and climate change on the dwindling pollinator populations (Goulson *et al.*, 2008a; Williams and Osborne, 2009; Potts *et al.*, 2010a).

Wild pollinator declines and the consequential potential detrimental impacts on existing and future crop yields, add support to the inclusion of pollinator conservation in policies for agricultural development (Aizen and Harder, 2009). Some have suggested that 'farming with alternative pollinators' (FAP) should be encouraged (Christmann and Aw-Hassan, 2012) and recent success has been found using FAP in sour cherry and cucumber crops (Christmann *et al.*, 2017). FAP policy encourages the provision of wild pollinator habitat corridors and ensures that floral resources are available. This would enable wild bees to compensate for possible future losses of managed pollinators. They are potentially capable of this; for example, native bees have been shown in watermelon crops to provide sufficient pollination if domestic honeybees are lost (Winfree *et al.*, 2007). FAP therefore gives native, as well as managed, pollinators an economic service value and crucially it would involve farmers, government and NGOs in order to influence policy.

Isaacs *et al.* (2017) eloquently combine the idea of using managed pollinators in combination with farming with alternative pollinators under their ‘integrated crop pollination’ approach. Their approach to ensuring the stability of pollination services is to collectively: consider the use of managed honeybees or alternative manged bees, enhance habitat for wild bees and consider crop management strategies that are potentially less harmful to pollinators, such as reduced pesticide use. This mixed approach would allow pollination strategies to be specialised for each spatial and temporal crop pollination requirement.

1.4 Pests, Natural Enemies and Biological Control Services

1.4.1 Importance to agriculture and suggested strategies

Biotic factors such as pest populations of weeds, pathogens, viruses and animal pests may inhibit the realisation of potential crop yield. Pests can reduce the yield quantitatively (yield loss) or via degradation of crop appearance and content (qualitatively) (Oerke, 2006). Oerke (2006) estimated that the crop loss to animal pests alone is around 10 - 40% depending on the crop in question. Due to the Green Revolution, world food production has increased whilst landscape complexity has decreased due to expansive crop monocultures, increasing crop vulnerability to pests; therefore, despite pesticide use, crop losses to pests still occur (Oerke, 2006). Of all the potential negative effects of agriculture, some think that the use of insecticides/fungicides have the most negative effects on biodiversity because insecticides also reduce the natural pest enemies (Geiger *et al.*, 2010). Natural pest enemies (hereafter, natural enemies) provide the regulating ecosystem service of biological control. Therefore, in order for the biological control ecosystem service to be utilised, biodiversity needs to be restored and protected in Europe and this must specifically include a reduction in the use of pesticides (Geiger *et al.*, 2010).

Typical biological control in agro-ecosystems could come from invertebrate natural enemies such as arthropods and parasitoids, vertebrates such as insectivorous birds and bats or even microbial pathogens (Tscharntke *et al.*, 2005). In order to encourage biological control services in agro-ecosystems, farmers will have to sustain and enhance non-crop habitats that are required to provide natural enemies with refuge and resources in close vicinity to the crop whose pests they will control (Tscharntke *et al.*, 2005). Although this potentially requires time and money, economically such management can be justified by predicting the value of biological control that is gained through the substitution of insecticide costs and the reduction in crop loss due to pest damage (Power, 2010). One previous economic estimate from 2006 estimated that natural enemies save the US alone approximately $13.6 billion annually, and of this, insects specifically (rather than pathogens) save $4.5 billion annually (Losey and Vaughan, 2006).

Biological control encompasses both augmentative and conservation biological control. Augmentative biological control involves the release of natural enemies on-site in order to supress pests. Whereas, conservation biological control involves improving the agricultural environment and practices (habitat management) to both protect and enhance specific natural enemies in situ in order to control certain pests (Eilenberg et al., 2001). These natural enemies may already be on-site, or they may be encouraged from the surrounding landscape into the local agro-ecosystem. Habitat management comprises the provision of floral resources (nectar and pollen), alternative hosts and prey, and shelter/refuge (Gurr *et al.*, 2017).

Biological control can be used in both ‘organic’ and ‘integrated pest management’ regimes. ‘Integrated pest management’ (IPM), is a varied pest management plan encompassing carefully considered strategies to ensure effective crop protection against pests resulting in the healthy growth of crops with a minimal negative depreciation of the ecosystem. IPM aims to reduce the reliance and over-use of pesticides, decreasing the risks of pesticides to human health and the environment (European Commission, 2009; FAO 2019a). IPM was thought of as one of the leading concepts within agriculture in the latter part of the 20th century with its history being founded as long ago as the 1800s when the first notion of ecology being important in scientific plant protection was realised (Kogan, 1998). IPM is now obligatory for all crop production in EU member states due to the Directive on Sustainable Use of Pesticides (EU Directive 2009/128/EC).

IPM methods include crop rotation, safer or fewer pesticide use, bio pesticides, biological control strategies, improved pesticide resistance management, using pest lifecycle analysis for population management and precision application methods. Landscape features could also be key to IPM programmes if they can affect a pest’s dispersal behaviour. Any management decisions made therefore need to incorporate these features into developing a suitable monitoring strategy for pest populations as well as aiding the most effective precise targeted interventions (Trematerra *et al.*, 2004).

As IPM involves both biological control and chemical control, economic thresholds are often established whereby pest damage must reach a certain critical point before resorting to chemical intervention. Economic thresholds are usually a specific population density of pests that once reached, means that it is cost-effective to apply control measures in order to prevent the populations from reaching the density at which they cross the 'economic injury level', and cause substantial economic damage to the crop (Ramsden *et al.*, 2017b). The use of set thresholds can allow biological control methods to try to ameliorate the pest problem first as some losses due to pests are expected. Setting a threshold for resorting to chemical application ensures a more sustainable approach that can also be economically viable (Oerke, 2006).

1.5 Ecological Intensification

'Ecological Intensification' is the practice of managing the landscape to specifically increase certain ecosystem services (and not degrading them or the natural capital) in order to increase the agricultural productivity of crop-land, reducing reliance on agro-chemicals to achieve this, resulting in more sustainable increases in crop productivity and yield outputs (Bommarco *et al*., 2013; Tittonell., 2014; Pywell *et al*., 2015). 'Sustainable intensification' encompasses a broader remit of approaches and definitions, whereas ecological intensification is a landscape-scale method, necessitating ecosystem services and functions, through which we can achieve sustainable agriculture (Tittonell., 2014; Struik and Kuyper., 2017).

Tilman *et al.* (2002) define sustainable agriculture as 'a practise that meets current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered'. In sustainable agriculture via ecological intensification, provisioning services could be maximised by management practices to increase yields whilst also enhancing biodiversity and regulating ecosystem services such as pollination and biological control which themselves play a role in agricultural productivity (Isaacs *et al.*, 2009; Power, 2010; Miñarro and Prida, 2013). To achieve sustainable agriculture, whereby we increase yields whilst simultaneously promoting the recovery of biodiversity lost from conventional agricultural intensification, which has not previously been 'sustainable' (see Section 1.1), pesticide use must be reduced (Armstrong McKay *et al.*, 2018). Therefore, sustainable agriculture must also mean that an effort is made to reduce the environmental impacts from agricultural energy use such as in the manufacturing and transport of agricultural goods (Tilman *et al.*, 2002).

Ecological intensification is agricultural intensification without the anthropogenic input to increasing yield i.e. without added inputs or enhancement of crop productivity. Instead, it focuses on increasing yields via environmentally friendly methods that enhance ecosystem services from biodiversity in crop production systems (Bommarco *et al*., 2013). Therefore, by considering ecological processes in agricultural management practices we have the potential to enhance yields whilst also being environmentally friendly (Bommarco *et al.*, 2013; Pywell *et al.*, 2015). In this way, ecological intensification is largely based upon the original concept of wildlife-friendly 'land sharing'. However, the key difference is that it takes what was originally thought of as 'extensive farming' and instead increases the productivity on that land via certain management practices aimed to increase the biodiversity present, in order to maximise ecosystem service provision for agricultural production.

The original debate of intensive (land sparing) vs. extensive (land sharing) agriculture has been deliberated for years regarding which one results in the best scenario for balancing the agricultural ecosystem disservices with services and academics have long believed it is an important issue that warrants research attention (Zhang *et al.*, 2007). The competing concepts are whether land should be separated for biodiversity conservation and agricultural production (i.e. the "land sparing" approach where agricultural area is separated from an area specified for conservation) or if it should be integrated together on the same land (the "land sharing" approach of wildlife-friendly farming) (Tscharntke *et al.*, 2012).

Although some studies have shown that land sparing is successful (Phalan *et al.*, 2011), others argue that land sharing is the best approach to incorporate real life complexity (Tscharntke *et al.*, 2012). They think that as most agriculture is not necessarily large scale, rather, smallholders dominate it; a land sparing approach would be difficult to implement. Whereas, smallholders would be able to implement management for land sharing on a local scale. A further argument for land sharing, is that some ecosystem services operate on a local scale and are required on-site in agro-ecosystems. For example, Zhang *et al.* (2007) identified that there are certain ecosystem services (and indeed disservices) that function at a field and farm scale such as: ground nesting bees for pollination, microbes, legumes, invertebrate communities for soil fertility and nutrient cycling.

Regarding pollination services, Deguines *et al.* (2014) argue that for crops that are heavily pollinator-dependent, land sharing is the most appropriate approach to ensure sustainable high yields. Indeed, there is a lot of evidence that pollination services need to be conserved and encouraged within the agricultural landscape (and not on separate land). For example, it was found that for 16 different crops over 5 continents, pollinator richness and visitation rates decreased in crops with increasing distance from natural/semi-natural habitats (Ricketts *et al.*, 2008). This could be due to flight costs which is why mean bee size increases in oil seed rape fields with increasing distance from the forest edge (Bailey *et al.*, 2014). More recently, Garibaldi *et al.* (2011) found that as well as floral visitation rate, fruit set decreased with increasing distance from natural areas, something that others had not previously found (Ricketts *et al.*, 2008). It was also shown that flower visitors in mango declined in diversity and abundance with increasing distance from their natural habitat (Carvalheiro *et al.*, 2010). It is not just pollination services that require on-site attention; distance from extra-orchard habitats have also been shown to affect biological control in orchards due to the distance effects on natural enemies such as some taxa of spiders and parasitoids (Miliczky and Horton, 2005).

Therefore, the value of functional biodiversity immediately within farmland should not be underestimated, it deserves adequate management and conservation attention (Tscharntke *et al.*, 2012). Managing the habitat within and around the agro-ecosystems can therefore ensure that these pollination and biological control services are sustained and encouraged on-site/in situ as they will then have the right resources necessary to contribute to crop productivity (Tscharntke *et al.*, 2005). Moreover, it is important to work with farmers in order to achieve this because the detrimental impacts that agricultural practices may have on the environment are not costs that are typically priorities to farmers when they are making choices about their agricultural practices (Tilman *et al.*, 2002). Farmers need proof that economic gain will come from certain sustainable agricultural management (Carvalheiro *et al.*, 2010) and must be encouraged appropriately. One of the key issues that needs to be overcome in the fight to ensure sustainable agriculture is to target farmer incentives (Tilman *et al.*, 2002).

1.6 Non-crop vegetation in agro-ecosystems

1.6.1 European agri-environment schemes

In the UK, agriculture has shaped much of what we consider to be our natural environment, and we have embraced the 'land sharing' approach and farmer incentives through the European Agri-Environment Schemes (AES). These are voluntary agreements enabling farmers and land managers to make environmentally sensitive management decisions on their land, more so than regulation alone requires. Natural England delivers these AES on behalf of the Department for Environment, Food and Rural Affairs (DEFRA) and there are different schemes within this such as entry-level stewardship, organic entry-level stewardship, upland entry-level stewardship, higher-level stewardship and organic higher-level stewardship.

AES have improved the abundance and diversity of pollinators and natural enemies in landscapes dominated by intensive agriculture via the increased complexity and diversification they offer, whereas, in non-intensive systems (such as grasslands) this complexity, and therefore alternative foraging habitats, already exists (Carvell *et al.*, 2011; Kennedy *et al.*, 2013; Scheper *et al.*, 2013).

AES can also help intensive farming to rival some of the organic farming benefits; Kennedy *et al.* (2013) showed that enhancing conventionally managed fields to have a higher vegetative diversity could result in a similar bee abundance and richness as organic fields with lower vegetative diversity. Therefore, farm management approaches should ensure that there are high quality habitats around the farm to sustain beneficial invertebrate populations, as well as management options in place to compensate for any potentially negative ecological impacts that intensive monocultures are associated with (Kennedy *et al.*, 2013).

One such 'high quality habitat' is non-crop vegetation. Non-crop vegetation provides beneficial invertebrates (pollinators and natural enemies) in intensive agro-ecosystems with resources such as alternative food supplies, nesting habitat, shelter and refuge. The non-crop vegetation focused on in this thesis are those on the crop perimeter such as hedgerows, windbreaks and non-arboreal floral resources.

1.6.2 'Hedgerows'

A linear row of woody vegetation (shrubs and/or trees) is defined as a hedgerow if it is a boundary line over 20 m long, with a base of less than 5 m wide (Defra, 2007). The components of a hedgerow are not just shrubs or mature trees, the 'complete hedge' must be considered. This includes any herbaceous growth at the base of the hedgerow as well as any margin (buffer/headland strip of land that is managed separately to the crop in agricultural land) and they may be on a bank or have a ditch on either side of them (Hedgelink). Additionally, hedgerows have a human component (i.e. their management) whether they were planted or spontaneous (Baudry *et al.*, 2000). Therefore, their exact composition depends partially on abiotic environmental conditions and what their management has been over time (Deckers *et al.*, 2004).

1.6.3 'Windbreaks'

'Windbreaks' are structures whose primary role it is to reduce the wind speed. They mitigate the potential damage from high winds by affecting the local airflow. This can potentially have a positive impact on the microclimate such as air temperature and humidity changes (Heisler and Dewalle, 1988; Nuberg, 1998). It is worth noting that 'hedgerows', although not specifically in place to be windbreaks, can also have this windbreak effect of a change in microclimate downwind (Nuberg, 1998).

1.6.3.1 The many benefits of hedgerows and windbreaks:

Even before the ecosystem services concept, it has long been acknowledged that hedgerows have an economic and ecological value (Forman and Baudry, 1984). They play a critical role in the aesthetics of the agricultural landscape, provide firewood/timber, inhibit erosion, act as fences for grazing animals, clearly show property boundaries, protect land from wind damage, provide nesting sites for natural enemies and play a role in general biological conservation. This entire composition of benefits makes them economically viable and outweighs the loss of farmland area/increased time it takes for farmers to manage smaller fields instead of one big one and any potential competition for soil nutrients, water or light (Forman and Baudry, 1984). Negative effects of these non-crop vegetation structures can also be mitigated by root pruning, ensuring that they are not too close to crops, choosing their general orientation carefully and managing their height (Cleugh, 1998; Nuberg, 1998).

Woody borders such as hedgerows and windbreaks have been shown to increase insect diversity in agro-ecosystems (Holland and Fahrig, 2000). Hedgerows and hedgerow restoration has been shown to promote native bee and hoverfly persistence and colonisation, thus greater species richness, as opposed to if edges of productive land were just left unenhanced or unrestored (M'Gonigle *et al.*, 2015; Sardiñas and Kremen, 2015), lending evidence to the importance of local habitat restoration in intensive agricultural landscapes to sustain species rich pollinator populations. Hedgerows also support greater predator species diversity and densities in crops; however, results are likely to vary depending on the crop (Paoletti *et al.*, 1997; Morandin *et al.*, 2014). Furthermore, parasitoid community composition is often dependent on the presence of hedgerows/windbreaks and their characteristics (Forman and Baudry, 1984; Maalouly *et al.*, 2013).

1.6.3.2 How hedgerows and windbreaks can affect beneficial species populations:

There are several mechanisms in which these non-crop vegetation structures can support beneficial invertebrates. Firstly, hedgerows and windbreaks may enhance beneficial species populations because they add to the non-crop complexity and thus the overall landscape complexity. Two different meta-analyses (Langellotto and Denno, 2004; Bianchi *et al.*, 2006) have both concluded that diverse landscapes are best for enhancing the pest control function of biodiversity as natural enemies are associated with complex landscapes of grassland, and non-crop herbaceous/woody habitat due to a higher availability of resources and area of refuge. For example, non-crop area and landscape complexity is negatively correlated to pest damage and positively to parasitism measured by pest larval mortality in oil seed rape (Thies and Tscharntke, 1999; Thies *et al.*, 2003).

As well as contributing to general landscape complexity, pest control services could also be enhanced by hedgerows because they can alter microclimates for natural enemy shelter (Landis *et al.*, 2000). The modification of nearby climatic conditions can also directly affect a pest's movement (Kührt *et al.*, 2006) and disrupt pest pheromones essential for mating, implying that hedgerows could reduce mate-finding efficiency (Ricci *et al.*, 2009). Hedgerows (and vegetative windbreaks) can either be ecological corridors or barriers to pests (Sciarretta and Trematerra, 2006). The optimum situation is to ensure that they are barriers to pests whilst acting as corridors to natural enemies. When choosing the composition of vegetation (windbreaks or hedgerows), care must be taken to ensure they do not host arthropod, fungus, bacteria, mycoplasma or virus pests (Norton, 1988; Rieux *et al.*, 1999).

Non-crop vegetative structures can also support beneficial invertebrates by providing alternative food resources for natural enemies and pollinators. Flowering hedgerow species can help to provide successional pollen and nectar resources for beneficial insects over the year that can enhance the agro-ecosystem through pollination and pest control services (Miñarro and Prida, 2013; Morandin and Kremen, 2013). Furthermore, hedgerow trees can offer reserves of alternative prey. For example, some have found that they have a higher species richness and abundance of macromoths than grassy field margins. These macromoths provide an alternative food source for natural enemies to sustain their populations when the pest populations are scarce (Merckx *et al.*, 2009; Merckx *et al.*, 2012).

1.6.4 Wildflower provision

Another way to ensure that floral resources are available for pollinators and natural enemies is to plant wildflower mixes. It is possible to sequentially sow floral resources to provide nectar and pollen from early summer to autumn to ensure the temporal availability of resources to beneficial insects in intensive crop systems and to support the different species that will be attracted at different times of the year and by different resources (Carreck and Williams, 2002; Goulson *et al.*, 2008b). Pywell *et al.* (2011) therefore recommend that nectar flower mixes should include both mid and late season resources in order to provide resources throughout the bumblebee reproductive season. Plants such as red clover are suggested to be useful because of their phenology; with later flowering than other species, the temporal availability of resources is ensured (Rundlof *et al.*, 2014). Additionally, others have recommended mixtures such as *Tanacetum vulgare*, *Chrysanthemum maximum*, *Aster tongolensis* and *Achillea millefolium* to attract hymenoptera and diptera, because they provide overlapping and successive flowering so there is a prolonged availability of resources with an additional overwintering refuge/resource element (Bostanian *et al.*, 2004). Overwintering resources are important not only for pollinators but also for natural enemies (Thomas *et al.*, 1992). Natural enemies (such as parasitic wasps, spiders, ants, hoverflies and minute pirate bugs) have been shown to prefer floral resources over mown grass (Blaauw and Isaacs, 2012) and natural enemy abundance has been found to be higher in crops with adjacent wildflower provision (Blaauw and Isaacs, 2015). These results add supportive evidence to an earlier study that showed that out of five different field margin types: 1 cropped, 2 sown tussocky grass mix, 3 grass and wildflower, 4 grass adjacent to hedge with wildflower next to crop and 5 natural regeneration – that pollinators and predatory insects preferred any field margin that contained wildflowers (Meek *et al.*, 2002).

As well as ensuring temporal availability of floral resources, there is a need to ensure that these mixes contain both annual and perennial species. Beneficial insects such as bumblebees, hoverflies and parasitoid wasps (that provide pollination and/or biological control services) have different preferences of floral traits which suggests that by having increased plant richness, there are functionally diverse floral resources that can attract a more species rich insect assemblage (Campbell *et al.*, 2012). Indeed, species richness of flowering plants has been shown by many to be the best predictor of bee species richness and equally the coverage of floral resources for bee and hoverfly abundance (Steffan-Dewenter and Tscharntke, 2001; Sutherland *et al.*, 2001; Rosa García and Miñarro, 2014). It is known that longer-tongued bumblebees prefer mixtures of perennials with dominant red clover (*Trifolim pratense)*, whereas shorter-tongued bumblebees and honeybees preferentially visit borage (*Borago officinalis)* in an annual mix (Carvell *et al.*, 2006). Hence a mixture of annual and perennial grasses and wildflowers on field margins is ideal for bumblebee forage resources and diversity (Backman and Tiainen, 2002; Carreck and Williams, 2002; Meek *et al.*, 2002; Carvell *et al.*, 2004; Pywell *et al.*, 2005; Pywell *et al.*, 2006; Carvell *et al.*, 2007).

Another benefit of adding wildflowers compared to other field margin options, such as conventional cropping, is that they require negligible herbicide applications, have a simple cutting regime and can provide benefits for at least three years (Carvell *et al.*, 2004). However, farmers can be reluctant to implement wildflowers, viewing them as having no economic return and as potential weeds that might spread into crops (Christmann *et al.*, 2017).

1.7 UK Apple Production

As a case study for ecological intensification and enhancing pollination and pest control services using non-crop vegetation, this PhD thesis focuses on UK dessert apple production. Research in this area has been very active in the years since the commencement of this doctoral work. The number of studies in the ISI Web of Science database last updated in August 2018, for the search term ‘TS=(apple AND ecosystem service$)’ was almost double in the four years from the start of this research in 2014 to 2018 (n = 89) compared to the four preceding decades put together 1970-2013 (n = 49).

Currently in the UK, 16,512 ha of land is dedicated to apple production. This land produces 481,100 tonnes of apples annually. Whereas less agricultural land is dedicated to pears, with only 1,524 ha producing 24,000 tonnes (FAO, 2016). To get the apple yields that we are able to produce in the UK today, the orchard growing systems have intensified over time. Originally, before the commercial production of orchard fruit, there were ‘traditional orchards’. Traditional orchards are still a valuable part of the British cultural landscapes but are becoming rarer. Traditional meadow orchards generally contain older fruit varieties (with a mixture of varieties in the same orchard) and large spaces between trees. Normally they are defined as having five or more fruit trees that are 20 m or less apart on grassland that is often grazed by livestock. In the UK, they are acknowledged as an important area to protect due to the saproxylic invertebrates and epiphytic lichen assemblages that they support, as well as other important invertebrates and grassland species. They are also a potential resource contributing to important species such as farmland birds (BAP, 2007). Whereas, in modern UK apple production, traditional orchards have gradually been replaced with a system that is higher yielding, with trees in uniform rows and more intensively managed (Figure 1.1).

An intensive orchard system that has now become commonplace in the UK is the ‘concept orchard’. Concept orchards (see comparison to traditional orchards in Table 1.1) were started in 2006 by Sainsbury’s, in collaboration with the Woodland Trust, in order to halt the decline of the British apple and pear orchards. Initially, they were used to develop and trial new varieties and to try innovative growing practices in order to increase yields. This increased yield per hectare then enables growers to maintain their livelihood in an increasingly competitive market.

Figure 1.1 Modern orchards with rows of uniform trees

Table 1.1 A comparison of the main determining features of traditional orchards and modern intensive concept orchards

Traditional Orchards	Concept Orchards
≥ 5 trees in the orchard	3,000 trees per hectare
Trees ≥ 20 m apart	Trees 1 m apart
No row structure	Uniform rows of fruit trees with 3 m between rows.
Often grazed by livestock	Not grazed by livestock
Extensively managed	Intensively managed

There are usually around 3,000 trees per hectare just under 1 m apart within the row, with just over 3 m between rows. Additionally, the growing system uses a 'Dutch table-top method' with posts and wires to support more fruit on the tree without bruising. Technological advances have enabled a system where neuron probes in the soil allow a computerised irrigation system to work effectively. Other management includes regular pruning of the trees to keep them the correct age of wood, cut out disease and keep the tree in the correct shape to enable evenly distributed sunlight for the required apple colour.

Most apple varieties are self-sterile and require pollen from other compatible varieties (Ramírez and Davenport, 2013). Therefore, within a genetically uniform row, there is also a 'pollinator tree' or 'polliniser' of a different variety every 5 - 10 trees. Insect mediated pollination is required to transfer the pollen from these 'pollinator trees'; in this way, pollination services in apples are essential for yield and quality (Garratt *et al.*, 2014).

Within the different apple-growing systems, there have also been different pest management regimes of organic, conventional (historic non-organic), or integrated. Organic orchards follow the fundamental elements of organic production; crop rotation, soil fertility management, along with pest and disease control via natural husbandry techniques that seek to protect the environment (European Commission, 2007; FAO, 2019b). The use of artificial agrochemicals, such as fertilisers and pesticides, are largely avoided unless they are on the limited list specifically approved to use in organic systems where necessary. Organic pest management therefore mainly relies on a variety of management techniques and informed planning to control pest populations. These include, pest lifecycle analysis, protecting and encouraging natural enemies and selecting pest resistant plant varieties. However, only around 5% of top fruit orchards are actually organic (DEFRA, 2014).

Conventional, non-organic orchards would instead have relied on the use of broad-spectrum insecticides to control pests. However, conventional orchards have now all embraced a degree of integrated pest management due to the EU Sustainable Use of Pesticides Directive (European Commission, 2009) rendering integrated pest management obligatory (EU Directive 2009/128/EC). Therefore, modern non-organic orchards all implement IPM (see Section 1.4 for definition) which combines practices from both the (historical) conventional management and organic management because they have a mixed approach to pest management i.e. integrated pest management. Essentially, they promote the use of biological control alternatives in addition to the more traditional chemical management system, with pesticides and herbicides (Blommers, 1994).

Although the modern apple-growing systems of today are generally more intensive, as well as implementing IPM, their closer tree proximity enables more efficient pesticide application, meaning that when applied, potentially less needs to be used. Furthermore, greater yields per hectare allows a reduction of input costs and as yield increases, the carbon footprint of the orchard reduces. This sustainability potential indicates that it is a good model system to use in order to investigate how various land management practices can ensure sustainable intensification. However, one of the areas still needing attention is the provision of non-crop vegetation in orchards to sustain beneficial invertebrates that underpin apple production by providing the regulating services pollination and biological pest control.

1.8 Growers' decisions and opinions on non-crop vegetation in apple and pear orchards for pest control and pollination services

1.8.1 The importance of incorporating farmers views into ecological research

Understanding the current management practices and perspectives of top fruit growers is central to increasing their involvement in wildlife-friendly strategies to enhance pest control and pollination services. This is especially important as non-crop vegetation, such as wildflower resources, have been shown to increase both pollinators (Scheper *et al.*, 2015) and natural enemies (Ramsden *et al.*, 2015) in agro-ecosystems. Furthermore, hedgerow structures support a greater species richness and abundance of native bees, syrphid flies and parasitoids than crops or unenhanced edges and these effects can be seen up to distances of 100-200 m into a crop from an adjacent hedgerow (Morandin and Kremen, 2013; Morandin *et al.*, 2014; M'Gonigle *et al.*, 2015; Sardiñas and Kremen, 2015). Therefore, non-crop vegetation in intensively managed agricultural landscapes, not only sustains and enhances biodiversity, it may also improve ecosystem services such as pollination and pest control on farms. This is both ecologically and economically valuable to a farmer's crop production.

Worryingly, although on-farm biodiversity is an important component of the farm ecosystem, research has not given enough attention to the rationale of the management choices that farmers make. It is crucial to understand the reasons behind specific farmer management (or neglect) of non-cropped edges; more research is needed into the technical, economic and social factors that determine farmers' capacity and willingness to enhance farm edge biodiversity (Brodt *et al.*, 2009). Indeed, it was recognised over 20 years ago that 'because most landscape ecologists are neither social scientists nor agronomists, human perceptions and decisions are often overlooked' (Burel and Baudry, 1995). This view has been reiterated over time, with others suggesting that agri-environmental measures should be planned with farmer attitudes and specific circumstances in mind (Herzon and Mikk, 2007), thus corroborating the necessity for an interdisciplinary research collaboration between social scientists and natural scientists (ecologists) (Phillipson *et al.*, 2009; de Snoo *et al.*, 2013). Therefore, agricultural conservation should also be thought of as a social challenge with farmer motivation and behaviour needing to be understood and influenced (de Snoo *et al.*, 2013).

Research into farmer motivations to implement environmentally friendly measures (such as AES options) has highlighted that farmer attitudes are pivotal in the uptake of such management decisions and their consequential environmental outcomes (Willock *et al.*, 1999; Defrancesco *et al.*, 2008; Sattler and Nagel, 2010). To understand farmer attitudes and motivations for implementing wildlife-friendly farming measures, it is often imperative to first realise that farmers are not all the same. Indeed, some have attempted to classify them into different groups. For example Brodt *et al.* (2006) categorised farmers into 3 types based on the order of rankings of goal statements. The three groups were 'environmental stewards', 'production maximisers' and 'networking entrepreneurs'. Alternatively, another study classified Australian farmers into four different groups: 'non-green dismissive', 'uncommitted', 'green adopters' and 'profit-driven adopters' (Morgan *et al.*, 2015).

Regardless of the different categories that are used to classify farmer types, to ensure involvement by every farmer in environmentally friendly practices, each 'group' will warrant a bespoke engagement strategy (Morgan *et al.*, 2015) with tailored/customised agro-environmental schemes that appeal to their different attitudes and characteristics (Schmitzberger *et al.*, 2005; O'Rourke *et al.*, 2012). For example, when measuring the effects of natural enemies on pest populations, the impact measurement should be customised to the specific farmer needs and pest problem at hand (Macfadyen *et al.*, 2015). Advice should focus on how they can best incorporate natural enemies to make valuable management decisions. For example, some systems may benefit from the timing of natural enemy arrival into a crop whereas in others, natural enemy diversity may be the key to enhancing the biological pest control services from natural enemies (Macfadyen *et al.*, 2015). The design and implementation of pollinator management decisions should also incorporate growers' opinions. For example, if they are apprehensive about enhancing hedgerow floral resources in case they are more attractive to pollinators than the crop plants themselves, there should be management options/suggestions available to implement plant species that do not bloom at the same time as their crops (Morandin and Kremen, 2013).

It is of course ideal for wildlife-friendly management regimes to be cost-effective, considering that the farmers will likely have the burden of the financial input and management costs (Brodt *et al.*, 2009). Furthermore, farmers are sometimes more likely to adopt certain agricultural practices if there are clear financial benefits outlined and they possess the relevant skills and knowledge required to implement a given farming practice (Morgan *et al.*, 2015). However, a farmer's actions are not necessarily driven by monetary factors alone (Siebert *et al.*, 2006). Other factors significantly contribute to how they make management decisions: the ability to implement them practically and the social influence of others around them, such as farmers and advisors (Siebert *et al.*, 2006). For example, interviews of mixed/arable farmers in Germany revealed that the economic cost of certain environmental measures was not the most important factor; other considerations such as effectiveness, time/effort and any associated risks were at least equally substantial (Sattler and Nagel, 2010). Farmers in Estonia and Finland both showed a willingness other than economic incentive to implement certain wildlife-friendly farming measures (Herzon and Mikk, 2007). However, for less popular options, such as hedge planting or reduction of chemical applications, the farmers did require reimbursement, showing that different management regimes could require different incentives, with economic factors more important for some than for others (Herzon and Mikk, 2007).

Most farmers think that their profession is responsible for the countryside (Macdonald and Johnson, 2000), often identifying as custodians of the land and showing a strong sense of responsibility for management decisions, such as those regarding hedgerows (Beedell and Rehman, 1999; Oreszczyn and Lane, 2000). However, farmers' understanding of care is often different from the experts, with a lack of trust in both directions. The experts themselves do not necessarily always trust farmers to care for the countryside (Oreszczyn, 2000; Oreszczyn and Lane, 2000) and farmers do not necessarily trust expert advice for management decisions. For example, some farmers disagree with the terms of hedgerow cutting in AES and instead want to cut hedgerows yearly (Darragh and Emery, 2018). Farmers often do not believe that decision makers will consider their views (Oreszczyn, 2000; Oreszczyn and Lane, 2000) but to ensure that policy is both informed by sufficient evidence and that the industry will put it into practice, all stakeholders must be involved in the farmed environment policy-making process.

1.8.2 Top-fruit grower survey and interview implementation

Targeting the views of farmers and those in agriculture is central to increasing their involvement in wildlife-friendly farming practices and management strategies that enhance ecosystem services. The perspectives of the select group of growers who would be the ones to implement the management suggestions are often lacking. Therefore, my overarching aim, via grower surveys and interviews, was to identify the existing range of non-crop vegetation in commercial apple and pear orchards and to investigate growers' perspectives regarding the possible services and disservices that they might provide to their fruit production in a case study area in Kent, UK. Secondary objectives were to uncover growers' opinions on the drivers of crop loss and what management practices they have in place to control orchard pests. The eventual goal was for this research to inform the design of the ecological field experiment (underpinning Chapters 2-4) in order to ensure that the ecological research and potential management recommendations remain applicable to the industry, and the geographical area, in which they would be applied.

The study area encompassed a total of over 400 hectares of apple and pear orchards in the county of Kent, south-east England. In 2013/2014 the planted area (hectares) in the UK for pears was estimated to be 1446 and 8757 for dessert apples and culinary apples, a total area of 10,203 hectares (excluding cider apples and pears) (DEFRA, 2014). The study area therefore represented 4% of this UK apple and pear production area. This study area of south-east England is prominent for apple and pear production with over half of most dessert apples and pears produced in England and Wales grown in the south-east and London region; for example, in 2013 this region produced 90% of the Braeburn and 80% of all Gala apples grown (DEFRA, 2013).

I sought to survey individuals who make day-to-day commercial orchard management decisions in this study area and those involved in the supply chain of a major UK supermarket. This ensured the information gathered was as relevant as possible to the design of the ecological fieldwork, in commercial orchards within this geographical area (Chapters 2-4). We identified 17 participants in a homogenous purposive sampling design in 2015; all participants were part of the same commercial top fruit supplier grower group in 2015. Growers therefore supplied the commercial retail market via the top-fruit supplier. The Technical Director of the supplier provided the contact details of the study participants.

I sent out a targeted paper survey/census (Appendix A) titled 'Land Management for Ecosystem Services in Orchards' to all identified participants. Survey design was an interdisciplinary collaboration; it was discussed, developed and piloted with academics at the University of Southampton, a retail representative, an apple grower and The Woodland Trust. I first sent out participation packs by post at the end of March 2015; they included the survey, a participant information sheet, consent form and a stamped-addressed envelope for the return of completed surveys and consent forms. After this initial contact, growers who did not respond with either a decline to participate or a completed response were contacted with a follow-up posted letter (and an e-mail), a second posted participation pack (and a follow-up e-mail) and a final e-mail with the participation pack attached in electronic form.

The respondents were asked for both quantitative and qualitative information, with specific questions under the following categories (Appendix A): 1.) Farm details, orchard type and varieties grown; 2.) Crop wastage and crop pests; 3.) Windbreaks – type and opinion; 4.) Pest control and pollination.

After the survey, the same respondents were also given the option of being involved further in the project. This meant that they were followed up with a semi-structured face-to-face interview (Appendix B). The aim of these interviews was to gain a further understanding of the personal current and historical views of non-crop tree/plant management and opinions on the ecosystem services pollination and pest control in the orchards. I asked respondents to expand on their answers from the postal survey and to clarify why certain decisions had been made surrounding the varieties of fruit grown. I also sought their opinion on the time investment and considerations of certain orchard management decisions. Interviews were rounded off with questions surrounding their involvement in AES and their opinions on pollination and pest control in apple orchards.

In total, twelve growers participated, two declined, and three did not respond; a 70.6% response rate. I conducted follow-up interviews with four of the respondents. All interviews were approximately one hour long and on two occasions were followed with a tour of the grower's orchards so that they could visually explain their current management. The respondents, although from a purposive sample, were from a range of locations across the study area in Kent, UK.

Given this small purposive sample size, the data presented is predominantly qualitative data from open ended questions along with descriptive statistics (as in Brodt *et al.* (2009)); I counted the number of farmers implementing different management practices. Data spread was shown by box and whisker plots of the median and interquartile range using R (R Core Team, 2015). The further insights received in the face-to-face interviews are integrated into the appropriate findings sections as they often build upon certain opinions given in the survey and the limited sample inhibits separate analyses.

1.8.3 Findings from the trop-fruit grower surveys and interviews

1.8.3.1 Top fruit production on the respondents' farms

All but one respondent grew both apples and pears. The number of different apple and pear varieties grown by the respondents on their farms ranged from 2-14 varieties (Figure 1.2). For apples, the most frequently grown variety were the dessert apples Gala (83.3%) and Cox (66.7%) and over half of the respondents also grew Bramley apples (58.3%) (Figure 1.3). It is unsurprising that the main apple varieties grown were Gala, Bramley and Cox. In 2012, the south-east and London grew 80% of Gala, 74% Bramley seedling and 74% Cox in England and Wales, hence they are popular varieties in this region (DEFRA, 2013). It is however unexpected that less than half grew Braeburn as 90% Braeburn is grown in this region (DEFRA, 2013).

There were fewer varieties of pears grown compared to apples (Figure 1.3). Over half of the respondents grew the pear varieties, Conference (83.3%) and Doyenne du Comice (58.3%). These are known to be popular varieties in this region; 81% of UK Conference pears and 86% of UK Comice pears are grown in this region (DEFRA, 2013).

The choice of varieties grown was due to economic, historical, social and biotic influences. The interviews uncovered that the choice of varieties grown was dependent on what varieties were already established on the farm, what varieties the consumer demands and the farm's soil type. The timing of harvest of each variety was also considered when choosing what varieties are grown together on the same farm. Choosing varieties with differing harvest times allows farmers to focus their time and resources sequentially by harvesting one variety at a time. This is increasingly valuable considering the future labour worries of the agricultural industry in the current political climate. Furthermore, having a mix of varieties might reduce the economic risk of some varieties not meeting the quality specifications required to sell to the UK supermarkets. If growers supply different fruit varieties to multiple customers, they have the potential to sell the fruit that does not meet the necessary supermarket specification to wholesalers instead. As one farmer mentioned 'we also send all our Bramley, Cox and Gala to wholesale market, meaning we can put our 'out of supermarket spec' fruit in'. Interestingly, one opinion was that the UK apple and pear industry is small and 'very market focused', with 'only 400 growers and probably only 100 that matter'.

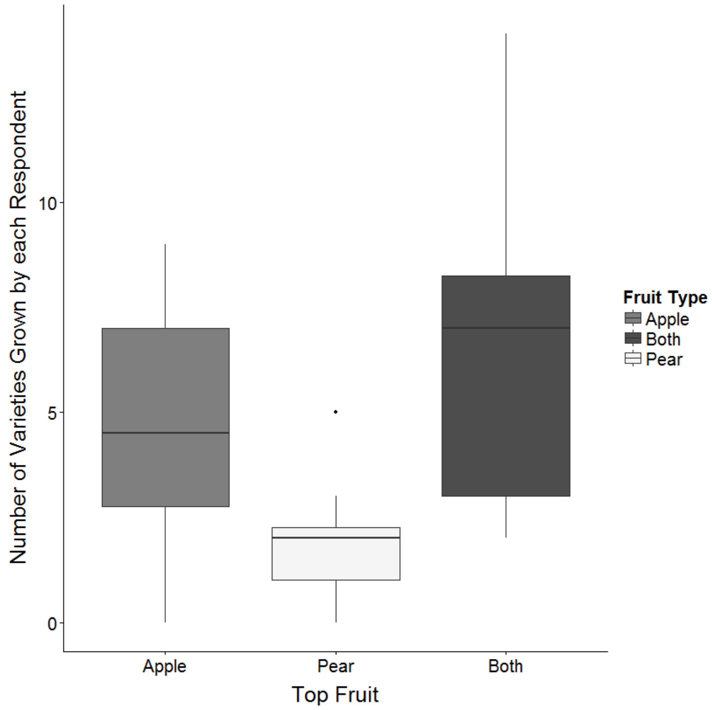


Figure 1.2 Box and whisker plots showing the median number of varieties grown by respondents of apple, of pear and of the combined apple and pear data. The lower and upper limits of the box represent the inter quartile range (IQR) of the data whiskers extend from the boxes to show maximum and minimum values.

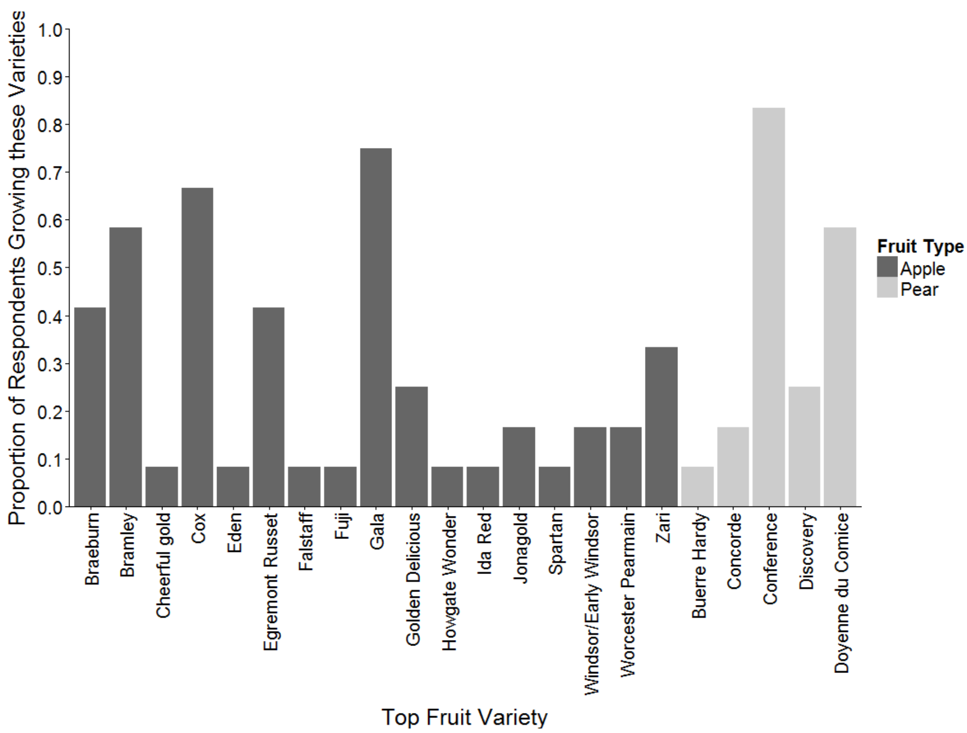


Figure 1.3 The proportion of respondents (n = 12) growing these varieties of apples and pears

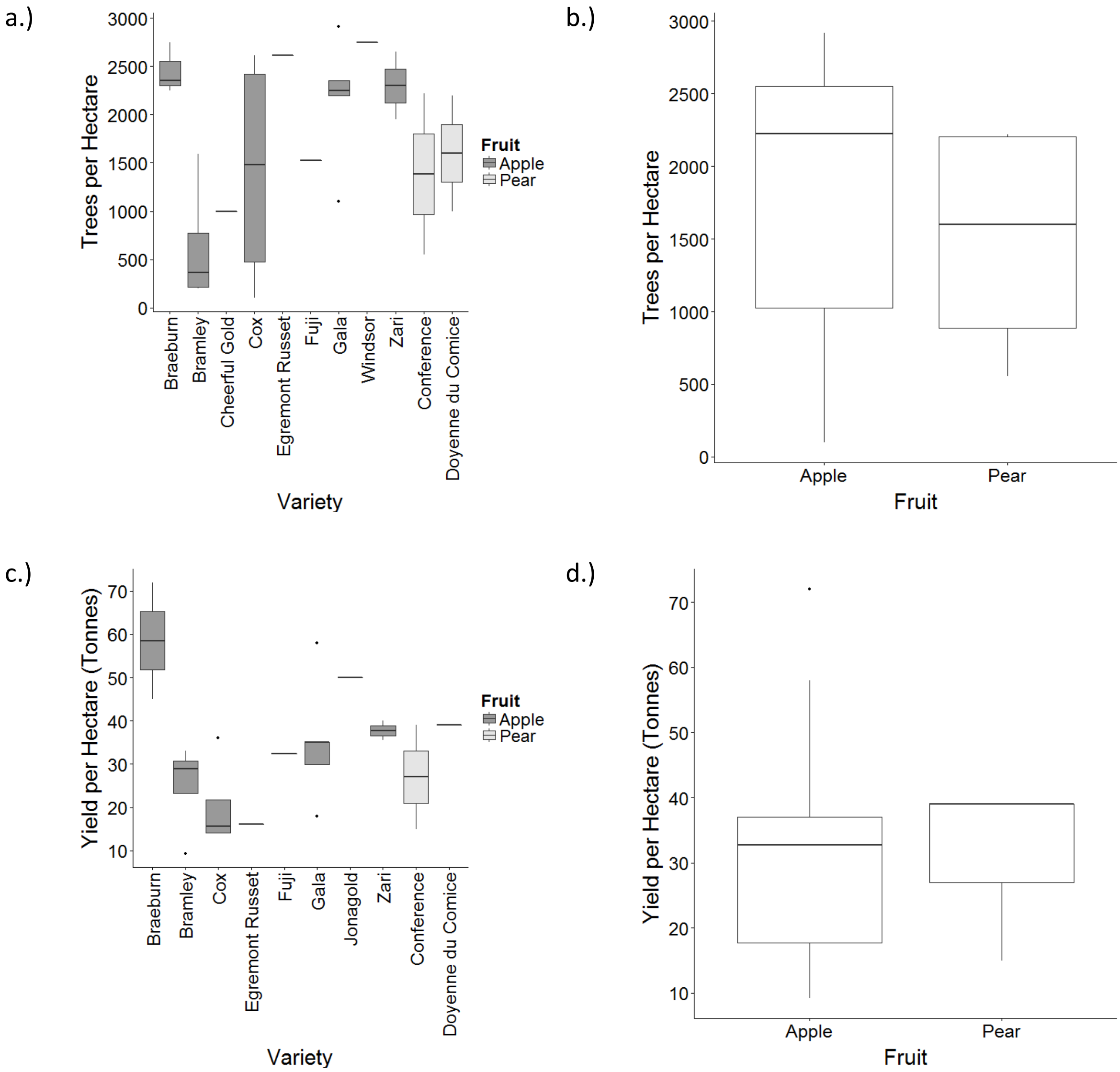


Figure 1.4 Box and whisker plots showing the number of trees per hectare by a.) variety and b.) fruit and the yield per hectare in tonnes by c.) variety and d.) fruit. The lower and upper limits of the box represent the inter quartile range (IQR) of the data and the horizontal line represents the median

The area of their farmed land ranged from 3.91 to 90.5 hectares. In terms of how intensive this top fruit production is, the responses to how many trees per hectare and yield per hectare for the orchards were heavily dependent on variety (Figure 1.4a,c). Although not all respondents gave their estimations by variety, the most intensive apple varieties of those given were Braeburn, Gala and Zari. As the intensity of the growing systems appeared to vary by variety, it might be due in part to the age of the orchards. The emergence of intensive methods is relatively recent (see Section 1.7) and due to the longevity of orchards, some trees are still grown in the less intensive, older, commercial systems. The lower average number of pear trees per hectare could be indicative of the less intensive pear growing systems compared to apples (Figure 1.4b), however, they were similar in yield per hectare (Figure 1.4d).

All respondents had at least five years of experience in managing their orchards; and half of them had more than 30 years. Furthermore, all but one respondent stated that the management of these orchards had been within their respective families for multiple generations. Farmer attitudes to conservation may depend on their value of farming, if it is thought of as a way of life, then they may have more motive to preserve the land so that the future generations can enjoy it (Willock *et al.*, 1999). Alternatively, if farming is a business then they might prioritise profit only and not consider family succession or sustainability in their management decisions (Willock *et al.*, 1999). It was therefore interesting that nearly all respondents had managed the farm over multiple generations, however, as the following findings will show, they still had varying attitudes and opinions.

1.8.3.2 Drivers of crop loss

Of the potential drivers of crop wastage/loss of yield, 'pest species' had the highest proportion of growers stating that it occurs every season (Figure 1.5). An equal proportion of respondents stated wind damage to occur 'every season' and 'every 6 years or more'. At interview, it became apparent that the minimal wind damage is attributed to the utilisation of windbreaks within the orchards. Careful pruning of the crop tree can also influence the wind rub present. However, a different respondent, who thought that wind damage was seen every season, claimed to lose trees every few years, especially in pears. Moreover, with the new post and wire growing system (as described in Section 1.7; Figure 1.1), they believed that there is an increased likelihood of losing the whole tree row. The only cause of crop loss that every respondent stated happened at least every 6+ years was frost. For the other causes, at least one person stated that they never occurred. In particular, flooding and drought were the least frequent causes of crop wastage/loss. Although frost and hail were not seen that frequently (Figure 1.5), when they do occur they may result in higher percentage losses per season in this region (Figure 1.6).

Further comments about apple crop wastage included that 'wastage/loss varies enormously; in nearly all cases it would be much higher but for corrective measures taken'. Another respondent agreed that mostly the wastage is 'negligible'. Others emphasised that they are 'at the mercy of the weather' because apple/pear orchards are not protected by polytunnels and gave the opinion that frost is 'potentially the biggest uncontrolled loss factor', which might explain the high average % loss per season seen in Figure 1.6. Inferences from Figure 1.6 alone should be made with restraint; one farmer cautioned 'It is hard to estimate due to the fact it is weather related each season' and presumably there is natural variation between years with adverse weather conditions occurring at different times. Additionally, another farmer mentioned that the proportion of crop lost due to these factors 'varies depending on the age of the orchard'. At interview, two participants identified that the public might also be responsible for some loss of yield but acknowledged that windbreaks and fencing can mitigate this potential loss.

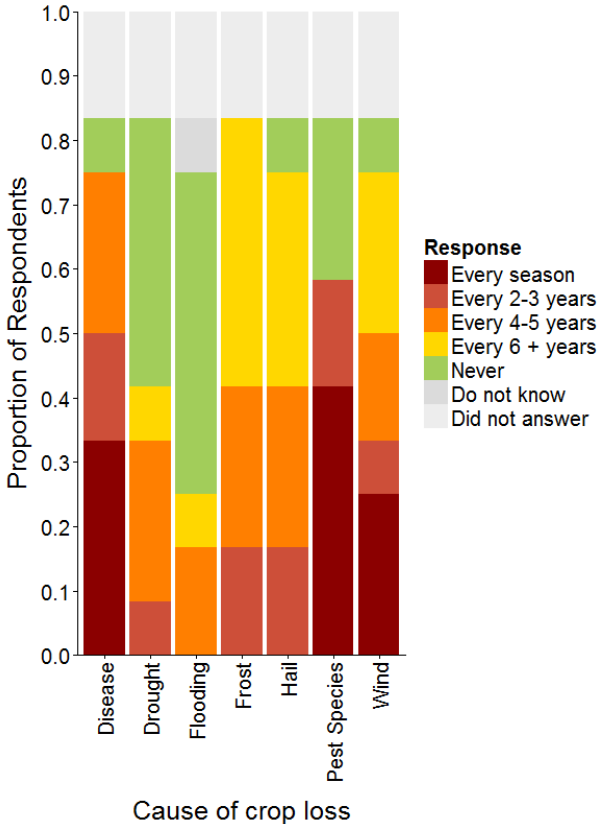


Figure 1.5 The proportion of respondents (n = 12) who stated that various causes of crop wastage (loss of yield) happened at certain frequencies over time

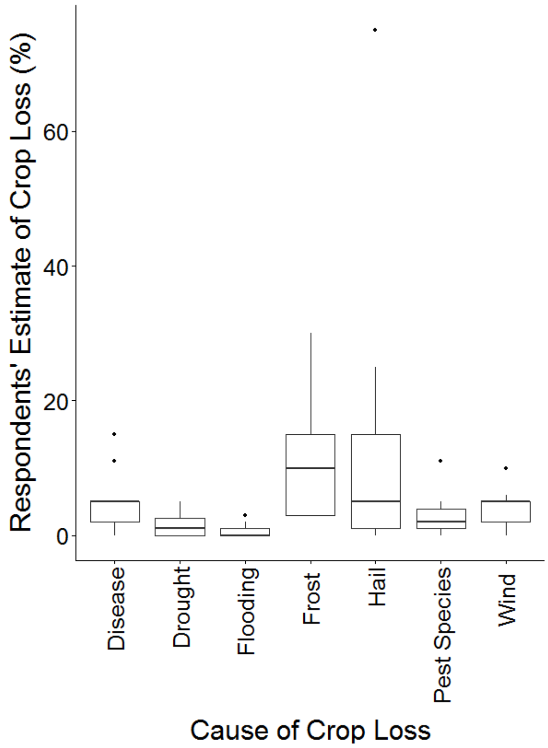


Figure 1.6 The average estimate of crop lost per season (%) for each potential cause of crop wastage. The lower and upper limits of the box represent the inter quartile range (IQR) of the data and the horizontal line represents the median.

1.8.3.3 Invertebrate pest damage and pest management strategies

The importance of crop protection and biological pest control services in orchard fruit production was apparent as many growers stated pest species as the most frequent causes of wastage. When considering the frequency of crop wastage each season due to specific invertebrate pests, 'codling moth' and 'other aphids' were thought to cause crop damage most frequently (every season). Whereas pests such as winter moth caterpillars, scale insects, woolly aphids, red spider mite, apple sawfly and 'other' varied across respondents from 'never' to 'every season'. For all pest species suggested, at least one respondent chose the 'every season' frequency option for each pest (Figure 1.7). However, one respondent commented that for the answer they gave of 'every 6 years or more' they believed that although they are present every year, control is often unnecessary due to the presence of natural enemies. Half of the respondents listed 'pear sucker' (*Cacopsylla pyricola*) as another pest. Other pests mentioned by more than one respondent included 'blossom weevil' (*Anthonomus pomorum*) and 'fruit tree tortrix' (e.g. *Archips podana* or *Pandemis cerasana*).

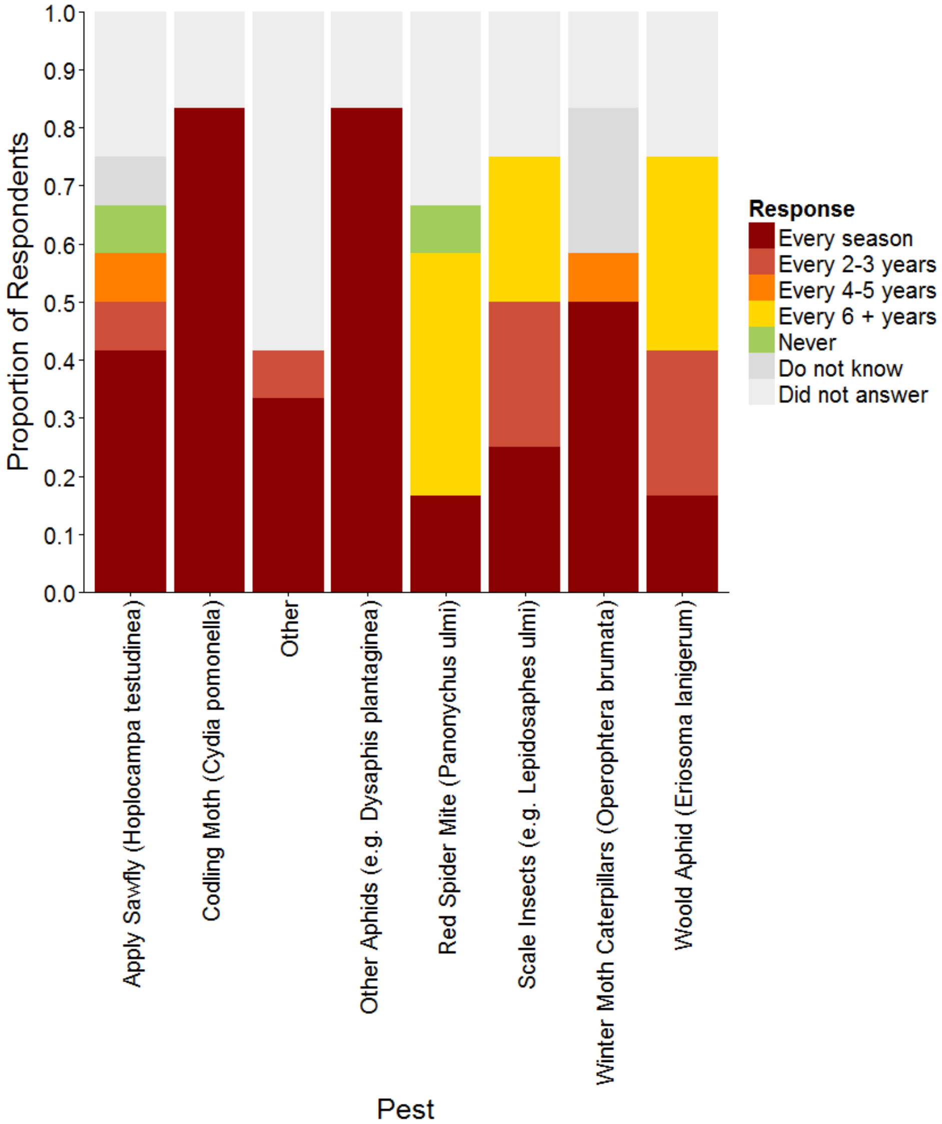


Figure 1.7 The proportion of respondents (n = 12) who agreed with various frequencies of crop damage for each pest species

Estimations for loss of yield due to each suggested pest varied from 0 to 20% (Table 1.2). The highest losses of yield were suggested to be from pear sucker, which was specifically labelled as the 'other' pest by two of the respondents. At interview, it became apparent that growers' believe that the percentage of crops lost due to pest species is low because of pesticide use which keeps pest damage at a low level.

Table 1.2 Respondents' estimations of the percentage of crop wastage each year due to the following pest species

Codling Moth *Cydia pomonella*	Apple Sawfly *Hoplocampa testudinea*	Red Spider Mite *Panonychus ulmi*	Scale Insects e.g. *Lepidosaphes ulmi*	Woolly Aphids *Eriosoma lanigerum*	Winter Moth Caterpillars *Operophtera brumata*	Other Aphids e.g. *Dysaphis plantaginea*	Other
0.5	0	0	0	0	0	0	0
1	0	0	0	0	1	2	3
2	< 1	< 1	< 1	< 1	< 1	2	2
5 to 10	< 2	0	0	0	< 2	5 to 10	0
2	3	0	0	0	0		20 (*Cacopsylla pyricola*)
0.25	0	0	0	0	0.25	0	15 (*Cacopsylla pyricola*)
< 2	< 1	< 0.5	< 0.5	< 0.5	< 1	0	0
0	0	0	0	0	0	0	2
3	2	0	0	0	2	2	0
1	0	2	2	2	2	0	0
< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5

When asked about whether they had any historical problems with certain pests and how these had been resolved, half of the respondents specifically mentioned pear sucker. All but one listed solely biological control methods (conservation or augmentative) to ameliorate this specific pest problem. One respondent noted the addition of hazel and willow trees as an example of habitat provision for biodiversity (conservation biological control). Other pests mentioned were codling moth, mussel scale, woolly aphids and weevils. Overall, the most frequent management strategies to control these previous pest outbreaks appeared to be pesticide applications and the release of natural enemies (augmentative biological control) (Table 1.3).

Table 1.3 Number of respondents (n = 12) who successfully used these practices to solve a previous pest problem (more than one could be chosen)

Resolution to a previous pest problem:	Number of growers that implemented these techniques:
Pesticide application	4
Interrupting pest life cycle	1
Enhance natural enemy habitat provision	2
Reduce potential harm to natural enemies (reduce pesticides)	3
Release of natural enemies	4

All respondents stated that they now currently apply a combination of the measures in Table 1.3 to control pests, except for one farmer who only uses pesticides (and may therefore be using other additional techniques which were not provided as an option to choose in Table 1.3). Some other alternative measures to control pests that growers listed included: mowing the grass less frequently to encourage beneficials, providing refuge for natural enemies (hedgerows/rough areas), encouraging stinging nettles and installing bug hotels. In addition, half of the growers stated that they are ‘careful’ of what insecticides are used; they try to use ‘soft’ chemicals and implement ‘minimal use of broad spectrum insecticides’.

This integrated approach to pest management, including a number of conservation and augmentative biological control measures as well as classic agrochemical use, shows that growers are aware of the need to diversify their pest management practices. This is echoed in other locations; Goldberger and Lehrer (2016) found that in California, USA 3/4 of the pear growers used at least one biocontrol practice as part of their pest management and an impressive 98% of them stated that they sometimes or always select the insecticides that are least disruptive to potential natural enemies. Salliou and Barnaud (2017) found that 2/3 of interviewees, in an area of southwestern France dominated by orchards, included natural enemies as part of their pest management.

All four of the interviewed growers said that they considered themselves to use IPM (see definition in Section 1.4). One respondent thought that they implemented IPM because they follow guideline timings on when to spray, another said it is because they use the ‘kindest possible chemicals’. Whereas, one grower said that they leave windbreaks and some orchards unmown and encourage natural enemy populations through stinging nettles and long grass.

Therefore, although IPM is now obligatory (EU Directive 2009/128/EC), quite what IPM implementation meant to the individuals seemed to vary. Furthermore, others have cautioned that there is sometimes a discrepancy between what is said and what is done, especially regarding the creation of wildlife refuges (Macfadyen *et al.*, 2015). For example, Herzon and Mikk (2007) found that 30% of farmers could not actually give an example of a biodiversity enhancement they had made, even if they had claimed that this was important on their farm.

Overall, in our survey, although growers had solved previous pest problems by use of biological control (conservation and augmentative), the survey responses and interviews corroborated the theory that fruit growers (especially apple growers) do still rely largely on chemical pesticides and attribute the low percentages of crop lost to pests to their use. This could be because biological control does not have a completely stable success rate, with many different factors that can affect the populations and success of natural enemies (Blommers, 1994; Jones *et al.*, 2009). To fulfil the expectations of retail customers, growers must often adhere to specifications of standardised fruits, with a perfect cosmetic appearance (lack of defaults) that can be hard to meet without any pesticide use. The risk of the potential fruit damage that may occur, in quantity or quality, due to solely relying on natural enemies, is too great. Goldberger and Lehrer (2016) found that the few growers who did not rely on any biological control stated this was due to perceived ineffectiveness, lack of knowledge, not recommended to them by specialists, a preference for another pest management approach such as chemical control, or the high cost.

The public's opinions of biocontrol practices might influence grower decisions in the future. A unique Canadian survey on the public perception of biocontrol (McNeil *et al.*, 2010) found that 70% of people would prefer food grown with biocontrol agents over insecticides. However, less than half would be willing to pay more for biocontrol even though they think there is a lower risk associated with eating food grown under biocontrol compared to synthetic pesticides (McNeil *et al.*, 2010). This public viewpoint might put growers in a difficult position whereby market prices do not reflect the economic risk they take if they rely on biological control alone.

As well as the public, the government has, and will, continue to influence grower pest control through the regulation of pesticides. One grower stated that there is a 'return of pests we have not seen in years or would have previously had adequate control over not to have had to make a specific treatment – this is largely due to the loss of broader spectrum products like Chlorpyrifos'. Chlorpyrifos was also mentioned by another respondent as it 'controls most major pests' and another considered the general the banning of certain pesticides as 'devastating'. The finding that bans of certain pesticides have negatively affected pest outbreaks, is echoed by recent studies on the continent. Salliou and Barnaud (2017) found that for fruit growers in southwestern France, pests such as the woolly apple aphid only became a problem for growers due to the ban of the pesticide Vamidothion in 2003. Pissonnier *et al.* (2016) also found that government regulations banning pesticides had contributed to French apple growers' pest protection strategies. With further restrictions possible, growers should consider assessing how they might increase their biological control practices on-site so that they have a strategy in place in case future chemical use restrictions are implemented. One of the ways to do this is via non-crop vegetation habitat management, a form of conservation biocontrol where the provision of refuge, shelter and floral resources are made available on-site to sustain and enhance natural enemy populations.

1.8.3.4 Non-crop vegetation in orchards – current practices and perceptions

1.8.3.4.1 Windbreaks and hedgerows

Non-crop vegetation is a current feature in top fruit growing systems; I found that all but one respondent had windbreaks on their farm (92%) and all had hedgerows (100%). Overall, the respondents listed eleven different trees found in their windbreaks and seventeen in hedgerows (Table 1.4). Alder was the most common found in both windbreaks and in hedgerows (Table 1.4), which is unsurprising as Italian alder (*Alnus cordata*) use in windbreaks is widespread (Cross *et al.*, 2010). At interview, one respondent emphasised that 20 years ago people thought Italian alder should be planted because it is quick growing and they have early leaf so there is wind attenuation during pollination. Alder use was also favoured because it is good at fixing nitrogen. There was, however, no mention of biological control in the choice of alder; indeed this species is thought to have little benefit to hosting predatory species (Cross *et al.*, 2010). One respondent stated that they had 'taken out most of the hawthorn' in favour of alder due to its early foliage and nitrogen fixing properties. Another reason given for switching to alder was that 'hedgerows containing hawthorn can host fireblight which is a big problem'. Other comments from interview uncovered a potential historical shift in planting from poplar to alder for windbreaks because poplars have been found to be 'too competitive'. However, some believe poplar still has specific value on farms; it was stated by two respondents to be the windbreak species used on the farm perimeter with alder used within farms.

Growers mainly listed the non-crop tree common names that could relate to a number of different species. In addition, two respondents answered 'mixed hedges' and one stated 'some more complex'. Therefore, the numbers in Table 1.4 likely underestimate the non-crop plant species diversity present on farm.

Table 1.4 Number of respondents (n = 12) who listed that they have these non-crop trees present on their farm

Non-Crop Tree	Windbreak (% of sample)	Hedgerow (% of sample)
Alder (*Alnus* spp.)	9 (75)	5 (42)
Ash (*Fraxinus* spp.)	0	2 (17)
Beech (*Fagus* spp.)	1 (8)	2 (17)
Birch (*Betula* spp.)	1 (8)	0
Blackthorn (*Prunus spinosa*)	0	1 (8)
Damson (*Prunus domestica* subsp. *insitita*)	1 (8)	0
Elder (*Sambucus nigra*)	0	3 (25)
Elm (*Ulmus* spp.)	1 (8)	1 (8)
Field Maple (*Acer campestre*)	0	2 (17)
Hazel (*Corylus* spp.)	0	1 (8)
Hawthorn (*Crataegus monogyna*)	0	2 (17)
Holly (*Ilex aquifolium*)	0	1 (8)
Hornbeam (*Carpinus betulus*)	2 (17)	1 (8)
Leylandii (*Cupressus* × *leylandii*)	1 (8)	1 (8)
Malus (*Malus* spp.)	1 (8)	1 (8)
Oak (*Quercus* spp.)	0	1 (8)
Plum (*Prunus domestica*)	0	1 (8)
Poplar (*Populu*s spp.)	2 (17)	3 (25)
Silver Birch (*Betula pendula*)	1 (8)	0
Sloe (*Prunus spinosa*)	1 (8)	0
Sweet Chestnut (*Castanea sativa*)	0	1 (8)

Table 1.5 Numbers of growers that agreed with the following statements on the design of their farm's current windbreaks and hedgerows (multiple agreements allowed)

	Windbreaks (% of sample who have them on farm)	Hedgerows (% of sample who have them on farm)
Already in place before farmer involvement	4 (36)	8 (67)
Beneficial species such as natural pest control were considered	4 (36)	2 (17)
Pollinators were considered	1 (9)	0
Advice from an external source	5 (45)	3 (25)
Other	1 (9)	1 (8)

When asked to choose the reason that best explained the species found in their windbreaks and hedgerows, double the respondents (eight) said that the hedgerows were already there before they were involved with the orchard compared to windbreaks (four) (Table 1.5). This could be because hedgerows have more of a traditional historical context as a landscape feature. In the UK, the general public regards hedgerows as part of the cultural landscape (Oreszczyn and Lane, 2000). Although hedgerows and windbreaks are sometimes very similar, windbreaks are primarily used in farm environments to increase agricultural production through their microclimatic effects (Nuberg, 1998).

It was apparent that growers actively upkeep their hedgerows, perhaps even changing their composition as ‘gapping up’ occurs. At interview, one respondent stated that they add a species like field maple if a section of it dies. Our survey did not ask questions about why farmers have kept these hedgerows and windbreaks, which were there originally. However, in other UK surveys, ‘wildlife habitat’ was given as a motivation for hedgerow retention; this was stated slightly more in a 1998 survey (75.7%) than its preceding one in 1981 (61.6%) (Macdonald and Johnson, 2000). Estonian and Finnish farmers have also been shown to be particularly willing to preserve existing trees, shrubs and semi-natural grasslands on their land as over 2/3 identified them as being valuable for wildlife (Herzon and Mikk, 2007).

Five respondents said they had received advice from an external source on the choice of species used for windbreaks, and three for hedgerows (Table 1.5). When the respondents were asked to provide additional comments on their choice of windbreak or hedgerows used, one explicitly stated that they 'followed neighbours'. Furthermore, at interview, two growers elaborated that the external source was expert advice however, one grower stated that this meant they had 'followed neighbours' decisions on non-crop vegetation design. Previous surveys have also shown that farmers take notice of neighbouring farm hedgerow management (Oreszczyn and Lane, 2000). These visual observations are pivotal for farmer management choices, they often copy what they can see their neighbours doing with one farmer stating "research is good, but you really need practical, useful models'', i.e. to see them in place in real farm situations (Brodt *et al.*, 2009).

Only four growers considered natural pest control in their orchard windbreak design and one considered pollinators (Table 1.5). Indeed, at interview, one respondent specifically stated that 'any new windbreaks would be designed to take into account habitat especially for beneficial insect species'. Further reasons for choosing windbreak types were tree characteristics such as 'size of tree and vigour', 'early into leaf to provide early protection', 'fix their own nitrogen to avoid competition' and 'suitable for mechanical trimming'. One grower specifically emphasised the windbreak's ecological properties: 'Mostly for wind to prevent russeting when originally planted but are now very well established and provide a fantastic haven for birds and other wildlife especially in winter allowing early arrivals and through season occupation'.

Two respondents had considered natural pest control in their hedgerow decisions but not one had incorporated pollinators into their hedgerow design (Table 1.5). Indeed hedgerows are thought to have contrasting functions depending on who is considering them: those who plant them, casual visitors or ecologists (Baudry *et al.*, 2000). The difference is of course that farmers' are running their farm as a business and this dominates their views of hedgerows (Oreszczyn and Lane, 2000). They may therefore focus less on the hedgerow's biodiversity conservation merits even though they do sometimes recognise the air, water and soil quality benefits (Brodt *et al.*, 2009). This is a real shame as flowering plant species that exist within hedgerow structures can potentially provide successional resources for beneficial insects and therefore enhance both pollination and pest control services (Miñarro and Prida, 2013). For example, codling moth larvae are less abundant in areas nearby to hedgerows with higher floral diversity (Ricci *et al.*, 2011). Hedgerows also support the diversity and abundance of native bees, hoverflies and parasitoids (Morandin and Kremen, 2013; Morandin *et al.*, 2014; M'Gonigle *et al.*, 2015; Sardiñas and Kremen, 2015). However, some farmers only view biodiversity as being outside of the farmed environment, indicating the importance of demonstrating to them the direct benefits that they could obtain from on-site wildlife-friendly measures, such as the positive effects on pollination and pest control that beneficial species provide (Herzon and Mikk, 2007).

When explicitly given a choice of the beneficial features of windbreaks, over half of the respondents agreed that natural pest control and efficient pesticide application were benefits (Table 1.6). This echoes a previous survey of 22 Californian farmers, where 6 individuals who had edge plantings said that the potential to attract beneficial invertebrates and corresponding reduced pesticide use were major motivational factors to their implementation (Brodt *et al.*, 2009). However, there was an unexpected lack of consideration for pollinator resources in the choice of windbreak species; less than half of the respondents recognised that pollinator species could also benefit from them (Table 1.6).

Table 1.6 Numbers of growers (n = 12) that thought windbreaks could be useful for the roles of: natural pest control, pollinator species, efficient pesticide application and wood-fuel

	Number in agreement (%) that windbreaks can be used for:
Natural pest control	8 (67)
Pollinator species	5 (42)
Efficient pesticide application	8 (67)
Wood-fuel	0

When asked to give any further opinions that they had about the use and role of windbreaks in apple orchards, the survey respondents generally left positive remarks about their use in orchards. Only one stated that they are ‘a wasted cropping area and cause more economic loss through shading. Single species windbreaks have no use within an orchard’. The others voiced that they are essential to keep the orchard temperatures up (i.e. they create a beneficial microclimate); ‘prevent wind damage’; ‘make spraying easier’; ‘reduce spray drift between different orchards’; ‘provide shelter’ and if well chosen, have a role in pest control, such as for pear sucker. Another benefit mentioned was their role as valuable ‘wildlife corridors’ and ‘an ideal place for winter hibernation’.

Schmidt and Hauck (2018) recently showed that although farmer opinions of hedgerows in Germany are mainly positive, some farmers do identify potential disservices of hedgerows.

Likewise, despite the mainly positive opinions surrounding windbreaks and hedgerows, growers in our study were certainly aware of the potential negative effects. At interview, they were asked what they considered, if any, the potential negative effects of windbreaks and hedgerows to be. One grower postulated that the physical space they take from crop trees, crop shading, water use and limited space for machinery to manoeuvre could be an issue for growers with smaller farming areas. These types of constraints are also common considerations for farmers in other continents. Farmers in California also emphasised that 'space' was an issue, limiting both productive area and the room for technical equipment to move freely (Brodt *et al.*, 2009). Other concerns in California included the time and cost commitment of maintenance, the time it takes for planted trees to establish and mature and the fear of harbouring potential weeds and rodents (Brodt *et al.*, 2009). Only one respondent in my study thought that 'they harbour pests' so they 'used to spray hedgerows to ensure no pests'. Other answers in my survey also emphasised the cost of management, for windbreaks in particular, as trees such as poplar are so fast growing that once established expensive yearly management could be required to keep them at ideal heights. In contrast to Macdonald and Johnson (2000), who saw a reduction in shelterbelt removal, another grower actually highlighted that windbreaks were now being taken out due to these management costs, despite their benefit when windy.

Whereas, hedgerow removal was not stated by our growers. However, one did mention specifically removing the hawthorn from hedgerows. Hawthorn can have a value for beneficial insects but it also poses considerable potential damage to orchard crops because it harbours fireblight bacterium, thus is often advised not to be used in orchards (Rieux *et al.*, 1999; Cross *et al.*, 2010). Macgregor and Warren (2006) did note that while interviewed farmers in Scotland did not explicitly state that they removed hedgerows, they did admit that when fences next to hedgerows fall into disrepair, the temptation to remove the whole structure is there due to the expensive maintenance costs. Perhaps it is due to the current legal protection of hedgerows, that there was no other indication of past or future hedgerow removal. In contrast, a couple of decades ago, farmers interviewed in Brittany were of the opinion that hedgerows should only be maintained on property boundaries and a quarter of farmers interviewed had already removed all but the boundary hedgerows on their farms as they did not realise their importance in erosion prevention or biodiversity conservation (Burel and Baudry, 1995). Additionally, although they identified that hedgerows had a windbreak effect on their land, they believed that there were enough in the surrounding region to sustain this effect (Burel and Baudry, 1995). This view of not needing to maintain or plant their own has been reported in other studies where farmers instead notice the benefits, such as pest control, from a neighbour's hedgerow adjacent to their own land (Brodt *et al.*, 2009).

On the whole though, despite the various potential disservices and management costs, farmers do often feel that it is their obligation to manage hedges (Beedell and Rehman, 1999). In our study, there appeared to be an overall emphasis on the importance of hedgerows as beneficial features in an intensively farmed landscape. One respondent even suggested that growers 'need to manage them with equal attention as cropped areas'. The main management regime was trimming hedgerows, agreeing with other UK surveys who showed that nearly all farmers (94%) trim their hedgerows, mainly for 'tidiness' (31%) and access (7.4%) (Macdonald and Johnson, 2000). Other management actions in our study included ensuring that there are areas of long grass and nettles for predators. This is promising as some farmers can lack an understanding of how environmental measures such as areas of thistles and stinging nettles could be useful of environmental protection (Schmidt and Hauck, 2018). A further management measure mentioned in my study was the removal of ivy to prevent tree death (gaps in the hedgerow). However, controversy surrounds the benefit to ivy removal because it has been shown in pear orchards to host parasitoid wasps, predatory Diptera and Neuroptera (Rieux *et al.*, 1999). Overall, the recognition of the benefits of hedgerow/windbreak structures might be increasing over time; Macdonald and Johnson (2000) saw that the number of UK farmers who encouraged existing hedgerows and planted new ones rose from 6.6% in 1981 to 35.4% in 1998. Twenty years later, it is plausible that this rate of hedgerow encouragement and planting has risen even further.

1.8.3.4.2 Wildflower provision and the implication for available pollinator resources

Although growers were aware of potential management practices to promote natural enemies, floral resources were largely underutilised. Moreover, not only did growers rarely consider pollinators for windbreak and hedgerow design but a surprising finding was that, for various reasons (Table 1.7), all but one respondent did not sow wildflowers on their farm. Agreeing with the non-economic farmer motivations that previous studies have highlighted in the implementation of such measures (Herzon and Mikk, 2007; Sattler and Nagel, 2010), economic cost was not the only reason that wildflowers were not established. In the additional comments, three respondents made it clear that there are no locations suitable for them to be planted onsite. One grower was more sceptical of the benefits of wildflower provision in general stating they are 'no good, a waste of time and money' and one grower stated that they 'haven't considered it before'. One respondent stated that they prefer perennial plantings to wildflowers. They felt that the benefits of wildflowers would have to match that of perennials. This is in contrast to Gontijo *et al.* (2013) who stated from personal experience and communication that apple growers preferred annual short-term plantings to avoid weeds by periodic tilling and replanting.

Table 1.7 Number of growers (n = 12) who agreed with the following statements as to why they do not currently sow wildflowers (multiple reasons allowed)

	Number (% of respondents who do not sow wildflowers)
Too expensive to put in place	2 (18)
Too time consuming to put in place	3 (27)
Not enough workers available to do so	1 (9)
Do not see the benefit of doing so	2 (18)
Do not want to have to manage them	1 (9)

It was apparent that not all growers understood the proven associated ecological benefits of wildflower implementation. Indeed, from the additional comments in the survey, it appeared that one respondent would use them if there was a 'proven benefit' to doing. At interview, two respondents agreed that they would plant them but needed scientific evidence to prove that it would work. These growers also stressed that they would appreciate clear guidance on which beneficial species to plant. Farmers can often lack a connection to the published scientific literature and are unaware of the benefits that can be obtained. A review of the pros and cons of wildflower strips found that the pros of flower strips for farmers outweigh the cons in terms of agronomic and ecologic processes, however, it also uncovered that there were a limited subset of studies that actually considered the advantages and disadvantages of wildflower strips to the farmer (Uyttenbroeck *et al.*, 2016). Furthermore, Christmann *et al.* (2017) found that farmers were reluctant to implement wildflower provision because farmers perceived them to have no economic return and viewed them as weeds that have the potential to spread into cropland.

One grower explained that wildflowers were not implemented due to the fruit growing being on an 'industrial nature' with 'honeybees imported for pollination'. This is concerning as previous studies have shown that honeybees (*A. mellifera*) require a higher temperature for activity than solitary species such as *O.cornuta*, and other wild bees (e.g. *Bombus* spp.), which are able to forage in lower temperatures, light rain and strong winds (Vicens and Bosch, 2000b; Brittain *et al.*, 2013a; Fründ *et al.*, 2013). Therefore, it is wise to provide floral resources to sustain wild pollinator populations in UK apple orchards because the climate during apple bloom in spring is variable and can often be sub-optimal for managed honeybees. Moreover, recent studies have shown that the fruit set of apples increases with native wild bee richness during apple blossom but not with managed honeybee presence (Mallinger and Gratton, 2015). In apple orchards, honeybees also forage differently to wild bees; they prefer densely blooming trees, whereas wild bees do not have a floral density preference, so visit trees evenly across the orchard (Mallinger and Gratton, 2015). Therefore, there is explicit value in maintaining wild bee populations and not relying on managed bees alone to maximise the fruit set. At interview, no growers thought that there was currently a pollination deficit in their top fruit orchards but even if they have adequate pollination for yields, pollinators have also been shown to increase the quality (size and shape) of some apple varieties and therefore their economic value (Garratt *et al.*, 2014). Growers may also not have considered how potential honeybee declines could impact their crop in the future.

This survey did not aim to investigate farmer knowledge on the benefits of wild bees to apple pollination; however, Park *et al.* (2018) found that over 90% of apple growers surveyed in the USA valued native bees, only 20% did not understand how much wild bee pollination services contribute to their crop, and most growers were willing to implement low cost bee friendly measures. It is therefore likely that given the benefit of wild bees to apple production, UK growers would also be willing to implement measures to aid these beneficial insect populations.

1.8.3.4.3 Agri-environment schemes

Field margins and hedgerows are often the focus of the European agri-environment schemes (AES) specifically aimed at enhancing areas out of production. Non-crop vegetative edges often have greater success at enhancing species richness than other agri-environmental measures (Batáry *et al.*, 2015). This could be because field margin schemes such as wildflower strips provide specific resources for flower visiting insects, whereas in-production schemes such as restricting fertiliser application do not have such targeted biodiversity benefits.

Of the four top-fruit respondents interviewed, although one voiced negativity about the prospect of new agri-environment schemes because they ‘farm for money and lifestyle’, two of the participants were currently involved in government agri-environment schemes and one would like to be. It was suggested from previous interviews with UK farmers that descriptions of place belonging, and consequently their aspirations of farm succession within a family, appeared to be an incentive for their involvement in AES (Saxby *et al.*, 2017). As our orchard respondents confirmed their farms to have been in the family for multiple generations, this might indicate why they were keen to be involved in AES implementation.

The grower interviewed who would have liked to have been involved in an AES, believed that it is often hard to participate as a fruit farmer because of inadequate space for field boundaries and the limited scope for specific hedge management. Indeed, unfortunately agri-environment schemes are less likely to be adopted in high intensity farming systems, such as fruit production, despite sometimes higher compensation in place than for the low intensity farming systems (Zimmermann and Britz, 2016). Therefore, although some growers might want to be involved in these schemes, they feel that as fruit farmers the options are limited, inhibiting their ability to qualify for the schemes. Until AES are modified for specific farmer groups, such as top fruit growers, there is scope for alternative smaller-scale suggestions of how they can enhance their farms to encourage biodiversity.

1.8.4 Conclusions about current provisions, decisions and opinions on non-crop vegetation in top-fruit orchards for pest control and pollination services

Understanding local growers' perspectives regarding non-crop vegetation, pollination and natural pest control is important in ensuring that any research carried out in that location remains applicable to the industry. Indeed, neighbouring farm management choices and 'professional norms' were found to influence orchard management decisions, highlighting a need for agro-ecological research to engage with growers. This investigation into top-fruit grower attitudes and opinions reiterates the importance of understanding and incorporating farmers' perspectives, in addition to the ecological experts, when planning local scale landscape enhancements.

Pests were found to be a frequent cause of crop loss, with growers implementing a range of pest management strategies (i.e. IPM) to mitigate this threat to their fruit production. However, the reliance on pesticides was clear and growers attributed their use to the low percentage of crop lost to pests annually. This reluctance to rely solely on natural pest control could be indicative of the low natural enemy populations present or of the pressure faced in the industry to produce good quality top fruit for fastidious consumers to purchase in the commercial market. Therefore, there is scope to further encourage farmers to engage with biological control options; to protect and enhance natural enemies on-site.

All farms had hedgerows, nearly all had windbreaks but only one had wildflower provision. The lack of wildflower implementation is concerning because additionally less than half recognised that pollinator species could benefit from windbreak design. Therefore, future non-crop vegetation in orchards should consider successional floral resource provision for pollinator and natural enemy populations. These beneficial invertebrates provide economically important regulating ecosystem services to orchards and so the cost of implementation could be justified as economically viable. Emphasising the potential costs and benefits of certain agri-environmental measures to growers in terms of their added ecosystem service benefits could increase the uptake of measures that enhance habitat provision for pollinators and natural enemies.

1.9 Thesis Aims and Objectives

From previous research, it can be seen that the ecosystem services concept is a way to drive more sustainable productive agriculture. In addition, the floral resource provision from non-crop vegetation that is suggested within the various agri-environment schemes appears to be valuable in sustaining and enhancing beneficial invertebrate species populations within agro-ecosystems. With space limited in intensive orchards, there is a need to enhance non-crop vegetation at the crop perimeter to provide floral resources and refuge. Therefore, the overarching aim of this thesis was to formulate and test a novel way to enhance the orchard edges with successional floral resources in order to protect and improve the pollination and pest control services to UK dessert apples (see the summary of objectives to reach this aim in Table 1.8).

The growers themselves are key to the implementation of management strategies to sustain and enhance pollinator and natural enemy populations. Research for this applied ecology thesis was carried out in conventionally managed commercial apple orchards in Kent, south-east England. I therefore first investigated the practices and perceptions of a select group of commercial apple and pear growers in this region, regarding non-crop vegetation (hedgerows, windbreaks and wildflowers) in their orchards and the possible benefits to apple production it can provide via the support to the regulating ecosystem services, pollination and biological control (Section 1.8). To do this I conceived a postal survey and follow-up semi-structured interviews. I found that all farms had hedgerows and nearly all had windbreaks, however, these non-crop tree structures had rarely been designed to maximise support for beneficial invertebrates. Furthermore, only one orchard had wildflower provision. Overall, growers’ opinions surrounding non-crop vegetation were largely positive. This information and grower feedback from this region therefore contributed to the design of a novel manipulative experiment using lavender and thyme to enhance orchard edges (Chapters 2-4). This is because there appeared to be an opportunity to plant perennial, non-arboreal vegetation at orchard perimeters to ensure that successional floral resources are available on-site. These non-arboreal floral resources were chosen in part as hedgerows and windbreaks were already present in the top-fruit growing systems but lacking focus on resources for beneficial invertebrates. Furthermore, they are perennial plants, an alternative to annual sown wildflower mixes which growers may be reluctant to implement and manage. Further detail surrounding the specific choice of lavender and thyme for pollinators is outlined within Chapters 2-4.

Apples require insect pollination to achieve optimum crop yield and quality. Managed honeybees are often used to deliver this pollination service but there is increasing evidence that wild pollinators are more effective pollinators for many crops. With wild pollinators in decline, one way to ameliorate population decreases is to provide successional resources to sustain the populations that are in these intensive agro-ecosystems after the mass apple flowing in spring. In Chapter 2, I investigate whether orchards with the enhanced floral edges of lavender and thyme (orchard edge treatments) sustain wild pollinator populations over the summer months and whether there are increased apple pollination visitation rates in these orchards during apple blossom.

With many pests threating apple production and most farmers ascribing pests as the most frequent driver of crop loss, growers often resort to the use of chemical control to ensure minimal crop damage (see Section 1.8). However, this reliance on chemical prevention and intervention can have detrimental effects to beneficial invertebrate populations such as pollinators or the natural enemies that could help to control these pest outbreaks. Considering that commercial orchards have to apply IPM, one way to ensure that natural enemy populations are sustained and enhanced on-site is to provide those, which specifically require pollen and nectar at some stage during their lifecycle, with alterative, successional floral resources. However, conversely, aromatic floral resources may have unintentional repellent effects on other important natural enemies. In Chapter 3, I therefore examine the effects of the orchard edge treatments on natural enemy abundance in the apple trees.

In order to quantify the effect of the orchard edge treatments on apple production in dessert apple orchards, I investigated apple yield and quality within these orchards (Chapter 4). To understand what contribution pollination services made to apple production I also carried out pollinator exclusion experiments and compared the apples to those where pollinators had access to the apple inflorescences during apple blossom.

Finally, I synthesise my overall findings, critically evaluate the methodology used and make suggestions for possible future work in this area and recommendations going forward (Chapter 5).

Table 1.8 A summary of the key research objectives

Objectives
• To implement a novel manipulative experiment providing successional floral resources at the orchard edge (Chapter 2-4) • To investigate if the orchard edge treatments affect the pollinator visitation rate (from different pollinator guilds) to Braeburn and Gala apples and at different distances from the orchard edge (Chapter 2) • To assess if the orchard edge treatments affect the abundance of aerial invertebrates over the summer months (June, July and August) after the mass flowering of apple and before apple harvest (Chapter 2) • To assess if the orchard edge treatments affect natural enemy abundances in the apple trees over the summer months (June, July and August) after the mass flowering of apple and before apple harvest (Chapter 3) • To determine if pollinator exclusion during apple blossom affects Braeburn and Gala fruit set (initial or final) or quality (Chapter 4) • To determine if the orchard edge treatments affect Braeburn and Gala fruit set (initial or final) or apple quality (size or seed number); and if this consistent at different distances away from the orchard edge (Chapter 4)

Chapter 2 Planting aromatic herbs along apple orchard edges can increase wild pollinator abundance

2.1 Abstract

Insect mediated pollination is crucial to achieving good apple fruit set and quality and there is mounting evidence that wild bees are more efficient apple pollinators than managed honeybees. However, the intensification of the apple-growing system (as outlined in Chapter 1, Section 1.7) has reduced the local habitat and resources available for native pollinators. Protecting the delivery of pollination services is of key importance to ensure that these intensive crop systems can still support wild pollinator populations nearby. Information obtained from local growers (Chapter 1, Section 1.8) uncovered that wildflower provision was not utilised in orchards nor necessarily viewed in a positive light, and that little consideration for pollinators had been given to the design of hedgerows or windbreaks. Therefore, an opportunity exists to provide alternative viable floral resources at the orchard edge. To fulfil this potential, a novel manipulative experiment was set-up to assess how planting perennial aromatic shrubby herbs, lavender (*Lavandula x intermedia* 'Sussex') and thyme (*Thymus vulgaris*), established at the orchard edges in apple orchards affect pollinators. I found that the orchard edge treatments with a mixture of both lavender and thyme or with lavender alone enhanced pollinator abundance in orchards during the late summer months. The mixed orchard edge treatment also increased the visitation rate of wild bees to apple flowers during the spring apple bloom. These results show that local, small-scale enhancements of orchard edges using both lavender and thyme potentially sustain and enhance populations of wild bees in this otherwise agriculturally intensive landscape.

2.2 Introduction

Flower visiting insects provide a crucial ecosystem service of pollination to wild and cultivated crop plants across the world (Klein *et al.*, 2007). Apple (*Malus domestica*) is an important global fruit crop; in the UK alone over 16,500 hectares of land are dedicate to apple production (FAO, 2016). As a largely self-incompatible crop, apple fruit set requires insect pollination services to ensure adequate pollen transfer from other compatible varieties (pollinisers) (Ramírez and Davenport, 2013). Pollinators also increase the quality (size and shape) of some apple varieties (Garratt *et al.*, 2014; Garratt *et al.*, 2016).

Apple pollination success is related to wild bee species richness and abundance (Blitzer *et al.*, 2016; Földesi *et al.*, 2016); apple fruit set increases with native wild bee richness during apple blossom but not with managed honeybee presence (Mallinger and Gratton, 2015). Flower handling behaviour, as well as pollinator abundance are predictors of pollination success in apple, which makes honeybees half as important as wild bees in apple orchards (Russo *et al.*, 2017). Bumblebees deposit more pollen onto apple stigmas than honeybees (Thomson and Goodell, 2001). This is because honeybees are often observed ‘side-working’, visiting flowers laterally in order to rob nectar resources from the nectaries at the flower base using their proboscis, and therefore they have low contact rates with the reproductive flower organs such as the stigma (Vicens and Bosch, 2000a; Thomson and Goodell, 2001; Schneider *et al.*, 2002; Martins *et al.*, 2015; Park *et al.*, 2016; Campbell *et al.*, 2017b). Honeybee pollination efficiency can however be improved by the presence of wild pollinators (Brittain *et al.*, 2013b); bumblebees might increase honeybee mobility and ‘top-working’ (Sapir *et al.*, 2017) where they come into contact with the reproductive organs of the flower and therefore have an increased efficiency of pollen transfer to the stigma (Vicens and Bosch, 2000a). Wild bees such as bumblebees and andrenid bees might also be more efficient pollinators due to higher mobility (i.e. between apple rows) (Campbell *et al.*, 2017b), however this would only improve pollination efficiency for orchards where pollinisers are located in a different row, unlike in the intensive orchards outlined in Chapter 1 where polliniser trees are within the same row and distributed every 10 trees.

Bumblebees and solitary bees such as *Osmia cornuta* forage in lower temperatures than honeybees (Vicens and Bosch, 2000b; Sapir *et al.*, 2017), a trait that is often useful for apple pollination which occurs in the spring when environmental conditions are variable. Honeybees have also been shown to have a reduced foraging activity in wind and rainy conditions (Brittain *et al.*, 2013a; Fründ *et al.*, 2013). Furthermore, the efficiency of honeybee pollination of apples, affecting apple fruit set, seed set and sugar content, greatly depends on the hive quality (Geslin *et al.*, 2017).

To maintain and enhance these important wild bee populations, the preservation of semi-natural habitat adjacent to apple orchards is important (Földesi *et al.*, 2016). Growers cannot necessarily impact the natural habitat in the adjacent landscape but could instead ensure that they restore and enhance natural habitat within their own farms (Morandin and Kremen, 2013). For example, local restoration of hedgerows on farms could be an optimum way of restoring the provision of ecosystem services in an intensively managed agricultural landscape. This is because they support a higher diversity and abundance of pollinators (Morandin and Kremen, 2013; M'Gonigle *et al.*, 2015; Sardiñas and Kremen, 2015; Ponisio *et al.*, 2016). Farmers have however voiced concerns about the time planted trees take to establish and mature (Brodt *et al.*, 2009); an alternative, or indeed complementary, implementation to hedgerows is floral resource provision within apple rows (Campbell *et al.*, 2017a; Campbell *et al.*, 2017b) or on field margins. The effects of wildflower strips might also be more immediate; for example wildflower strips at the edge of agricultural fields in the UK showed increases in bumblebee abundance straight from the first year of implementation (Scheper *et al.*, 2015).

Information obtained from grower surveys and interviews (Chapter 1, Section 1.8) uncovered that in reality the apple and pear growers do not utilise wildflower mixes at the orchard perimeter and do not necessarily view them in a positive light, despite the growing academic input into wildflower provision for beneficial invertebrates. Indeed other studies have also found that farmers reject wildflower provision due to the association with weeds but view herbs and medicinal plants as preferential beneficial floral resources (Christmann *et al.*, 2017). Wildflower plantings can also be unpredictable, the species present are often variable across the years and they can become dominated by a single plant species (e.g. *Phacelia cilata* in Lundin *et al.* (2017)). These considerations, as well as the knowledge that many apple growers already have hedgerows and windbreaks in place on their farms that have not been designed to provide pollinators with successional floral resources (Chapter 1, Section 1.8), uncovered both a need and an opportunity to offer alternative pollinator foraging resources on-site with an alternative. In this study, I propose the implementation of targeted shrubby aromatic herb floral resources.

Thyme (*Thymus* spp.) and lavender (*Lavandula* spp.) are both aromatic herbs of the mint (*Lamiaceae*) family, distributed across the Mediterranean, Asia and Africa and are attractive floral resources for insect pollinators. A study into the lists of pollinator friendly plants that are recommended to the public found that lavender was in 14 out of 15 lists and thyme in 12 (Garbuzov and Ratnieks, 2014a). The addition of lavender and thyme in apple orchards provides continued temporal floral resource availability to pollinators in the intensive commercial apple system, *Thymus vulgaris* flowers in June, and *Lavandula x intermedia* 'Sussex' flowers from the end of June all the way until September. The aim was therefore that these plants would provide crucial floral resources to sustain the local pollinator communities after the mass bloom of apple. This also avoids the possibility of alternative floral resources co-flowering with apple bloom, which might be a potential concern for some growers.

In this chapter, I used commercial dessert apple orchards to examine the effects of lavender and thyme at the orchard edge on the abundance of pollinators in orchards. This is the first application of shrubby aromatic herbs to enhance successional floral resource provision at the apple orchard perimeter. The overarching aim was to improve the abundance of wild pollinators in the orchards to reduce the reliance on managed honeybees alone during apple bloom. I aimed to answer two key research questions: 1.) Can orchard edge treatments of lavender and/or thyme increase pollinator abundance in orchards during the summer months after the mass apple bloom and; 2.) Are pollinator visitation rates to apple during the spring apple bloom higher in the orchards with these orchard edge treatments?

2.3 Methods

2.3.1 Study area

All apple orchards were located in Kent; spread across three main farms (Figure 2.1): Gore Farm (N 51021.883 E 000038.805), Howt Green Farm (N 51021.801 E 000043.113) and Pump Farm (N 51 0 22.647 E 000035.757). Kent is located in the south-east of England, an important region for dessert apple production; 90% Braeburn apples and 80% Gala apples in England and Wales are grown in the southeast and London region (DEFRA, 2013). All experiments were conducted in Braeburn and Gala orchards in 2016, 2017 and 2018. These two varieties flower at a similar time and are important UK dessert apples; between 2009 and 2012 there was a 50% increase in the area of Gala grown and 68% increase for Braeburn (DEFRA, 2013).

Orchards smaller than 4ha were identified and a total of 22 initial study orchards were chosen across the three farm locations. The orchards were all under the same conventional management, which incorporated the use of chemical pesticides and fertilisers, similar to other commercial apple orchards. All orchards were established but it was not possible to have orchards of exactly the same age. Due to the nature of the farm set-up, most of the orchards were surrounded by other plantations of various varieties of apples, pears or, in some cases, cherries.

In order to ensure that orchards had the same management, similar soil type and local weather conditions there was a trade-off in terms of distance from one another (160 m was the average minimum distance between orchard edge treatments). A closer distance did however enable efficient travel around sites allowing for one person to get all of the orchards sampled twice within the time constraints of both apple blossom itself (2-3 weeks) and the necessary weather and time conditions for consistent invertebrate sampling across all orchards. This distance was also deemed acceptable because observations were only taken up to approximately 50 m away from the orchard edge, aiming to determine local effects.

2.3.2 Experimental set-up

After apple bloom, at the end of May/beginning of June 2016, a total of 300 lavender (*Lavandula x intermedia* 'Sussex') (2L pot) and 300 common thyme (*Thymus vulgaris*) (1.5L pot) plants were planted in 30 m strips, along the south (SE-SW) side of the orchard edge, adjacent to existing non-crop vegetation. Orchard plots were allocated to one of four treatments (Figure 2.2): 'mixed' of alternating lavender and thyme (n = 5 of which: Braeburn = 3, Gala = 2; Figure 2.3), lavender (n = 5 of which: Braeburn = 3, Gala = 2), thyme (n = 5 of which: Braeburn = 3, Gala = 2), neither (i.e. control) (n = 7 of which: Braeburn = 3, Gala = 4). The control orchards were reduced to five in 2017 (exclusion of two Gala orchards) and one lavender (Braeburn) and one thyme (Braeburn) orchard were also excluded in 2018, due to unforeseen orchard removal ready for a new planting.

Figure 2.1 Location of the orchard plots, at the three main farm locations in Kent, UK (Google Inc., 2018)

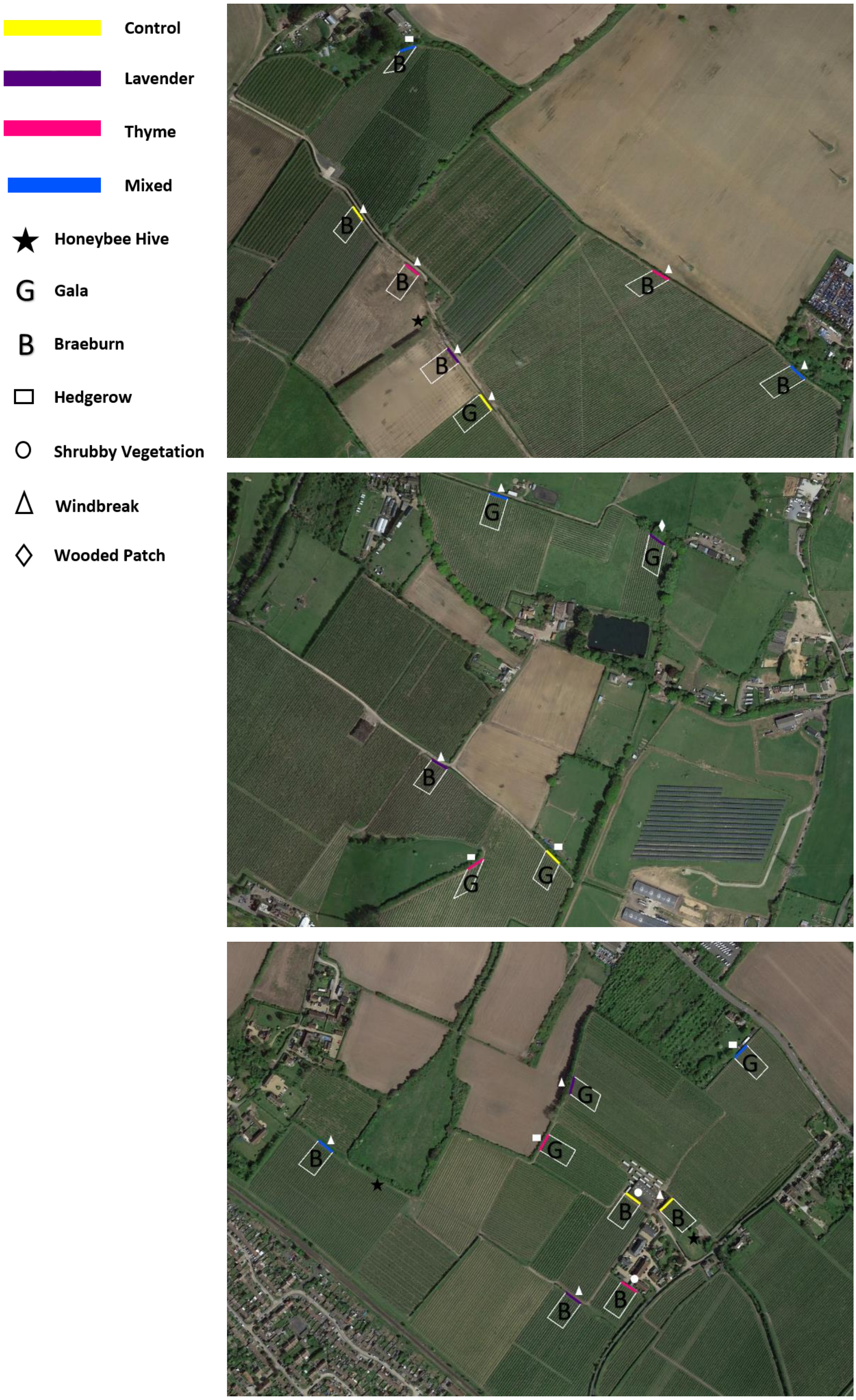


Figure 2.2 The orchards plots showing the different orchard edge treatments (30 m) adjacent to existing non-crop vegetation, apple variety and location of managed honeybee hives (Google Inc., 2018)

All lavender and thyme plants were surrounded with netting to protect them from rabbits but which allowed pollinators to freely access the plants (Figure 2.3). This is the same method of protection as for safeguarding new orchard trees. In June 2017, 100 Lavender (*Lavandula x intermedia* 'Sussex') (2L pot) and 100 thyme (*Thymus vulgaris*) (1.5L pot) plants from the original suppliers were planted to replace those that had not established to ensure that the plots still had comparable numbers of thriving lavender and thyme plants across the study years.

Figure 2.3 The experimental set-up of a mixed orchard edge treatment of alternating lavender and thyme plants

2.3.2.1 Annual field surveys after apple blossom: pollinator transect walks of 'potential' apple pollinators

To determine if the lavender and thyme plants can attract pollinators after the mass apple flower bloom, I carried out additional visual observations and net collections of aerial invertebrates in the orchards during the period after apple blossom until apple harvest, once a month in June, July and August in both 2016 and 2017. In each orchard, I conducted linear transect walks along the 30 m orchard edge treatment and also along the 30 m central apple row, perpendicular to the orchard edge treatment (to minimise the edge effects from other boundaries of the orchards), each for 10 minutes. Invertebrates were recorded in a fixed 1 m band either side of the transect route. Data from the orchard edge treatment transect and the perpendicular apple row transect were then pooled for analysis. Due to time constraints, these surveys were not carried out in 2018.

2.3.2.2 Annual field surveys during apple blossom: apple pollination observations

To firstly determine if the pollinator visitation rate to apple flowers differed between apple varieties or at different distances from the orchard edge before the experiments, I sampled 22 orchards in May during apple blossom (4th May – 20th May), prior to the experimental planting in June 2016. To investigate the effects of lavender and thyme plantings on the pollinator visitation rate during apple flowering season, I repeated sampling for 20 orchards with the same method during apple blossom in 2017 (9th April – 21st April; 1 year after treatment). In 2018, I carried out the same surveys again in 18 orchards during apple blossom (24th April- 9th May; 2 years after treatment). In all years, I sampled the orchards from 10% apple flower bloom until 90% petal fall, between 10:00 and 16:30 on days of ambient sampling conditions (no more than light wind or rain and at least 12^{o}C). Each orchard was sampled at least twice annually on different days.

The pollinator visitation rate to apple flowers was measured at four increasing distances (approximately: 5 m, 15 m, 30 m and 50 m) perpendicular to the orchard edge treatment estimated by number of trees away from the orchard edge. 5 m, or distance 1, therefore represents the first tree of the row. At each distance, a section of apple inflorescences (200 flowers) on a tree was observed for 10 minutes and the number and type of visitors to the apple flowers recorded. The pollinator visitation rate is expressed as number of visitors min^{-1}.

Where possible, pollinators were identified to species on the wing but they were not captured during apple blossom in order to avoid altering visitation frequencies (as in Monzón *et al.* (2004)). Pollinators were classified into the groups of: (1) *Apis mellifera* (Honeybees; Figure 2.4a), (2) *Bombus* spp. (Bumblebees; Figure 2.4b), (3) *Other Apidae* (Solitary bees, Figure 2.4c), (4) Syrphidae spp. (Hoverflies), (5) All other Diptera, (6) Lepidoptera, (7) Other Hymenoptera and (8) All other insects. This level of identification is similar to other studies in which insects are counted (but not collected) whilst they are foraging on focal flowers (e.g. Garbuzov and Ratnieks (2014b)).

a.) b.) c.)

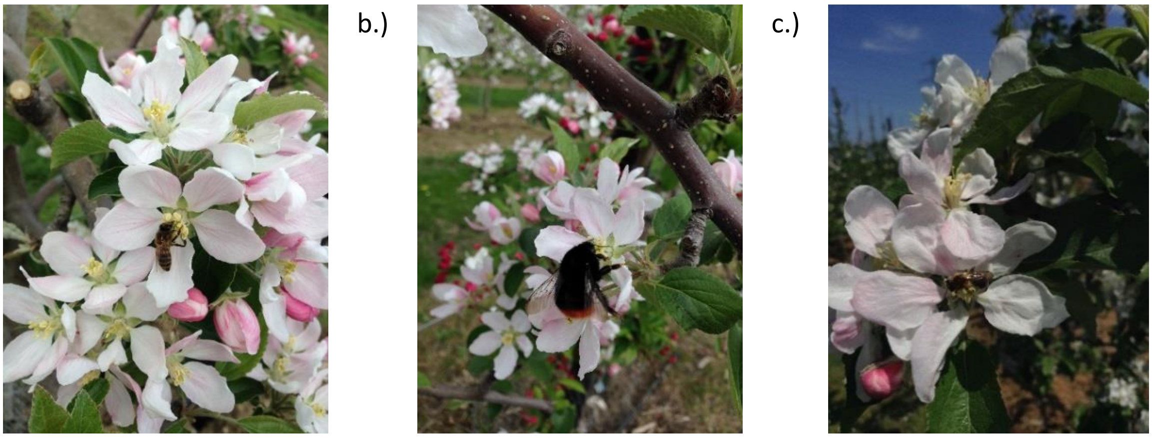


Figure 2.4 The main hymenoptera pollinator groups; a.) honeybees (*Apis mellifera*); b.) wild eusocial bees i.e. bumblebees (*Bombus* spp.); and c.) solitary bees (e.g. *Andrena* spp. and *Osmia* spp.)

2.3.3 Statistical analysis

2.3.3.1 Pollinator transects during the summer months

Data from pollinator transects in 2016 and 2017 were analysed separately, in order to check for variations in the results from 2016 to 2017. To determine the effect of the orchard edge treatment on pollinator abundance after apple blossom of each year (i.e. 2016 and 2017), I used the package glmmADMB in R to apply generalised linear mixed models (GLMMs) with a negative binomial distribution and log-link function (the models could not be fitted with Poisson distributions due to over dispersion of the count data) for each of the response variables: total aerial invertebrate abundance, wild bee abundance (total number of bumblebees and solitary bees), bumblebee abundance, solitary bee abundance, hoverfly abundance and managed honeybee abundance. The fixed factors of these analyses were orchard edge treatment (4 levels: Control, Lavender, Thyme, Mixed), month (3 levels: June, July, August) and the interaction between treatment and month. To account for the hierarchical experimental design and the repeated measures, I included transects nested in orchards as random effects in all models. Model assumptions were checked visually by assessing residual plots. Post-hoc Tukey tests were carried out on the minimum adequate models that had significant fixed effects ($p < 0.05$) from likelihood ratio tests (LRTs), using the package emmeans in R (Length, 2018).

2.3.3.2 Pollinator visits to apple flowers

Data from the three years of apple blossom observations (2016, 2017 and 2018) were analysed separately. To determine the effects on the pollinator visitation rate at apple blossom of each year (i.e. 2016, 2017 and 2018), I used the package lme4 in R (Bates *et al.*, 2015) to fit linear mixed models (LMM) for each of these response variables: all pollinators pooled, wild bees (bumblebees and solitary bees pooled), bumblebees, solitary bees, managed honeybees and hoverflies. For 2016 (prior to the establishment of orchard edge treatments) the fixed factors of these analyses were apple variety (two levels: Braeburn or Gala), distance away from the orchard edge (four categorical levels: 1, 2, 3, 4) and their interaction. For 2017 (one year after orchard edge treatment) and 2018 (two years after orchard edge treatment) the fixed factors also included the orchard edge treatment (4 levels: Control, Lavender, Thyme, Mixed) and the interactions between all fixed factors. To account for the hierarchical experimental design and the repeated measures, day of sample, nested in orchard, was included as a random effect. The minimum adequate models were selected based on the significance of fixed effects as determined from anova comparisons of models to their null. Post-hoc pairwise Tukey contrasts were performed to understand the significant fixed effects ($p < 0.05$) of the best plausible models using the emmeans package in R (Length, 2018).

2.3.3.3 Pollinator abundance at apple blossom compared to the previous summer

To test for a correlation between pollinator abundance during the summer months and pollinator abundance in the same orchards during the following apple blossom season, pollinator transect data along the orchard edge of all three summer months (June, July, August) were pooled for each pollinator type (in 2016 and 2017) and compared to the following years' pollinator abundance during apple blossom (2017 and 2018 respectively). Pollinators were grouped into: all wild insects pooled, all wild bees pooled, honeybees, hoverflies, bumblebees and solitary bees. Due to non-parametric data, a small sample size and 'tied' observations, Kendall's Tau correlation was carried out.

All statistical analysis were performed in R (R Core Team, 2015).

2.4 Results

2.4.1 'Potential' apple pollinators in orchards

A total of 2,880 aerial invertebrates were observed during the pollinator transects in orchards during the months post-apple blossom and pre-apple harvest (June, July and August) in 2016 and 2017. Of these, *Bombus* spp. were the most abundant in both years accounting for 34% individuals in 2016 and 33% in 2017 (Table 2.1). Lavender plants established quicker than thyme plants, flowering soon after planting in 2016 and were predominantly visited by *Bombus* spp. (Figure 2.5a,b). Solitary bee nests were observed in the earthy soil next to a mixed orchard edge treatment in 2017 (Figure 2.5c).

Table 2.1 Total abundance (and proportion) of aerial invertebrates in orchards from the transects in June, July and August in 2016 and 2017

	2016	2017
Honeybees	52 (0.07)	161 (0.08)
Bumblebees	253 (0.34)	704 (0.33)
Solitary bees	22 (0.03)	148 (0.07)
All Other Hymenoptera	24 (0.03)	57 (0.03)
Hoverflies	107 (0.14)	150 (0.07)
Other flies	98 (0.13)	680 (0.32)
Butterflies	69 (0.09)	125 (0.06)
Other	120 (0.16)	110 (0.05)
Total	745	2135

a.)  b.)  c.) 

Figure 2.5 a.) and b.) *Bombus* spp. observed foraging on the *Lavandula x intermedia* 'Sussex' in the orchard edge treatment and c.) solitary bee nests in the ground next to a mixed orchard edge treatment

In the first summer of orchard edge treatment establishment (2016), there was a significant interaction effect between treatment and sampling month (Table 2.2) for total aerial invertebrate abundance (Figure 2.6a), wild bee abundance (Figure 2.6b) and bumblebee abundance (Figure 2.6c). However, the post-hoc Tukey tests did not find any significant differences ($p > 0.05$ for all) in the pairwise comparisons (Figure 2.6a,b,c). In 2016, there were no significant effects of treatment, sampling month or an interaction between them ($p > 0.05$) for solitary bees or for managed honeybees (Table 2.2).

Table 2.2 Results from GLMM analyses of aerial invertebrate abundances in June, July and August in 2016 and in 2017. Fixed effects included treatment (T; control, lavender, thyme, mixed), month (M; June, July August), and the interaction between treatment and month (T x M)*;* *p* values of fixed effects included in final models are presented in bold (*p* < 0.05). NB: The two models that failed to converge in 2016 are shown by 'FTC'

		2016			2017		
Response	Predictor	d.f.	L-Ratio	p	d.f.	L-Ratio	p
Total Aerial Invertebrates	T	3	5.91	0.116	3	24.45	**< 0.001**
	M	2	14.42	**< 0.001**	2	5.20	0.074
	T x M	6	13.62	**0.034**	6	15.30	**0.018**
Wild Bees	T	3	3.20	0.362		FTC	
	M	2	4.40	0.111	2	17.53	**< 0.001**
	T x M	6	15.96	**0.014**	6	29.02	**< 0.001**
Bumblebees	T	3	3.04	0.386	3	13.27	**0.004**
	M	2	6.70	**0.035**	2	10.82	**0.004**
	T x M	6	25.89	**< 0.001**	6	28.08	**< 0.001**
Solitary bees	T	3	0.92	0.822	3	9.42	**0.024**
	M	2	0.56	0.755	2	5.11	0.078
	T x M		FTC		6	3.57	0.735
Honeybees	T	3	1.36	0.714	3	2.03	0.566
	M	2	3.15	0.207	2	0.31	0.856
	T x M		FTC		6	18.45	**0.005**
Hoverflies	T	3	1.93	0.588	3	7.97	**0.047**
	M	2	15.39	**< 0.001**	2	13.06	**0.001**
	T x M	6	8.68	0.193		FTC	

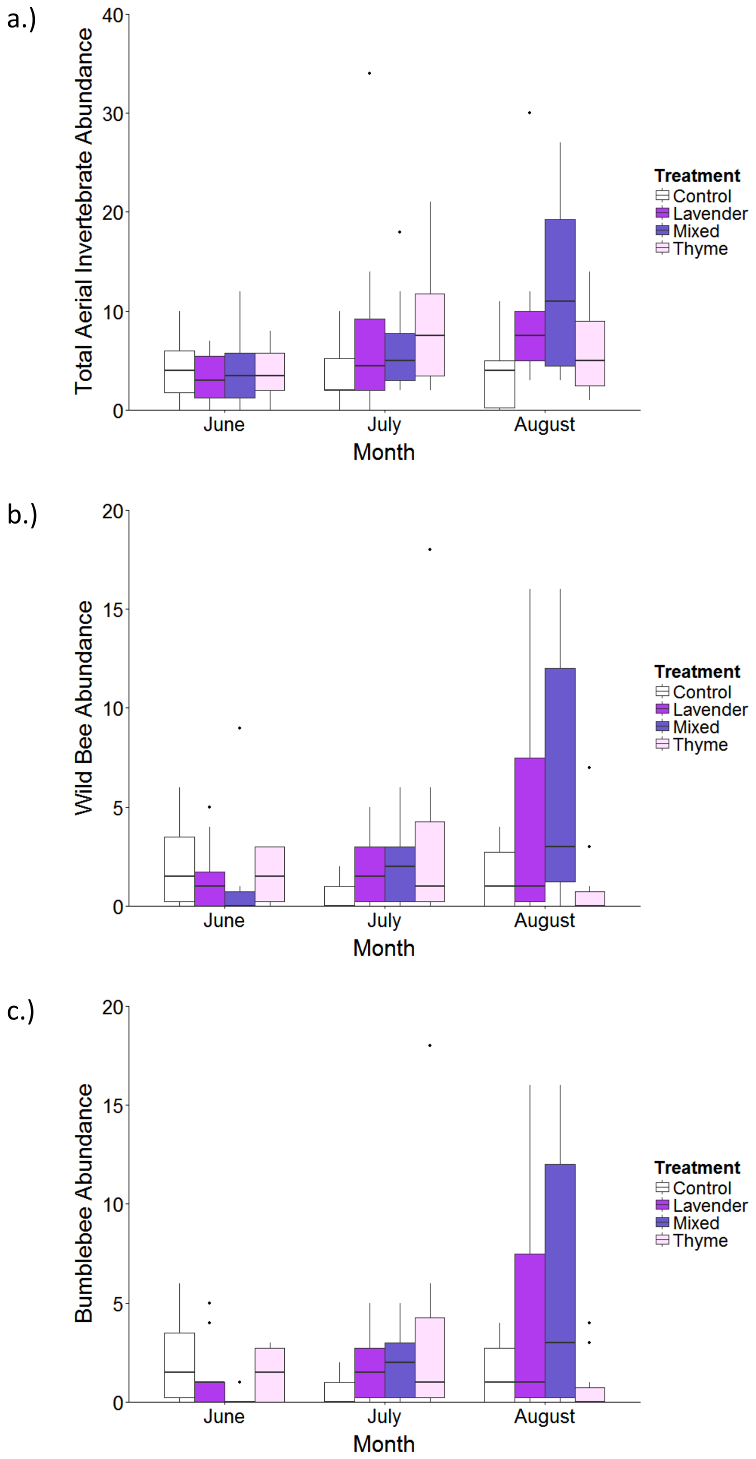


Figure 2.6 Significant effects ($p < 0.05$) of orchard edge treatment on aerial invertebrate abundance in orchards during June, July and August in 2016 for a.) all invertebrates; b.) wild bees (bumblebees and solitary bees); and c.) bumblebees

In the second year of orchard edge treatment establishment (2017), there was a significant interaction effect between treatment and sampling month (Table 2.2) for total aerial invertebrate abundance (Figure 2.7a). There were no detectable differences between orchards with different orchard edge treatments in June ($p > 0.05$). The orchards with a mixed lavender and thyme treatment had a significantly higher aerial invertebrate abundance than the control orchards in both July and August. However, orchards with a lavender edge and those with a thyme edge did not have the same effect on aerial invertebrate abundance in those months.

Additionally, there was a significant interaction effect between treatment and sampling month for wild bee abundance (Figure 2.7b). Pairwise comparisons showed that in June and July there was no difference in wild bee abundance between orchard edge treatments but in August, orchards with a lavender orchard edge and a mixed orchard edge had a higher wild bee abundance than orchards with a control orchard edge treatment. A difference in wild bee abundance between the control orchard edge treatments was detected between June and August.

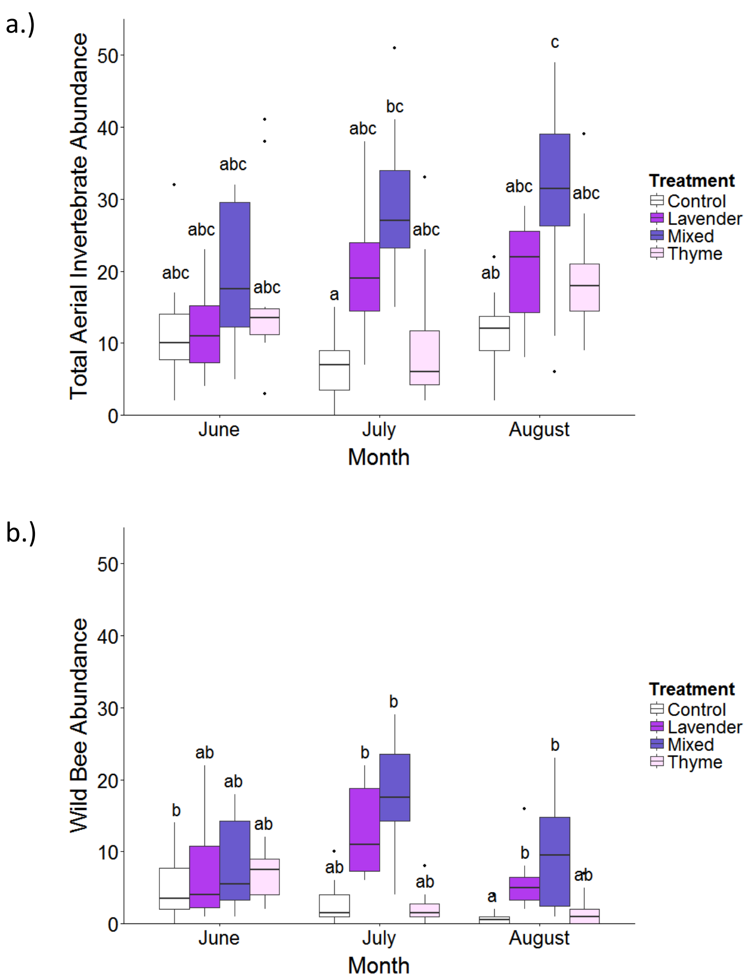


Figure 2.7 Significant effects ($p < 0.05$) of orchard edge treatment on aerial invertebrate abundance in orchards during June, July and August in 2017 for a.) all invertebrates and b.) wild bees (bumblebees and solitary bees). Different letters illustrate a significant difference found by the Tukey post-hoc multiple comparison tests ($p < 0.05$) and the same letters indicate no significant difference

There was also a significant interaction effect between treatment and sampling month for bumblebee abundance (Figure 2.8a). Pairwise comparisons showed that in June and July there was no difference in bumblebee abundance between orchard edge treatments but in August, orchards with a lavender orchard edge treatment and a mixed orchard edge treatment had a higher bumblebee abundance than orchards with a control orchard edge treatment. A difference in bumblebee abundance between the control orchard edge treatments was also detected between June and August.

For solitary bees and hoverflies, a significant effect of treatment was detected, with a higher abundance in orchards with a mixed orchard edge treatment than a control orchard edge treatment (Figure 2.8c,d, Table 2.2). For honeybee abundance, a significant interaction between orchard edge treatment and sampling month was detected (Figure 2.8b). Pairwise comparisons showed that in August, there was no difference in honeybee abundance between orchard edge treatments but in June, orchards with a thyme orchard edge treatment had a higher honeybee abundance than orchards with a control orchard edge treatment. In July, orchards with a mixed orchard edge treatment had a higher honeybee abundance than all other orchard edge treatments; orchards with a lavender edge had a higher honeybee abundance than thyme and control orchards and; orchards with a thyme edge had a higher honeybee abundance than control orchards.

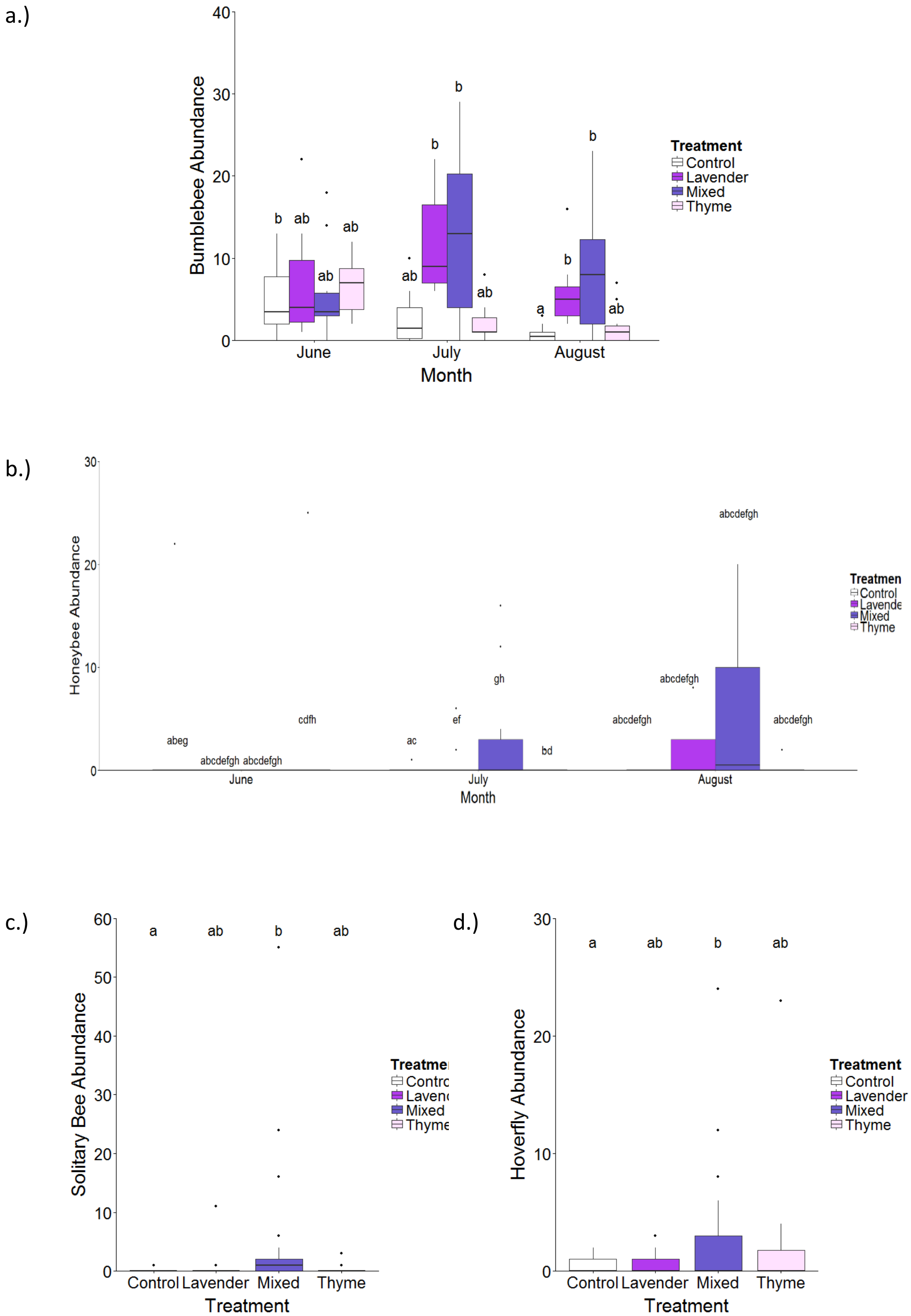


Figure 2.8 Abundance of aerial invertebrates in orchards from transects in 2017 for a.) bumblebees; b.) honeybees; c.) solitary bees; and d.) hoverflies. Letters indicate significant differences of Tukey post-hoc multiple comparison tests ($p < 0.05$).

2.4.2 Pollinator visits to apple flowers

A total of 1,286 individual bees were observed during the timed observations in 2016 (prior to the establishment of orchard edge treatments), 2017 (one year after orchard edge treatments) and 2018 (two years after edge treatments), accounting for 4,292 visits to individual apple flowers. Overall, honeybees (*Apis mellifera*) were the most abundant visitors for all the years (Table 2.3). The other pollinators observed were: bumblebees (e.g. *Bombus lapidarius, Bombus pratorum, Bombus pascorum, Bombus terrestris, Bombus lucorum, Bombus hortorum, Bombus hypnorum*); solitary bees: (e.g. *Anthophora plumipes, Osmia bicornis, Andrena cineraria, Andrena fulva*); *hoverflies; other flies* (e.g. *Bombylius major*) *and butterflies.*

Table 2.3 Apple flower visits from the main pollinator groups

	Honeybees	Bumble bees	Solitary bees	Hoverflies	Other flies	Other	All Pollinators Pooled
2016 (22 orchards)							
Total Abundance	80	30	62	10	46	17	245
Total apple flower visits	308	155	205	11	58	18	755
Average visits per individual	3.85	5.17	3.31	1.10	1.26	1.06	3.08
2017 (20 orchards)							
Total Abundance	402	39	103	20	32	7	603
Total apple flower visits	1686	236	279	51	37	9	2298
Average visits per individual	4.19	6.05	2.71	2.55	1.16	1.29	3.81
2018 (18 orchards)							
Total Abundance	207	21	72	22	112	4	438
Total apple flower visits	705	122	220	35	153	4	1239
Average visits per individual	3.41	5.81	3.06	1.60	1.37	1.00	2.83

In 2016 (prior to orchard edge treatment establishment), an interaction between apple variety and distance was detected for wild bee visitation rate ($p < 0.05$); the wild bee visitation rate in Braeburn was lower at the furthest distance away (distance 4) from the orchard edge than for Gala at the furthest distance away from the orchard edge (Figure 2.9). There were no further significant fixed effects of apple variety, distance from the orchard edge or their interaction ($p > 0.05$) on apple flower visitation rates for the other pollinator groups tested (Table 2.4).

Table 2.4 Results from LMM analyses of insect visitation rates (number of visits min^{-1}) to apple flowers in 2016; *p* values of significant fixed effects included in final models are presented in bold ($p < 0.05$)

			2016	
Response	Predictor	d.f.	X^2	pr>Chi
All Pollinators Pooled	Distance (D)	3	0.25	0.969
	Variety (V)	1	2.13	0.144
	D x V	3	7.30	0.063
Honeybees	Distance (D)	3	5.21	0.157
	Variety (V)	1	0.03	0.872
	D x V	3	2.48	0.479
All Wild Bees Pooled	Distance (D)	3	2.19	0.534
	Variety (V)	1	2.54	0.111
	D x V	3	8.01	**0.046**
Bumblebees	Distance (D)	3	2.68	0.444
	Variety (V)	1	1.02	0.313
	D x V	3	7.51	0.057
Solitary bees	Distance (D)	3	11.48	0.244
	Variety (V)	1	2.12	0.145
	D x V	3	3.22	0.359
Hoverflies	Distance (D)	3	0.77	0.857
	Variety (V)	1	0.70	0.403
	D x V	3	1.22	0.748

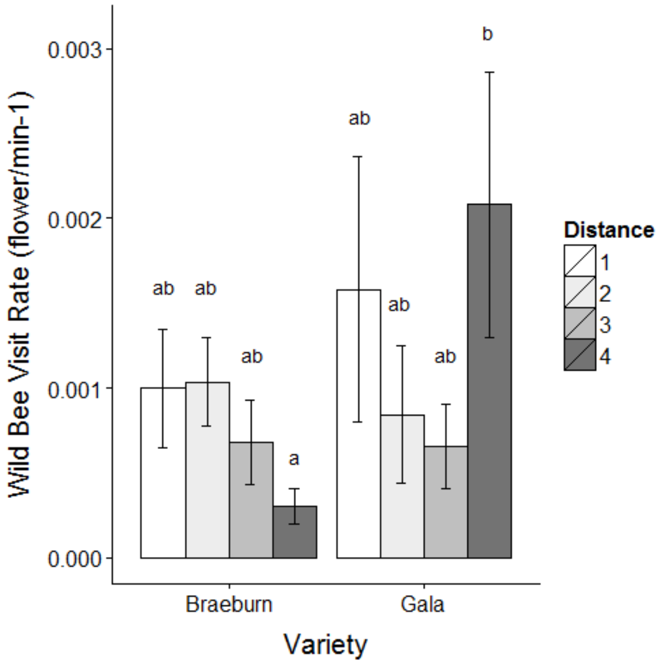


Figure 2.9 Significant interaction effect ($p < 0.05$) of distance from the orchard edge and apple variety on the wild bee visitation rate to apple flowers in 2016 (see Table 2.4 for details). Bars represent group means +/- SE, letters represent the specific differences detected from the Tukey post-hoc multiple comparison tests ($p < 0.05$)

In 2017 (one year after orchard edge treatment establishment) and 2018 (two years after orchard edge treatment establishment), the proportion of wild insects visiting the apple flowers was higher in the orchards with a mixed (both lavender and thyme) orchard edge treatment (Figure 2.10).

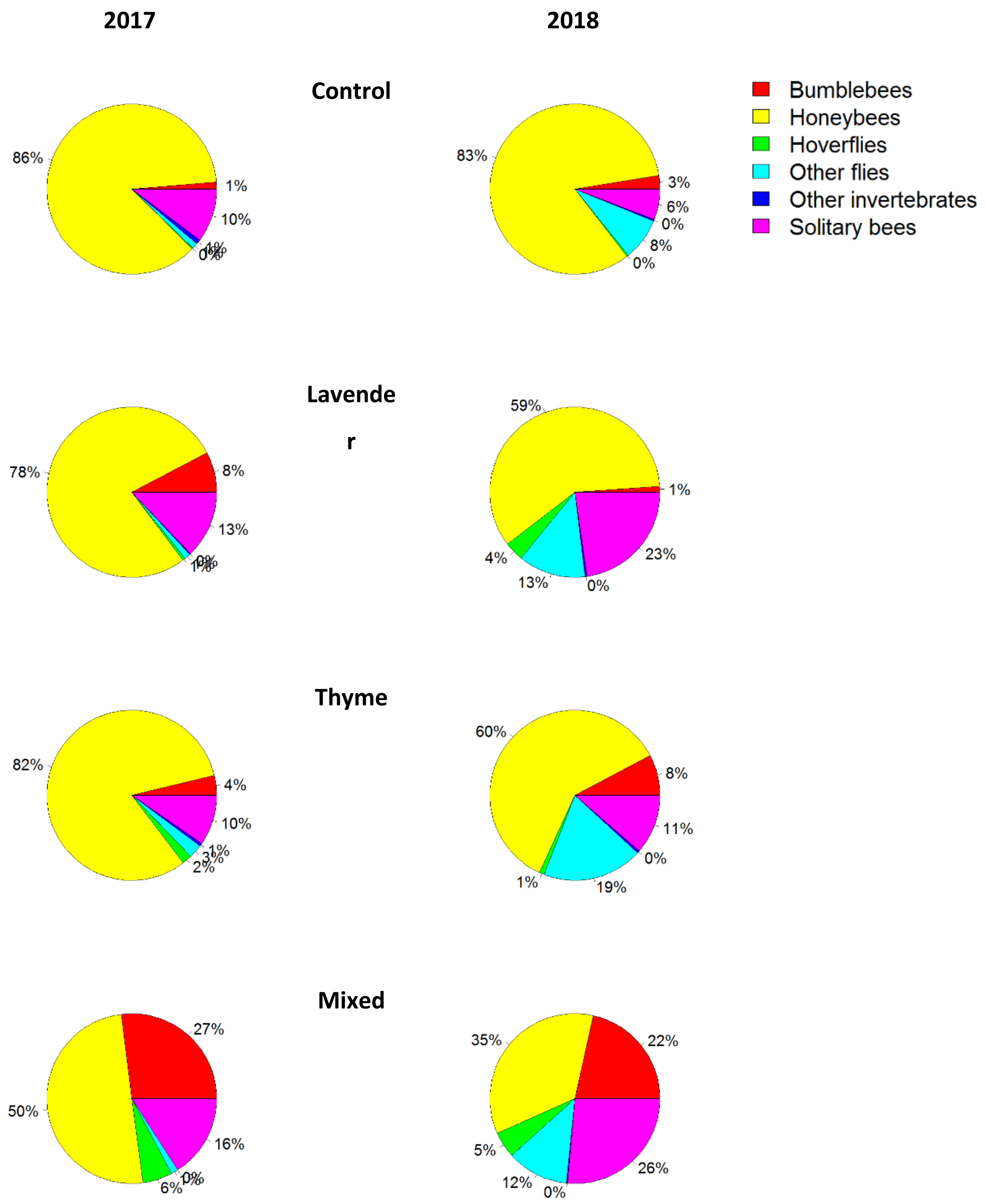


Figure 2.10 Proportion of the visits to apple flowers from the pollinator community in orchards with the different orchard edge treatments in 2017 and 2018

In 2017 (one year after orchard edge treatment establishment), a significant effect of distance from the orchard edge was found for all pollinators pooled ($p < 0.001$) and for honeybees ($p < 0.05$) (Table 2.5). The total pollinator visitation rate was lower at the furthest distance away from the orchard edge than the closest distance to the orchard edge (Figure 2.11a). Honeybee visitation rate was lower at the distance furthest away from the orchard edge than at the two closest distances to the orchard edge (Figure 2.11b).

An interaction of treatment and variety were found to influence the visitation rate of all wild bees pooled ($p < 0.05$) and of bumblebees ($p < 0.01$) to apple flowers. The post-hoc pairwise comparisons found that there was only a difference between the visitation rate in mixed orchards compared to the control in the Braeburn orchards but not the Gala orchards (Figure 2.11c; Figure 2.11d).

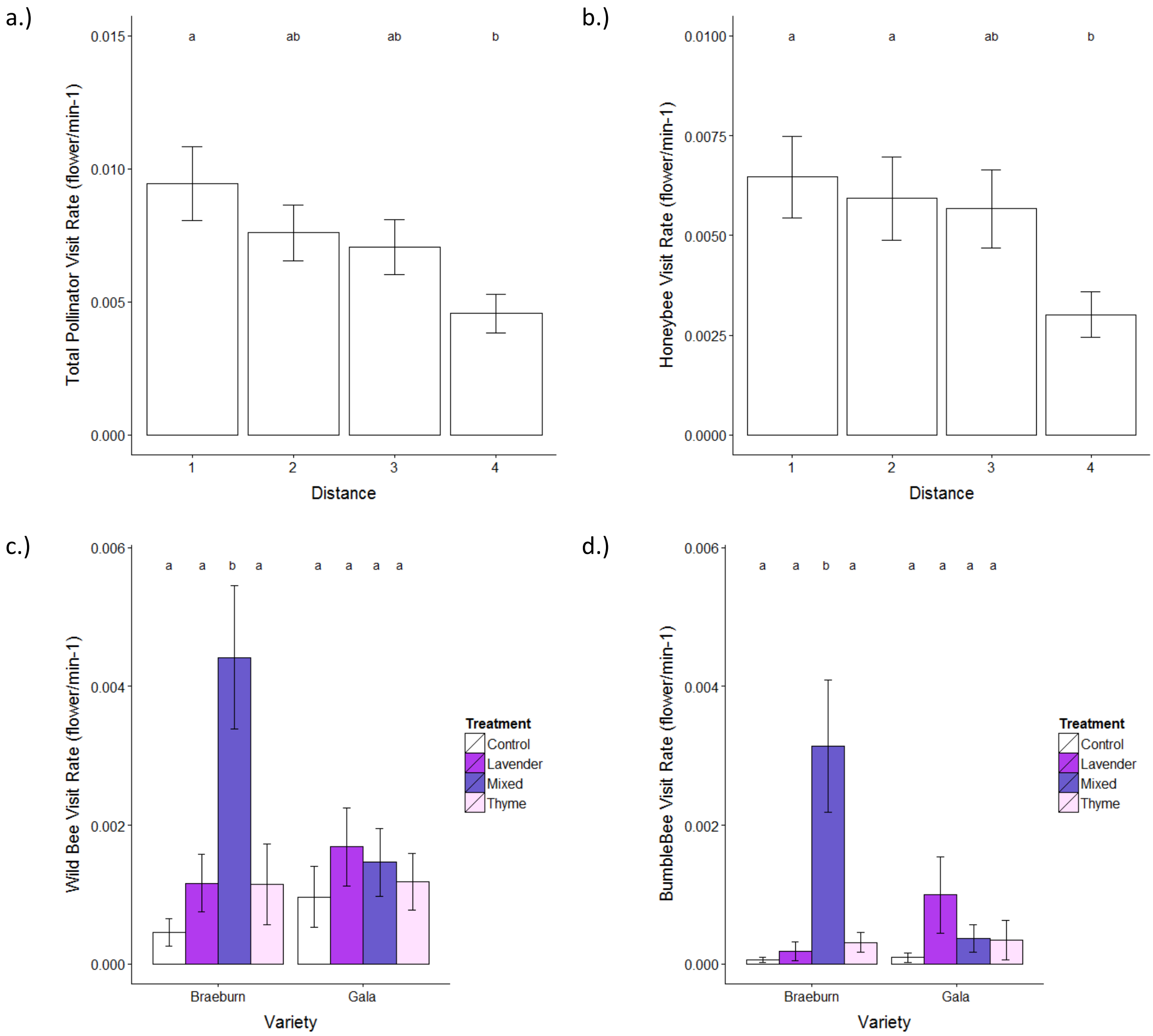


Figure 2.11 The effect of orchard edge treatment on apple visit rates in 2017 from a.) all pollinators pooled; b.) honeybees; c.) wild bees pooled; and d.) bumblebees; (see Table 2.5 for details). Bars represent group means +/- SE, letters represent the specific differences detected from the Tukey post-hoc multiple comparison tests ($p < 0.05$)

Table 2.5 Results from LMM analyses of insect visitation rates (number of visits min-1) to apple flowers in 2017 and 2018; chi-square values (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$) are shown for all explanatory variables included in the models tested

	Treatment (T)	Variety (V)	Distance (D)	T x V	T x D	D x V	T x V x D
D.F	3	1	3	3	9	3	24
2017							
All Pollinators Pooled	3.07	0.34	**12.91*** **	2.29	8.66	0.02	26.21
Honeybees	0.31	1.08	**10.98***	0.88	9.01	1.31	13.37
All Wild Bees Pooled	**12.62****	0.53	3.26	**10.76***	6.88	0.14	25.10
Bumblebees	**9.00***	0.68	4.55	**12.17****	9.26	1.45	32.85
Solitary bees	2.04	0.00	2.79	0.90	11.46	0.52	20.35
Hoverflies	2.91	1.66	2.68	2.34	9.67	1.88	21.08
2018							
All Pollinators Pooled	4.95	**5.31***	2.48	1.36	13.02	0.85	26.44
Honeybees	2.69	1.17	1.10	2.40	13.32	0.06	27.66
All Wild Bees Pooled	**14.10****	2.10	1.90	3.08	2.99	1.95	18.5
Bumblebees	**8.50***	0.68	0.62	0.50	3.80	2.85	16.70
Solitary bees	**9.05***	2.13	0.62	**8.76***	3.85	0.76	18.00
Hoverflies	3.48	1.50	2.15	2.57	3.85	1.06	13.17

In 2018 (two years after orchard edge treatment establishment), there was no effect of distance on pollinator visitation rate for any pollinator taxa ($p > 0.05$) (Table 2.5). There was a difference ($p < 0.05$) between visitation rates to different apple varieties though, with a higher visitation rate from all pollinators pooled in Braeburn orchards than Gala orchards (Figure 2.12a). There was also a treatment effect on visitation rate for all wild bees pooled ($p < 0.01$) and for bumblebees ($p <$

0.05); the wild bee visitation rate was higher in orchards with a mixed treatment compared to all other orchard edge treatments (Figure 2.12b). The bumblebee visitation rate was higher in orchards with a mixed orchard edge treatment than the control or lavender orchard edge treatments (Figure 2.12c).

A significant interaction effect between treatment and variety was found for solitary bee visitation rates ($p < 0.05$); the post-hoc pairwise comparison found that there was a higher solitary bee visitation rate in Braeburn orchards with a mixed edge compared to control or to thyme, but there was no difference between treatments in Gala orchards (Figure 2.12d).

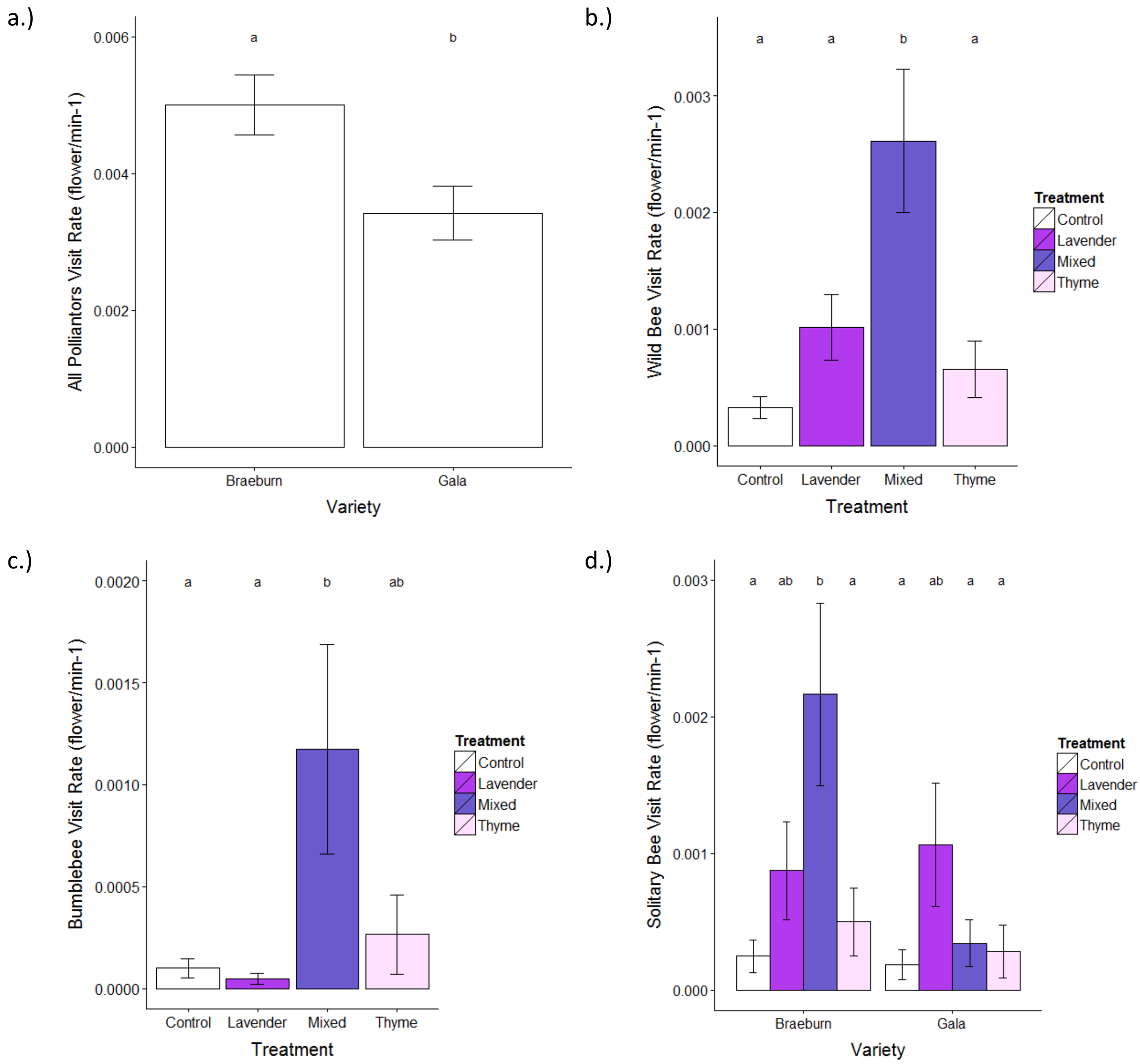


Figure 2.12 The effect of orchard edge treatment on apple visit rates in 2018 from a.) all pollinators pooled; b.) honeybees; c.) wild bees pooled; and d.) bumblebees; (see Table 2.5 for details). Bars represent group means +/- SE, letters represent the specific differences detected from the Tukey post-hoc multiple comparison tests ($p < 0.05$)

2.4.3 Pollinator abundance at apple blossom compared to the previous summer

In terms of pollinator abundance, there were significant positive correlations between apple blossom and the summer months (June, July, August) of the previous year for: all wild insects pooled (Kendall's τ correlation coefficient = 0.386, $p < 0.01$; Figure 2.13a) and solitary bees (Kendall's τ correlation coefficient = 0.277, $p < 0.05$; Figure 2.13b). However, no correlation ($p > 0.05$) was found for total wild bee abundance, honeybee abundance, bumblebee abundance or hoverfly abundance (Table 2.6; Figure 2.13c-f).

Table 2.6 Relationship between pollinator abundance during apple blossom and pollinator abundance in orchards during June, July and August of the previous year

	p value	Kendall's τ correlation coefficient
All Wild Insects Pooled	**< 0.001**	0.386
All Wild Bees Pooled	0.064	0.219
Honeybee	0.695	0.049
Hoverflies	0.755	0.042
Bumblebee	0.390	0.107
Solitary bee	**0.033**	0.277

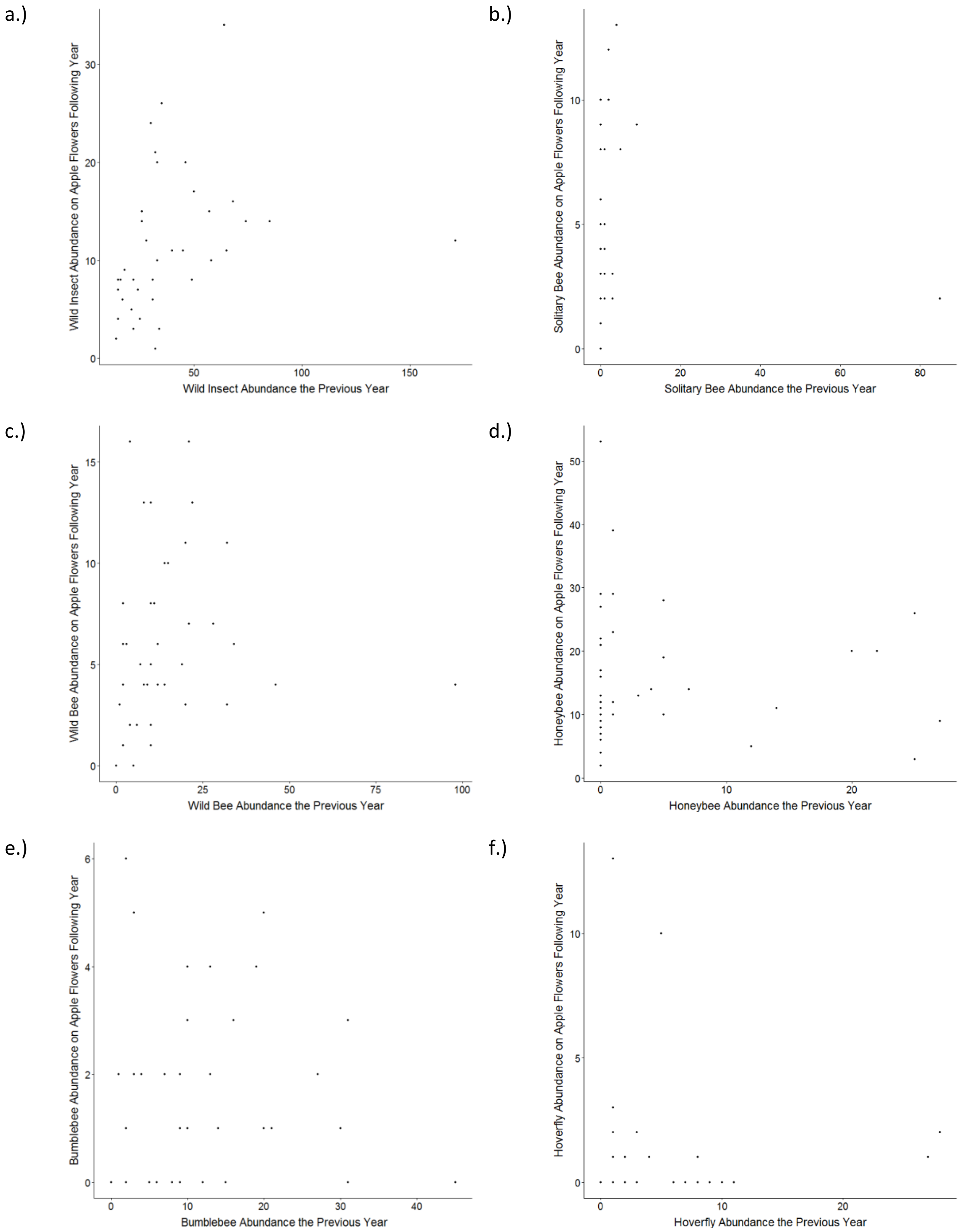


Figure 2.13 Relationship between pollinator abundance during apple blossom and insect abundance in orchards from transects during June, July and August of the previous year for a.) all wild insects pooled; b.) solitary bees; c.) all wild bees pooled (bumblebees and solitary bees); d.) honeybees; e.) bumblebees; f.) hoverflies

2.5 Discussion

In the summer immediately after the establishment of orchard edge treatments (2016), the abundance of all aerial invertebrates appeared to be higher in August in the orchards with a mixed orchard edge treatment of lavender and thyme. One year after orchard edge treatment establishment (2017) there was a higher abundance of bumblebees and all wild bees pooled in August in the orchards with either a mixed lavender and thyme treatment or a lavender treatment than in the control orchards. Honeybee abundance was higher in these orchards during July but not in August and regardless of month; solitary bee abundance and hoverfly abundance was higher in the mixed orchards compared to control orchards. Furthermore, during apple blossom in 2017 (one year after orchard edge treatment establishment), visitation rates to apple flowers from all wild bees pooled, and bumblebees were higher in the Braeburn orchards that had a mixed lavender and thyme orchard edge treatment but not in Gala orchards. In 2018 (two years after orchard edge treatment establishment), the solitary bee visitation rate was higher in Braeburn orchards with a mixed orchard edge treatment but not in Gala orchards. Whereas, in 2018, regardless of apple variety, all wild bees pooled and bumblebee visitation rates were higher in orchards with a mixed orchard edge treatment.

It is surprising that there were such rapid changes to aerial invertebrate abundances in the orchards in the months following orchard edge treatment establishment. This may therefore be due in part to those orchards already having established communities of pollinators foraging on nearby floral resources. Alternatively, the larger increase in vegetative abundance of having both lavender and thyme plants may have aggregated pollinators from nearby into those orchards. Whether or not landscape features are exporters or concentrators of pollinators is particularly important when determining if floral resources will attract pollinators away from crop plants that co-bloom (Morandin and Kremen, 2013). In this study, however, lavender and thyme flowered after crop bloom so did not directly compete with the apple flowers. Moreover, the visit rates to apple flowers the following year in 2017, from wild bees, were also enhanced in orchards that had a mixed lavender and thyme orchard edge treatment. This, as well as the positive correlation between the pollinator abundance in orchards during apple bloom and their abundance in the summer the year before for all wild insects pooled and solitary bees, indicates a potential link between the floral resource provision and abundance of some pollinator groups present the following year. This is still a very quick effect; in highbush blueberry it took until three-four years after adjacent wildflower establishment to detect effects on wild bees and hoverflies (Blaauw and Isaacs, 2014). Similarly, in lowbush blueberry, it took four years after floral provision establishment for wild bee visitation rates to increase (Venturini *et al.*, 2017). However, such rapid increases in bee abundance have been shown in cider apple orchards a year after alleyway wildflower establishment (Campbell *et al.*, 2017a). The close proximity of floral resources in these apple orchards, either in the alleyways or at the orchard edge could account for this difference in time lag between blueberry and apple studies.

The difference between the pooled wild bee abundance and bumblebee abundance observed between the mixed, or the lavender, orchard edge treatments compared to the control orchard edge treatments in August demonstrates the importance of this late season floral resource for bumblebees. The temporal provision of these resources could be positively affecting wild bee populations in the orchards; late season floral resources coincide with the bumblebee colony cycle and production of sexual offspring (Rundlof *et al.*, 2014). Others have also shown that the survival of bumblebee linages from workers over the summer to the emergence of the queen in the spring are dependent on local foraging resources in the habitat, however, they have attributed this more to the availability of spring floral resources very close to the establishing colony (Carvell *et al.*, 2017).

A positive correlation between solitary bee abundances in orchards during apple bloom and their abundances in the summer before could be, in part, due to the high number of solitary bees observed nesting in the ground next to a mixed orchard edge treatment. In a previous study, over 75% of *O. cornuta* were found to forage on trees within 50 m of their nests (Monzón *et al.*, 2004), demonstrating the short range of some solitary bee species. However, further research is needed in order to link these shrubby aromatic herbs to possible nesting locations.

It appeared that the effect of orchard edge treatments on pollinator visitation rate was dependent on apple variety; the pollinator visitation rates of wild bees and bumblebees in 2017, and of solitary bees in 2018 were higher in Braeburn orchards with a mixed lavender and thyme orchard edge treatment but not in Gala orchards. The difference in pollinator visits to apples of different varieties may be in part because of differing floral morphology and therefore different compositions of pollen and nectar (Schneider *et al.*, 2002). Although other studies have found no difference in the rates of pollinator visitation between different varieties of apple (Quinet *et al.*, 2016), Garratt *et al.* (2016) found that different apple cultivars have different pollinator communities; bumblebees contribute more to Braeburn (38%) than Gala (13%).

Apple pollinator communities, and the proportion of honeybee visits to apple, differed between years. This could be due to the different environmental conditions and flowering phenology each year. The lower number of honeybees in 2016 might also be attributed to the apple bloom co-occurring with oil seed rape, another mass flowering field crop. Oilseed rape is a known competitor to apple flowers for honeybee visits (Balfour and Ratnieks, 2017), the effect of which could have been even more pronounced as oilseed rape fields were located adjacent to two of the apple orchards in 2016 (personal observation).

Unlike wild bees, visit rates to apple flowers from managed honeybees were not enhanced in orchards that had a mixed lavender and thyme orchard edge treatment. In cider apples it was also found that honeybee visitation rate did not increase in wildflower strips but non-*Apis* bees did (Campbell *et al.*, 2017b). As a managed bee species, honeybee hive presence is the main determining factor of honeybee abundance (Blaauw and Isaacs, 2014); such local scale floral resources therefore might not affect honeybee populations in the same way as they do for unmanaged, wild bees. Indeed, overall, more bumblebees were observed in the orchards over the summer months than honeybees. This could be due to the larger foraging range of honeybees, allowing them to forage at further distances away from the orchards (Beekman and Ratnieks, 2000). Furthermore, it could also be due to the attractiveness of lavender to bumblebees. Lavender has been shown to attract a greater number of wild bees, such as bumblebees (*Bombus* spp.), than honeybees, even if honeybees are present at the same location (Balfour *et al.*, 2015). Bumblebees are also known to dominate lavender visits; they handle lavender flowers three times faster than honeybees, thus outcompeting them on lavender due to their more efficient foraging (Balfour *et al.*, 2013; Balfour *et al.*, 2015).

The yearly variability of honeybee abundance during apple blossom reiterates the importance of supporting wild bee communities that can buffer fluctuating honeybee visitation rates. Lavender and thyme offer successional, alternative, floral resources for these wild bee communities. Thyme varieties have been shown to attract many different bee species (e.g. *Thymus longicaulis,* Campolo *et al.* (2016)) and lavender flowers are also attractive to a wide range of insects (Herrera, 1988; Herrera, 1989). A recent UK wide citizen science project found that lavender (*Lavandula angustifolia*) was one of only a few plants that all six of their specified bumblebee groups visited, making it a highly recommended plant to support common native bumblebees (Foster *et al.*, 2017). However, not all lavender varieties are equally attractive to pollinators; recent research from Garbuzov and Ratnieks (2014b) found that *Lavandula x intermedia* varieties (such as that used in this study) are more attractive than those of *L. angustifolia* and *L. stoechas*. They also attract a high proportion of wild pollinators; for example, one study reported that *Lavandula x intermedia* 'Grosso' attracted 76.9% bumblebees (*Bombus* spp.), 22.4% flies (Diptera) and 0.7% butterflies (Lepidoptera), which did not change with differing patch sizes (Garbuzov *et al.*, 2015).

These aromatic shrubby herbs are also quite low-maintenance in comparison to some alternatives, alleviating a common grower concern of non-crop vegetation management. Furthermore, growers can simply plant them from pots when an orchard is established and the typical lifespan of lavender matches that of the orchard, roughly 20 years in temperate climates. This permanency offers stability to the system and some growers might prefer these longer-term perennial plantings to annuals (Chapter 1, Section 1.8). Furthermore, lavender and thyme both have volatile constituents that are used for a variety of applications, as flavouring agents and in the pharmaceutical industry (Lubbe and Verpoorte, 2011; Nabavi *et al.*, 2015). Lavender and thyme oil also have antibacterial properties (Sienkiewicz *et al.*, 2011). Lavender oil is also commonly used in fragrance and aromatherapy, with widespread use in perfumes, toiletries and cosmetics. The lavender species usually used as remedies are typically *Lavadula angustifolia* (English lavender), *Lavandula stoechas* (French lavender) and *Lavandula latifolia* (spike lavender); however, the cultivated hybrid *Lavandula x intermedia* can produce more essential oil from its flowers than the traditional English Lavender (Gul *et al.*, 2015). These additional properties offer the potential for growers to utilise these plants for alternative commercial purposes if they were grown appropriately and on a large enough scale.

This short-term study took place in the few years during and after floral resource establishment. A longer-term study will therefore be needed to see if the effects on wild bee visitation rates to apple are sustained and increase year on year. Future studies that are able to replicate orchards at a larger scale with more spatial independence from each other are also required to corroborate the findings and assess if these floral orchard edge treatments concentrate or export pollinators into crops.

With agriculture today moving towards intensification, heavy reliance on one pollinator species, such as the managed European honeybee, could result in a vulnerable system and therefore threaten global food security. The potential pollination service delivery could therefore be compensated for by an increase in the pollination services from native/wild pollinator species (Rader et al. 2013). The stability of pollinator populations is very important financially (Gallai *et al.*, 2009). Ensuring that there are adequate pollination services for crop plants is essential; the human population is predicted to rise to 9.8 billion by 2050 (United Nations, 2017) which will increase the need for agriculture to provide larger yields from the land available to feed the growing population (as outlined in Chapter 1). However, the recent global decline of both managed and wild pollinators (Biesmeijer *et al.*, 2006; Potts *et al.*, 2010b) threatens to leave pollinator-dependent crops with a pollination deficit. One of the drivers for this decline of pollinators is the loss of habitat and the reduction of floral resources (Biesmeijer *et al.*, 2006). This study adds to the existing evidence that small-scale local habitat and foraging changes can maintain and enhance wild pollinator abundance and pollination services in adjacent agricultural crops (Benjamin *et al.*, 2014; Morandin *et al.*, 2016). It is especially important to conserve bees because the loss of wild pollinators in some parts of the world have resulted in a reliance on hand pollination for apple and pear production (Goulson, 2012).

2.5.1 Conclusion

It is of key importance to ensure that intensive commercial apple-growing systems can support the necessary populations of wild pollinators to achieve the pollination service requirement for optimum fruit set and quality (see Chapter 4). One way that apple growers can do this is to ensure that their orchards have adequate successive floral resources nearby, which are often lacking in commercial orchards (Chapter 1), to support these beneficial species throughout the year. Although growers should continue to support healthy honeybee hives, to ensure the stability of the pollination service, they could also provide floral resources to sustain wild pollinator populations in these otherwise intensive agricultural landscapes. This study shows that lavender and thyme, when planted together, are a novel alternative floral resource provision to sown wildflower strips at the orchard edge, providing a late season floral resource to pollinators after the mass blooming of crops such as apple. This is especially valuable for wild bees such as bumblebees. Provision of this late season floral resource could be responsible for the increase in the wild bee visitation rate to apple flowers observed in orchards that have a mixed lavender and thyme edge treatment. This effect might be more pronounced in some dessert apple cultivars (Braeburn) over others (Gala) however, further research is needed to understand how such floral resources affect the pollinator populations in orchards of different apple cultivars.

Chapter 3 The effects of planting aromatic herbs along apple orchard edges on pest control services

3.1 Abstract

Building on the work in Chapters 1 and 2, this chapter examines how planting the perennial aromatic shrubby herbs, lavender (*Lavandula x intermedia* 'Sussex') and thyme (*Thymus vulgaris*), at the orchard edge in apple orchards affects natural enemy populations within the apple trees. These floral resources could potentially sustain and enhance specific natural enemies with an aerial life stage that relies on pollen or nectar. However, to control apple pest populations using biological control there must be a diverse community of natural enemies present, including both parasitoids and generalist predators such as spiders and earwigs. Not all of these different natural enemy populations would benefit from floral resources and worryingly there is a risk that these aromatic herbs could instead repel them. I found that one year after establishment, there was a higher abundance of total invertebrates, as well as earwigs in orchards with a lavender orchard edge treatment. However, the effect was dependent on sampling technique. I discuss the time it takes for natural enemy populations to be affected by habitat enhancement and the potential influence of agrochemicals on these beneficial invertebrate populations.

3.2 Introduction

Invertebrate pests are responsible for extensive global crop losses (Oerke, 2006). Apples, an important fruit globally (FAO, 2016), are vulnerable to many invertebrate pest species which can hamper the crop in terms of yield and quality (Simon et al., 2010). Pest control in intensive orchard systems currently relies on chemical input in the form of pesticides and fungicides. Unsprayed orchards can result in an average of 50% of the crop lost, therefore European apple orchards are typically sprayed with at least 5 insecticide applications annually (Cross *et al.*, 2015). This agrochemical application is expensive due to the multiple products included in the spray mix, as well as the cost of labour, fuel and the depreciation of mechanical vehicles used to spread these products (Cross *et al.*, 2015). Heavy use of chemical control also raises ecological concerns over the possible effects on non-target beneficial invertebrate species in these orchard systems (Fountain and Harris, 2015) and the potential of increasing pest resistance.

Furthermore, there are concerns surrounding pesticide use and the human consumption of fruit. A large number of pesticide residues are found on apples, however, these are rarely above the maximum recommended limit (MRL). The MRL is the highest tolerated level of a pesticide residue on an apple following the legal application of that specific pesticide to the crop. In 2017, although there were no pesticides found on apples that were above the MRL, of the 97 samples tested that year, 78 had pesticide residues at or below the MRL and 62 of these samples had more than one pesticide residue (Expert Committee on Pesticide Residues in Food (PRiF), 2017).

To improve the sustainability of this fruit production system, conventional commercial orchards now all utilise a degree of integrated pest management (IPM) practices (see Chapter 1, Section 1.8). One of the ways that orchards can become more sustainable is by protecting and enhancing populations of natural enemies. These natural enemies provide a biological control service that can help to keep the pest populations below the economic thresholds (as outlined in Chapter 1, Section 1.4). Pest control services offer a sustainable alternative to the heavy reliance on chemical control in orchards that is prevalent across Europe (Cross et al., 2015).

However, the intensification of agriculture has led to large monoculture crop systems and landscape simplification that has reduced the habitat, refuge and resources available for natural enemies (Tscharntke *et al.*, 2005). Therefore, in order to encourage biological pest control services in intensive agro-ecosystems, farmers will have to sustain and enhance the non-crop habitats that are required to provide natural enemies with refuge and resources in close vicinity to the crop (Tscharntke *et al.*, 2005). This is 'habitat management', a form of conservation biological control (see definition in Section 1.4). Habitat management aims to provide natural enemies with floral resources (pollen and nectar), overwintering shelter and refuge from pesticides (Landis *et al.*, 2000; Gurr *et al.*, 2017). However, to achieve the current level of apple production in the UK today, orchard growing systems have intensified over time, limiting the available space for natural enemy refuge and resources to orchard perimeters.

One method to achieve this is by local restoration of hedgerows on farms. Hedgerows support a high diversity and abundance of natural enemies, such as predatory ladybirds, parasitoids and hoverflies (Haenke *et al.*, 2014; Morandin *et al.*, 2014). These beneficial invertebrates can spill over into the entire crop field if sufficient hedgerows surround it, showing a clear economic return from hedgerow restoration via fewer pesticide applications (Morandin and Kremen, 2013; Morandin *et al.*, 2014). However, farmers have voiced concerns about the time planted trees take to establish and mature (Brodt *et al.*, 2009). Indeed, hedgerows can take 5-10 years to influence some natural enemy populations and over 50 years to achieve an even distribution of predator abundance (Burgio *et al.*, 2006). Therefore, an alternative, or indeed complementary implementation to hedgerows, is non-arboreal floral resource provision.

Floral resources in intensive agricultural landscapes could aid biological control; studies have shown that natural enemies (such as parasitic wasps, spiders and hoverflies) prefer floral resources over mown grass edges (Blaauw and Isaacs, 2012). It is not necessarily the increased plant diversity that attracts these natural enemies to wildflower strips but more likely the presence of specific attractive species within the wildflower mixes (Wäckers and van Rijn, 2012; Hatt *et al.*, 2017). Indeed Fiedler *et al.* (2008) note that four specific plant species are often focused on in natural enemy habitat management experiments: *Phacelia tanacetifolia* (phacelia), *Fagopyrum esculentum* (buckwheat), *Lobularia maritima* (sweet alyssum) and *Coriandrum sativum* (coriander).

More recently, a further study on sweet alyssum in apple orchards showed that generalist predator presence increased nearer the plants as did the suppression of aphid pests (Gontijo *et al.*, 2013). In this way, targeted floral resources within the agri-environment have been shown to be an ideal measure to enhance predators and parasitoids in situ both before and during aphid infestation (Ramsden *et al.*, 2015). This beneficial effect is because some natural enemies of pest populations are also nectar or pollen feeders at some stage of their lifecycle, such as lacewings, hoverflies (Diptera: Syphidae) and ladybirds (Venzon *et al.*, 2006; van Rijn *et al.*, 2013). Therefore, these specific natural enemy communities rely on the provision of floral resources to support their delivery of effective biological control to crops (van Rijn *et al.*, 2013).

However, despite the specific attractiveness of some plant species to natural enemies, others could instead have repellent properties. For example, there is the risk that plants chosen to specifically attract other beneficial invertebrates, such as pollinators, might have repellent effects on natural enemies due to their aromatic nature. Studies that consider the potential effects of floral enhancement for pollination services on pest control services often only focus on the cost as being an unwanted attractiveness to pests, or encouraging pests into crops due to their required management regimes, rather than the risk of repelling natural enemies. For example, Simon *et al.* (2010) in a review of 30 case studies on plants added to orchards, classified 5 as showing a negative effect on pest control. However, this effect on pest control in these case studies was assessed by the density of pests on fruit trees, fruit damage or the number of pesticide applications, rather than focussing on the added plant's effect on natural enemy populations. However, Wäckers (2004) found that some flowering plants species: *Erigeron annuus* (annual fleabane)*, Trifolium pratense* (red clover)*, Vicia sepium* (bush vetch) *and Achillea millefolium* (common yarrow), have repellent properties on certain parasitic wasp species.

Repellent properties of aromatic plants (such as lavender and thyme) would only be beneficial if they repel just the crop pests themselves and not their natural enemies. In this way, the essential oils of aromatic plants could have a role in the development of more environmentally friendly, safe agrochemicals. Notably for orchards fruits, lavender oil (from *L. officinalis*) has been shown in olfactometer bioassays to be effective in arresting codling moth movement upwind towards apples (Landolt *et al.*, 1999). Furthermore, both lavender (*Lavandula angustifolia*) and thyme (*Thymus vulgaris*) oils have toxic insecticidal activity, growth inhibitory activity and affect digestive enzyme activity in the elm leaf beetle pest (*Xanthogaleruca luteola*) (Khosravi and Sendi, 2013). These essential oils have also been shown to have acaricidal properties on the carmine spider mite (*Tetranychus cinnabarinus*), though thyme has a higher acaricidal activity (Sertkaya *et al.*, 2010). The volatiles of Lavender oil (extracted from *L. Angustifolia*) have also been successfully demonstrated as useful in pest control of the pollen beetle *Meligethes aeneus* in oil seed rape due to their repellent nature, both in laboratory bioassays (Mauchline *et al.*, 2005) and in field conditions of treated crop (Mauchline *et al.*, 2013). Although it is a repellent for the pest, it does not affect the behaviour of their most important hymenopterous parasitoids (Cook *et al.*, 2007).

In apple crops, both generalist and specialist natural enemies can contribute to pest control such as hoverflies, ladybirds, lacewings, parasitic wasps, spiders and earwigs (Dib *et al.*, 2010; Gontijo *et al.*, 2012; Cross *et al.*, 2015). Indeed, to control apple pest populations using biological control there must be a diverse community of natural enemies, including both parasitoids and generalist predators (Gontijo *et al.*, 2015). For example, to control the woolly apple aphid, the specialist endoparasitoid *Aphelinus mali* needs to also be found with a generalist predator (Gontijo *et al.*, 2015). These generalist predators include invertebrates such as spiders, aphidophagous hoverflies, earwigs and predatory bugs (Gontijo *et al.*, 2012). Considering that a diverse community of natural enemies is required to control apple pests, we must consider how non-crop floral resources, such as lavender and thyme, might affect these different natural enemy groups.

Building on the evidence in favour of lavender and thyme in apple orchards (as outlined for pollinators in Chapter 2), these plants could potentially provide useful resources for some natural enemies and therefore could provide ‘stacked ecosystem services’ to the orchard growing system (Fiedler *et al.*, 2008). However, this would only be the case for specific natural enemies that have an aerial life stage which relies on pollen or nectar resources. Whereas, many of the important natural enemies in apple orchards will not benefit from floral resources due to a lack of aerial life stage that relies on pollen or nectar, such as spiders that feed mainly on insects (Cross et al., 2015). Consequently, lavender and thyme may have an undesired negative effect due to their aromatic properties repelling these natural enemies.

It is therefore important to not only consider the potential positive effects on natural enemies, but rather to assess the negative effects of these aromatic shrubby herbs on beneficial invertebrates that are natural enemies. In this chapter, I aimed to assess whether lavender and thyme orchard edge treatments in dessert apple orchards would result in a higher or lower number of invertebrates and natural enemies in the apple trees themselves.

3.3 Methods

3.3.1 Experimental set-up

After apple blossom, at the end of May/beginning of June 2016, 300 lavender (*Lavandula x intermedia 'Sussex'*) (2L pot) and 300 thyme (*Thymus vulgaris*) (1.5L pot) plants were planted in 30 m strips, along the orchard perimeter. Orchards had one of four orchard edge treatments: 'mixed' of alternating lavender and thyme (n = 5), lavender (n = 5), thyme (n = 5), neither (i.e. control) (n = 5).

Please refer to Chapter 2 for full details of the study area, orchards and experimental set-up.

3.3.2 Sampling methods

To investigate if the lavender and thyme plants can attract natural enemies after apple flower bloom, I carried out beat-tray sampling and double-sided yellow sticky trapping of invertebrates in all orchards during the period after apple blossom until apple harvest, once a month in June, July and August in both 2016 and 2017.

In each orchard, I conducted beat-tray sampling on apple trees at four distances (approximately: 5 m, 15 m, 30 m and 50 m) along a central apple row perpendicular to the orchard edge treatment. I sampled all orchards between 10:00 and 16:30 h on days of ambient sampling conditions (no more than light wind or rain and at least 12^{o}C). I sampled four branches on each tree with a beating tray using a 'tap' technique. Any invertebrates collected were counted and identified to order.

In addition to beat-tray sampling, I sampled invertebrates using double-sided yellow sticky traps (10 cm x 10.5 cm; Fargro, Vinery Fields, Arundel Road, Arundel, West Sussex, UK). The size of the sticky trap used in June 2016 was larger (10 cm x 24 cm) than those used in other months. Traps were hung from apple tree branches, on different apple trees to the beat-tray samples, (approximately 1m above ground level) facing the same orientation at each of the four distances (approximately: 5 m, 15 m, 30 m, 50 m) away from the orchard edge. A total of 80 traps were set-up across all orchards each month; and the total sampling effort was therefore 240 traps across all orchards for each year. I collected the traps after 7 days and wrapped each in a clear plastic wallet to be frozen at -30^{o}C on the same day of collection. All invertebrate individuals over 5 mm collected on each trap were counted to obtain the total abundance per trap and identified to order. Note that to minimise the disturbance to pollinator abundances sampled by the monthly pollinator transects (in Chapter 2), the sticky traps were set-up after the pollinator transects had been carried out each month.

3.3.3 Statistical analysis

3.3.3.1 Beat-trays

To determine the effect of orchard edge treatment on the abundance of invertebrates from beat-tray sampling, I used the package 'glmmADMB' in R (R Core Team, 2015) to apply generalised linear mixed models (GLMMs) (log-link function) with negative binomial distributions (as the models could not be fitted with Poisson distributions due to over dispersion of the count data) for each of the response variables. The response variables were: natural enemy order richness, total invertebrate abundance, total number of "beneficial individuals" (natural enemies) consisting of earwigs, ladybirds, lacewings, hoverflies, spiders and parasitic wasps), and total abundance of beneficial groups that had sufficient data for statistical analysis – earwigs, spiders, lacewings, and ladybirds. Two beneficial groups – hoverflies and parasitic wasps – had insufficient data to be analysed separately. Due to sample size, I pooled the data across the four distances for analysis. The fixed factors of these analyses were treatment (4 levels: Control, Lavender, Thyme, Mixed) and sampling month (3 levels: June, July, August) and the interaction between treatment and month. To account for the hierarchical experimental design and the repeated measures, orchard was included as a random effect. Model assumptions were checked visually by assessing residual plots. Data from the year of orchard edge treatment establishment (2016) and the following year after treatment (2017) were analysed separately to check for variations in the results from both years. The minimum adequate models were selected based on the significance of fixed effects as determined from anova comparisons of models to their null. Post-hoc Tukey tests were carried out on the minimum adequate models that had significant fixed effects ($p < 0.05$) from likelihood ratio tests (LRTs), using the package lsmeans in R with a P-value < 0.05 as the threshold for significance.

3.3.3.2 Sticky traps

To determine the effects of orchard edge treatment on the abundance of invertebrates on sticky traps, I analysed the data from 2016 and 2017 separately using the same approach, i.e. applying GLMMs (log-link function) with negative binomial distributions, for the response variables: natural enemy order richness, total number of invertebrates over 5 mm, total abundance of beneficial individuals, and abundance of beneficial groups which had sufficient data for statistical analysis – earwigs, spiders and lacewings. Three beneficial groups – ladybirds, hoverflies and parasitic wasps – had insufficient data to be analysed separately. Due to sample size, I pooled the data across the four distances for analysis. I included orchard as a random effect in all models, and both treatment and sampling month as fixed factors and the interaction between treatment and month. Data collected from June 2016 were excluded and analysed separately, with just treatment as a fixed factor, due to the difference in size of the sticky traps used. Again, model assumptions were checked by assessing residual plots. Post-hoc Tukey tests were carried out on the minimum adequate models that had significant fixed effects ($p < 0.05$) from likelihood ratio tests (LRTs), using the package lsmeans in R with a P-value < 0.05 as the threshold for significance.

3.4 Results

A total of 1972 natural enemies were found over the two years (Table 3.1), accounting for 30% of the total number of invertebrates over 5mm collected (n = 6590).

Combining the surveys from both sampling methods, I found 679 beneficial natural enemies in the apple trees in 2016 (36% of the 1867 invertebrates found in 2016). The beneficial invertebrates were composed of 49.9% earwigs (n = 339), 2.8% ladybirds (n = 19), 38.8% spiders (n = 260), 1.8% lacewings (n = 12), 4.6% ichneumons (n = 31) and 2.7% hoverflies (n = 18).

In 2017, 1293 natural enemies were found (27% of the 4723 invertebrates found in 2016). The beneficial invertebrates were composed of 61.4% earwigs (n = 794), 1.2% ladybirds (n = 15), 27.9% spiders (n = 361), 2.5% lacewings (n = 32), 6.5% ichneumon (n = 84), 0.5% hoverflies (n = 7).

Table 3.1 Number and percentage of natural enemies pooled over the two years from the different sampling methods

	Beat-tray (% of natural enemies from this method)	**Sticky trap** (% of natural enemies from this method)
Earwig	462 (54.5)	671 (59.7)
Spider	338 (39.9)	283 (25.2)
Ladybird	16 (1.9)	18 (1.6)
Lacewing	30 (3.5)	14 (1.2)
Parasitic Wasp	1 (0.1)	114 (10.1)
Hoverfly	1 (0.1)	24 (2.1)

A chi-square test, based on a contingency table with total abundances of the six natural enemy groups captured by the two different methods confirmed differences in the number of each beneficial group captured by the two methods (X^2 = 145.78, d.f. = 5, p < 0·001), therefore results are presented separately for each method.

There was no significant effect of treatment, month or their interaction on richness of natural enemy groups found in the orchards in 2016 or 2017, by beat-tray or sticky traps (Table 3.2)

Table 3.2 Results from GLMM analyses of natural enemy group richness for the beat-tray sampling (BT) and sticky trap sampling (ST) in 2016 and in 2017; chi-square values from likelihood ratio tests are shown for all explanatory variables, treatment (T; control, lavender, thyme, mixed); month (M; June, July, August); and the interaction between treatment and month (T x M), included in the models tested.

	2016									**2017**				
	BT			ST (June)			ST (July & August)			BT			ST	
	d.f.	X^2	*p*	*d.f.*	X^2	*p*	*d.f.*	X^2	*p*	*d.f.*	X^2	*p*	X^2	*p*
Treatment	3	0.68	0.878	3	1.50	0.683	3	0.44	0.932	3	0.87	0.833	1.02	0.796
Month	2	0.84	0.659	n/a	n/a	n/a	2	0.05	0.825	2	1.69	0.429	0.45	0.799
T x M	6	1.65	0.949	n/a	n/a	n/a	3	0.965	0.810	6	0.68	0.995	0.70	0.995

3.4.1 Beat-tray surveys

Eight invertebrate orders of individuals were observed in the orchards overall from beat-tray sampling. These included: Diptera (1.7%, n = 19), Lepidoptera (0.1%, n = 11), Dermaptera (42.3%, n = 462), Hymenoptera (8.2%, n = 90), Araneae (31%, n = 338), Neuroptera (2.7%, n = 30), Coleoptera (6%, n = 66), and Hemiptera (3.9%, n = 43). Some individuals were unidentified (2.9%, n = 32). A total of 848 natural enemies were found over the two years (Table 3.1), accounting for 78% of the total number of invertebrates collected by this method (n = 1091).

In the same year as orchard edge treatment establishment (2016), there were no treatment effects and no significant interactions between treatment and sampling month for any of the invertebrate response variables tested (Table 3.3; Figure 3.1a,c,e,g). In the following year (2017), there was a significant treatment effect for total pooled invertebrate abundance; pairwise comparisons showed that orchards with a lavender edge had a significantly higher abundance than the orchards with a control edge (Table 3.3; Figure 3.1b). In (2017), there was also a significant treatment effect for earwig abundance; pairwise comparisons showed that orchards with a lavender edge had a significantly higher abundance than the orchards with a control edge (Table 3.3; Figure 3.1f).

Table 3.3 Results from GLMM analyses of invertebrate abundances from beat-tray sampling in 2016 and in 2017; chi-square values (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$) from likelihood ratio tests are shown for all explanatory variables included in the models tested. Effects of treatment (T; control, lavender, thyme, mixed) and month (M; June, July August), and the interaction between treatment and month (T x M). The models that failed to converge in are shown by 'FTC'

	Treatment (T)	Month (M)	T x M
D.F	3	2	6
2016			
Total Invertebrates Sampled	3.60	0.53	11.97
Total Beneficials Pooled	2.41	2.30	10.9
Earwigs	7.62	3.58	10.12
Spiders	4.42	4.32	11.60
Lacewings	1.21	FTC	FTC
Ladybirds	3.44	FTC	FTC
2017			
Total Invertebrates Sampled	**8.50***	**6.60***	3.31
Total Beneficials Pooled	9.54	**11.4****	10.58
Earwigs	**8.68***	**17.05*****	8.04
Spiders	3.12	**7.00***	9.58
Lacewings	2.2	FTC	FTC
Ladybirds	1.70	**23.90*****	FTC

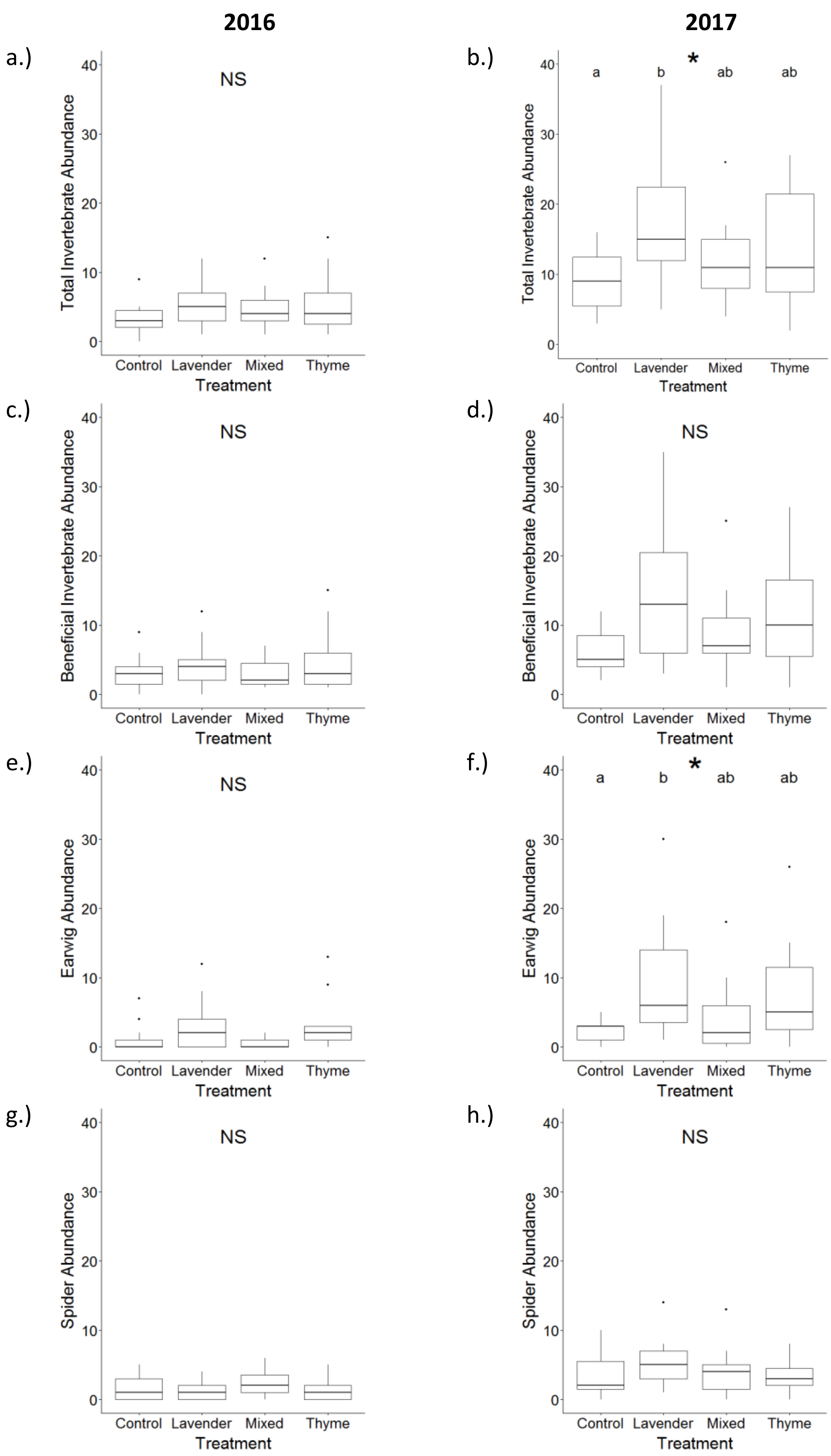


Figure 3.1 The effect of orchard edge treatment on invertebrate abundance in apple trees from beat-tray sampling in 2016 and in 2017; (NS = $p > 0.05$, * = $p < 0.05$) reported in LRTs from GLMMS (see Table 3.3 for details). Different letters illustrate a significant difference found by the Tukey post-hoc multiple comparison tests ($p < 0.05$) and the same letters indicate no significant difference

3.4.2 Sticky trap results

13 invertebrate orders of individuals over 5 mm were observed in the orchards from the sticky trap sampling (14 including invertebrates under 5 mm). These included: Diptera, Lepidoptera, Odonta, Dermaptera, Hymenoptera, Araneae, Neuroptera, Coleoptera, Ephemeroptera, Plecoptera, Mecoptera, Rappidioptera, Hemiptera, (and Thysanoptera, < 5 mm). A total of 1124 natural enemies were found over the two years (Table 3.1), accounting for 20% of the total number of invertebrates over 5 mm collected by this method (n = 5499). The other most abundant invertebrates on the sticky traps were ants (n = 1786), solitary bees (n = 588), flies (n = 549) and wasps (n = 259).

For June 2016, there was a significant treatment effect for earwig abundance in apple orchards (Table 3.4; Figure 3.2); however, the post-hoc Tukey test did not detect any significant differences for all pairwise comparisons ($p > 0.05$).

Table 3.4 Results from GLMM analyses of invertebrate abundances on sticky traps in June 2016; chi-square values (* = $p < 0.05$) from likelihood ratio tests are displayed; d.f. = 3.

	Treatment (T)
Total Invertebrates Sampled (> 5 mm)	2.87
Total Beneficials Pooled	5.62
Earwigs	**8.43***
Spiders	4.13

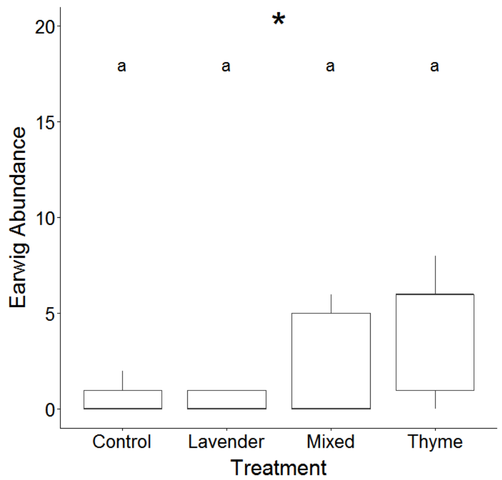


Figure 3.2 The effect of orchard edge treatment on earwig abundance from sticky trap sampling in June 2016

For July and August in the same year as orchard edge treatment establishment (2016), there was a significant interaction of treatment and month (Table 3.5) for total abundance of invertebrates over 5 mm; only the abundances in control orchards differed between July and August (Figure 3.3a). There were no significant effects of treatment alone for any of the other response variables tested (Table 3.5; Figure 3.3b,c).

In the second year of orchard edge treatment establishment (2017), there was only a significant interaction of treatment and month (Table 3.6) for pooled beneficials (Figure 3.4); however the post-hoc Tukey tests did not find any significant differences ($p > 0.05$) for all pairwise comparisons.

Table 3.5 Results from GLMM analyses of invertebrate abundances on sticky traps in July and August 2016; chi- square values (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$) from likelihood ratio tests are shown for all explanatory variables included in the models tested. Effects of treatment (T; control, lavender, thyme, mixed) and month (M; July, August), and the interaction between treatment and month (T x M). The models that failed to converge in are shown by 'FTC'

	Treatment (T)	Month (M)	T x M
D.F	3	1	3
2016			
Total Invertebrates Sampled (> 5 mm)	0.79	2.29	**11.83****
Total Beneficials Pooled	2.17	2.16	6.16
Earwigs	3.49	0.77	6.44
Spiders	FTC	0.64	FTC
Lacewings	FTC	0	FTC

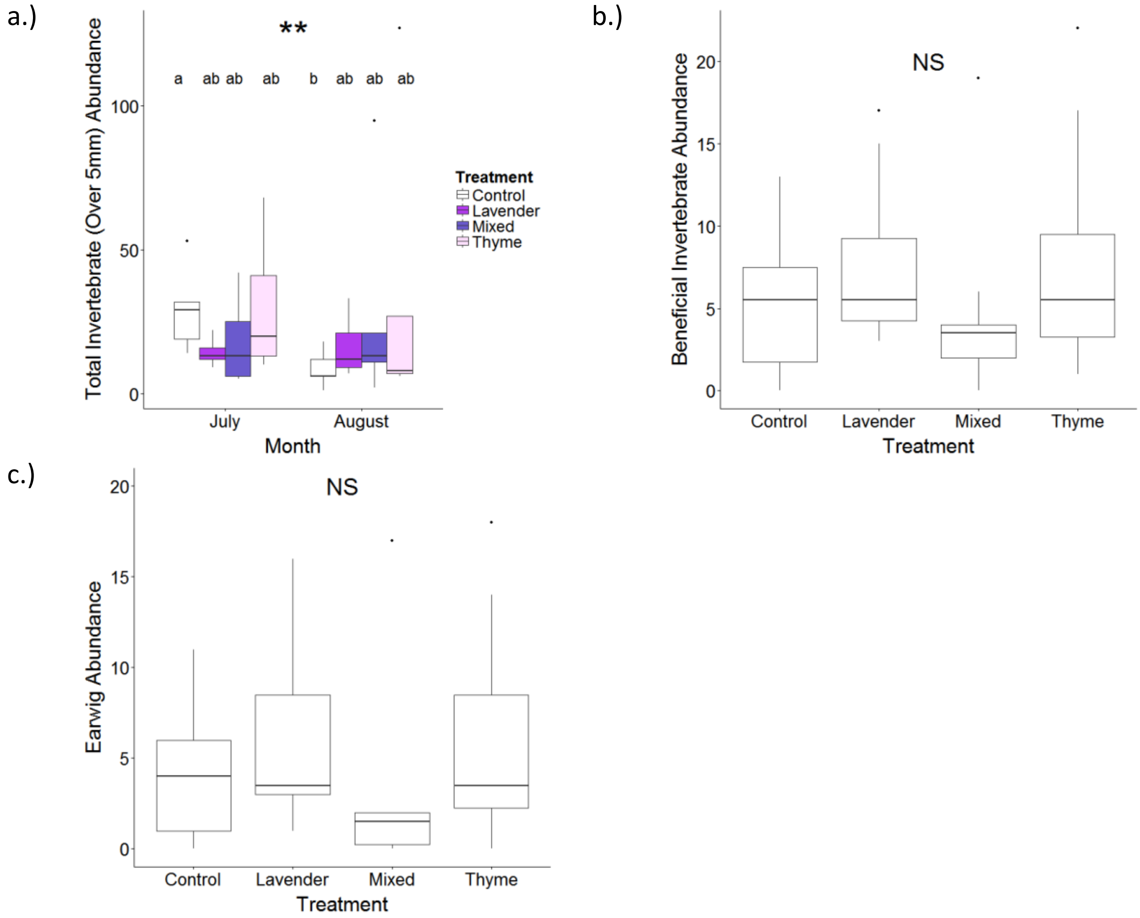


Figure 3.3 The effect of orchard edge treatment on invertebrate abundance in apple trees from sticky trap sampling in July and August 2016; (NS = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$) reported in LRTs from GLMMS (see Table 3.5 for details).

Table 3.6 Results from GLMM analyses of invertebrate abundances on sticky traps in 2017; chi-square values (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$) from likelihood ratio tests are shown for all explanatory variables included in the models tested. Effects of treatment (T; control, lavender, thyme, mixed) and month (M; June, July August), and the interaction between treatment and month (T x M). The models that failed to converge in are shown by 'FTC'

	Treatment (T)	Month (M)	T x M
D.F	3	2	6
2017			
Total Invertebrates Sampled (> 5 mm)	4.19	**27.57*** **	8.54
Total Beneficials Pooled	2.12	2.94	**13.90***
Earwigs	3.06	**6.716***	7.02
Spiders	6.31	**10.95****	10.64
Lacewings	1.28	FTC	FTC

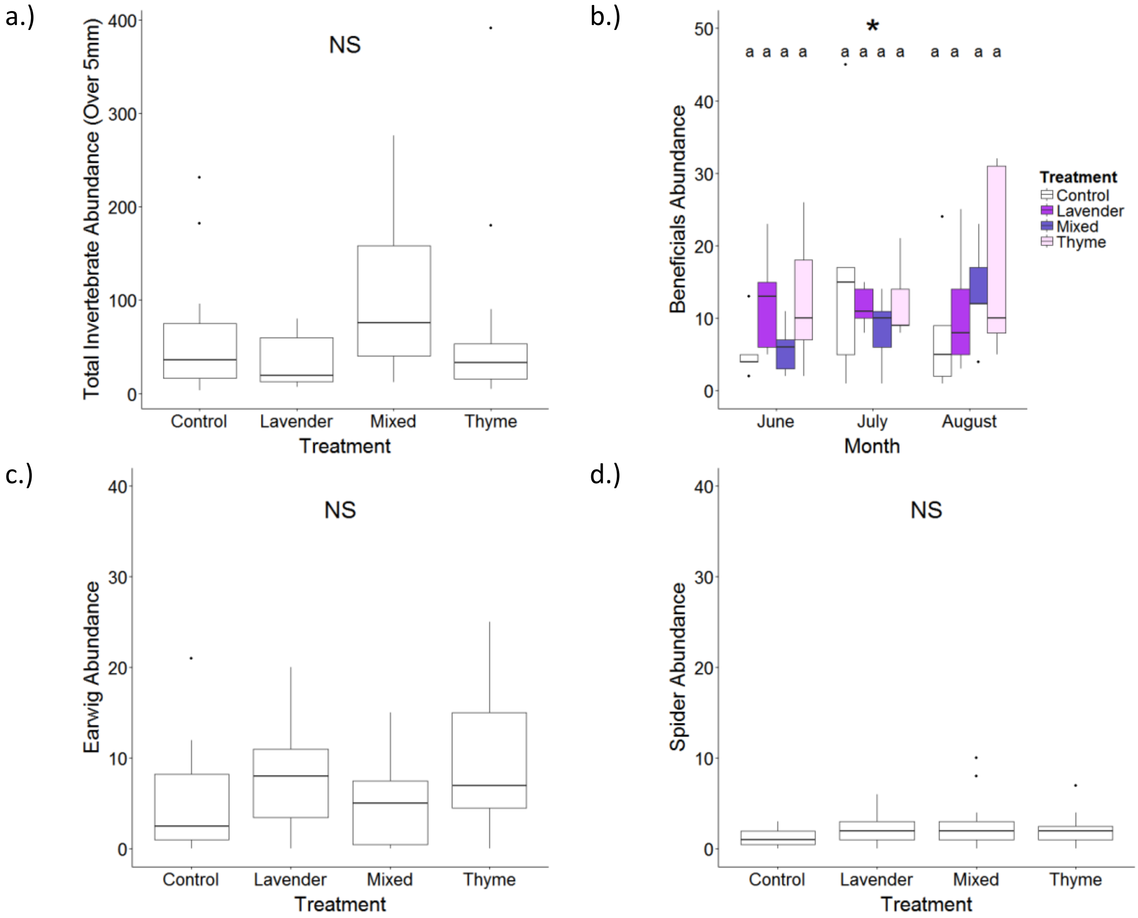


Figure 3.4 The effect of orchard edge treatment on invertebrate abundance in apple trees from sticky trap sampling in 2017; (NS = $p > 0.05$, * = $p < 0.05$) reported in LRTs from GLMMS (see Table 3.6 for details)

3.5 Discussion

In 2017, a year after the establishment of orchard edge treatments, the total pooled invertebrate abundance and earwig abundance was higher in the orchards with a lavender orchard edge treatment compared to the control orchards from the beat-tray tap sampling. However, the sticky traps did not detect this effect. The sticky trap sampling instead indicated that there was an effect of treatment and sampling month for all natural enemies pooled but this finding was not explained with post-hoc multiple comparisons. Overall, there was no effect, be it positive or negative, of orchard edge treatment on the richness of natural enemy groups found in the apple trees. Methodology considerations and possible explanations for the findings are discussed below.

Earwigs and spiders were two of the most abundant natural enemies found in the orchards but overall, the effect of the orchard edge treatment on the abundance of natural enemy groups was not consistent across the sampling techniques. Indeed, Beers *et al.* (2016) found that different sampling methods might attract specific natural enemies. Beat-tray tap samples might be better at assessing a broader range of natural enemies on the crop trees but they are likely to underestimate mobile adults (such as hoverflies, ladybirds, lacewings and parasitic wasps) and might under-represent adults with nocturnal behaviour (earwigs) (Beers *et al.*, 2016). Blaauw and Isaacs (2015) also found that natural enemy abundances differed between sampling methods used due to the greater efficiency of some sampling methods, depending on the groundcover and functional diversity of natural enemies. For example, vacuum sampling is appropriate for short vegetation but might miss ground dwelling arthropods. Vacuum sampling was not used in this study but could have been incorporated in order to further understand natural enemy abundances.

Although the beat-tray and sticky trap methods used in this chapter did not collect enough hoverflies for an individual analysis, there was a higher abundance of aerial hoverflies over the summer months in orchards with a mixed lavender and thyme orchard edge treatment (see Chapter 2). Hoverflies are thought to contribute less to apples than bee pollinators (Garratt *et al.*, 2016), however, this increased hoverfly abundance could potentially result in increased pest control services if there was an increase in aphidophagous hoverflies. Adult aphidophagous hoverfly species, (e.g. Diptera: Syrphidae) require nectar and pollen floral resources as well as aphid prey; when floral resources are present in non-crop vegetation, it facilitates these hoverfly populations to suppress aphid pests on crops as the floral resources increase hoverfly fecundity (van Rijn *et al.*, 2013), and therefore increase the abundance of their zoophagous larvae.

Floral resources must be accessible for hoverfly feeding if they are to be of benefit (van Rijn and Wäckers, 2016) and hoverflies have previously been observed foraging on the variety of lavender (*Lavandula x intermedia '*Sussex') used in this study (Garbuzov and Ratnieks, 2014b). However, as hoverflies were not determined to species level here, or in Chapter 2, it cannot be determined if there was a specific increase in the abundance of zoophagous hoverflies. It is possible that the abundance increases in Chapter 2 were attributed to non- aphidophagous hoverflies such as the common *Eristalis* spp., which although could provide pollination services, cannot be considered a natural enemy as their larvae are saprophytic. Therefore, the effect of lavender and thyme on the specific hoverflies that could provide pest control services in these orchards remains unknown.

More research is also required to understand the variation in earwig populations in orchards and future work would need to uncover exactly why there were more earwigs observed from the beat-tray sampling in 2017 in the orchards with a lavender orchard edge treatment compared to the control orchard edge treatment. It would be interesting to carry out laboratory experiments to uncover if their nocturnal feeding behaviour extends to lavender and thyme flowers. Furthermore, to determine the exact attractant/repellent qualities of lavender and thyme to these, and the other, natural enemies in apple orchards, laboratory and greenhouse experiments would need to be conducted with lavender and thyme volatiles and whole plants respectively.

Other than the potential repellent properties of floral resources in non-crop vegetation, there are other significant challenges to protecting and encouraging these natural enemies into orchards. Agricultural practices in commercial orchard systems may themselves hamper the possibility of establishing bountiful natural enemy communities (Tscharntke *et al.*, 2016; Campbell *et al.*, 2017a) due to the chemical input that is often used to ensure there is no risk of pest populations detrimentally affecting the crop quality. Spiders are an abundant generalist predatory arthropod in apple orchards and feed mainly on insects (Cross *et al.*, 2015), yet spider populations could be adversely affected by broad spectrum insecticide treatments through short-term toxicity as well as prey reduction which is especially detrimental to adult female spiders (Marko *et al.*, 2009). Earwigs are also voracious predators of many apple pests (Cross *et al.*, 2015) such as the woolly aphid (Nicholas *et al.*, 2005). Healthy populations of earwigs on apple trees can provide a first level of defence against this pest and if earwig abundance is greater than 14 per tree during the first 7 weeks post-apple blossom then chemical insecticides may not be required (Quarrell *et al.*, 2017). However, earwigs are also affected by agrochemical sprays (Fountain and Harris, 2015).

Indeed Malone *et al.* (2018) found that differences between invertebrates in orchards are determined by agrochemical input. Others have found that a major difficulty in showing hedgerow effects within orchards is that modern agricultural practices include the use of insecticides that dramatically alter populations. This is because surrounding orchard hedges are susceptible to the treatments via insecticide drift, therefore, their populations of beneficial insects may be affected accordingly (Forman and Baudry, 1984; Debras *et al.*, 2006; Maalouly *et al.*, 2013; Monteiro *et al.*, 2013). The orchard edge treatments in this study could therefore have been subjected to agrochemical spray drift in this way and as all the orchards were all under the same management regime; it is therefore not surprising that there are few differences between the orchards, even with different orchard edge treatments. The negative (repellent) effects of lavender and thyme, or the potential positive effects for some specific natural enemies, may therefore have been masked by the dominant effect of agrochemical use within these orchard plots.

It might, therefore, be useful to explore how lavender and thyme plants affect natural enemy populations in orchards with differing pesticide regimes or in commercial organic orchards. Alternatively, to understand the effects on natural enemies, the floral resource provision may need to be external to the cropping area, and thus the agrochemical use. For example, Blaauw and Isaacs (2015) successfully enhanced natural enemy abundance in highbush blueberry fields by establishing wildflowers on adjacent land. As wildflowers were separate to the cropland where insecticide use could affect natural enemy populations, these wildflowers may have provided essential refuge from agrochemical sprays. However, it could be that these wildflowers are more beneficial to natural enemies than lavender and thyme as they lack repellent effects. For example, open nectar plants in wildflower strips have been shown to increase natural enemy densities on apple trees (Campbell *et al.*, 2017a). Likewise, in potato crops, Tschumi *et al.* (2016) found that hoverfly, lacewing and ladybird abundances were enhanced in adjacent tailored wildflower strips, increasing egg deposition and reducing aphids.

However, it is often difficult to ascertain if selected plants implemented in orchards contribute to pest control; they will not always have a clear positive or negative effect. For example, Simon *et al.,* (2010) found that in their review of 30 case studies on plants added to orchards; nearly a third (9) showed a neutral (null) effect on pest control. Many other factors such as floral timing need to be considered because regardless of the effects on natural enemies, the control of pests like the apple blossom weevil which emerges early in the year, may be unaffected by late season floral resources.

The variability in the results and lack of consistent effects on natural enemy abundance may also have been because there was an insufficient quantity of lavender and thyme in order to provide enough resources to affect natural enemy populations (be it negatively or positively). On the other hand, the effects might only be noticeable at very small distances away from the plant. For example, a study using intercropping of rosemary in sweet pepper plants to curtail aphid performance showed that rosemary was effective at only 0.5-2.5 m away from the plant itself (Ben Issa *et al.*, 2017).

Future work should consider a longer-term study on a larger spatial scale in order to ascertain whether using lavender and thyme in apple orchard perimeters is beneficial or detrimental to natural enemies in orchards. For example, providing floral resources to a simple, agriculturally intensive landscape might mean there is a time lag for any positive changes to natural enemy abundance to be seen, until their populations build up (Tscharntke *et al.*, 2005). My sampling was immediately after orchard edge treatment establishment as well as one year afterwards; thus, there may not have been enough time since establishment to see the effects on the natural enemy abundances within the orchards. For example, it took 5 years in Quebec apple orchards, that went insecticide free, for selective planting to more than double beneficial insect populations and result in a fruit harvest over 90% clean in quality (Bostanian *et al.*, 2004).

As in Walton and Isaacs (2011), this study focused on abundances rather than diversity as local scale changes to immediate farm features can affect abundance but not necessarily diversity (Wyss, 1996). Diversity is likely to depend on landscape complexity (Tscharntke *et al.*, 2007). For example, beneficial farmland spider species richness in agro-ecosystems is influenced by landscape composition (Schmidt *et al.*, 2005). Areas of natural habitat in the landscape may therefore need to be maintained for natural enemies to provide effective pest control in orchards as pest control services are likely dependent on the wider landscape (Grab *et al.*, 2018).

3.5.1 The future of natural enemy use in pest control

In the United States, apple and pear producers are increasingly relying on natural enemies as a pest control method because of pesticide restrictions and growing pest resistance; such as that seen in codling moths due to the intensive insecticide treatment in orchards (Reyes *et al.*, 2007). Additionally, there are general public health concerns over insecticides and residues along with their possible effects on non-target species. Therefore, considering a possible future of heightened pesticide restrictions and stricter policy to protect humans and non-target species, progressively more farmers and producers may need to embrace a wide variety of natural pest control and implement agricultural practices that encourage these natural enemies before resorting to insecticide applications.

As part of this, pest thresholds may need to be adjusted; indeed recently, there has been a call for the revaluation of outdated pest thresholds in order to achieve sustainable intensification (Leather and Atanasova, 2017). Many of the current pest thresholds, defined largely by pest abundance per plant or unit area, in arable crops are not based on peer-reviewed evidence or are now outdated (Ramsden *et al.*, 2017b) and Ramsden *et al.* (2017a) specifically recommend that the abundance of natural enemies should also be a factor in determining the pest threshold for the crop.

Simon *et al.* (2010) noted that natural enemy abundance due to plant manipulation is rarely measured. Therefore, studies such as this, assessing the increase or decrease in abundance of natural enemies in the crop itself from plant manipulation could have a growing role in conservation biological control research. This, along with studies such as that from Quarrell *et al.* (2017) who estimate a threshold for the number of natural enemies needed to control pests, could help to inform growers of ways in which to obtain the necessary natural enemy thresholds to reduce reliance on agrochemical applications.

Incorporating natural enemy abundances into pest thresholds might also be of increasing importance considering that pest damage to cereal crops is likely to increase in temperate regions under global warming (Deutsch *et al.*, 2018). Understanding how warming will affect the beneficial invertebrates that provide biological control services should also be considered in future predictions of crop losses to pests. Furthermore, both natural enemy abundance and diversity should feature in an integrated management approach to mitigate these potential increases to pests in UK crops. Regarding the stability of the biological control service, it is possible that higher natural enemy diversity could help to stabilise the service. For example, it was shown that having additional parasitoid species, as well as the primary natural enemy to an apple orchard pest, temporally stabilised the biological control of the pest during changes to climate (Mody *et al.*, 2011).

3.5.2 Conclusion

Due to the ban of some insecticides and greater use restrictions, as well as public safety concerns instigating stringent maximum residue limits on fruits, orchard production systems will increasingly need to rely on alternative pest control measures. As regulation of chemical insecticide use continues, there is a need for an improved understanding of how we can protect and encourage natural enemies, that provide biological pest control services, in these intensive agro-ecosystems. This involves ensuring that any non-crop vegetation designed to protect and enhance other ecosystem services such as pollination, do not provide a biological control disservice by unintentionally repelling natural enemies.

In Chapter 2 I proposed lavender and thyme as a potential alternative to wildflower provision for enhancing pollinators at the orchard perimeter. Although aerial hoverfly abundance increased accordingly, this does not necessarily indicate an increase in biological pest control, as only aphidophagous hoverfly species would contribute to this. Although the possibility exists that floral resources may benefit some specific natural enemies, there is a risk that these same resources may negatively affect natural enemy populations in orchards through repellent effects. This study highlights that measurable effects on natural enemy populations might be limited or masked by the methods used as well as the current use of agrochemicals in these orchards. Further research is needed to identify the true effects on natural enemy groups before these shrubby aromatic herbs can be considered to have a negative, neutral or even potentially positive role in the pest control regime of these orchards.

Chapter 4 Planting aromatic herbs along apple orchard edges in order to: Increase apple fruit set and quality

4.1 Abstract

Pollination and pest control services are essential for apple production to achieve the desired yields and high quality standards of apples for retail. One way to sustain and enhance these ecosystem services is by providing the invertebrates underpinning them with successional floral resources to support their populations in these intensive agro-ecosystems. This chapter builds upon the work in Chapters 2 and 3 to assess if the orchard edge treatments of lavender and thyme plants affect apple yield or quality. Pollinator exclusion experiments demonstrated the benefits of pollinators in these dessert apple orchards; branches that were bagged to exclude pollinators during apple blossom had a lower fruit set and seed set than branches open to pollinators. The effect of pollinator exclusion on apple size was dependent on apple variety with only Gala, but not Braeburn apples decreasing in size with pollinator exclusion. There was, however, no detectable effect of the orchard edge treatments on apple fruit set or apple quality. A longer-term study may be required to determine if there is an effect on apple production because there is often a time lag before added floral resources affect crop productivity. Moreover, considering the finding from Chapter 2 that orchard edge treatments enhance wild pollinator abundances, these orchard edge treatments could potentially help to stabilise apple production via increased wild pollination service delivery. Wild bees could buffer the system in the event of inadequate managed honeybee pollination services.

4.2 Introduction

Apples are an important global fruit crop and in the United Kingdom alone over 480,000 tonnes of apples are produced each year (FAO, 2016). In order to produce good yields, apples rely on insect pollination services to ensure adequate pollen transfer from other compatible varieties (pollinisers) as they are largely self-incompatible (Ramírez and Davenport, 2013). Due to this pollination service input to apple production, apples contribute the highest percentage to Europe's economic valuation of insect pollinated crops (Leonhardt *et al.*, 2013).

As well as increases in crop yield, apple quality can be improved with these insect ecosystem services; pollinators improve apple quality in some varieties by improving the size and shape of apples, thus their classification and ultimately their economic value at market (Garratt *et al.*, 2014; Garratt *et al.*, 2016). In the apple Fuji; inadequate pollination results in misshapen fruits as a low seed number and uneven seed distribution from partial pollination cause asymmetric fruit development (Matsumoto *et al.*, 2012). The effect of low seed numbers on different quality parameters is often dependent on the apple variety. Buccheri and Di Vaio (2005) found that low seed numbers resulted in more misshapen apples of Annurca Tradizionale, Annurca Rossa del Sud, Red Delicious, and Golden Delicious but only three of these varieties had lower fruit weights and just one had lower calcium. Garratt *et al.* (2014) showed that seed number did not influence apple size in Cox apples whereas in Gala apples pollination positively affected fruit size. Therefore pollination contributes differing economic values to apple varieties when apple quality, as well as yield, is considered; pollinating insects contribute £36.7 million annually to Gala and Cox apples in the UK via improved apple yield and quality (Garratt *et al.*, 2014).

Apple 'quality' not only encompasses apple measurements such as shape and size but also includes visual properties such as colour and a smooth skin with an absence of defects or damage. These aesthetic characteristics, along with the size of apples, are economically important because they determine the fruit classification via legislative specifications in the form of the European Union (EU) Commission Implementing Regulation No 543/2011 (European Commission, 2011)**.** Additional specifications for acceptable fruit quality are also set by supermarkets, driven in part by consumer preferences for high quality fruits with an absence of visual imperfections; de Hooge *et al.* (2017) recently showed that consumers were reluctant to purchase or consume sub-optimal fruit. The result of these stringent requirements for apple visual perfection result in a loss of 5-25% of UK apples due to cosmetic grade-out (Porter *et al.*, 2018).

As well as pollination, biological pest control services can also have positive effects on apple quality; natural enemies, such as spiders, syrphid flies and earwigs (Gontijo *et al.*, 2012; Cross *et al.*, 2015) help to control a variety of apple pest species that can degrade the apple crop (Simon *et* *al.*, 2010). Biological control therefore contributes to the final marketable apple yield by reducing the proportion of apples that would not meet the quality required for sale if pests damaged them. Furthermore, the control of pest species that attack at apple blossom can add a direct benefit to initial apple fruit set; successful biological control of the apple blossom weevil would prevent the laying of eggs in apple buds, which could inhibit the flowers from setting fruits. However, whether the apple blossom weevil is a detriment, or a benefit, to crop production depends on the density of these pests, as low-density infestations could be considered an alternative to the commercial thinning practices in orchards that are often undertaken to avoid overloaded branches (Blommers, 1994).

Considering the benefits of pollination and biological control services to apple production, a way in which these orchards can become more sustainable and secure is by protecting and enhancing populations of the beneficial invertebrates that provide them. However, the intensification of orchard growing systems, much like other intensive agriculture, has simplified and degraded the semi-natural habitat left available to support biodiversity in these agricultural landscapes (Tscharntke *et al.*, 2005). Therefore, it is important in these intensive systems to make the most of the limited land that is available to provide resources and refuge for beneficial species that underpin the ecosystem services necessary for crop production.

The effects of lavender and thyme implementation on pollinators and natural pest enemies were outlined in Chapters 2 and 3. In this chapter, I aim to see if lavender and thyme plants at the edge of these dessert apple orchards result in a higher apple fruit set or an increase in the quality of apples produced at harvest. To achieve this I (1) firstly assessed if the initial or final fruit set, seed set or quality in terms of apple size (weight and maximum width) are affected by fruit variety (Braeburn or Gala) or distance from the orchard edge; (2) investigated if orchard edge treatments affect the initial or final fruit set, seed set or quality in Braeburn and Gala apples; (3) determined if pollinator exclusion affects the initial or final fruit set, seed set or quality in terms of apple size in these Braeburn and Gala orchards.

4.3 Methods

4.3.1 Experimental set-up

After apple blossom, at the end of May/beginning of June 2016, 300 lavender (*Lavandula x intermedia 'Sussex'*) (2L pot) and 300 thyme (*Thymus vulgaris*) (1.5L pot) plants were planted in 30 m strips, along the orchard perimeter. Orchards had one of four orchard edge treatments: 'mixed' of alternating lavender and thyme (n = 5), lavender (n = 5), thyme (n = 5), neither (i.e. control) (n = 7). The control orchards were reduced to 5 in 2017 and 2018 due to the removal of two orchards ready for a new planting. Furthermore, due to unforeseen orchard removal, one lavender and one thyme orchard were also excluded in 2018.

Please refer to Chapter 2 for full details of the study area, orchards and experimental set-up.

4.3.2 Apple yield

To assess the effect of apple variety and distance from the orchard edge on fruit production in 2016 (before the orchard edge treatments were established), one week prior to apple blossom I tagged two branches on two different trees (in different rows), at four distances from the orchard edge (approximately 5 m, 15 m, 30 m, 50 m) with a different coloured cable tie. A total of sixteen branches were marked in each orchard, across eight different trees.

The number of flower buds on each marked branch were counted immediately prior to apple blossom (Figure 4.1a). The number of developing fruits on these branches were then counted a month later (Figure 4.1b) before the apples were thinned according to industry practices to ensure that branches were not overloaded. A final fruit count was completed just before apple harvest (Figure 4.1c). Initial fruit set is the proportion of flowers that were successfully pollinated and turned into fruitlets on branches. Final fruit set is the proportion of those flowers that turned into apples ready for harvest at the end of the apple-growing season. Initial fruit set is therefore the best gauge of successful pollination as it is the fruit count before the commercial thinning process and before any apples are potentially lost due to pest or disease. Final fruit set is important in terms of the economic return for the grower as these are the fruits that are potentially marketable for sale.

To assess the effects of orchard edge treatment on fruit production in 2017 (one year after orchard edge treatment establishment) and 2018 (two years after orchard edge treatment establishment), the protocol was repeated however the number of tagged branches was revised. I marked one branch on five different trees (each in a different row) at each of the four distances away from the orchard edge. This gave a total of twenty marked branches per orchard, across twenty different trees. All marked branches were at roughly the same height on each tree. In 2018 (two years after orchard edge treatment establishment), only the initial fruit set was recorded.

a.)

b.)

c.)

Figure 4.1 Apple trees with branches marked using different coloured cable ties showing a.) inflorescences during apple blossom; b.) apple fruitlets formed a month later just before commercial thinning; c.) apples ready for harvest

4.3.3 Apple quality

To assess effects of the orchard edge treatment on apple quality, I picked at least one apple from each marked branch one-two weeks prior to commercial harvest in the year of establishment (2016) and repeated the protocol one year after (2017). I transported the apples in the same boxes and moulds, as they would be for supermarket sale to ensure that no damage was inflicted on them whilst in transit. I labelled each apple with a waterproof sticker that was coded corresponding to the specific orchard, distance from the orchard edge, row, branch and sample number. I completed all external and internal visual quality checks within a week. Following Garratt *et al.* (2016), I measured fresh apple mass (g), maximum diameter (cm) of the equatorial section (hereafter maximum width), and counted the number of viable seeds (the large, fully formed seeds as defined by Park *et al.* (2016) in each apple). I assessed the external and internal visual appearance (e.g. apple shape, skin defects and damage) of each apple according to industry standards (personal communication) to assess if the fruits collected would meet the quality of apples required for supermarket sale.

4.3.4 Exclusion experiment

To assess the effect of pollinator exclusion on apple yield and quality, I covered one branch on five different trees at approximately 5 m (the first tree of the row) and at approximately 50 m away from the orchard edge (ten branches per orchard) with a PVC coated fiberglass insect mesh bag (Figure 4.2) a week prior to apple blossom in 2017, in order to exclude insect pollinators. This netting had an aperture of 1.18 mm x 1.36 mm thus was wind permeable but excluded any potential invertebrate pollinators. At the end of the apple blossom period, I removed all the exclusion bags and marked the branches with an orange cable tie to be easily located for apple yield and quality assessments.

a.)

b.)

Figure 4.2 The experimental set-up of the pollinator exclusion net bags on branches of the apple trees in the study orchards pre-blossom in 2017

4.3.5 Statistical analyses

Open branches

I applied generalised linear mixed models (GLMMs) to assess both initial fruit set (i.e. pre-thinning) and final fruit set (i.e. at harvest) on open branches for 2016 and 2017 and for initial fruit set in 2018. As the initial and final fruit set data are proportional, I used a binomial error distribution for the models. The random effects were nested: rows within orchards; trees within rows; and branches within trees. For the response of initial fruit set in 2016, the fixed factors were: apple variety (Braeburn and Gala), distance away from the orchard edge (four categorical levels: 1, 2, 3, 4), and their interaction. Since the orchard edge treatments were implemented at the start of the apple-growing season in 2016, these treatments could have potentially affected the final fruit set (but not initial fruit set). Therefore, the effect of the orchard edge treatment (lavender, thyme, mixed, and control) and all consequential two-way interactions on the final apple fruit set were also analysed in 2016. Due to the apparent apple variety effect in 2016, Braeburn and Gala fruit sets were analysed separately in 2017 and 2018 with the fixed factors of orchard edge treatment, distance from the orchard edge and their interaction.

Apple weight and width were square root transformed to meet normality assumptions and analysed with linear mixed effect models (LMMs). Seed number is a count so was analysed using GLMMs with a Poisson error distribution and log-link. Random effects included in the models were nested: trees within orchards. Fixed effects were orchard edge treatment, apple variety, distance from the orchard edge and all two-way interactions.

In 2016, I excluded two branches from the analyses as they had a higher initial fruit set than the number of apple buds on the branch (due to the late formation of apple buds after the initial counting). I also excluded sixteen further branches from the analyses as they included final fruit set values greater than the initial fruit set. In 2017, I excluded thirteen branches from the analyses as they were accidentally pruned during the growing season.

To test for a correlation between the fruit set and pollinators during apple blossom (see Chapter 2), the average initial fruit set and pollinator visitation rate, at each distance away from the orchard edge in each orchard in all years (2016, 2017 and 2018), were analysed using Kendall's Tau correlation.

Exclusion experiment

To investigate the effect of branch treatment (open or closed to insect pollinators) on fruit set and seed number, I used GLMMs. Seed number is a count so I used the Poisson error structure and log-link; fruit set is a proportional response so I used a binomial error structure. Apple weight and maximum width were square root transformed and analysed using LMMs. The interaction of branch treatment with distance from the orchard edge was also included as a fixed effect. Random effects for fruit set were rows nested in orchards, trees nested in rows, and branches nested in trees; and for apple quality, trees were nested in orchards.

All analyses were performed in R Studio and all GLMMs and LMMs were applied using the package lme4. Model assumptions were checked by visually assessing the residual plots. The significance of fixed factors and *p* values were obtained from likelihood ratio tests. For significant fixed effects ($p < 0.05$) with more than two levels, post-hoc pairwise Tukey contrasts were performed using the emmeans package (Length, 2018).

4.4 Results

4.4.1 Apple yield

In 2016, there was a significant effect of apple variety on initial fruit set (X^2 = 15.71, d.f. = 1, $p <$ 0.001, Figure 4.3a) and final fruit set (X^2 = 7.10, d.f. = 1, $p <$ 0.01, Figure 4.3b); Gala had a higher fruit set than Braeburn. There was also a significant effect of distance from the orchard edge on initial fruit set (X^2 = 10.27, d.f. = 3, $p <$ 0.05, Figure 4.4a) and final fruit set (X^2 = 16.04, d.f. = 3, $p <$ 0.01, Figure 4.4b). Initial fruit set was higher at the second distance (2) away from the orchard edge than the closest (1) or furthest (4) distance away from the orchard edge. Final fruit set was higher at the second distance (2) away than at the closest (1). No interaction of apple variety and distance were detected on initial fruit set or final fruit set. For final fruit set, which was measured after the orchard edge treatments had been implemented, there was no effect of orchard edge treatment. There was no interaction effect of orchard edge treatment and distance, or of orchard edge treatment and variety (Table 4.1).

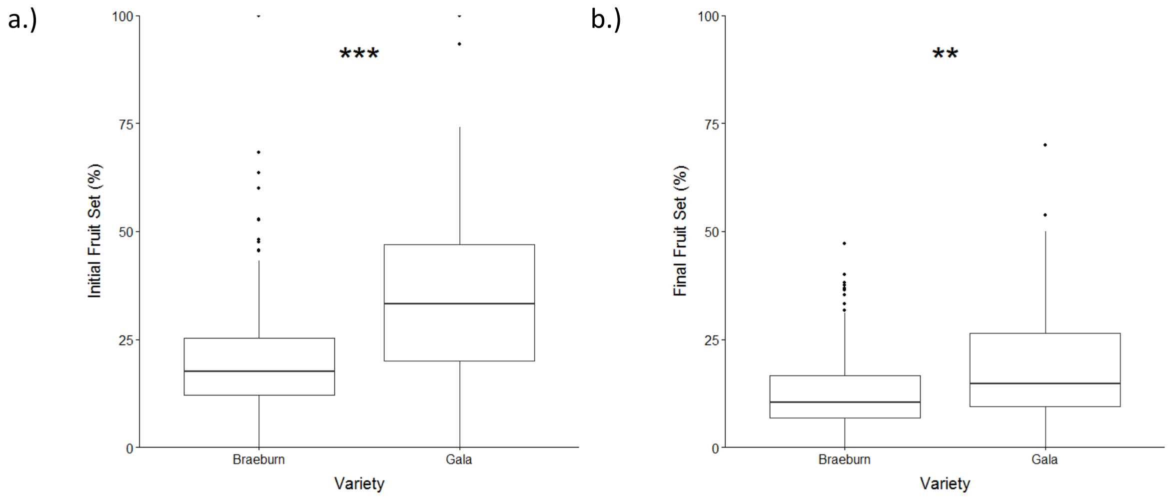


Figure 4.3 Percentage fruit set a.) pre-thinning (initial fruit set) and b.) at harvest (final fruit set) for Braeburn and Gala in 2016; ** = $p < 0.01$, *** = $p < 0.001$, reported in LRTs from GLMMS

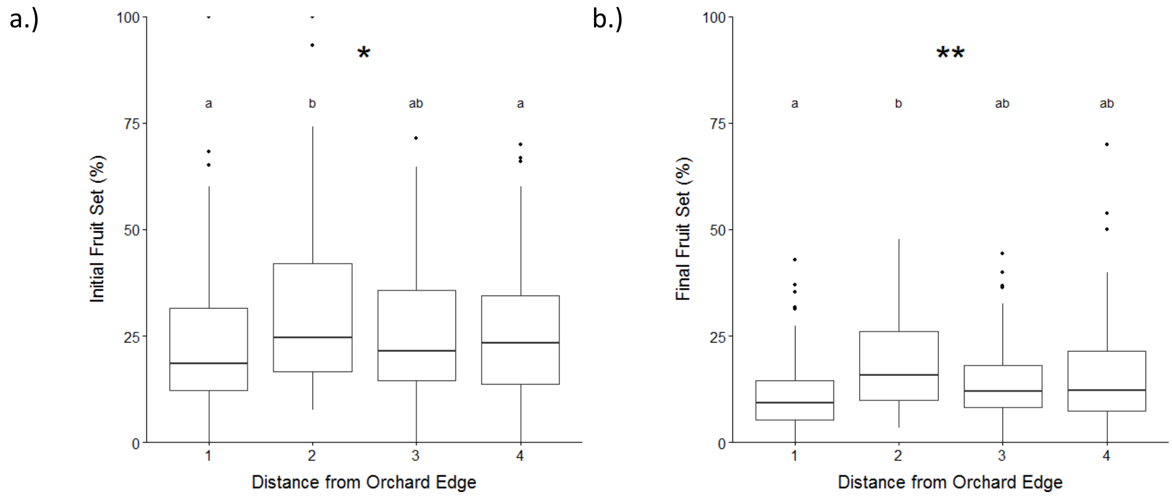


Figure 4.4 Percentage fruit set a.) pre-thinning (initial fruit set) and b.) at harvest (final fruit set) at the different distances away from the orchard edge in 2016; * = $p < 0.05$, ** = $p < 0.01$, reported in LRTs from GLMMS. Different letters represent the significant differences ($p < 0.05$) detected from the Tukey post-hoc pairwise comparison tests

Table 4.1 Results from GLMM analyses of initial fruit set and final fruit set in 2016; chi-square values (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$) from likelihood ratio tests are shown for all explanatory variables included in the models tested.

Response	Predictor	d.f.	X^2	p
Initial Fruit Set	Variety (V)	1	15.71	**< 0.001**
	Distance (D)	3	10.27	**0.016**
	V x D	3	1.27	0.737
Final Fruit Set	Variety (V)	1	7.10	**0.008**
	Distance (D)	3	16.01	**0.001**
	Orchard Edge Treatment (T)	3	1.37	0.712
	V x D	3	4.13	0.248
	T x V	3	2.76	0.430
	T x D	9	11.43	0.248

In 2017, there was no significant effect of apple variety on initial fruit set (X^2 = 3.68, d.f. = 1, p = 0.055, Figure 4.5a) but at final fruit set Gala had a higher fruit set than Braeburn (X^2 = 3.68, d.f. = 1, p = 0.046, Figure 4.5c). At initial fruit set in 2018, there was a significant effect of apple variety with a higher Gala fruit set than Braeburn (X^2 = 5.54, d.f. = 1, p = 0.019, Figure 4.5b). The other effects on fruit set for Braeburn and Gala were analysed separately within each year (Table 4.2).

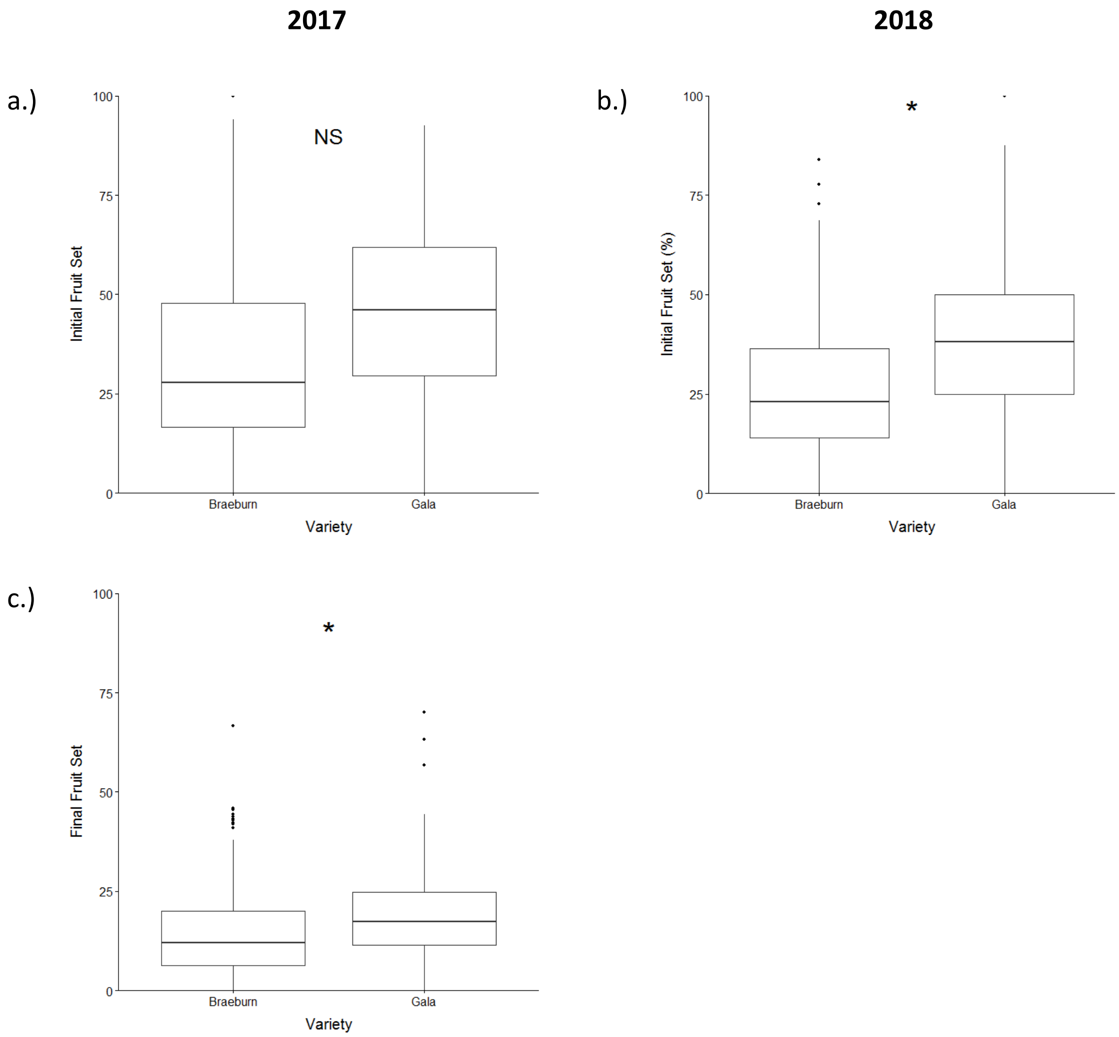


Figure 4.5 The effect of apple variety (Braeburn or Gala) on percentage fruit set a.) pre-thinning (initial fruit set) in 2017; b.) 2018; and c.) at harvest (final fruit set) in 2017; NS = p > 0.05, * = p < 0.05 reported in LRTs from GLMMS

I detected no effect of orchard edge treatment on Braeburn or Gala initial fruit set in 2017 (one year after orchard edge treatment establishment), or in 2018 (two years after orchard edge treatment establishment) (Table 4.2; Figure 4.6a-d) and no effect of orchard edge treatment on Braeburn or Gala final fruit set in 2017 (Table 4.2; Figure 4.8a,b). There was however, an effect of distance on Gala initial fruit set in 2017 (X^2 = 12.37, d.f. = 3, p = 0.006). The post-hoc pairwise comparison found that there was a higher initial fruit set for Gala apples at the first two distances away from the orchard edge than the furthest distance away from the orchard edge (Figure 4.7c). Distance did not affect any of the other initial or final fruit sets (Figure 4.7a,b,d; Figure 4.8c,d). Furthermore, there was no interaction effect of orchard edge treatment and distance for Braeburn or Gala fruit sets in either year (Table 4.2).

Table 4.2 Results from GLMM analyses of Braeburn and Gala initial fruit set and final fruit set in 2017 and initial fruit set in 2018. The table shows chi-square values, d.f. and *p* values from likelihood ratio tests for all explanatory variables included in the models tested.

				2017		2018	
Response		Predictor	d.f.	X^2	*p*	X^2	*p*
Initial Fruit Set	Braeburn	Orchard Edge Treatment (T)	3	0.51	0.916	5.99	0.112
		Distance (D)	3	0.12	0.990	0.96	0.811
		T x D	9	4.38	0.885	9.37	0.404
	Gala	Orchard Edge Treatment (T)	3	1.69	0.639	5.52	0.137
		Distance (D)	3	12.37	**0.006**	4.50	0.212
		T x D	9	11.33	0.254	8.18	0.516
Final Fruit Set	Braeburn	Orchard Edge Treatment (T)	3	1.66	0.647		
		Distance (D)	3	1.77	0.620		
		T x D	9	2.84	0.970		
	Gala	Orchard Edge Treatment (T)	3	3.67	0.300		
		Distance (D)	3	1.93	0.588		
		T x D	9	13.47	0.143		

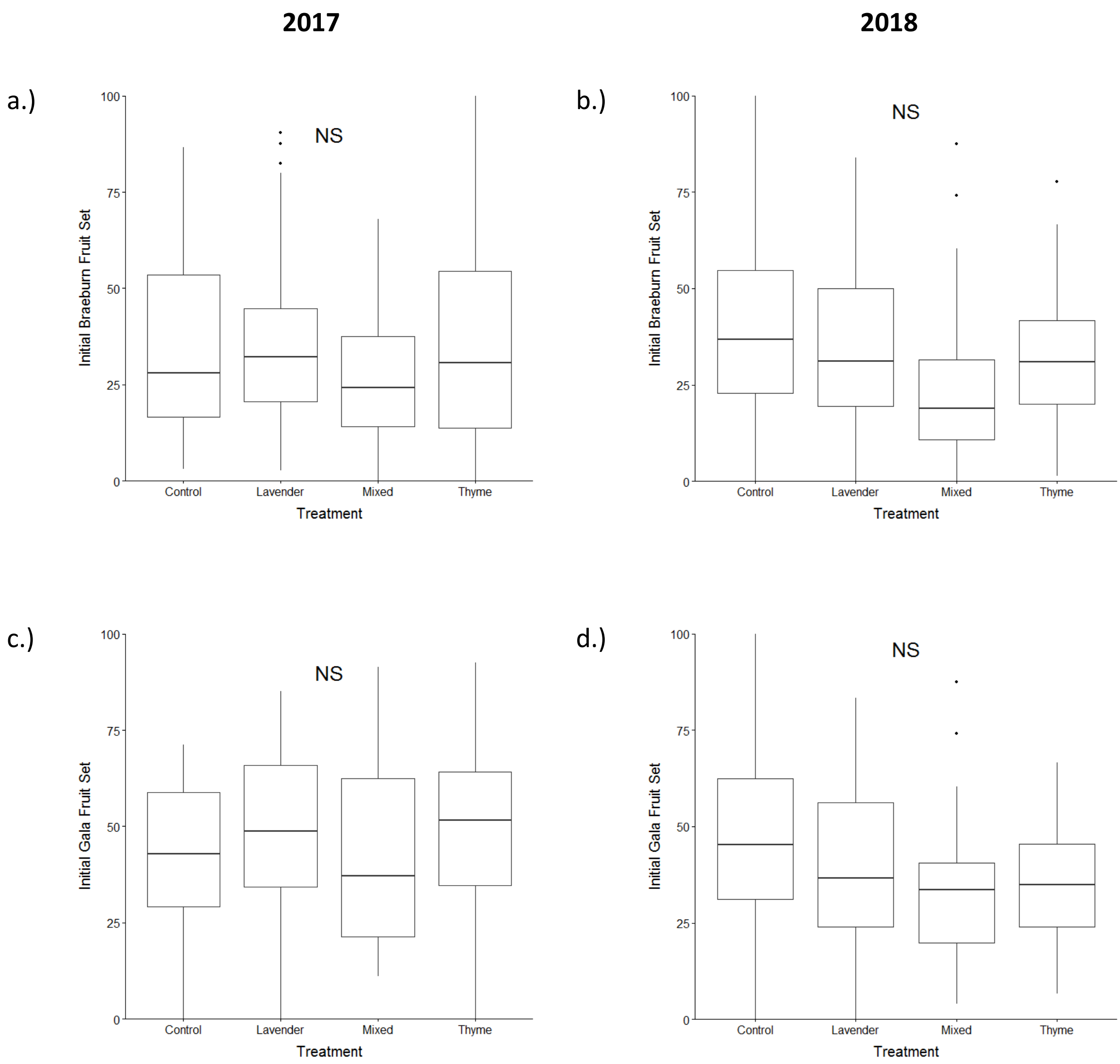


Figure 4.6 There was no effect of orchard edge treatment on the initial fruit set (pre-thinning) of Braeburn apples in a.) 2017 and b.) 2018 or of Gala apples in c.) 2017 and d.) 2018; NS = $p > 0.05$, reported in LRTs from GLMMS (see Table 4.2 for details)

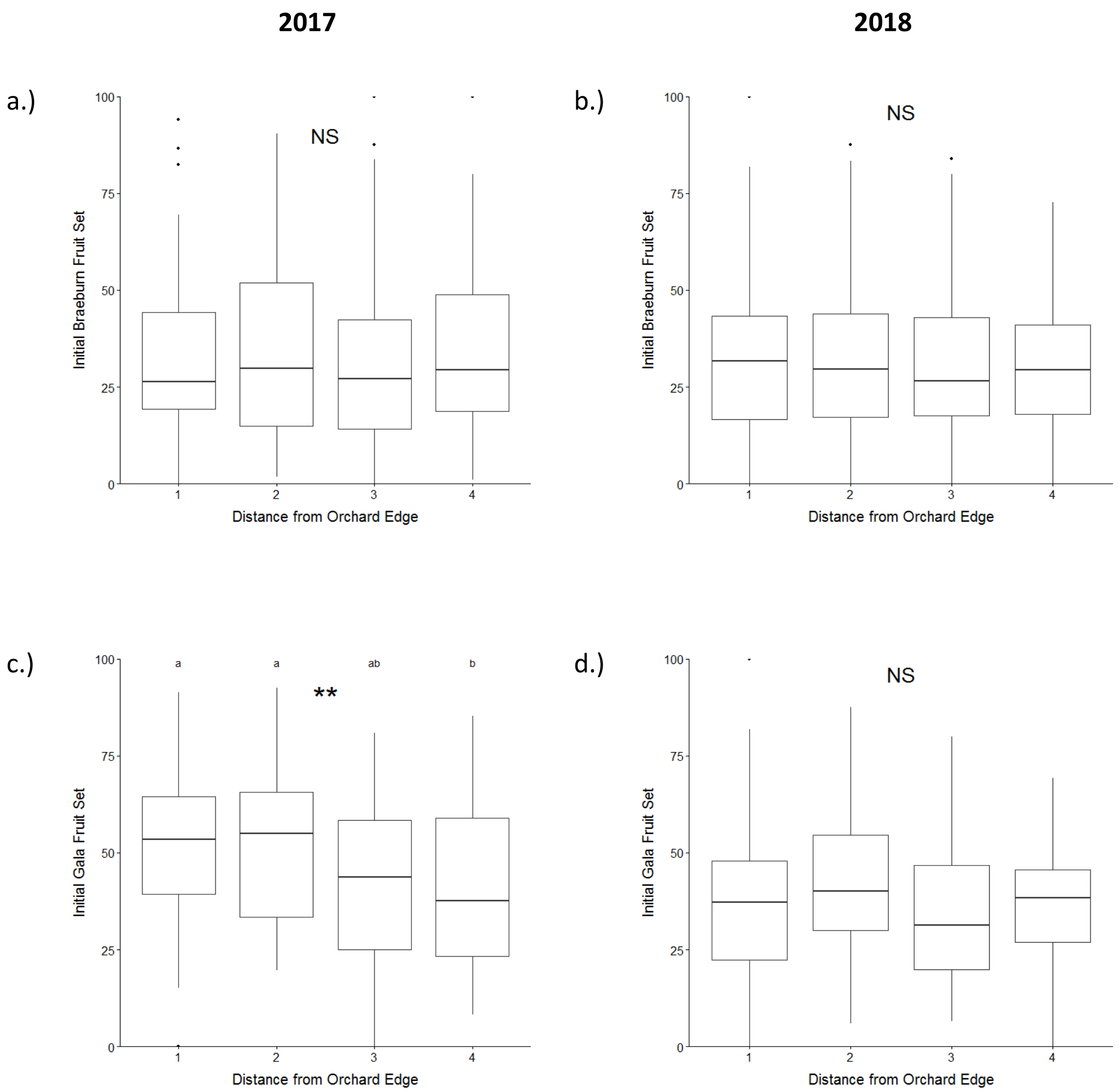


Figure 4.7 The effect of distance from the orchard edge on the initial fruit set (pre-thinning) of Braeburn apples in a.) 2017 and b.) 2018 and of Gala apples in c.) 2017 and d.) 2018; NS = $p > 0.05$, ** = $p < 0.01$ reported in LRTs from GLMMS (see Table 4.2 for details). Different letters represent the significant differences ($p < 0.05$) detected from the Tukey post-hoc multiple comparison tests

2017

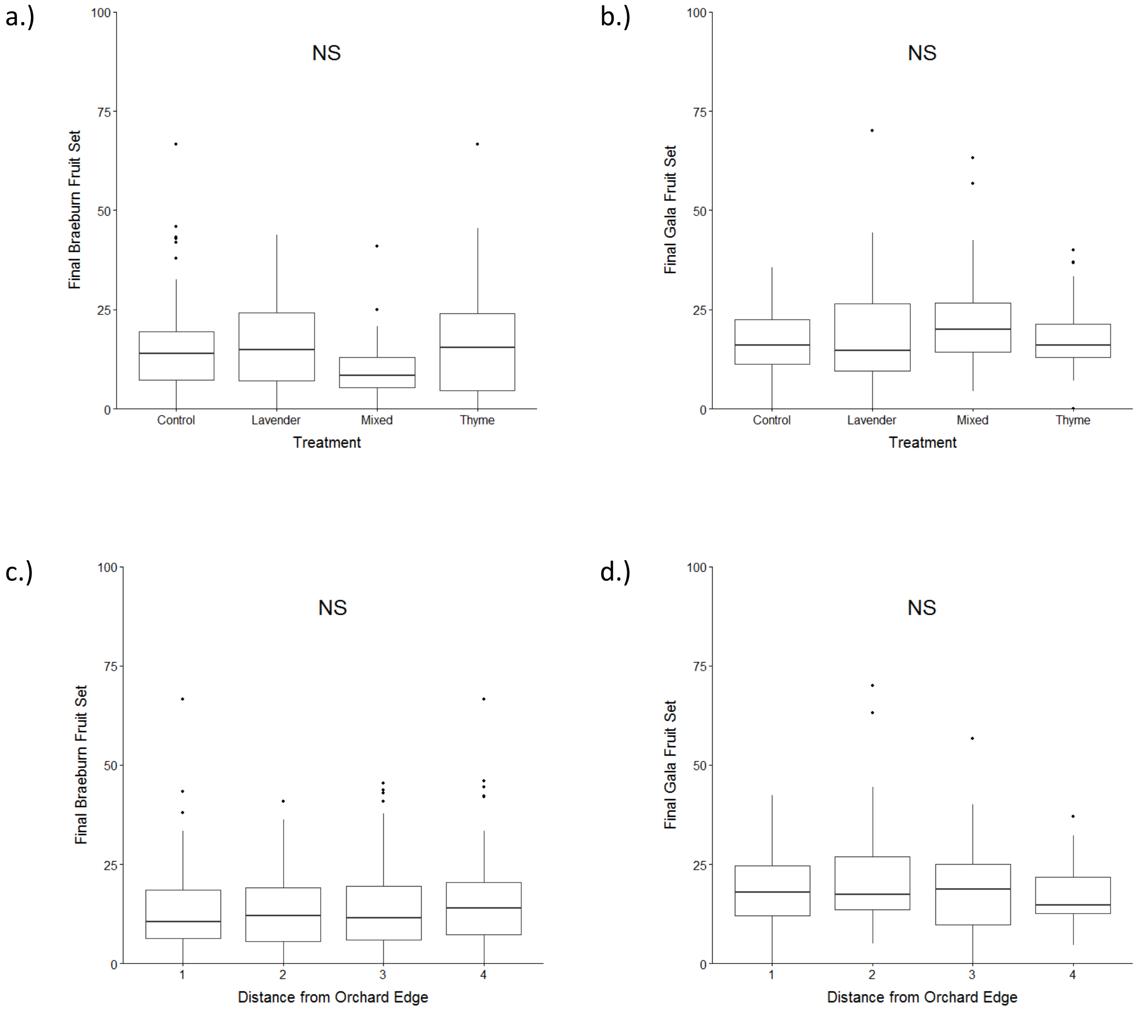
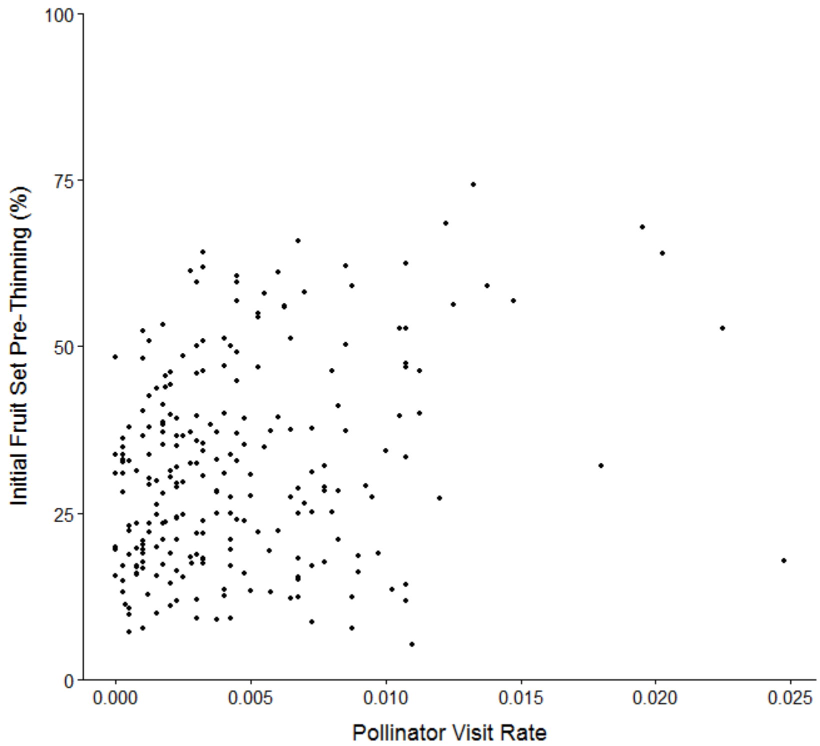


Figure 4.8 There was no effect of orchard edge treatment on final fruit set (at harvest) in 2017 in a.) Braeburn or b.) Gala and no effect of distance on final fruit set in c.) Braeburn or d.) Gala; NS = $p > 0.05$ reported in LRTs from GLMMS (see Table 4.2)

For the branches open to pollinators in all years (2016, 2017, 2018), there was a significant positive correlation between initial fruit set and pollinator visitation rate during apple blossom (Kendall's τ correlation coefficient = 0.159, $p < 0.001$; Figure 4.9a). Whereas, for the branches open to pollinators in 2016 and 2017, there was no significant positive correlation between final fruit set and pollinator visitation rate during apple blossom (Kendall's τ correlation coefficient = 0.060, p = 0.262; Figure 4.9b).

a.)



b.)

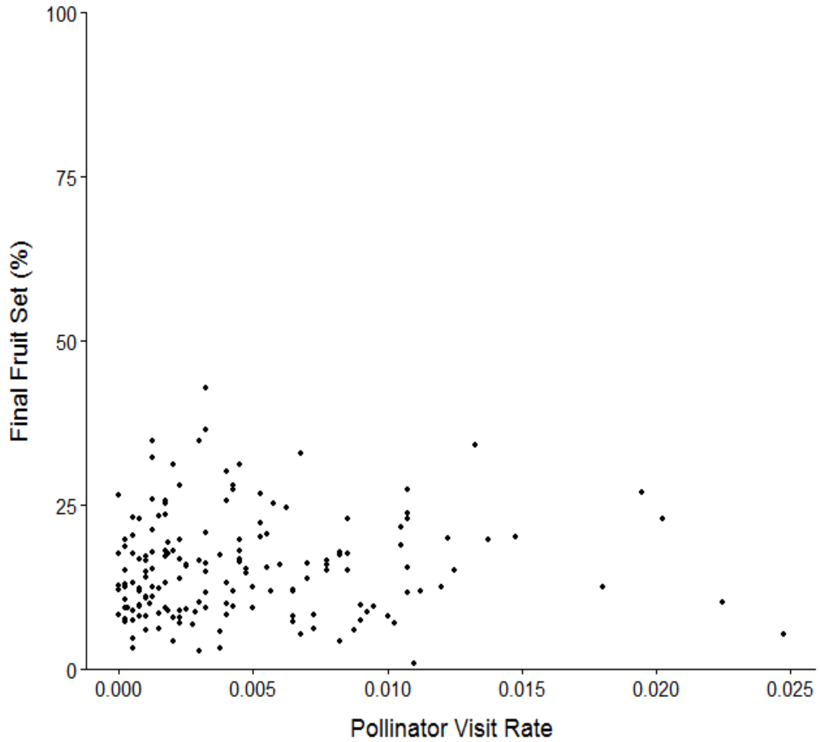


Figure 4.9 Relationship between a.) initial fruit set and pollinator visitation rate on apple branches open to insect pollinators in 2016, 2017 and 2018 b.) final fruit set and pollinator visitation rate on apple branches open to insect pollinators in 2016 and 2017

4.4.2 Apple quality

According to my visual quality assessments, 40% of the apples collected from branches open to pollinators in 2016 (n = 147/368) and 51% in 2017 (n = 203/400) would have been accepted for the supermarket retail market according to the cosmetic industry standards (symmetrical shape, none or minimal external and internal visual defects). On the pollinator-excluded branches in 2017, only 22% of the apples (n = 32/144) would have met these standards. Apple shape alone was acceptable to supermarket standards in 45% (n = 164/368) of apples in 2016 and 59% (n = 234/400) of apples in 2017. On the pollinator-excluded branches in 2017 30% (n = 43/144) of apples met the standard for apple shape. Invertebrate pest damage was only observed on one apple out of the entire 2016-2017 sample. There were five other apples with negligible visual defects, which could potentially be attributed to pests, but that did not detract from the quality of the apple and therefore the apples remained within the quality tolerance.

The following results in this sub-section apply only to apple quality from apples on branches open to pollinators.

There was a significant effect of apple variety on apple mass in 2016 (X^2 = 12.90, d.f. = 1, p < 0.001, Figure 4.10a) and in 2017 (X^2 = 18.04, d.f. = 1, p < 0.01, Figure 4.10b); Braeburn apples were heavier than Gala apples in both years. Although the average fresh apple mass was higher in orchards with a mixed lavender and thyme orchard edge treatment, this was not a significant effect in either 2016 or in 2017 (Table 4.3; Figure 4.10c, 4.10d).

There was a significant effect of apple variety on the maximum apple width in 2016 (X^2 = 11.59, d.f. = 1, p < 0.001, Figure 4.11a) and in 2017 (X^2 = 17.03, d.f. = 1, p < 0.01, Figure 4.11b); with wider Braeburn than Gala apples in both years. There was no effect of orchard edge treatment on maximum apple width of harvested fruit in 2016 or in 2017 (Table 4.3; Figure 4.11c,d). A significant effect of distance from the orchard edge on maximum apple width was detected in 2017 (X^2 = 9.73, d.f. = 3, p < 0.05). The post-hoc pairwise comparison found that there was a higher maximum apple width closest (1) and furthest (4) away from the orchard edge than at the second distance (2) away from the orchard edge (Figure 4.11f).

There was no effect of apple variety, distance from the orchard edge or orchard edge treatment on the number of seeds in apples in 2016 or 2017 and there were no interaction effects (Table 4.3, Figure 4.12).

Table 4.3 Results from the LMM and GLMM analyses of apple quality in 2016 and in 2017. The table shows chi-square values, d.f. and *p* values from likelihood ratio tests for all explanatory variables included in the models tested. The fixed factors were orchard edge treatment (T), apple variety (V), distance from the orchard edge (D) and their interactions.

			2016		**2017**	
Response	**Predictor**	**d.f.**	X^2	***p***	X^2	***p***
Apple Mass (g)	T	3	5.43	0.143	1.87	0.600
	V	1	12.90	**< 0.001**	18.04	**< 0.001**
	D	3	2.80	0.424	7.17	0.067
	T x V	3	6.84	0.078	0.52	0.914
	T x D	9	11.96	0.216	11.87	0.221
	D x V	3	1.34	0.718	1.73	0.631
Maximum Width (cm)	T	3	6.33	0.097	0.88	0.83
	V	1	11.59	**< 0.001**	17.03	**< 0.001**
	D	3	5.30	0.151	9.73	**0.021**
	T x V	3	6.32	0.097	0.95	0.814
	T x D	9	13.46	0.143	16.17	0.063
	D x V	3	0.66	0.882	0.58	0.902
Seed Number	T	3	1.41	0.703	3.38	0.336
	V	1	0.02	0.881	0.09	0.765
	D	3	0.55	0.908	5.34	0.148
	T x V	3	3.63	0.304	1.09	0.779
	T x D	9	14.91	0.093	8.25	0.509
	D x V	3	4.37	0.224	7.43	0.059

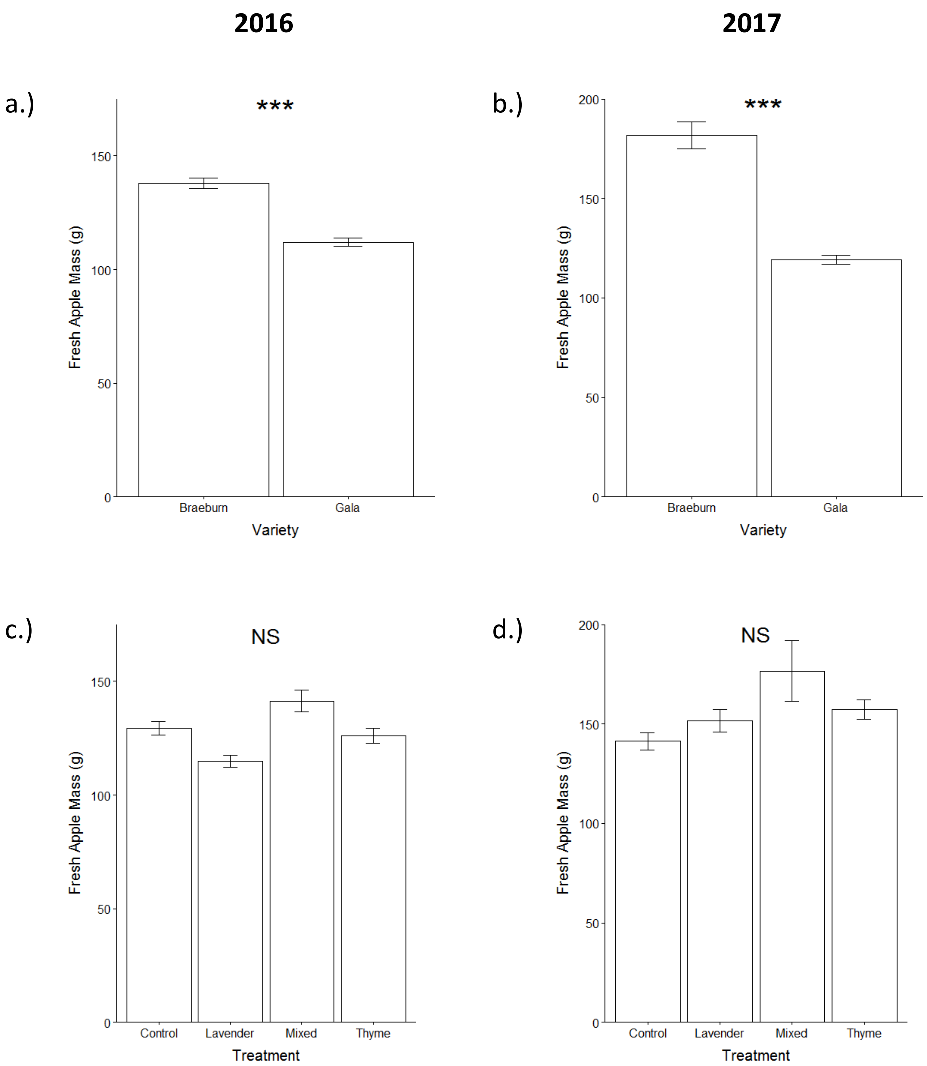


Figure 4.10 Mean +/- SE apple mass (g) by apple variety in a.) 2016 and b.) 2017 and by orchard edge treatment in c.) 2016 and d.) 2017; NS = $p > 0.05$, *** = $p < 0.001$ reported in LRTs from LMMS (see Table 4.3 and main text for details)

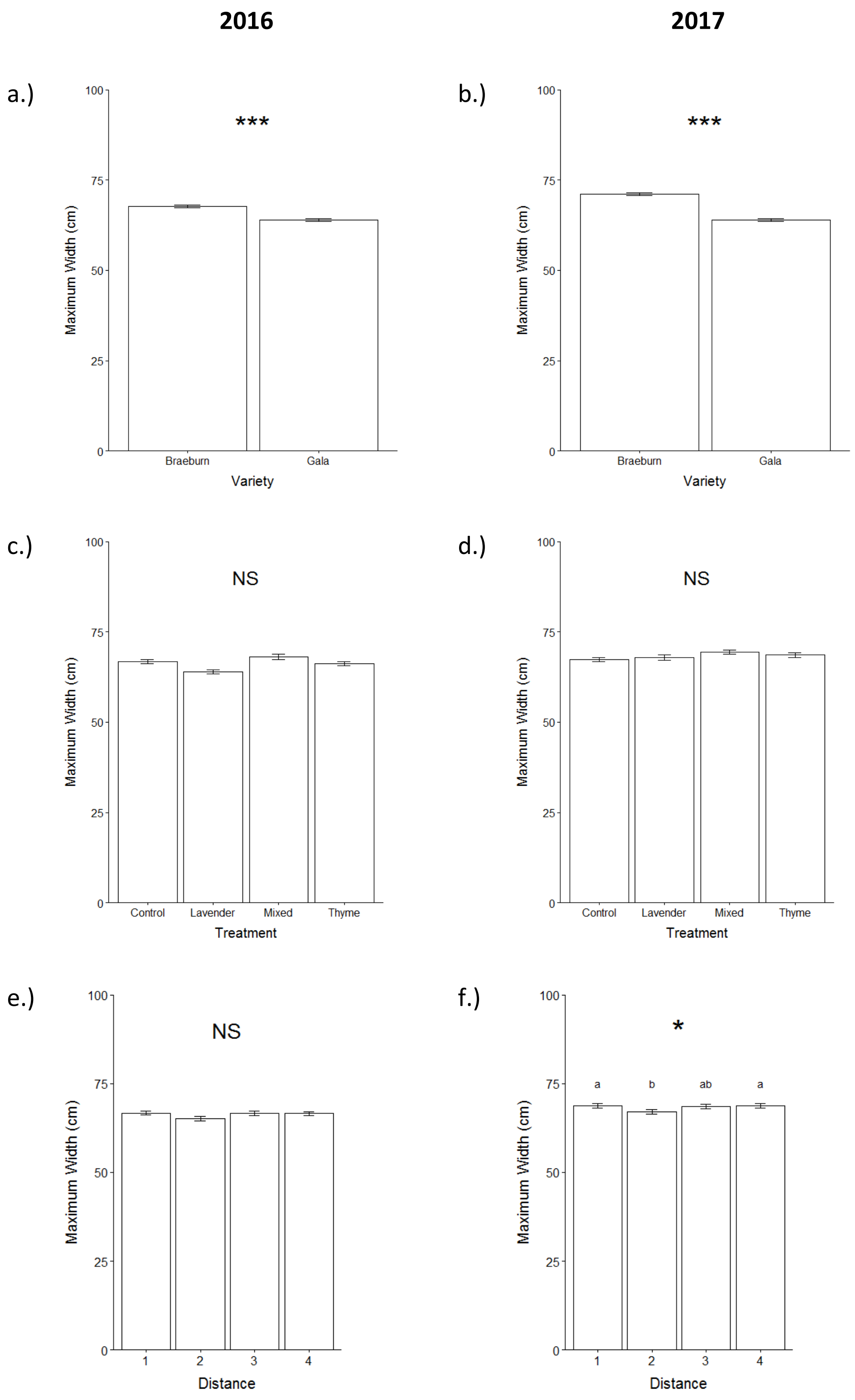


Figure 4.11 Mean +/- SE maximum apple width (cm) by apple variety in a.) 2016 and b.) 2017; by orchard edge treatment in c.) 2016 and d.) 2017; and by distance from the orchard edge in e.) 2016 and f.) 2017; NS = $p > 0.05$, * = $p < 0.05$, *** = $p < 0.001$ reported in LRTs from LMMS (see Table 4.3 and main text for details). Different letters represent the significant differences ($p < 0.05$) detected from the Tukey post-hoc multiple comparison tests

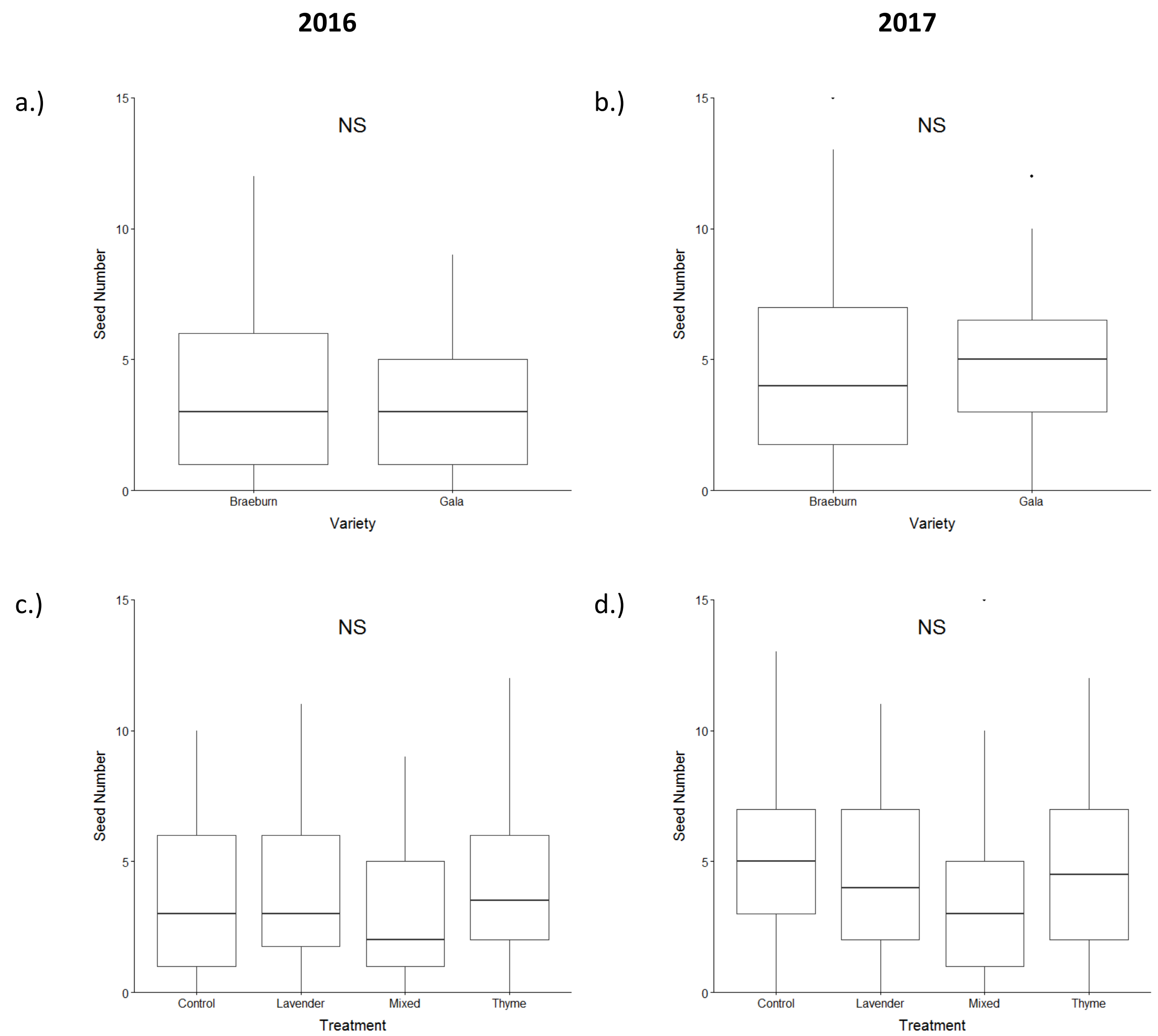


Figure 4.12 Seed number by apple variety in a.) 2016 and b.) 2017 and by orchard edge treatment in c.) 2016 and d.) 2017; NS = $p > 0.05$, reported in LRTs from GLMMS (see Table 4.3 for details)

4.4.3 Exclusion experiment

When both apple varieties were analysed together, pollinator exclusion significantly affected fruit set with higher initial and final fruit set for open branches than for insect excluded branches (Figure 4.13). I also detected a significant interaction effect between branch treatment and apple variety on initial fruit set; the initial Gala fruit set was higher than Braeburn for the open branches, but not for the insect excluded branches (Table 4.4, Figure 4.13a).

a.) b.)

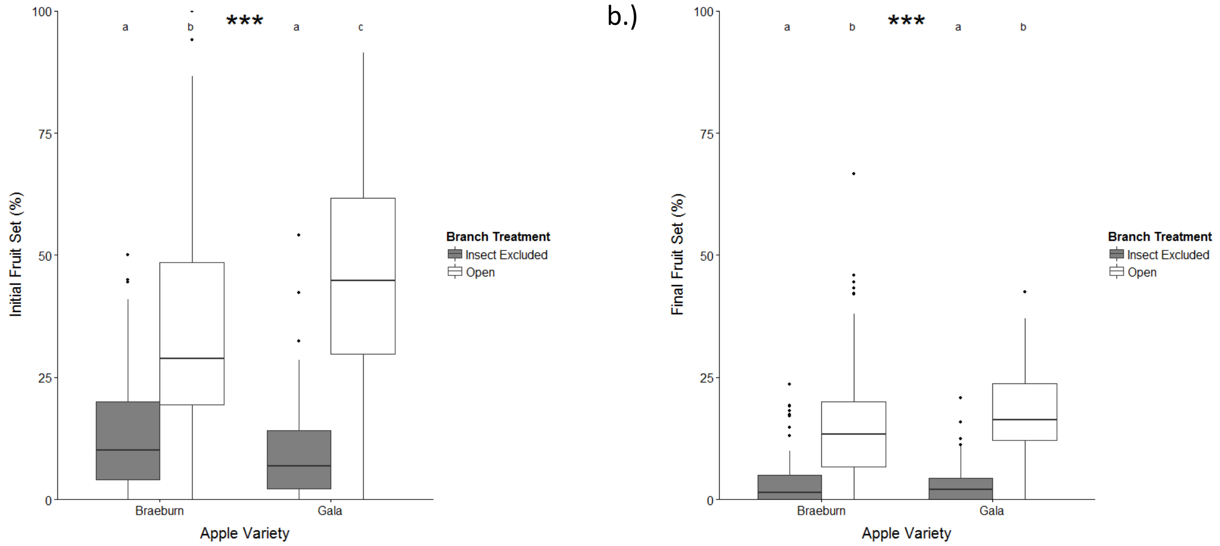


Figure 4.13 Percentage fruit set from Braeburn and Gala apples following the pollinator exclusion branch treatment a.) pre-thinning (initial fruit set) and b.) at harvest (final fruit set); *** = $p < 0.001$ reported in LRTs from GLMMs. Different letters represent the significant differences ($p < 0.05$) detected from the Tukey post-hoc multiple comparison tests

When analysed separately, pollinator exclusion significantly affected fruit set in both Braeburn and Gala orchards at initial fruit set (Braeburn: $X^2 = 96.86$, d.f. = 1, $p < 0.001$; Gala: $X^2 = 134.94$, d.f. = 1, $p < 0.001$) and at final fruit set (Braeburn: $X^2 = 106.41$, d.f. = 1, $p < 0.001$; Gala: $X^2 = 158.52$, d.f. = 1, $p < 0.001$). However, there was no detectable interaction effect of branch treatment with distance (Table 4.4).

Table 4.4 Results from GLMM analyses of fruit set for the pollinator exclusion experiment in 2017; chi-square values (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$) from likelihood ratio tests are shown for all explanatory variables included in the models tested.

			Initial Fruit Set	Final Fruit Set
	Predictors	d.f.	X^2	X^2
All Apples	Branch Treatment	1	**222.97*** **	**252.37*** **
	Branch Treatment x Variety	**3**	**19.27*** **	**5.19* **
	Branch Treatment x Distance	3	0.10	0.19
Braeburn	Branch Treatment	1	**96.86*** **	**106.41*** **
	Branch Treatment x Distance	3	0.046	0.00
Gala	Branch Treatment	1	**134.94*** **	**158.52*** **
	Branch Treatment x Distance	3	1.42	1.51

Pollinator exclusion also affected some apple quality attributes (Table 4.5). There was a significant effect of pollinator exclusion on Gala apple mass (Figure 4.14b) and maximum width (Figure 4.14d) but not for Braeburn apples (Figure 4.14a,c). Gala apple mass and maximum width were higher for apples from branches open to pollinators than for apples from insect excluded branches. There was an interaction of branch treatment and distance from the orchard edge on the maximum width of Braeburn apples (X^2 = 5.07, d.f. = 1, $p < 0.05$) but this effect was not detected by the post-hoc Tukey pairwise comparisons (Figure 4.15). The number of seeds in both Braeburn and Gala apples was higher in apples from branches open to pollinators than for apples from insect excluded branches (Table 4.5; Figure 4.14e,f).

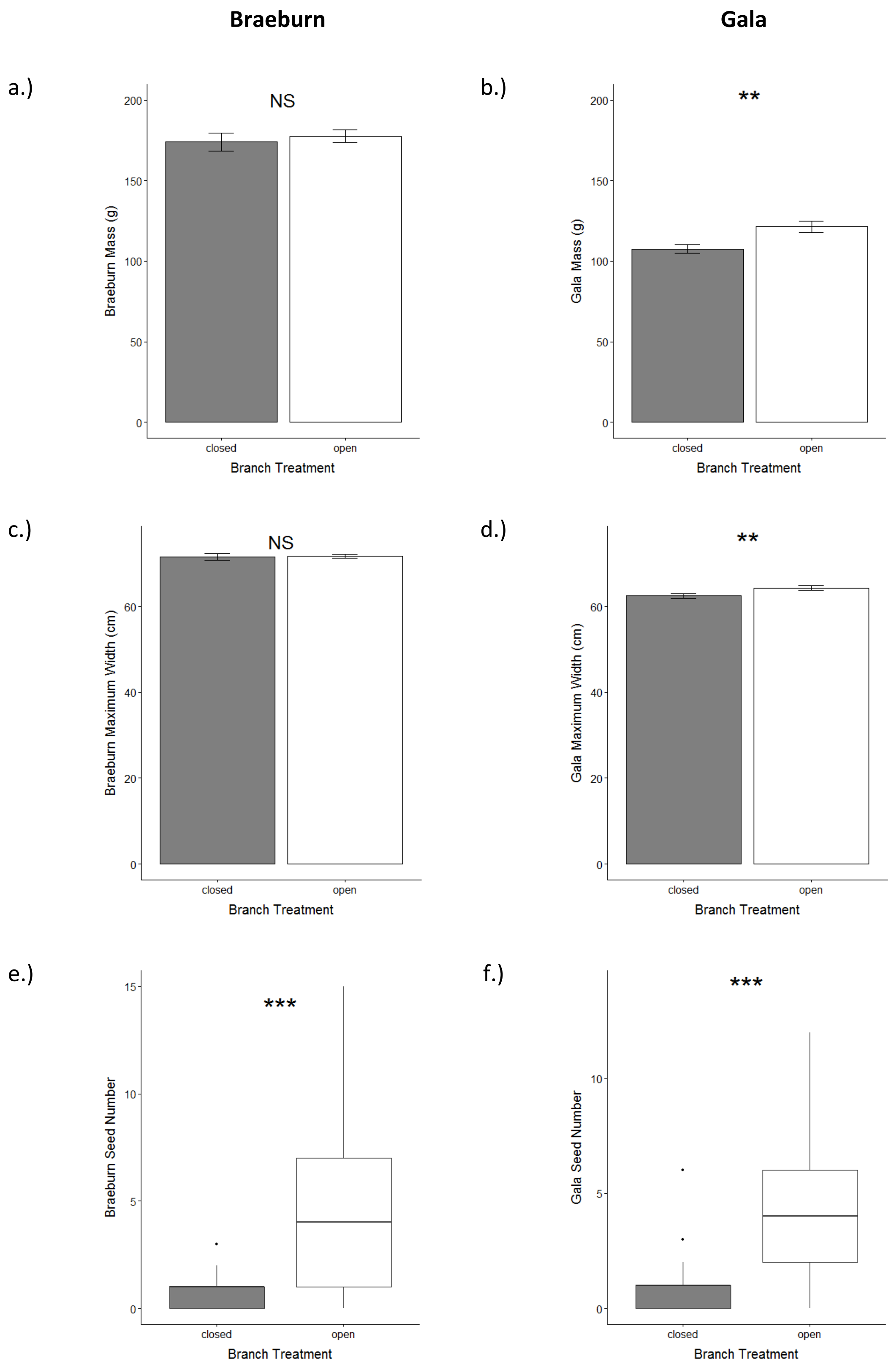


Figure 4.14 Effects of branch treatment (closed or open to insect pollinators during apple blossom) on a.) Braeburn and b.) Gala apple mass; on c.) Braeburn and d.) Gala maximum width; and on e.) Braeburn and f.) Gala seed number; NS = $p > 0.05$, ** = $p < 0.01$, *** = $p < 0.001$ reported in LRTs from LMM & GLMMS (see Table 4.5 and main text for details)

Table 4.5 Results from the LMM and GLMM analyses of the pollinator exclusion experiment on apple weight, maximum width and seed number in 2017. Degrees of freedom (d.f.), test statistics (X^2) and *p*-values from the likelihood ratio tests are shown.

			Braeburn		Gala	
Response	Predictor	d.f.	X^2	*p*	X^2	*p*
Weight	Branch Treatment	1	1.60	0.206	15.16	**0.001**
	Branch Treatment x Distance	1	2.99	0.084	0	1
Maximum Width	Branch Treatment	1	0.06	0.803	8.50	**0.004**
	Branch Treatment x Distance	1	5.07	**0.024**	1.15	0.979
Seed Number	Branch Treatment	1	177.57	**< 0.001**	144.20	**< 0.001**
	Branch Treatment x Distance	1	0.03	0.861	0.04	0.841

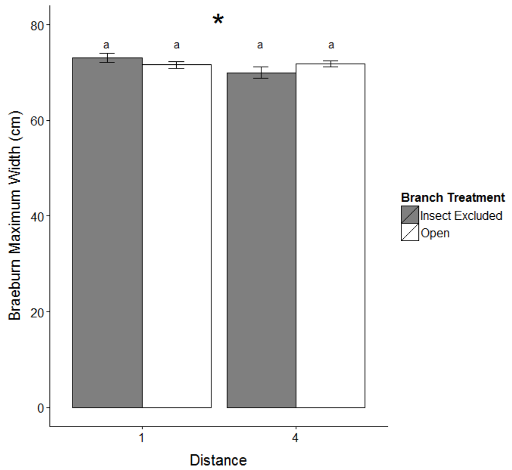


Figure 4.15 The interaction effect of branch treatment (open or closed to insect pollinators during apple blossom) and distance from the orchard edge on Braeburn maximum width; * = $p < 0.05$ reported in LRT from LMM however, the same letter (a) indicates that there was no detectable difference from the post-hoc Tukey pairwise comparison ($p > 0.05$)

4.5 Discussion

I did not detect an effect of orchard edge treatment on apple yield but apple fruit set was dependent on apple variety with a higher fruit set for Gala than for Braeburn. This was more apparent for the initial fruit set than for the final fruit set. In both varieties, the initial fruit set was higher than the final fruit set, displaying how during the apple-growing season apples are thinned from branches or are aborted due to environmental conditions or due to pest damage. The practice of thinning in these commercial apple orchards also indicates that there may not currently be a pollination deficit. The pollinator exclusion experiment did however confirm existing knowledge that pollinators are important for apple fruit set (Garratt *et al.*, 2014; Garratt *et al.*, 2016; Campbell *et al.*, 2017b) as fruit set was lower on branches where pollinators were excluded.

Orchard edge treatments also had no effect on apple quality parameters. However, apple size (mass and maximum width) but not the number of apple seeds were affected by apple variety. Gala apples were smaller than Braeburn potentially because Gala fruit set was higher than Braeburn. Yield and quality are linked due to the competition for resources such as carbon allocation (Miranda *et al.*, 2005; Demestihas *et al.*, 2017); a higher density of apples on the tree results in smaller apples (Serra *et al.*, 2016). This is why it is often commercial practice to thin apple fruitlets that have formed on branches (post-apple blossom), so that the branches are not overloaded.

The pollinator exclusion experiment found that apples on branches where pollinators had been excluded during apple blossom, had less seeds compared to the apples from branches open to pollinators. Cage experiments excluding pollinators have also found lower fruit and seed sets as well as a higher percentage of misshapen fruits when no pollinators are present (Ladurner *et al.*, 2004). However, despite fewer seeds in both apple varieties, pollinator exclusion only had an effect on Gala, not on Braeburn apples, in terms of reduced size (weight and maximum width). This corroborates the findings from Garratt *et al.* (2016) who also found a varietal difference in terms of pollinator exclusion effects on apple size, with no effect on Braeburn apples.

Apple seeds are related to fruit shape and size (Brookfield *et al.*, 1996; Buccheri and Di Vaio, 2005), important criteria for apple specifications. The distribution of the seeds is also important for fruit shape; when two adjacent carpels are without seeds this leads to asymmetry in fruit shape due to the lack of hormonal production from seed development influencing tissue growth on that side (Sheffield, 2014). The lower number of seeds in pollinator-excluded apples might explain why less than a third of the apple samples met the shape requirements for supermarket sale.

According to my visual quality assessments, just over a third of the collected apples in 2016 and just over half in 2017 would have been of acceptable standard for the supermarket retail market, and on pollinator-excluded branches in 2017, this was even lower. However, as Musacchi and Serra (2018) warn, visual apple quality checks for defects and the classification of apples into grades can be quite subjective depending on who is making the assessment. I found negligible invertebrate pest damage on the apple fruits collected at harvest, which could be due to the loss of affected fruits naturally from the tree or manually by workers during the growing season. This could also be because of effective agrochemical use, which growers attributed with the low proportion of yield lost to pests in Chapter 1, Section 1.8. Environmental weather conditions also affect some detrimental cosmetic apple quality attributes such as sunburn, russeting and hail damage but these apples are also likely to be removed during the growing season.

I did not detect an effect of orchard edge treatment on any measured parameters of apple production. This might be due in part to the other factors that contribute to and regulate production success such as those controlling pathogens, soil nutrients and water availability (Bommarco *et al.*, 2013; Lundin *et al.*, 2013; Klein *et al.*, 2015) which were not considered in this study. Another possible contributing factor to apple fruit set, not accounted for in this analyses, might have been the total number of flowers on the tree; Monzón *et al.* (2004) found that small trees with fewer flowers have a higher fruit set, regardless of pollinator visitation by different pollinator types. Apple fruit set in some varieties will also depend on the abundance, diversity and distribution of the polliniser trees present in the orchards (Kron *et al.*, 2001; Kron and Husband, 2006). Furthermore, apple trees are biennial bearing whereby if one year an individual tree has a high fruit yield; it will have a lower yield the consecutive year as abundant buds are followed by a year of fewer (Meland, 2009; Samach and Smith, 2013).

In cider apples, Campbell *et al.* (2017a) also noted that apple yield had not increased one-two years after floral provision (wildflower strips). This might indicate that one-two years after orchard edge treatment establishment is not enough time for the orchard edge treatments to affect apple yield or quality. This is confirmed by studies in other fruits, for example, it took until three years after wildflower establishment to see increases in pollination services to highbush blueberry and therefore for an effect on fruit set, weight and seed number to materialise (Blaauw and Isaacs, 2014). In lowbush blueberry, it took four years after floral provision establishment for wild bee visitation rates to increase and only then, a very small increase in yield (10%) was found at the 0.10 level of significance (Venturini *et al.*, 2017). These studies add evidence to the proposal that long-term experiments, with perhaps a minimum of 3 or 4 years after floral resource establishment, would be beneficial. This would allow floral resources adequate time to establish, thereby increasing the nectar and pollen resources available to beneficial invertebrates that can affect crop productivity and which also need time to build up their populations.

The typical lifespan of lavender matches that of the orchard, the semi-permanency of which allows time for the floral resources to benefit beneficial invertebrate populations of both pollinators and natural enemies and therefore offers potential for improvements to future apple production. Considering both regulating services together (pollination and pest control) is likely to produce an economic return estimate of a lower number of years until the initial investment is repaid, than if only one ecosystem service was considered in isolation. For example, Morandin *et al.* (2016) showed that hedgerows break even in seven years when both pest control and pollination are incorporated into a cost-benefit analysis, compared to sixteen years if pests alone are included. Considering these two services together helps to give growers a full picture of the possible benefits that these non-crop features can provide to their farm business and the local land that they manage.

4.5.1 Conclusion

Pollinator exclusion experiments confirmed that insect pollination services improve apple yield and quality in Braeburn and Gala orchards. However, orchard edge treatments had no effect on apple production in terms of yield and quality. Other studies show that economic returns from ecological intensification take 3-5 years to materialise (Blaauw and Isaacs, 2014; Pywell *et al.*, 2015), therefore, it is difficult to determine the yield benefits from short-term studies (1-2 years) as there may be a time lag before the benefits to commodity production are realised (Garbach *et al.*, 2017). If apple production is not limited by pollination, then the increased wild bee visitation rates to apple flowers in orchards with a mixed lavender and thyme orchard edge treatment, seen in Chapter 2, are unlikely to have an effect on fruit set. Nevertheless, increases in wild bee populations are beneficial for apple production as they could alleviate the reliance on managed honeybees, which if lost in the future would result in an unstable delivery of pollination services and therefore could have detrimental consequences to apple yield and quality.

Chapter 5 General Conclusion

5.1 Research Synthesis

5.1.1 Non-crop vegetation exists in orchards but is rarely designed for successive floral resource provision

Chapter 1, Section 1.8 revealed that nearly all respondents had hedgerows and windbreaks in their orchards but that the design and potential ability of these structures to provide resources for pollinators was not recognised. Adding to this, most growers did not utilise wildflower mixes at the orchard perimeter. Pollination is crucial to apple production, but pollinator communities in these intensive agro-ecosystems will require floral resources after the mass apple bloom in spring. With pest damage listed as a frequent cause of crop loss and with most respondents understanding the importance of integrated pest management, this chapter thereby identified the scope to enhance the orchard edges with targeted floral resources to increase both pollinator and natural enemy populations.

5.1.2 Planting lavender and thyme offers a novel way to enhance floral resources at the orchard perimeter

For ecological conservation to be successful, farmer opinions should be taken into account when planning wildlife-friendly farming measures (de Snoo *et al.*, 2013). Therefore, the findings from Chapter 1, Section 1.8 helped to shape the ecological experiment that I set-up for Chapters 2-4. To maximise the possibility that growers would want to take up the measures (if proved to be beneficial), I decided to test a novel alternative option to wildflower provision, an option with a potentially quicker return than planting flowering trees and with a low space demand so it could be implemented alongside existing non-crop tree structures at the orchard perimeter. Therefore, I planted lavender and thyme from pots to enhance orchards edges. The overarching aim was that these floral resources would increase pollinator and natural enemy populations in apple orchards (that provide the regulating ecosystem services pollination and biological pest control), thereby improving apple yield and quality. Others have also recently targeted both pollination and natural pest control services by floral resource provision (habitat management) to achieve improved crop yields. For example, in cucumbers Quinn *et al.* (2017) aimed to enhance pollinators and natural enemies with the flower treatments: buckwheat, mustard and alyssum, chosen for their known benefits to pollinators or natural enemies. In cider apple orchards, Campbell *et al.* (2017a) found that wildflower strips, with specifically chosen plant species that have an adequate range of floral traits in the mixes, can increase both pollinator and natural enemy abundances.

To alleviate any concern that growers may have of competing floral resources with the apple trees, I selected plants that flower after apple blossom (which typically occurs in late April/early May); *Thymus vulgaris* flowers in June and *Lavandula x intermedia* ‘Sussex’ flowers for a long period, from the end of June to the middle of September. Therefore, together, they can help to provide successional floral resources to pollinator communities after the mass flowering of apple in spring. These shrubby aromatic herbs are also relatively low-maintenance and can simply be planted from pots when an orchard is established. This is ideal as the typical lifespan of lavender matches that of the orchard. These floral resources also have their own economic value; lavender and thyme have a range of uses in culinary, medicinal, and toiletry products so there is the novel potential option of increasing the scale of their planting for harvest as a complementary crop, an opportunity that wildflower provision would not necessarily offer.

5.1.3 Pollinator populations respond positively to lavender and thyme orchard edge treatments

In Chapter 2, I showed that there were more pollinators over the summer months in the orchards with a mixed lavender and thyme orchard edge treatment and these were particularly attractive to wild bees such as bumblebees. There was also a higher wild bee visitation rate to apple flowers in these orchards. This is an important benefit as wild bees are valuable pollinators to apple, contributing more to Gala and to Braeburn apples than managed honeybees alone (Garratt *et al.*, 2016).

5.1.4 The overall effect of lavender and thyme on natural enemies may be masked by agrochemical use and differing sampling methods

Although hoverfly abundance also increased in August in orchards with a mixed lavender and thyme orchard edge treatment (Chapter 2), to affect pest control services, it would need to be determined if there was a specific increase in aphidophagous species. Indeed, further research is needed to identify the potential benefits to natural enemy groups that require nectar or pollen during an aerial adult life stage. The sampling techniques in Chapter 3 were likely insufficient to uncover how ground or tree dwelling natural enemy groups were affected by the orchard edge treatments. There were more earwigs collected on the apple trees by tap sampling in orchards with a lavender orchard edge treatment but this was not consistent with sticky trap sampling (Chapter 3). Overall, it is likely that the effect (be it positive of negative) of lavender and thyme on natural enemy abundances was masked due to agrochemical use in these orchard plots. Indeed the potential of natural enemy populations to contribute to the control of apple pests in commercial non-organic orchards might currently be limited by the use of these agrochemicals.

5.1.5 Orchard edge treatments do not affect apple production in the first two years but could safeguard future apple production through the increase to wild pollinators

I did not find an effect of orchard edge treatment on apple yield or quality (Chapter 4). However, it might take more time than the study allowed in order to see an effect. Other studies show that it has taken at least four years for yield effects in wildlife-friendly farming (Pywell *et al.*, 2015); and three-seven years for additional floral provision nearby to have a significant effect on the crop yields of apple or blueberries, if at all (Bostanian *et al.*, 2004; Blaauw and Isaacs, 2014; Campbell *et al.*, 2017a; Venturini *et al.*, 2017).

The pollinator exclusion experiment (Chapter 4) confirmed that pollination is important in both Braeburn and Gala orchards for fruit set and seed set. Pollination was also important for apple size, but this was variety dependent. Therefore, pollinators in these orchards are playing a crucial role in apple production. The finding from Chapter 2 of increases to wild bee abundance in orchards with mixed lavender and thyme orchard edge treatments shows that enhancing floral resources in orchards can change the pollinator assemblage. This could offer stability to the pollination system if honeybee abundance is variable between years (as observed in Chapter 2), or if conditions during apple blossom are sub-optimal to honeybee foraging. Wild bees can deliver temporal stability to the pollination service for apples as they can forage in lower temperatures than honeybees (Vicens and Bosch, 2000b; Sapir *et al.*, 2017), a trait which can be crucial for apple systems in the UK which flower when climatic conditions might be less than optimum for manged honeybees. Wild bees are also more effective pollinators than managed honeybees (Mallinger and Gratton, 2015) and can improve honeybee pollination through complementarity effects (Brittain *et al.*, 2013b; Sapir *et al.*, 2017). Sustaining wild bee populations in these orchards may also buffer the system from potential species loss. In general, pollination services are likely stabilised with a more diverse pollinator community (Klein *et al.*, 2007). This is because the diversity of bee communities helps to sustain crop pollination despite fluctuations of pollinator community composition over time; the diversity buffers fluctuations in pollinator abundance between years (Kremen and Miles, 2012; Bartomeus *et al.*, 2013). Therefore, the increase of wild bees in orchards with lavender and thyme floral resource provision (Chapter 2) could have future potential apple yield and quality benefits not yet realised (Chapter 4).

5.2 Study Limitations and Suggestions for Future Research

5.2.1 Targeted grower surveys

The sample size of the apple grower survey (Chapter 1, Section 1.8) was quite small and due to the purposive design, the findings are not necessarily representative of the UK top fruit grower population. This method was however fit for the objective of finding out the management practices and perceptions of a select group of top fruit growers, in the study region, regarding drivers of crop loss, pest management and non-crop vegetation. Habitat management needs to be targeted for specific growers in a local land area and their growing systems and conditions in order to be successfully taken up (de Snoo *et al.*, 2013). Therefore, in this case, investigating the views of commercial growers in Kent, who are likely to be the ones deciding whether to implement proposed non-crop habitat enhancement was appropriate. If the aim were to target the practices and perceptions of growers in other parts of the UK, or to draw a comparison from a local area to the whole population, then it would be beneficial to carry out a survey on a nationwide level. There may also be the scope to hold focus groups with different local grower groups which could develop the findings by incorporating a 'willingness to pay' study or a cost-benefit analysis of valuing nature in orchard ecosystems.

5.2.2 Spatial and temporal effects

To ensure that all the orchards were managed in the same way and were under similar climatic conditions, there was a trade-off with the distance between the orchards selected for the study. Future studies that can select orchards with more spatial independence from each other should be undertaken. However, it would need to be ensured that the orchards were still under the same management regime (as they were in this study) because agrochemical use is a major determining factor of arthropod communities (Malone et al., 2018).

Additionally, I did not consider the landscape scale effects in this study as I sampled invertebrates locally to the orchard edge treatment and it was not an objective to assess the effects of landscape composition. Landscape features can however affect populations of natural enemies and pollinators and therefore landscape composition is a potential factor influencing the communities of beneficial invertebrates in these orchards. Additionally, the local composition of existing non-crop vegetation in orchards is likely to affect the invertebrate population dynamics when additional floral resources are added into the system.

This study took place in the few years during and after orchard edge treatment establishment. Although this was sufficient to see an effect on pollinator abundance over the summer months and wild bee visitation rate to apple flowers (Chapter 2), a long-term study would confirm if these effects are sustained. Additionally, as discussed in Chapter 4, yield effects may take years to establish, thus in order to fully understand the effect of the orchard edge treatments on apple production, a study of at least four years is advised.

5.2.3 Pollinator nesting habitat

My novel manipulative experiment focused on enhancing the orchard edge with successional floral resources; however, providing appropriate habitat for nesting is also important for pollinator communities (Potts *et al.*, 2005). Solitary bees are valuable pollinators in fruit tree orchards and their management needs to target not only floral resources but also aspects such as nesting material (Sedivy and Dorn, 2014). For example, *Osmia lignaria* have an increased reproductive success when there are more nest boxes in orchards (Artz *et al.*, 2013) and woody forest edges have been suggested as suitable habitats for nesting for Andrena males (Bailey *et al.*, 2014). For bumblebees, a ‘tussocky’ grass is a habitat of potentially great value because it provides suitable bumblebee nesting sites (Meek *et al.*, 2002). In Chapter 2, I report the observation of solitary bee nests in the sandy soil adjacent to a mixed lavender and thyme orchard edge treatment but the lavender and thyme plants are not necessarily responsible for this occurrence. For example, Sardiñas *et al.* (2016) concluded that hedgerows do not necessarily increase nesting habitat for bees that are ground nesting. It has however been highlighted that there is limited evidence to support the notion that nesting resources limit or increase wild bee abundance if they are implemented in farmland (Dicks *et al.*, 2015), so this area deserves further research attention in an orchard setting.

5.2.4 The effect of lavender and thyme on biological pest control in orchards

As outlined in Chapter 3, the essential oils of both lavender and thyme have been shown to deter a variety of crop pests. It would therefore be interesting to carry out laboratory and greenhouse experiments, with lavender and thyme volatiles and whole plants respectively, to determine their exact attractant/repellent qualities to the various apple pests and natural enemies.

Furthermore, although I examined the orchard edge treatment effects on natural enemy abundance in Chapter 3, to get an idea of the potential pest control service that these communities can provide within the orchards, the pest control service could be measured using either real or artificial sentinel prey. Sentinel prey has been used by others for this purpose, such as Blaauw and Isaacs (2012) and Campbell *et al.* (2017a). The use of sentinel prey is not necessarily representative of the range of pests that natural enemies can control in the orchards; nevertheless, it would give a measurable response of the biological control service.

Moreover, Tscharntke *et al.* (2016) proposed that one of the five reasons that natural habitat provision might not affect biological pest control is that the habitat is insufficient in amount to have an effect. As my orchard edge treatments were only 30 m in length, it would be useful to conduct a future study with lavender and thyme on a larger scale, for example, planted around the entire orchard perimeter.

5.2.5 The interaction of invertebrate mediated pollination and biological control in apple orchards:

In order to investigate the two-way interactive effects of pollination and biological control in dessert apple orchards, a factorial field experiment with open pollination and pollinator exclusion vs. natural enemies and natural enemy exclusion could be carried out. Garibaldi *et al.* (2018) identified only seven studies that evaluated interactions between pollination and pest control on crop yield or quality. This might uncover a synergistic effect, such as in red clover, where the yield is higher with both high pollination and pest control than with either service separately (Lundin *et al.*, 2013). Sutter and Albrecht (2016) have offered a novel explanation for the synergistic interaction effect that they found in oilseed rape for pollination and pest control services. Flower lifetime was shortened by pest presence, resulting in a reduction of pollinator visits to these flowers; the benefit of pollinators is therefore limited by pest presence due to a reduced flowering time (Sutter and Albrecht, 2016). Alternatively, there may be no interactive effects of these ecosystem services in apple, such as in coffee production systems, where pollinators and vertebrate mediated biological pest control increase quality and yield respectively but with no interaction effects between the two regulating ecosystem services (Classen *et al.*, 2014). These studies cover a variety of different crops, yet a knowledge gap remains for apple production as no study has yet to look at these interactive effects for invertebrates in apple orchards (although see Saunders and Luck (2016) who considered vertebrates). Once these interaction effects (or lack of) are understood, it might allow for an even more targeted enhancement of habitat and resources for both pollinators and natural enemies.

5.3 Recommendations

This study implemented a novel way to provide floral resources at the perimeter of apple orchards by planting lavender and thyme to provide successional resources to the beneficial invertebrates responsible for the regulating ecosystem services pollination and biological control.

Mixed orchard edge treatments with both lavender and thyme attracted wild pollinators and increased the visit rates to apple flowers from wild insects and wild bees. Therefore, they are a useful floral resource addition in Braeburn and Gala apple orchards. A combination of further studies or more time is needed to assess if they also increase natural enemies and crop yield/quality. Understanding the current practices and perceptions of some of the local growers in the industry was significant to the direction of the ecological study design.

In the following sections I make recommendations of how the commercial sponsor Sainsbury's could collaborate with growers to encourage efficient design of non-crop vegetation in orchards for beneficial invertebrates.

5.3.1 Collaboration with growers and grower groups

Commercial customers should collaborate with farmers and growers to ensure that they are making the most of their farms' non-crop areas within the confines of what is possible in their farming system and to help them to identify their own opportunities for improvement onsite to enhance beneficial invertebrate populations. de Snoo *et al.* (2013) argue that agricultural biodiversity should be placed "in the hands and minds of farmers" and if the knowledge is derived from the farmers' themselves, instead of simply imposed upon them by others, then it may enable a 'degree of social legitimacy' to conservation knowledge by incorporating the farmers' perspective. This could lead to a more efficient uptake of wildlife-friendly measures, as the growers themselves would be pivotal to the design of the habitat enhancements.

Furthermore, working collectively with groups of growers, rather than individuals, could help to identify possible synergies of opportunities to enhance the landscape as a whole, as well as their individual local land. To achieve sustainable agriculture on a landscape scale, individuals must cooperate, or their efforts must coordinate in a way that positively benefits the landscape (Pretty et al., 2018). Collective social learning could allow them to adapt these methods over time in a flexible manner in the face of potentially volatile environmental, as well as social and political conditions (Pretty *et al.*, 2018).

There is often a discrepancy between expert biodiversity knowledge and public/farmer awareness; in the past, some farmers were unfamiliar with terms such as biodiversity and wildlife corridors unless they had received advice from an expert (Oreszczyn, 2000; Oreszczyn and Lane, 2000). Establishing and maintaining successful grower groups will therefore also allow for the easy transfer of knowledge from the research community. Grower meetings could provide the ideal place in which to convey the scientific evidence behind beneficial habitat enhancements; which some growers explicitly stated they would need in order to implement measures such as wildflower strips (Chapter 1, Section 1.8). This could also help to improve their knowledge surrounding the need for successional floral resources (such as lavender and thyme) to sustain diverse native pollinator communities in case of a future managed honeybee decline or pollination inefficiency.

A good connection with growers would also allow updates to be shared on the current issues facing the implementation of resource enhancement. For example, there is currently a risk of the bacterial plant disease *Xylella* entering the UK. When the project was conceived this was not an emerging UK threat but with clear information on the high risk hosts (DEFRA, 2018) that include some lavenders, growers should be recommended to source only UK lavender, as was done in this study (although note that DEFRA & APHA (2018) do provide further information and guidance for importers).

5.3.2 Identifying leaders for implementation

The 'small' size of the UK grower network and the prevalence of growers copying their neighbours' management regimes (Chapter 1, Section 1.8), supports the conclusions of previous farmer interviews (Brodt *et al.*, 2009) where it became clear that socially influential farmers could collaborate with public and private agencies to raise awareness and build support in the industry for these habitat management implementations. A recent survey of landholders in California's Sacramento Valley also found that most farmers implementing field edge plantings had communication networks, indicating the crucial role that leaders provide by promoting new practices to fellow landholders (Garbach and Long, 2017). This includes farmers who have implemented field edge plantings as leaders and organisational representatives that help the 'leading' farmers to achieve field edge implementation (Garbach and Long, 2017). Therefore, if supermarkets or researchers can identify and collaborate with socially influential farmers, then the likelihood of others adopting these measures could increase, as they would be able to see the measures in place in a real farm situation. In this way, novel measures such as the planting of lavender and thyme at the orchard edge could potentially be adopted by the industry as the new standard practice.

5.3.3 Relaying the economic value of ecosystem services from lavender and thyme in apple orchards and implementing economic incentives: a one-off start-up payment method to boost uptake

In addition, a clear economic benefit of an ecosystem service can inform management decisions and policy. In apples, the economic contribution of pollinators to only two varieties of UK apples

(Cox and Gala) has been calculated at £36.7 million per annum (Garratt *et al.*, 2014) and individual pollinator guilds have been estimated to contribute different amounts to apple; wild bees contribute £70.7 million per year to four UK apple varieties whereas honeybees contribute £21.4 million (Garratt *et al.*, 2016). These economic valuations give researchers and growers motivation to invest time and money in the development of management strategies for wild bees.

Even if landholders already recognise that enhanced field edges are beneficial to the environment and provide habitat for wildlife, pollinators and natural enemies, they might not be aware of the potential economic benefit to their production system in terms of the regulating services that they provide. The research area of pollination services and natural pest control services attributing to increased yield, quality and ultimately farm profit is quite recent and may yet to have crossed the border from scientific literature into the knowledge base of growers (Garbach and Long, 2017).

The economic viability of habitat management, such as lavender and thyme floral resource provision in this thesis, could be assessed if ecosystem services are given a monetary value. To increase the farmer uptake of lavender and thyme planting, it might be necessary to carry out an economic cost-benefit analysis. For example, Morandin *et al.* (2016) led the way for combined pest control and pollination valuations in this respect by carrying out a cost-benefit analysis of hedgerow implementation. They considered the return time for the beneficial impacts on natural pest control and pollination services in adjacent crops to outweigh the costs of instillation. The data used for the cost-benefit model were insecticide reduction and pollination increase but economic valuation can be achieved via many methods: just a few of which are: crop price, dependence ratios, and replacement costs (see Breeze *et al.* (2016) for a full comprehensive review and critique of economic valuations for pollination services).

Furthermore, it has long been postulated that farmer incentives are important for the uptake of sustainable intensification (Tilman *et al.*, 2002); an initial economic investment might therefore also be required to provide an incentive for farmers who may not see the benefit of these habitat conservation measures for a number of years after implementation. Once established though, there should not be a need for continual payments because it will eventually provide the benefit itself via increased ecosystem services on-site.

English agriculture has not yet reached sustainable intensification, as biodiversity on farmland is yet to recover from the degradation that initial conventional crop intensification delivered (Armstrong McKay *et al.*, 2018). More work must be done across the range of farming systems in the UK to ensure that post-Brexit we continue to strive for biodiversity improvements whilst maintaining and increasing yields. One way that this could be done is via educating growers on the potential economic return they could see from personally investing in wildlife-friendly farming in terms of the benefit to ecosystem services that underpin their production. Additionally, commercial retail customers i.e. supermarkets could invest in start-up incentives for volunteer 'leader' growers to implement the measures, thereby increasing social learning and the likelihood of others taking up these measures.

The original overarching aim of this research was **to formulate and test a novel way to enhance orchard edges with successional floral resources for pollinators and natural enemies in order to protect and improve the pollination and pest control services to UK dessert apples.** To achieve this aim, several objectives were set out within Chapter 1 (see Table 1.8) which have been addressed within this thesis. By first identifying the current practices and perspectives of a select group of commercial top fruit growers on crop loss, pest control strategies and non-crop vegetation in orchards (Chapter 1, Section 1.8), I designed a novel manipulative experiment providing successional perennial floral resources at the orchard edge (Chapter 2-4). The orchard edge treatments of mixed lavender and thyme floral resources were shown to increase wild pollinator abundances in orchards and pollination services (wild bee visitation rates) to apples (Chapter 2). It was more difficult to determine a clear orchard edge treatment effect on natural enemies within the crop trees (Chapter 3). Sampling natural enemy populations in the crop trees themselves might not be indicative of the potential effects (positive or negative) as these populations are subjected to agrochemical applications. Although no effects of orchard edge treatment on apple yield or quality were detected up to two years after establishment (Chapter 4), the effect of pollinator exclusion during apple blossom demonstrated the importance of invertebrate pollinators to apple production (Chapter 4). This indicated that the increase in wild pollinator abundances in the orchards and wild bee visitation rates to apple flowers could provide future stability to the apple production system. Relaying the possible long-term ecological benefits of non-crop vegetation to crop production systems and working with growers to encourage their own design of habitat enhancements for beneficial invertebrates on-site is recommended.

Appendix A Land Management for Ecosystem Services in Orchards - a survey of a commercial top-fruit supplier grower group

Section 1. Farm details

Question 1.1 What is the name of the farm where you work?

Question 1.2 What are the business postcodes of the orchards that belong to the farm that you are responsible for/working with?

Question 1.3 How long have you managed the orchard for?

Question 1.4 Has it been managed within the family for generations?

Section 2. Orchard Type and Important Information

Question 2.1 What varieties are currently grown on your particular orchard/farm? (please tick all that apply)

- Braeburn
- Bramley
- Conference
- Cox
- Discovery
- Doyenne du Comice
- Egremont Russet
- Fuji
- Gala
- Kanzi
- Rubens

- Spartan
- Worcester Pearmain
- Zari
- Other

Question 2.2 Please state any other varieties that you grow that are not on the list above:

Question 2.3 How many trees do you have per hectare? If possible, by variety.

Question 2.4 What is your current yield per hectare? If possible, by variety.

Question 2.5 Relative to each other, how frequently do you have wastage/loss of yield due to the following:

	Every season	Every 2-3 years	Every 4-5 years	Every 6 years or more	Never	Don't know
Disease	☐	☐	☐	☐	☐	☐
Drought	☐	☐	☐	☐	☐	☐
Flooding	☐	☐	☐	☐	☐	☐
Frost	☐	☐	☐	☐	☐	☐
Hail	☐	☐	☐	☐	☐	☐
Pest Species	☐	☐	☐	☐	☐	☐
Wind	☐	☐	☐	☐	☐	☐

Question 2.6 Please give any details or comments about your apple crop wastage here:

Section 3. Windbreaks - Type and Opinion

In this section the questions will focus on the non-crop trees present on the orchard. The term windbreak refers to the non-crop trees within the orchard that are primarily in place to shelter the fruit trees from the wind. The terms boundary hedges and hedgerows refer to the trees, shrubs and other plants around the edge of the orchard.

Question 3.1 Does your particular farm currently have windbreaks in place within the orchard?

- ○ Yes
- ○ No
- ○ Don't Know

Question 3.2 If there are currently windbreaks in place within the orchard, what type of windbreaks are they? Please give as much detail and be as species specific as possible.

Question 3.3 Does your particular farm currently have boundary hedges/trees in place around the orchard perimeter? (These may otherwise be thought of as hedgerows).

- ○ Yes
- ○ No
- ○ Don't Know

Question 3.4 If there are currently boundary hedges/trees in place around the orchard edges, what type are they? Please give as much detail and be as species specific as possible.

Question 3.5 Please choose the reason(s) that best explains why the windbreaks and hedgerows are the type that they are:

	Windbreaks	Hedgerows
They were already there before you were involved with the orchard	○	○
Beneficial species such as natural pest control were considered when choosing what to use	○	○
Pollinators were considered when choosing what to use	○	○
You heard from an external source that a certain type was best	○	○
Other	○	○

Question 3.6 Please give any additional comments on the choice of windbreak or hedgerows used here:

Question 3.7 In addition to their use in preventing wind damage, please choose any of the following that windbreaks may play a useful role in:

- ☐ Natural pest control
- ☐ Pollinator species
- ☐ Efficient pesticide application
- ☐ Wood-fuel

Question 3.8 Please give any other opinions that you have about the use and role of windbreaks in apple orchards here:

Question 3.9 Please give any other opinions that you have about the use and role of hedgerows in apple orchards here:

Section 4. Pest Control and Pollination

Question 4.1 Please tick how often these pests are present in your apple orchards:

	Every Season	Once every 2- 3 years	Once every 4-5 years	Once every 6 years or more	Never	Don't Know
Codling Moth	☐	☐	☐	☐	☐	☐
Apple sawfly	☐	☐	☐	☐	☐	☐
Red Spider Mite	☐	☐	☐	☐	☐	☐
Scale Insects	☐	☐	☐	☐	☐	☐
Wooly Aphid	☐	☐	☐	☐	☐	☐
Winter Moth Caterpillars	☐	☐	☐	☐	☐	☐

Other Aphids	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐

Question 4.2 Please state any 'other' pests that cause damage in your orchards that are not listed above and give any general comments on the above pests here:

Question 4.3 Please estimate your average % loss of yield each year due to these pest species

Pest Species:	Average % Loss of Yield:
Codling Moth	
Apple Sawfly	
Red Spider Mite	
Scale Insects	
Wooly Aphids	
Winter Moth Caterpillars	
Other Aphids	
Other	

Question 4.4 Have you previously had any problems with particular pests (such as those from the previous list) that have now been resolved? Please explain what the pests were and the measures taken to manage them.

Question 4.5 What types of pest management do you currently implement in your orchards? (For example: pesticides, pest mating disruption traps, encouragement of natural enemies, release of natural enemies, etc.)

Question 4.6 If pesticides are used, please can you give an indication of the type and the times of year that they are applied.

Question 4.7 What measures (if any) do you currently take to encourage the potential natural enemies/biological control of pests (e.g. the use of 'earwig sanctuaries')?

Question 4.8 If you currently sow wild flowers in your orchards, where are they sown?

☐ Middle of the rows

☐ Around the orchard edges

☐ As part of the windbreaks

☐ On adjacent land

☐ Other

☐ No wild flower mixes sown

☐ Don't know

Question 4.9 Please use this space to explain what you mean if you chose 'other' and also to give any additional comments on the use of wild flower strips:

Question 4.10 If you do not currently sow wild flowers, please choose all the reasons that apply:

☐ Too expensive to put in place

☐ Too time consuming to put in place

☐ Not enough workers available to do so

☐ Don't see the benefit of doing so

☐ Don't want to have to manage them

☐ Don't know

Question 4.11 Please give any additional detail and explain here why you do not currently sow wild flowers if none of the above choices are suitable:

Thank you for completing the survey. Please put the completed consent form and survey into the stamped and addressed envelope provided.

If you are happy to be contacted for further research into improving the effectiveness of land management in apple orchards please tick here

Please feel free to provide any comments or details here on how you would prefer to be contacted (e.g. by phone, e-mail or post):

For any further information about the use of this survey and the research project, please do not hesitate to contact Emma by e-mail on ej4g11@soton.ac.uk

Appendix B Land Management for Ecosystem Services in Orchards – a follow-up semi-structured interview

At the beginning of the interview I will introduce myself and present them with an interview consent form which would be identical to the consent form that they would have completed for their participation in the survey. Before I ask them any questions I will ensure that they have the opportunity to ask any questions that they would like answered about the survey or about the study in general. The interview will be semi-structured (mostly focusing on their answers to the survey) and will not be recorded.

The following questions will be asked relating to the sections of the completed survey:

Section 1. Farm details

- Ambiguous answers?
- Clarify how many different sites the farm has.
- Involvement of the person who is being interviewed in the management of that farm.
- Farm History – family history if they want to talk about it.

Section 2. Orchard Type and Important Information

- Clarify why certain varieties are grown on that particular farm
- Are different varieties are grown at different sites?
- Clarify any ambiguous answers to questions 2.3 and 2.4 regarding the apple tree per hectare and yields per variety.
- Elaborate on causes of yield loss.
- Elaborate on crop wastage.

Section 3. Windbreaks - Type and Opinion

- If there are not windbreaks/hedgerows in place (i.e. they answer no to question 3.1) I will ask them to explain why.
- If they do have windbreaks/hedgerows I will clarify what type they are and how they are managed and the cost of management.

- Why certain windbreaks/hedgerows are used and their opinions of what they are useful for.
- Opinions on whether windbreaks/hedgerows have any potential negative effects.

Section 4. Pest Control and Pollination

- Occurrences of specific pests that they mention in their survey response.
- Elaborate on any historic pest problems and their opinions on the successful management of these.
- The implemented integrated pest management practices and the costs of certain management choices.
- I will ask their opinions about the use of wild flower mixes in and around orchards.
- I will ask about whether they are involved with any agri-environment schemes.

They will have a chance to discuss any other opinions that they have regarding the project and the use of non-crop trees to enhance pollination and natural pest control within the orchards. They will be welcomed to make any suggestions that they wish to about this research.

I will ask them if they would like to be involved further with the research. For example, there may be the possibility of me carrying out some observational field-work on their farms which would include methods such as tree/plant species identification, measurements and insect sampling.

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