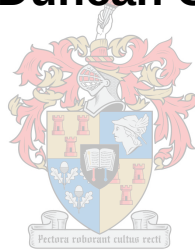


The influence of local and landscape factors on arthropod predator diversity in the Sundays River Valley, Eastern Cape, South Africa

by

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1918-2018

Thesis presented in partial fulfilment of the requirements for the degree of
Master of Science

at

Stellenbosch University

Department of Conservation Ecology and Entomology,
Faculty of AgriSciences

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April 2019

DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: 11/02/2019

SUMMARY

Globally, agriculture is under pressure to feed the increasing human population, leading to greater cropland extensification and intensification. This has numerous negative impacts on both cropland and native biodiversity, including arthropod predators (which refer to both arthropod predators and parasitoids within this study). Much of the research investigating the influence of management and landscape factors on the predator complex has taken place in highly transformed, less-biodiverse developed countries relative to biodiverse developing countries. This, in combination with both high population growth rates and climate change impacts predicted for developing countries (particularly sub-Saharan Africa), emphasises the need for greater research in these regions.

This study therefore aimed to determine whether, and to what extent, local and landscape factors influence arthropod predators in the Sundays River Valley, Eastern Cape, South Africa. The predator complex between citrus orchards (conventional and organic) with and without neighbouring natural vegetation was investigated, in addition to their environmental drivers. The presence of natural vegetation bordering alongside citrus orchards (either conventional or organic) was also investigated to determine whether it has an influence on the predator complex across the natural vegetation-orchard edge.

The influence of local farm management (organic and conventional) was greatest in simpler landscapes, where organic farming was significantly associated with greater predator species richness, abundance and diversity. This was associated with an increase in cover crop and soil surface heterogeneity which provides habitat, shelter and food resources to predators. Natural vegetation, interestingly, increased environmental heterogeneity at the landscape scale and subsequently was associated with greater predator species richness in neighbouring conventional but not organic orchards. Edges between natural vegetation and orchards influenced the predator complex of both habitats. Total, ant and wasp species richness, and wasp abundance increased towards the natural vegetation-orchard edge, whilst beetle species richness and diversity increased in natural vegetation near the edge. Edges between natural vegetation and orchards can therefore be detrimental for native biodiversity in neighbouring natural vegetation.

Local and landscape factors were thus found to significantly influence arthropod predators, with organic farming techniques and the presence of natural vegetation being associated with improvements in the predator complex. Conservation and restoration of well-managed and highly connected natural vegetation in the agricultural landscape can promote the predator complex in cropland whilst limiting negative edge effects on native biodiversity.

OPSOMMING

Die landbou is wêreldwyd onder druk om die toenemende menslike bevolking te voed, wat lei tot groter extensivering en intensivering van die land. Dit het talle negatiewe impakte op beide gewasland en inheemse biodiversiteit, insluitend geledpotige roofdiere (wat verwys na beide geledpotige roofdiere en parasitoïede in hierdie studie). Baie van die navorsing wat die invloed van bestuurs- en landskapsfaktore op die roofdierkompleks ondersoek het, het plaasgevind in hoogs getransformeerde, minder-biodiverse ontwikkelde lande relatief tot ontwikkelende lande met hoë vlakke van biodiversiteit. Dit, in kombinasie met beide hoë bevolkingsgroeikoerse en klimaatsveranderings-impakte wat voorspel word vir ontwikkelende lande (veral Afrika suid van die Sahara), beklemtoon die behoefte aan groter navorsing in hierdie streke.

Hierdie studie het dus daarop gemik om te bepaal of en in watter mate plaaslike en landskapsfaktore geledpotige-roofdiere in die Sondagsriviervallei, Oos-Kaap, Suid-Afrika beïnvloed. Die roofdierkompleks tussen sitrusboorde (konvensioneel en organies) met en sonder naburige natuurlike plantegroei is, benewens invloedryke omgewingsveranderlikes, ondersoek. Die teenwoordigheid van natuurlike plantegroei langs langs sitrusboorde (konvensioneel of organies) is ook ondersoek om vas te stel of dit 'n invloed op die roofdierkompleks het oor die natuurlike plantegroei-sitrusboord grens.

Die invloed van plaaslike plaasbestuur (organies en konvensioneel) was die grootste in eenvoudiger landskappe, waar organiese boerdery aansienlik geassosieer word met groter roofdierspesies-rykheid, talrykheid en diversiteit. Dit is geassosieer met 'n toename in dekkingsgewas en grondoppervlak heterogeniteit wat habitat, skuiling en voedselhulpbronne aan roofdiere bied. Natuurlike plantegroei het omgewings heterogeniteit op die landskapskaal verhoog en is gevolglik geassosieer met groter roofdiere spesiesrykheid in naburige konvensionele maar nie organiese boorde nie. Grense tussen natuurlike plantegroei en boorde het die roofdierkompleks van beide habitatte beïnvloed. Totale, mier- en wesp-spesies rykheid, en wesp-talrykheid het toegeneem teenoor die natuurlike plantegroei-grens, terwyl die kewerspesiesrykheid en diversiteit in natuurlike plantegroei naby die grens toegeneem het. Grense tussen natuurlike plantegroei en boorde kan dus nadelig wees vir inheemse biodiversiteit in naburige natuurlike plantegroei.

Plaaslike- en landskaps-faktore is dus gevind om 'n aansienlike invloed op geledpotige roofdiere te hê, met organiese boerdery tegnieke en die teenwoordigheid van natuurlike plantegroei wat verband hou met verbeterings in die roofdierkompleks. Bewaring en herstel van goed bestuurde en hoogs verbonde natuurlike plantegroei in die landbou landskap kan die roofdierkompleks in gewasland bevorder, terwyl negatiewe grenseffekte op inheemse biodiversiteit beperk word.

DEDICATION

This thesis is dedicated to:

My Lord and Saviour, Jesus Christ

My loving family

My late friend, Stephen Cousins (20-11-1986 – 16-06-2018)

ACKNOWLEDGEMENTS

I gratefully thank the following people and organisations:

- My Lord and Saviour, Jesus Christ, without whom none of this would have been possible. Isaiah 40 : 31 – “But those who trust in the Lord for help will find their strength renewed. They will rise on wings like eagles; they will run and not get weary; they will walk and not grow weak.”
- My family for their love, support and encouragement from start to finish.
- My friends for keeping me sane during this period.
- Dr James Pryke, Dr René Gaigher and Dr Colleen Seymour for their valuable support, guidance, insight and positivity.
- My funders, South African National Biodiversity Institute (SANBI), Stellenbosch University, Ernst & Ethel Eriksen Trust and NRF Global Change Grant.
- The Sundays River Citrus Company (SRCC), particularly Andre Combrink, and affiliated farmers for their abundant support, patience and farm access.
- The Sundays Organic Growers Association (SOGA) farmers and managers for their enthusiasm, support, patience and farm access.
- Stephan Gericke and Oliver Hansen for their field assistance, positivity and perseverance through the heat, thorns and long drives.
- Liesel Kets, Adionah Chiomadzi, Alheit du Toit and Alexander Heiberg for diligent laboratory assistance.
- The Stratford family for their generous Eastern Cape hospitality, love and support.
- Charles Marais and Joe Pringle for their interest, patience, plant identification assistance and farm access.
- San Miguel for farm access to their thicket areas.
- XSIT for their assistance and delivery of sterile False Codling Moth (FCM) egg sheets to the Sundays River Valley.
- Chempac for delta traps, sticky pads and FCM lures.
- Department of Conservation Ecology and Entomology administrative staff for their patience and assistance.
- Mathew Addison for his advice on the sentinel egg approach.
- Department of Economic Affairs, Environment and Tourism (Province of the Eastern Cape) for the sampling permit (permit number: CRO 51/17CR and CRO 52/17CR).

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Chapter 1

General introduction

1.1 Impacts of global agricultural growth

There is increasing pressure worldwide on agriculture to feed the rapidly growing human population (Godfray et al. 2010). Over a decade ago, as much as 40% of the Earth's terrestrial biomes served as cropland or pasture to meet this need (Foley et al. 2005). As agricultural intensification and expansion occurs, so too do its environmental impacts, causing a rise in species extinctions worldwide (Tilman 1999, Tilman et al. 2001, Tscharntke et al. 2005a, Geiger et al. 2010). Agriculture impacts natural ecosystems in a number of ways, through habitat destruction, fragmentation as well as chemical contamination through fertilizer and pesticide use on crops (McLaughlin and Mineau 1995, Tilman 1999, Stoate et al. 2001, Tilman et al. 2001, Donald and Evans 2006). These chemicals can disseminate into the surrounding environment and lead to long-term negative effects such as loss of biodiversity, contamination of water sources and direct negative impacts on human health (Pimentel et al. 1992, Tilman 1999, Stoate et al. 2001, Wilson and Tisdell 2001, Geiger et al. 2010). An additional disadvantage is that the continual application of pesticides can select for resistance to pesticides amongst pest species, which subsequently increase in abundance and impact until a new pesticide is required, to which the pest then also develops resistance and so the cycle continues (Pimentel et al. 1992, Wilson and Tisdell 2001). This cycle, known as the 'pesticide treadmill', often requires increasingly harmful chemicals to be used, and in greater quantities, as pests develop resistance (Thrupp 2000, Wilson and Tisdell 2001). These agricultural impacts, habitat loss and pesticide usage, lead to the simplification of biodiversity in the landscape and can reduce ecosystem functioning (Tilman et al. 2001, Kremen et al. 2002, Tscharntke et al. 2005a, Geiger et al. 2010).

1.2 Functional diversity

Biodiversity can be seen to consist of a number of components which can be viewed at various scales, namely genotypes (at the smallest scale), species, functional types and landscape units (at the largest scale) (Noss 1990). The diversity and composition of one of these components, functional types, can greatly impact on and determine ecosystem processes and functioning in the environment (Tilman et al. 1997, Díaz and Cabido 2001, Tilman 2001). Ecosystem functioning, which includes plant production, nutrient cycling and predation, is performed by organisms interacting with their environment (Tilman 2001). Species can be

classified into functional types based on the effect they have on ecosystems, such as herbivores, detritivores and predators (Tilman 2001). Although functional diversity is a complex concept and has many definitions, it can be seen as the array of things that organisms do in the broader scale of ecosystems and communities, and subsequently can be an important measure of the influence of organisms on ecosystems (Petchey and Gaston 2006). Increased diversity both across and within functional types can stabilise ecosystems against changes in environmental conditions and improve ecosystem functioning through species complementarity (Tilman et al. 1997, Díaz and Cabido 2001, Tilman 2001, Hooper et al. 2005, Tscharrntke et al. 2005a, Greenop et al. 2018). An increase in diversity within functional types further stabilises ecosystem functions, such as biological control, across space and time in the event of species loss or disturbance (Tscharrntke et al. 2005a, Macfadyen et al. 2011). Farmers can promote and stabilise ecosystem functioning on their farms by maintaining a high level of environmental heterogeneity as well as providing the necessary resources needed for species survival and population growth (Gurr et al. 2003, Bianchi et al. 2006, Isaacs et al. 2009).

1.3 Land sharing and land sparing

Landowners have usually taken either one of two options to achieve higher environmental heterogeneity and provision of resources to biodiversity in farmland: namely, a 'land sparing' approach or a 'land sharing' approach (Fischer et al. 2008, Grau et al. 2013). 'Land sparing' emphasises conserving separate areas of land purely for biodiversity conservation whilst the remaining land is farmed intensively for maximum yield production (Fischer et al. 2008). This approach is particularly suitable to those species that are highly sensitive to agricultural disturbance (Grau et al. 2013). Alternatively, 'land sharing' emphasises the integration of biodiversity conservation with agricultural production by maintaining diversity (for example: species, vegetation and habitat diversity) across the entire farmed area (Fischer et al. 2008). Species targeted for conservation would need to be adapted to agricultural disturbance in order for this approach to be successful (Grau et al. 2013).

Both 'land sparing' and 'land sharing' have their own respective advantages and disadvantages and are heavily dependent on the landscape and socioeconomic context (Fischer et al. 2008, Grau et al. 2013, Ekroos et al. 2016). Combining land sparing and land sharing can potentially provide a number of complementary benefits such as conserving functional biodiversity in remnant natural habitat areas, maintaining biodiversity across cropland and allowing for sustainable production of food (Fischer et al. 2008, Tscharrntke et al. 2012a).

1.4 Benefits of organic agriculture for arthropod predator diversity

Organic agriculture, which excludes the use of chemical pesticides and fertilizers in agricultural practices, is a farming method known to usually benefit biodiversity when compared to conventional agriculture (Kremen et al. 2002, Aude et al. 2003, Hutton and Giller 2003, Bengtsson et al. 2005, Birkhofer et al. 2008, Gomiero et al. 2011, Tuck et al. 2014, Lichtenberg et al. 2017, Katayama et al. 2019). Predator species richness, abundance and evenness in particular can benefit from this environmentally friendly farming approach (Bengtsson et al. 2005, Birkhofer et al. 2008, Crowder et al. 2010, Inclán et al. 2015, Lichtenberg et al. 2017, Djoudi et al. 2019). The term predator refers to both predators and parasitoids within this study.

Pesticides can have a substantial impact on predators by reducing their abundance, and can trigger secondary pest outbreaks due to the reduction of predators in the agroecosystem (Theiling and Croft 1988, Pimentel et al. 1992, Van Hamburg and Guest 1997). Pesticides tend to bioaccumulate in species at higher trophic levels such as predators, resulting in poor development and mortality (Fry 1995, Gerber et al. 2016). Of the array of pesticides, organo-phosphates, carbamates and synthetic pyrethroids have the highest toxicity and therefore cause high levels of predator mortalities (Theiling and Croft 1988). Reducing pesticide usage is therefore a highly effective way of improving field conditions for predators (Zehnder et al. 2007, Geiger et al. 2010, Rusch et al. 2010, Baba et al. 2018). In addition, habitat management techniques, such as increasing environmental heterogeneity and amount of non-crop habitat, provides predators with resources such as alternative prey or hosts, nesting sites, shelter from disturbances, nectar and pollen which can increase their diversity and abundance in the agroecosystem (Landis et al. 2000, Bianchi et al. 2006, Jonsson et al. 2008, Rusch et al. 2010). Increased predator diversity can help to stabilise the ecosystem function of pest control in the landscape and region following disturbances and during environmental change when species ranges either expand or contract as is predicted to happen during climate change (Tscharntke et al. 2005a, 2007, Lin 2011). More diverse assemblages of predators in cropland can potentially prevent the establishment of new pest species and provide a resilient biological barrier to new pest species outbreaks (Lin 2011).

Groundcover between crop rows in organic agriculture (consisting either of sown or naturally present weedy species) can provide predators with the resources and habitat required to survive, ability to move within and across the crop matrix, and increase their population size (Gurr et al. 2003, Altieri et al. 2005, Berndt and Wratten 2005, Danne et al. 2010, Silva et al. 2010). Organic farming (which generally applies manure, compost, mulch, cover cropping or a combination of these methods) additionally improves both soil and water

conservation owing to greater soil carbon concentrations associated with organic farming practices (Gomiero et al. 2011). Organic agriculture therefore falls under the 'land sharing' narrative of integrating agricultural production with biodiversity conservation (Fischer et al. 2008, Phalan et al. 2011).

1.5 Conserving non-crop habitat to improve arthropod predator diversity and connectivity in the agricultural landscape

In agroecosystems, non-crop habitat can improve predator survival (Landis et al. 2000). Conserving and restoring non-crop habitat on farms and in the agricultural landscape greatly increases non-crop habitat heterogeneity and connectivity (Bianchi et al. 2006, Donald and Evans 2006). This can improve and maintain a high diversity and abundance of predators in the agricultural landscape (Bianchi et al. 2006, Chaplin-Kramer et al. 2011, Gaigher et al. 2015, Šálek et al. 2018). An increase in landscape complexity can benefit both predator generalists and specialists (Chaplin-Kramer et al. 2011). Generalist predators illustrate strong positive responses to landscape complexity at a wide array of scales, whilst predator specialists (for example: parasitoids) illustrate a stronger positive response to landscape complexity at smaller scales (Chaplin-Kramer et al. 2011). Non-crop habitats include sown floral strips or islands, beetle banks, hedgerows or other vegetation corridors which aim to provide predators with essential resources such as nectar, pollen, shelter as well as alternative host or prey species (Landis et al. 2000, Collins et al. 2002, Pfiffner and Wyss 2004, Altieri et al. 2005). Non-crop habitats may also provide resources and refugia to crop pests, especially polyphagous species, however, which can lead to pest populations that are able to persist in the agricultural landscape (Macfadyen et al. 2015). Conserving areas of non-crop habitat separate from intensified cropland can be seen to fall under the 'land sparing' narrative that separates agricultural production from biodiversity conservation (Fischer et al. 2008).

Remnant natural vegetation can provide important non-crop habitat for predator species and can be a vital source of predators to neighbouring agricultural fields (Bianchi et al. 2008, Thomson and Hoffmann 2009, 2013, Thomson et al. 2010). As agricultural intensification increases and natural vegetation decreases, a shift in the predator to prey ratios can occur with higher predator-prey ratios in traditional agriculture transitioning to low predator-prey ratios in intensified agriculture (Klein et al. 2002).

Predators are generally known to disperse across the non-crop – crop interface with species either moving towards crop areas or to non-crop areas (Duelli et al. 1990, Tscharrntke et al. 2005b, Rand et al. 2006, Blitzer et al. 2012, Macfadyen and Muller 2013, Frost et al. 2015). Predator dispersal into crop areas usually follows a pattern of decreasing predator

diversity and abundance as the distance from the non-crop habitat increases (Altieri and Schmidt 1986, Thies and Tscharntke 1999, Miliczky and Horton 2005, Sackett et al. 2009, Thomson and Hoffmann 2009, Henri et al. 2015, Boetzi et al. 2019). The successful dispersal of predators often depends on the agricultural matrix being hospitable enough for predators to survive in, otherwise they may be isolated in non-crop habitats and potentially experience a decrease in species richness due to local extinction debt (Kuussaari et al. 2009, Gaigher et al. 2015).

An often understudied perspective of predator movement and assemblage dynamics between non-crop and crop habitats, is the movement of predators into non-crop habitats from cropland (Blitzer et al. 2012). Due to the generally higher productivity of cropland in comparison to non-crop habitat, predators that build up large cropland populations, can spillover into nearby non-crop habitats (Tscharntke et al. 2005b, Rand et al. 2006, Frost et al. 2015). This can potentially have numerous adverse effects on native biodiversity in non-crop habitats, such as increased predation and parasitism of native herbivores (Tscharntke et al. 2005b, Rand et al. 2006, Blitzer et al. 2012, Frost et al. 2015).

1.6 The interaction of local management practices and landscape complexity on arthropod predators

The relative influence of different farming practices on the predator complex is likely to vary greatly depending on the surrounding landscape complexity. High agricultural landscape complexity, associated with the presence of non-crop areas, can promote the predator complex in nearby cropland, with local crop management practices potentially having a minor effect (Purtauf et al. 2005, Schmidt et al. 2005, Tscharntke et al. 2005a, Bianchi et al. 2006). Similarly, local crop management practices should not influence the predator complex in simple landscapes with very little remaining non-crop habitat as the predator complex is generally depauperate throughout the landscape (Tscharntke et al. 2005a). According to the intermediate landscape-complexity hypothesis, however, the influence of local crop management on the predator complex should be greatest in landscapes with intermediate complexity (Tscharntke et al. 2005a, 2012b).

Research on biodiversity and predator dynamics in perennial crops of the biodiverse, developing world is sparse when compared to the amount of studies on annual crops in transformed, developed countries (Tuck et al. 2014, Katayama et al. 2019). It is therefore important to investigate whether the biodiversity responses to farm management and landscape context that have been recorded in northern temperate countries hold in biodiverse areas of the world. The developing world, particularly Africa, is predicted to experience high

human population and diet growth in the coming years which will require reciprocal agricultural growth (Tilman et al. 2001, Godfray et al. 2010, Gerland et al. 2014). In addition, developing countries are heavily-dependent on agriculture and therefore vulnerable to future climate change effects (Rosenzweig and Parry 1994, Schmidhuber and Tubiello 2007). This emphasises the importance of investigating and implementing sustainable farming and landscape practices in developing countries to ensure both sufficient food production and biodiversity conservation.

1.7 The South African citrus industry

As of 2017, the South African citrus industry occupies an area of 74 902 hectares with the highest hectarage occurring in the Limpopo (32 334 ha), Eastern Cape (20 171 ha) and Western Cape (12 960 ha) provinces (Citrus Growers' Association of Southern Africa, 2018). The major citrus varieties grown in the northern region of South Africa are Valencias and Midseasons whilst in the southern region it is Navels (Citrus Growers' Association of Southern Africa, 2018). The majority of citrus fruit is exported overseas with 1.845 million cartons being exported in 2017 alone, yielding R17.7 billion in export revenue and highlighting the importance of this industry to the South African economy (Citrus Growers' Association of Southern Africa, 2018).

The landscape of the Sundays River Valley (Eastern Cape, South Africa) consists of highly transformed areas along the valley base, the majority of which are citrus farms, whilst the valley sides remain largely untransformed with large areas of remnant natural vegetation (thicket). Citrus farms, however, continue to expand into these neighbouring areas of remnant natural vegetation, resulting in increasing amounts of natural habitat destruction and transformation. The Albany Thicket Biome is a highly biodiverse region with many rare and endemic species, particularly geophytic and succulent plants, and subsequently falls within the Albany Centre of Floristic Endemism (Victor and Dold 2003, Hoare et al. 2006). However, it has a long history of mis-management and is still faced with many threats, including cultivation, urbanisation and over-grazing, which have destroyed or degraded the majority of thicket (Lloyd et al. 2002). The combination of high biodiversity, endemism and habitat destruction within the Albany Thicket Biome resulted in it being classified within the Maputaland-Pondoland-Albany Biodiversity Hotspot, and therefore stresses the importance of this region for global biodiversity conservation efforts (Steenkamp et al. 2004, Mittermeier et al. 2011). Thicket conservation and restoration, particularly of spekboom – *Portulacaria afra*, can, amongst other ecosystem services, provide great levels of carbon sequestration and

therefore can directly benefit farmers financially through the international carbon crediting system (Mills and Cowling 2006).

Most citrus in the Sundays River Valley is conventionally farmed, with a few emerging organic farms. The conventional farmers, however, are increasingly incorporating Integrated Pest Management (IPM) practices into their farm management strategies. Chemical-free control methods have been increasingly researched, developed and applied in the South African citrus industry (Grout and Moore 2015). This due to a major South African citrus pest, the False Codling Moth (FCM) – *Thaumatotibia leucotreta* (Lepidoptera: Tortricidae), developing pesticide resistance in the past, in addition to the strict requirements of export markets for low pesticide levels on fruit and the potential for secondary pest outbreaks (Pimentel et al. 1992, Hofmeyr and Pringle 1998, Grout and Moore 2015).

1.8 Thesis outline and study aims

The purpose of this study is to determine whether, and to what extent, different local and landscape factors influence the predator complex of citrus orchards in the Sundays River Valley, Eastern Cape, South Africa. In the second chapter, I assess the interaction between local management intensity and landscape context. The key questions of this chapter, entailing comparisons between organic and conventional farming practices, are:

1. Are there differences in predator species richness, abundance, diversity and assemblage composition between citrus orchards with and without neighbouring natural vegetation?
2. What environmental variables drive the observed arthropod predator patterns in different local and landscape contexts?

It is hypothesised that organic citrus orchards with natural vegetation will have the highest abundance and diversity of predators, whereas conventional orchards without natural vegetation will have the lowest. Support will be given for the conservation and restoration of natural vegetation in the landscape instead of removal in favour of agricultural expansion.

The third chapter aims to determine whether, and to what extent, the presence of natural vegetation bordering alongside citrus orchards (organic and conventional) influences predator species richness, abundance, diversity and assemblage composition across the natural vegetation-orchard edge. The key questions of this chapter, entailing comparisons between organic and conventional farming practices, are:

1. Are there differences in predator species richness, abundance and diversity across the natural vegetation-orchard edge?

2. Do predator and environmental variable edge patterns differ between different orchard management types (organic and conventional)?
3. Are there differences in predator assemblage composition and beta diversity across the natural vegetation-orchard edge?

Predator species richness, abundance and diversity is hypothesised to be greatest at the natural vegetation-orchard edge. Organic orchards are hypothesised to have greater predator species richness, abundance, diversity and similarity to natural vegetation than that of conventional orchards. Orchards are hypothesised to influence the natural vegetation predator complex nearest to the natural vegetation-orchard edge.

The fourth chapter outlines the study conclusions and management recommendations for biodiversity conservation in agriculture. Methods to promote predator diversity in citrus orchards at a local and landscape scale will be recommended in the agricultural landscape. Although future research is needed to better understand the full agroecosystem, sustainable farming and biodiversity-friendly landscape practices can be integrated to be mutually beneficial for both agriculture and biodiversity conservation.

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Chapter 2

Organic farming, higher local and landscape complexity improve arthropod predator species richness and abundance in orchards

ABSTRACT

Agricultural management, on both a local and landscape scale, can be used to promote the arthropod predator complex. The term predator included parasitoids in this study. Research into the arthropod predator dynamics in perennial croplands and in areas outside of transformed, temperate zones is sparse. This study therefore investigated what impact citrus farming management types (conventional and organic) within different landscape contexts (with and without natural vegetation neighbouring orchards) have on arthropod predator species richness, abundance, diversity and assemblage composition. Using vacuum sampling and pitfall trapping, arthropod predators were sampled during spring and summer in the Sundays River Valley, Eastern Cape, South Africa. Local environmental variables were also recorded to investigate what drove the predator patterns observed. Organic management improved total predator species richness and abundance, and three of the major predator groups (predaceous beetles, spiders and wasps). Environmental heterogeneity of the understorey was significantly positively correlated with both predator species richness and abundance. Conventional orchards were recorded to have a greater improvement in predator species richness associated with nearby natural vegetation than organic orchards, which was an interactive effect. This study, in line with the intermediate landscape-complexity hypothesis, found that organic farming significantly influenced predator species richness and abundance in simpler landscapes. Additionally, natural vegetation in orchard surrounds increased the landscape complexity and resulted in greater predator species richness in conventional orchards. It is therefore recommended that in order to improve predator species richness and abundance, farmers should aim to diversify both local- and landscape-level environmental heterogeneity.

Keywords: citrus, conventional, environmental heterogeneity, landscape, management, natural vegetation, organic, predators, South Africa

2.1 Introduction

With agriculture facing numerous future challenges, such as climate change and feeding an ever-growing human population – particularly in developing countries, emphasis needs to be

placed on sustainable farming and landscape practices (Tilman 1999, Thrupp 2000, Godfray et al. 2010, Beddington et al. 2012). This is needed to increase the resilience of agriculture to future environmental fluctuations and reduce the impact on the remaining native ecosystems surrounding and within agricultural landscapes (Tilman 1999, Beddington et al. 2012).

Organic farming practices may benefit agricultural biodiversity, particularly predator species richness and abundance, compared to conventional farming practices (Mäder et al. 2002, Birkhofer et al. 2008, Tuck et al. 2014, Inclán et al. 2015, Lichtenberg et al. 2017, Djoudi et al. 2019, Katayama et al. 2019). Parasitoids were included in the term predator within this study. Environmentally friendly farming benefits predator species due to the lack of chemical pesticides, herbicides and fertilisers used as well as the application of a variety of compost, manure, mulch and cover cropping practices (Birkhofer et al. 2008, Gomiero et al. 2011, Baba et al. 2018). Cover cropping, together with a layer of either compost, manure, mulch or combination thereof, greatly improves soil health and provides the diverse habitat and crucial resources needed by predators for survival and lifecycle completion (Birkhofer et al. 2008). Organic farming practices can be seen as in-field practices to increase the presence of predators and other beneficials such as pollinators and detritivores.

There is increasing evidence that the presence of non-crop habitat in the agricultural landscape is beneficial for predator species richness and abundance in adjacent or nearby cropland (Thies and Tschardt 1999, Collins et al. 2002, Bianchi et al. 2006, Thomson and Hoffmann 2009, Šálek et al. 2018). Non-crop habitat refers to areas of land containing native or introduced plants that are protected from agricultural disturbances such as pesticide applications, mowing and ploughing. These non-crop habitats have the potential to provide refuge to predators during unfavourable cropland and environmental conditions, and can provide additional shelter and food resources needed for survival and population growth (Landis et al. 2000).

Agrobiodiversity, particularly of predators, has been increasingly researched in developed, highly-transformed countries worldwide but with far fewer studies conducted in the developing world which still contains high levels of biodiversity (Tuck et al. 2014, Katayama et al. 2019). Additionally, the majority of these studies are conducted on annual crops whilst perennial crops have been less studied (Tuck et al. 2014). This study therefore aims to investigate what impact different citrus farming management types (conventional and organic) within different landscape contexts (with and without natural vegetation neighbouring cropland) have on the arthropod predator complex. The study objectives are:

1. To determine if there are differences in predator species richness, abundance, diversity and assemblage composition between organic and conventional citrus orchards with and without neighbouring natural vegetation.
2. To determine what environmental variables drive the observed arthropod predator patterns.

It is expected that organic orchards with neighbouring natural vegetation will have the greatest predator diversity and abundance due to high spillover from the natural vegetation, a diverse and dense cover crop, and no pesticide applications. This study will provide motivation to citrus farmers that there are effective methods to increase arthropod predators in cropland, and that natural vegetation can benefit agriculture and therefore should be kept in the landscape instead of being removed in favour of continual agricultural expansion.

2.2 Methods

2.2.1 Study area and sites

The 36 study sites were spread across 15 citrus farms within the Sundays River Valley, Eastern Cape, South Africa (33°27'08.7" S, 25°31'30.6" E, Figure 2.1). Rainfall is nonseasonal, although there are peaks in rainfall during November and March (Hoare et al. 2006). The natural vegetation within the study area consists of Albany Alluvial Vegetation, Sundays Noorsveld and Sundays Thicket (Hoare et al. 2006). This study area falls within the Albany Centre of Floristic Endemism and, due to the high levels of endemism and habitat destruction, the Maputaland-Pondoland-Albany Biodiversity Hotspot (Victor and Dold 2003, Steenkamp et al. 2004). Much of the valley consists of citrus farms, the most of which are conventionally farmed, with a few organic farms. Study sites were chosen according to the farm type (either conventional or organic farms) and whether there was any remnant natural vegetation bordering alongside citrus orchards. Conventional citrus farms with similar pesticide regimes were chosen for this study. Study site selection was limited by the number of organic citrus farms available, especially those with neighbouring natural vegetation. Navel citrus orchards were selected as far as possible to maintain consistency between study sites. Fieldwork was conducted in early spring (September 2017) and late summer (February 2018).

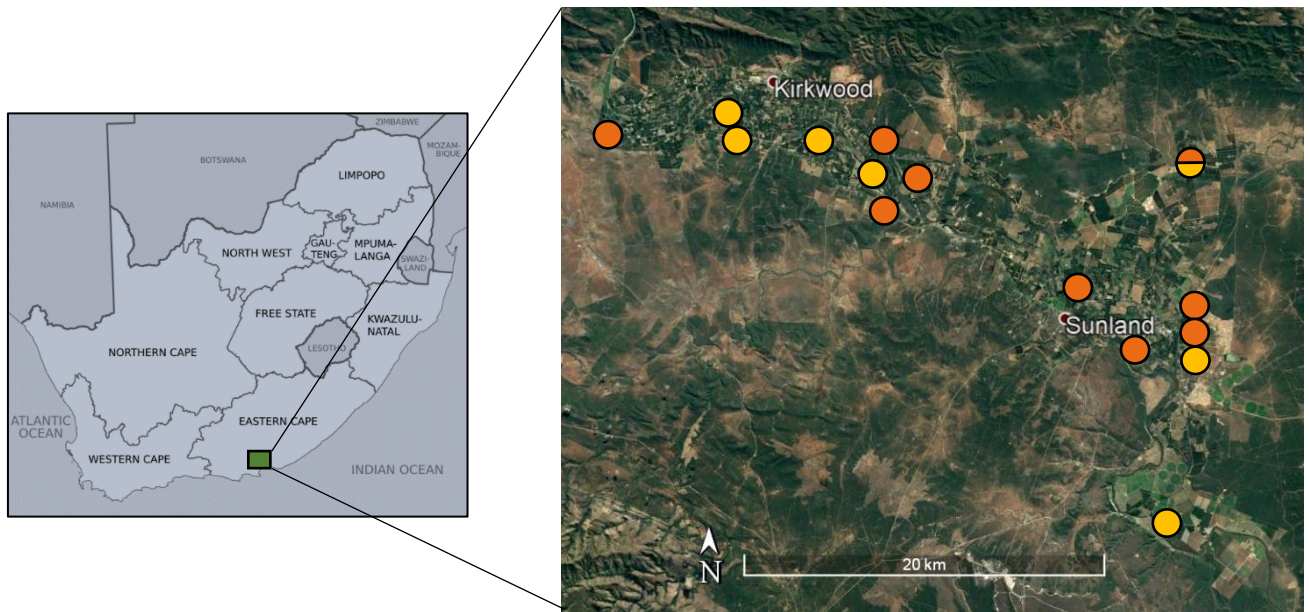


Figure 2.1 – The 15 citrus farms containing 36 study sites in the Sundays River Valley, Eastern Cape, South Africa. Orange – conventional farm, yellow – organic farm. Satellite image: Google Earth, 2018.

2.2.2 Arthropod predator sampling

Arthropods were sampled in each of six treatments (conventional orchards with and without neighbouring remnant natural vegetation, organic orchards with and without neighbouring remnant natural vegetation, as well as remnant natural vegetation itself neighbouring either conventional or organic orchards), with each treatment being replicated with six sites. Sampling in citrus orchards without natural vegetation was performed at least 450 m away from the nearest patch of remnant natural vegetation. Where more than one study site occurred on a farm, they were separated by minimum of 150 m. To avoid edge effects, sampling of predators took place between 40 m and 50 m from the edge of the orchard or natural vegetation study site (Figure 2.2).

Canopy-dwelling predators at each study site were sampled using a vacuum sampler (Stihl SH 86) that captures arthropods in a fine mesh bag attached to its nozzle (Southwood and Henderson 2000, Gaigher et al. 2015). Each sampling point received a standard 100 insertions into the vegetation with the vacuum sampler, with 50 insertions in the lower canopy (below 50 cm) and 50 insertions in the upper canopy (above 50 cm). Each vacuum insertion lasted approximately one second. The 50 lower canopy insertions were sampled by walking 50 m away from the sampling point in a perpendicular direction whilst the 50 upper canopy insertions were sampled on the returning 50 m walk towards the starting point (Figure 2.2). Due to the thickness of the natural vegetation, the 100 insertions (50 lower and 50 upper canopy) were performed as close to 50 m away from the starting point as was possible. In

the orchards, the insertions took place between 0 m and 2 m from the base of the citrus trees. Vacuum samples were transferred to and frozen in plastic resealable bags to be preserved for sorting later.

Ground-dwelling predators were sampled using pitfall traps placed underneath orchard rows to prevent damage from vehicles and people moving in the inter-row area (Southwood and Henderson 2000, Magoba and Samways 2012). Three paired sampling points were arranged in a grid shape (3 x 2) with 5 m separating each sampling point (Figure 2.2) (Thomson et al. 2010). The relative biodiversity of the ground-dwelling predators was sampled by installing two pitfall traps at each sampling point, resulting in six pitfalls per grid. Pitfall traps (6.5 cm diameter, 9 cm deep) were half-filled with an ethylene glycol solution (50% ethylene glycol, 50% water and a drop of detergent to break the surface tension). The pitfalls were left in the field for one week before being retrieved. When sampling in orchards, pitfalls were placed between 0 m and 1 m away from the base of the citrus trees, depending on the location of the irrigation sprayers. Pitfall samples were transferred to a 96% ethanol solution to be preserved for sorting later.

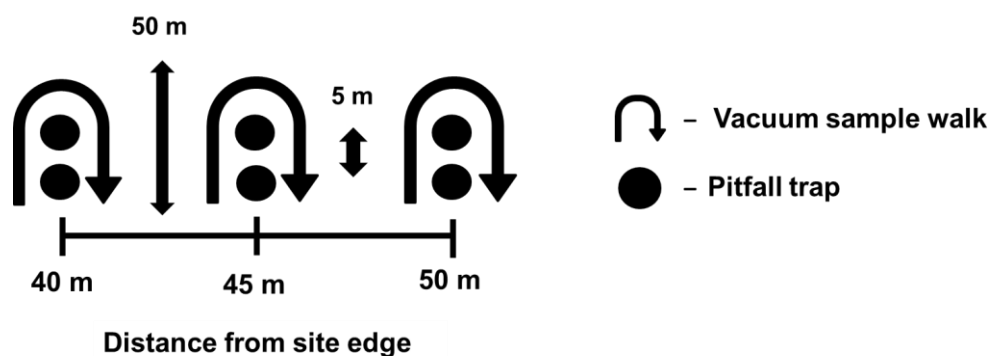


Figure 2.2 – Vacuum sampling and pitfall trapping design used to sample canopy and ground-dwelling predators respectively at each site.

Sampled arthropods were sorted to morphospecies (referred to as species from this point onwards) and their abundance recorded. Due to time constraints, identification to either class, order or family level was performed (Picker et al., 2004). The following predator taxa were recorded: Araneae, predaceous Coleoptera, Chilopoda, Formicidae, Hymenoptera (wasps), Mantodea, Neuroptera, Opiliones, Orthoptera, Pseudoscorpiones, Scorpiones and Solifugae (Appendix A).

2.2.3 Environmental variable sampling

Plant species richness and abundance, number of flowering plants, average plant height, percentage vegetation cover in three categories (grass, herb, woody) and ground cover (litter, bare ground and rockiness) as well as average leaf litter depth at each study site was sampled using a 1 m² quadrat for the lower canopy (below 50 cm height) and a 5 m² quadrat for the upper canopy (above 50 cm height) (Gaigher et al. 2015). The two quadrat types were replicated at each of the three each sampling points per site. Although percentage grass and herb cover, ground cover as well as average leaf litter depth were below 50 cm in height, they were included in the 5 m² quadrat recordings as they incorporated greater variance in these lower canopy environmental variables. Quadrats in the orchards were placed 1 m away from the base of the citrus trees. Plant species were identified as far as possible using relevant field guides and plant species abundance in each quadrat counted (Appendix B) (Bromilow 2010, Vlok and Schutte-Vlok 2010, Manning 2013).

2.2.4 Data analysis

Total predator species data and the four major predator groups (ants, beetles, spiders and wasps) were included in data analyses and analysed independently. Arthropod predator data from the stations, between different sampling methods (vacuum sampling and pitfall methods) and seasons (spring and summer), were pooled cumulatively. Environmental variable data, except plant species richness and abundance, were recorded across both seasons and pooled together (averaged). Plant species richness and abundance were only recorded in spring.

For the first objective, differences in predator species richness, abundance and Simpson's Index of Diversity between the two management types (conventional and organic), three biotopes (orchards with neighbouring natural vegetation, orchards without neighbouring natural vegetation and natural vegetation neighbouring orchards) and the interaction between management type and biotope were investigated. Differences in predator species richness, abundance and Simpson's Index of Diversity between the six treatment types (conventional and organic orchards with and without neighbouring natural vegetation, and natural vegetation neighbouring conventional and organic orchards) were tested separately. The statistics

programme R (version 3.5.1) (R Core Team 2018) was used with the R *lme4* package (Bates et al., 2016) to perform linear mixed models (LMMs) for Gaussian distributed data (Bolker et al. 2009). Over-dispersed data were either log or square root transformed. Simpson's Index of Diversity (1-D value), a value between 0 and 1 that represents greater diversity as the value increases, was calculated using the R *vegan* package (Oksanen et al. 2018). Distinct geographic regions of study sites in the Sundays River Valley were included as a random variable to reduce bias from spatial nestedness. Study sites that were near to one another in clearly separate geographic areas of the Sundays River Valley were grouped into a region. Significant LMM results were followed up with Tukey post hoc tests, using the R *multcomp* package, to determine differences between management types, biotopes and treatment types (Hothorn et al. 2017).

Differences in assemblage composition between management types, biotopes and their interaction were tested for the first objective. Treatment type differences in assemblage composition were also tested separately. Geographic region was again used as the random variable. Primer 6 (version 6.1.13) and the PERMANOVA+ add-on (version 1.0.3) (PRIMER-E 2008) were used to investigate predator assemblage patterns. Total and ant species data were fourth root transformed to reduce the impact of study sites with very high abundances. The Bray-Curtis similarity function was used to construct a similarity matrix between study site assemblages (Anderson et al. 2008). A Permutational Multivariate Analysis of Variance (PERMANOVA) main test was then performed to calculate significant differences ($p < 0.05$) in similarity between study site assemblages. Significant differences were followed up with PERMANOVA pairwise-tests to determine which biotopes, management types or treatment types significantly differed from one another. In order to better visualise the differences between predator communities, a Canonical Analysis of Principal Coordinates (CAP) test was performed on treatment types.

To determine which environmental variables drive the observed patterns in arthropod predator species richness, abundance and Simpson's Index of Diversity (objective two), the R *AICcmodavg* package (Mazerolle 2017) was used. Scaled environmental variables with the lowest Akaike's second-order information criterion (AICc), based on forward selection, were chosen (Symonds and Moussalli 2011). These environmental variables were then analysed with LMMs, using the *lme4* package in R (Bates et al. 2016), to determine whether they significantly explained predator species richness, abundance and Simpson's Index of Diversity. Prior to analyses, similar environmental variables that were highly correlated ($-0.6 < r > 0.6$), using Spearman rank-order correlations, had the least relevant variable excluded (it could be best encapsulated by the included variable) (Appendix C). Environmental variables that were included were: plant species richness (1 m²), plant species abundance (1 m²),

average plant height (1 m²), plant species richness (5 m²), total flowering plants (5 m²), average plant height (5 m²), average % grass cover (5 m²), average % herbaceous cover (5 m²), average % litter cover (5 m²) and average leaf litter depth (5 m²).

Distance-based linear models (DistLM), based on forward selection with 9999 permutations, were used to analyse which environmental variables best explained the observed predator assemblage structure patterns (objective two). The environmental variable data were normalised (standardised across environmental variables) before the Euclidean distance function was performed on the data (Anderson et al., 2008). The same environmental variables used in the univariate analyses were used for these multivariate analyses. DistLM marginal tests were firstly performed to determine the AICc scores and how much each environmental variable contributed to the overall variance of the predator assemblages. DistLM sequential tests, using forward selection, were used to select significant environmental variables that had the lowest AICc scores and best explained the variation in predator assemblage patterns. DistLM analyses were performed using Primer 6 (version 6.1.13) and the PERMANOVA+ add-on (version 1.0.3) (PRIMER-E 2008).

2.3 Results

Overall, 1 237 predator species and 84 704 individuals were sampled during this study. The predator assemblage sampled consisted of Araneae (352 spp., 3 681 ind.), predaceous Coleoptera (103 spp., 2 637 ind.), Chilopoda (8 spp., 120 ind.), Formicidae (84 spp., 73 554 ind.), Hymenoptera – wasps (658 spp., 3 349 ind.), Mantodea (7 spp., 57 ind.), Neuroptera (8 spp., 88 ind.), Opiliones (4 spp., 18 ind.), Orthoptera (1 spp., 2 ind.), Pseudoscorpiones (5 spp., 1 178 ind.), Scorpiones (4 spp., 4 ind.) and Solifugae (3 spp., 16 ind.). Hymenoptera – wasps (53% spp., 4% ind.), Araneae (28% spp., 4% ind.), predaceous Coleoptera (8% spp., 3% ind.) and Formicidae (7% spp., 87% ind.) dominated the predator assemblage. A total of 730 predator species and 23 504 individuals were sampled in organic orchards, in comparison with conventional orchards which consisted of 428 predator species and 6998 individuals.

2.3.1.1 Impact of management and landscape factors on predator species richness, abundance and Simpson's Index of Diversity (SID)

Management type was found to have a prominent impact on predator species richness, abundance and SID across all taxonomic groupings (Table 2.1). Species richness and abundance was significantly greater under organic management across all groupings with the exception of ant species richness (Appendix D; Table 2.1). Total and ant SID however were greater under conventional management (Appendix D; Table 2.1). Biotope, in comparison to management type, varied across predator groupings in its effect on species richness, abundance and SID (Appendix D; Table 2.1). Natural vegetation had significantly greater ant species richness than the two orchard biotopes and significantly greater ant SID than orchards without natural vegetation (Appendix D; Table 2.1). Beetle species richness, abundance and SID were all significantly greater in the two orchard biotopes than in natural vegetation (Appendix D; Table 2.1). Orchards with natural vegetation had significantly greater beetle species richness than orchards without natural vegetation (Appendix D; Table 2.1). Orchards with natural vegetation had significantly greater wasp species richness and abundance than orchards without natural vegetation and natural vegetation itself (Appendix D; Table 2.1).

Total species richness was greatest for the organic orchards with and without natural vegetation (Appendix E; Figure 2.3a). In comparison, the conventional orchards without natural vegetation had the lowest total species richness (Appendix E; Figure 2.3a). Total abundance was significantly greater for the organic orchards without natural vegetation than the conventional orchards without natural vegetation – may have resulted from particularly high ant abundances in organic orchards without natural vegetation (Appendix E; Figure 2.3b). The only significant difference in total SID was that of the conventional orchards with natural vegetation, which was significantly greater than the organic orchards without natural vegetation (Appendix E; Figure 2.3c).

Ant species richness was significantly greater in the two natural vegetation treatments than the two conventional orchard treatments (Appendix E; Figure 2.4a). The organic orchards without natural vegetation had significantly higher ant abundance when compared to the two conventional orchard treatments (Appendix E; Figure 2.4b). Ant SID was significantly lower for the organic orchards without natural vegetation than the conventional orchards with natural vegetation and two natural vegetation treatments (Appendix E; Figure 2.4c).

The two organic orchard treatments and conventional orchards with natural vegetation had significantly greater beetle species richness than the conventional orchards without natural vegetation and natural vegetation treatments (Appendix E; Figure 2.4d). Similarly, organic orchards with natural vegetation had significantly greater beetle abundance than

conventional orchards without natural vegetation and natural vegetation treatments (Appendix E; Figure 2.4e). Beetle SID was significantly greater for the conventional orchards with natural vegetation and organic orchards without natural vegetation than the natural vegetation neighbouring conventional orchards (Appendix E; Figure 2.4f).

Spider species richness and abundance were significantly greater in organic orchards without natural vegetation than the other treatments, except for organic orchards with natural vegetation (species richness) and natural vegetation neighbouring conventional orchards (abundance) (Appendix E; Figure 2.5a & b). The conventional orchards without natural vegetation had the lowest significant spider species richness and had significantly lower spider SID than the natural vegetation neighbouring conventional orchards and organic orchards without natural vegetation (Appendix E; Figure 2.5a & c).

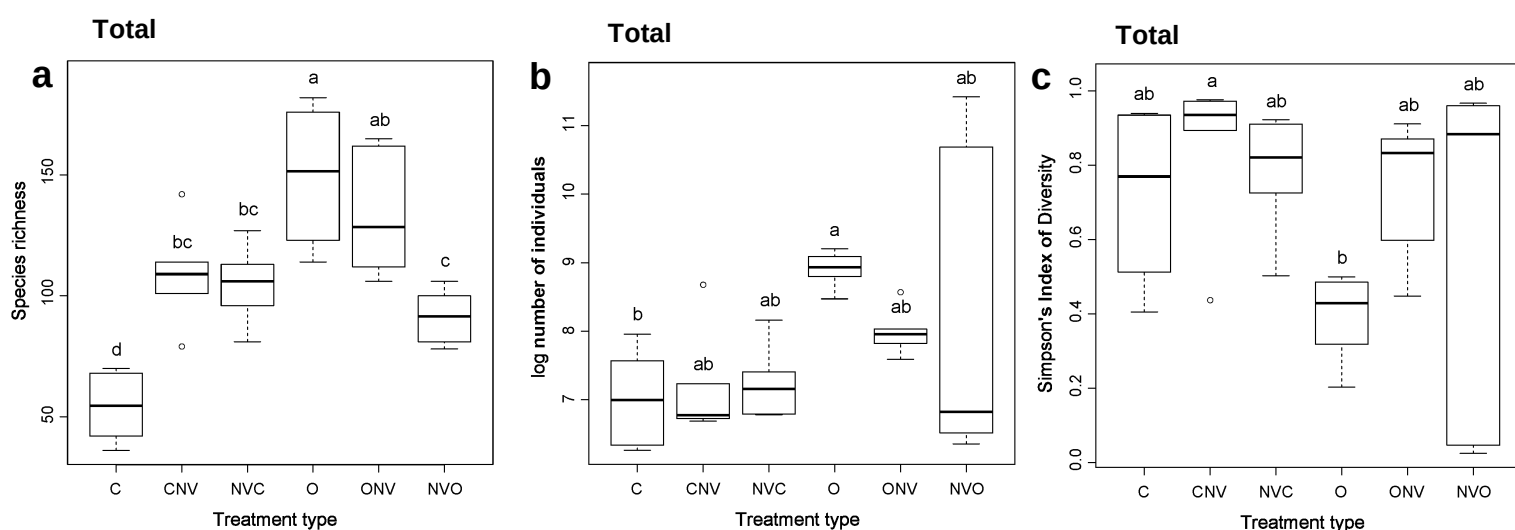


Figure 2.3 – The impact of treatment type on total (a) species richness, (b) abundance and (c) Simpson's Index of Diversity (median $\pm$ quartiles). The alphabetical letters indicate significant differences recorded using a LMM followed by a Tukey post hoc test. C – conventional orchards without natural vegetation, CNV – conventional orchards with natural vegetation, NVC – natural vegetation neighbouring conventional orchards, O – organic orchards without natural vegetation, ONV – organic orchards with natural vegetation, NVO – natural vegetation neighbouring organic orchards.

Table 2.1 – Linear mixed model (LMM) results of predator species richness, abundance and Simpsons' Index of Diversity differences between management types, biotopes, their interaction and treatment types. Treatment type is the combination of management type and biotope that is viewed at the landscape scale. Significant chi-square results are indicated using a (*), *p < 0.05, **p < 0.01, ***p < 0.001. > and < indicates significant differences based on Tukey post hoc tests.

Predator grouping	Landscape factor	Species richness		Abundance		Simpson's Index of Diversity	
		Main test	Post hoc	Main test	Post hoc	Main test	Post hoc
Total	Management (MNG)	11.34***	Org > Conv	10.81**	Org > Conv	6.21*	Org < Conv
	Biotope (BIO)	4.12	-	0.97	-	5.17	-
	MNG x BIO interaction	36.82***		2.17		1.30	-
	Treatment type	51.22***		13.7*		12.72*	
Ant	Management (MNG)	2.46	-	9.63**	Org > Conv	4.83*	Org < Conv
	Biotope (BIO)	16.48***	OrchNV < NV, Orch < NV	3.00	-	8.87*	Orch < NV
	MNG x BIO interaction	3.94		2.62		2.06	
	Treatment type	21.99***		14.57*		15.14**	
Beetle	Management (MNG)	11.25***	Org > Conv	6.80**	Org > Conv	0.30	-
	Biotope (BIO)	57.71***	OrchNV > NV, Orch > NV, OrchNV > Orch	42.69***	OrchNV > NV, Orch > NV	13.79**	OrchNV > NV, Orch > NV
	MNG x BIO interaction	12.49**		7.25*		3.08	
	Treatment type	72.76***		52.15***		17.09**	
Spider	Management (MNG)	7.96**	Org > Conv	8.68**	Org > Conv	0.14	-
	Biotope (BIO)	2.74	-	1.96	-	0.43	-
	MNG x BIO interaction	32.65***		7.10*		14.79***	
	Treatment type	42.82***		17.3**		15.35**	
Wasp	Management (MNG)	8.93**	Org > Conv	5.76*	Org > Conv	3.74	-
	Biotope (BIO)	9.93**	OrchNV > NV, OrchNV > Orch	10.84**	OrchNV > NV, OrchNV > Orch	4.48	-
	MNG x BIO interaction	22.58***		16.78***		16.24***	
	Treatment type	39.47***		31.97***		24.03***	

Org = organic, Conv = conventional, OrchNV = orchard with natural vegetation, Orch = orchard without natural vegetation, NV = natural vegetation neighbouring orchards

The two organic orchard treatments had significantly greater wasp species richness than the two natural vegetation treatments and conventional orchards without natural vegetation (Appendix E; Figure 2.5d). Wasp abundance was significantly greater for conventional orchards with natural vegetation, natural vegetation neighbouring conventional orchards and two organic orchard treatments than conventional orchards without natural vegetation (Appendix E; Figure 2.5e). Similarly, conventional orchards without natural vegetation had significantly lower wasp SID than the other treatments (Appendix E; Figure 2.5f).

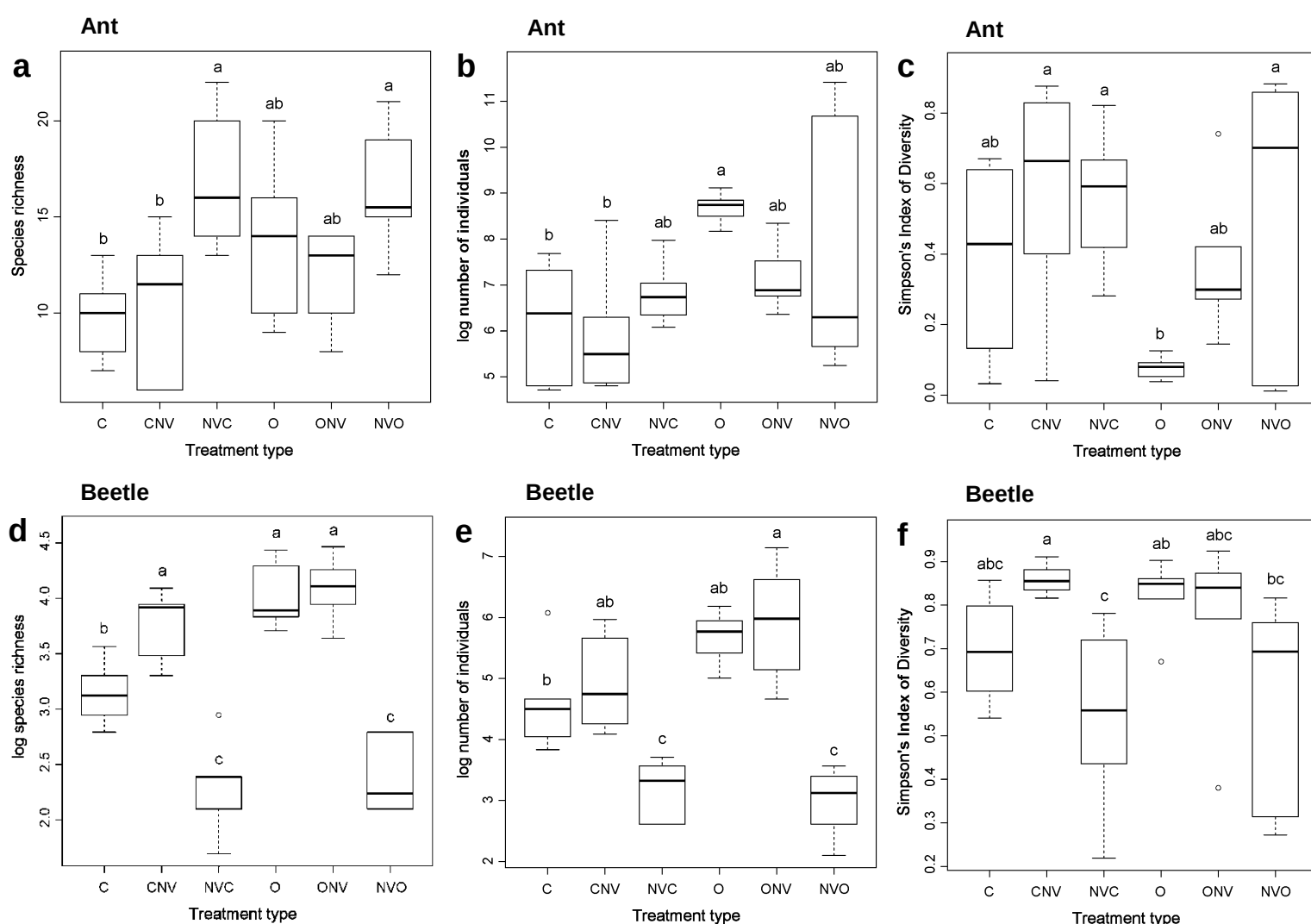


Figure 2.4 – The impact of treatment type on ant (a) species richness, (b) abundance and (c) Simpson's Index of Diversity, beetle (d) species richness, (e) abundance and (f) Simpson's Index of Diversity (median $\pm$ quartiles). The alphabetical letters indicate significant differences recorded using a LMM followed by a Tukey post hoc test. C – conventional orchards without natural vegetation, CNV – conventional orchards with natural vegetation, NVC – natural vegetation neighbouring conventional orchards, O – organic orchards without natural vegetation, ONV – organic orchards with natural vegetation, NVO – natural vegetation neighbouring organic orchards.

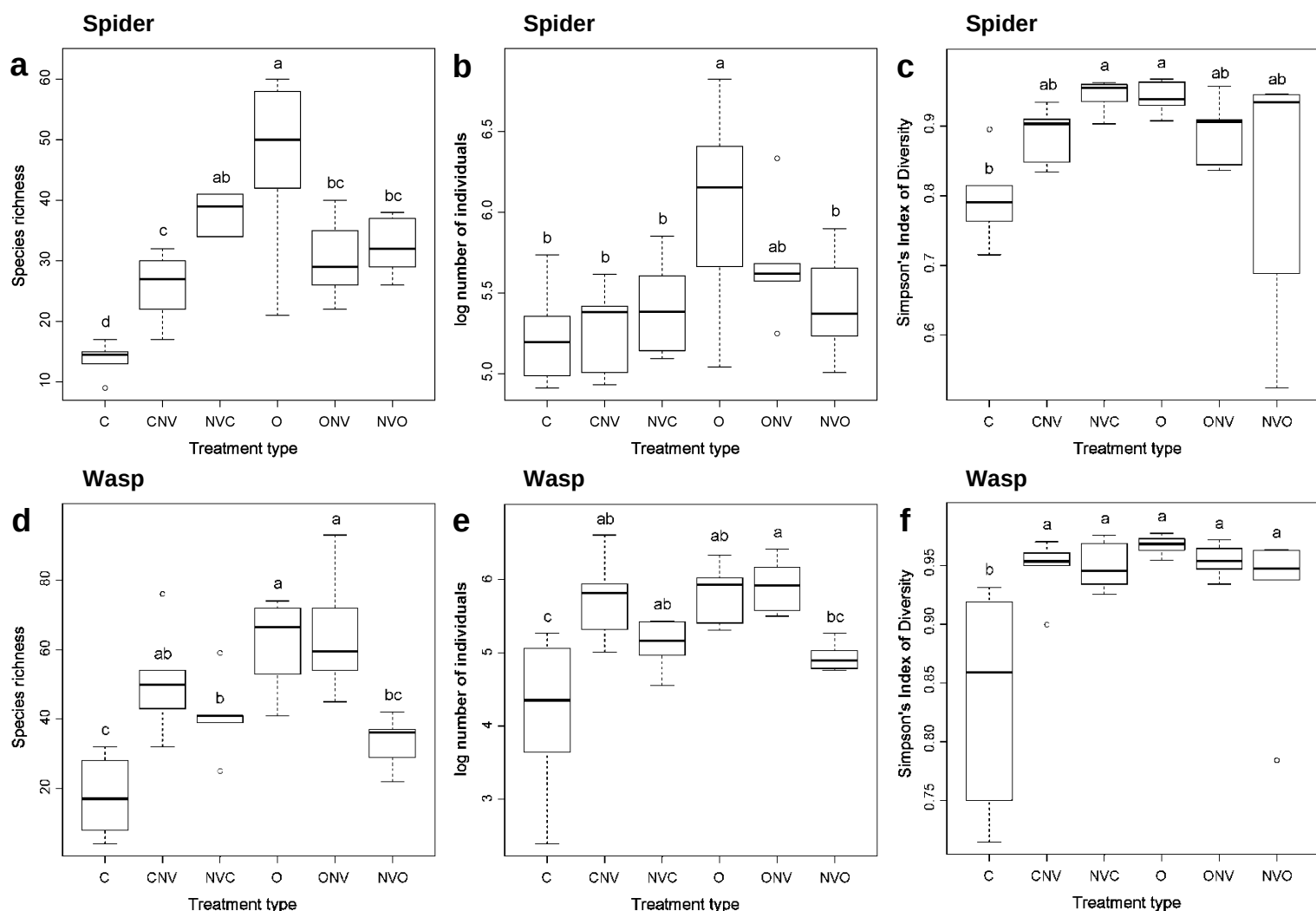


Figure 2.5 – The impact of treatment type on spider (a) species richness, (b) abundance and (c) Simpson's Index of Diversity, and wasp (d) species richness, (e) abundance and (f) Simpson's Index of Diversity (median $\pm$ quartiles). The alphabetical letters indicate significant differences recorded using a LMM followed by a Tukey post hoc test. C – conventional orchards without natural vegetation, CNV – conventional orchards with natural vegetation, NVC – natural vegetation neighbouring conventional orchards, O – organic orchards without natural vegetation, ONV – organic orchards with natural vegetation, NVO – natural vegetation neighbouring organic orchards.

2.3.1.2 Impact of management and landscape factors on predator assemblage composition

Each predator grouping was found to differ significantly within each of the landscape contexts (Table 2.2). Predator assemblage composition between organic and conventional management types were all significantly different to one another (Table 2.2). Whilst total, spider and wasp assemblage composition differed significantly between all biotopes, ant and beetle assemblage composition between the orchard with and without natural vegetation biotopes did not differ significantly (Table 2.2). The only consistent assemblage composition comparison that did not differ significantly throughout was that between the two natural vegetation treatments (Figure 2.6; Table 2.2). Ant, beetle and wasp assemblage composition within conventional orchards without natural vegetation also did not differ significantly from conventional orchards with natural vegetation and natural vegetation neighbouring organic orchards (Figure 2.6; Table 2.2).

Table 2.2 – Permutational Multivariate Analysis of Variance (PERMANOVA) results on predator assemblage relationships between management types, biotopes, their interaction and treatment types. Significant Pseudo-F results from PERMANOVA main tests are indicated using a (*), *p < 0.05, **p < 0.01, ***p < 0.001. # indicates significant differences based on PERMANOVA pairwise tests.

Predator grouping	Landscape factor	Main test	Pairwise test
Total	Management type	2.30***	Org ≠ Conv
	Biotope	3.82***	OrchNV ≠ NV, Orch, Orch ≠ NV
	MNG x BIO interaction	2.23***	
	Treatment type	2.96***	C ≠ CNV, NVC, NVO, O, ONV, CNV ≠ NVC, NVO, O, ONV, NVC ≠ O, ONV, NVO ≠ O, ONV, O ≠ ONV
Ant	Management type	2.30**	Org ≠ Conv
	Biotope	3.08***	OrchNV ≠ NV, Orch ≠ NV
	MNG x BIO interaction	3.35***	
	Treatment type	3.11***	C ≠ NVC, O, ONV, CNV ≠ NVC, O, NVC ≠ O, ONV, NVO ≠ O, ONV, O ≠ ONV
Beetle	Management type	1.95*	Org ≠ Conv
	Biotope	3.34***	OrchNV ≠ NV, Orch ≠ NV,
	MNG x BIO interaction	1.72*	
	Treatment type	2.60***	C ≠ O, CNV ≠ NVC, NVO, O, NVC ≠ O, ONV, NVO ≠ O, ONV, O ≠ ONV
Spider	Management type	3.09***	Org ≠ Conv
	Biotope	3.24***	OrchNV ≠ NV, Orch, Orch ≠ NV
	MNG x BIO interaction	2.58***	
	Treatment type	3.01***	C ≠ CNV, NVC, NVO, O, ONV, CNV ≠ NVC, NVO, O, ONV, NVC ≠ O, ONV, NVO ≠ O, ONV, O ≠ ONV
Wasp	Management type	1.34*	Org ≠ Conv
	Biotope	2.39***	OrchNV ≠ NV, Orch, Orch ≠ NV
	MNG x BIO interaction	1.37**	
	Treatment type	1.81***	C ≠ NVC, O, CNV ≠ NVC, NVO, O, ONV, NVC ≠ O, ONV, NVO ≠ O, ONV, O ≠ ONV

Org = organic, Conv = conventional, OrchNV = orchard with natural vegetation, Orch = orchard without natural vegetation, NV = natural vegetation neighbouring orchards, C = conventional orchards without natural vegetation, CNV = conventional orchards with natural vegetation, NVC = natural vegetation neighbouring conventional orchards, NVO = natural vegetation neighbouring organic orchards, O = organic orchards without natural vegetation, ONV = organic orchards with natural vegetation

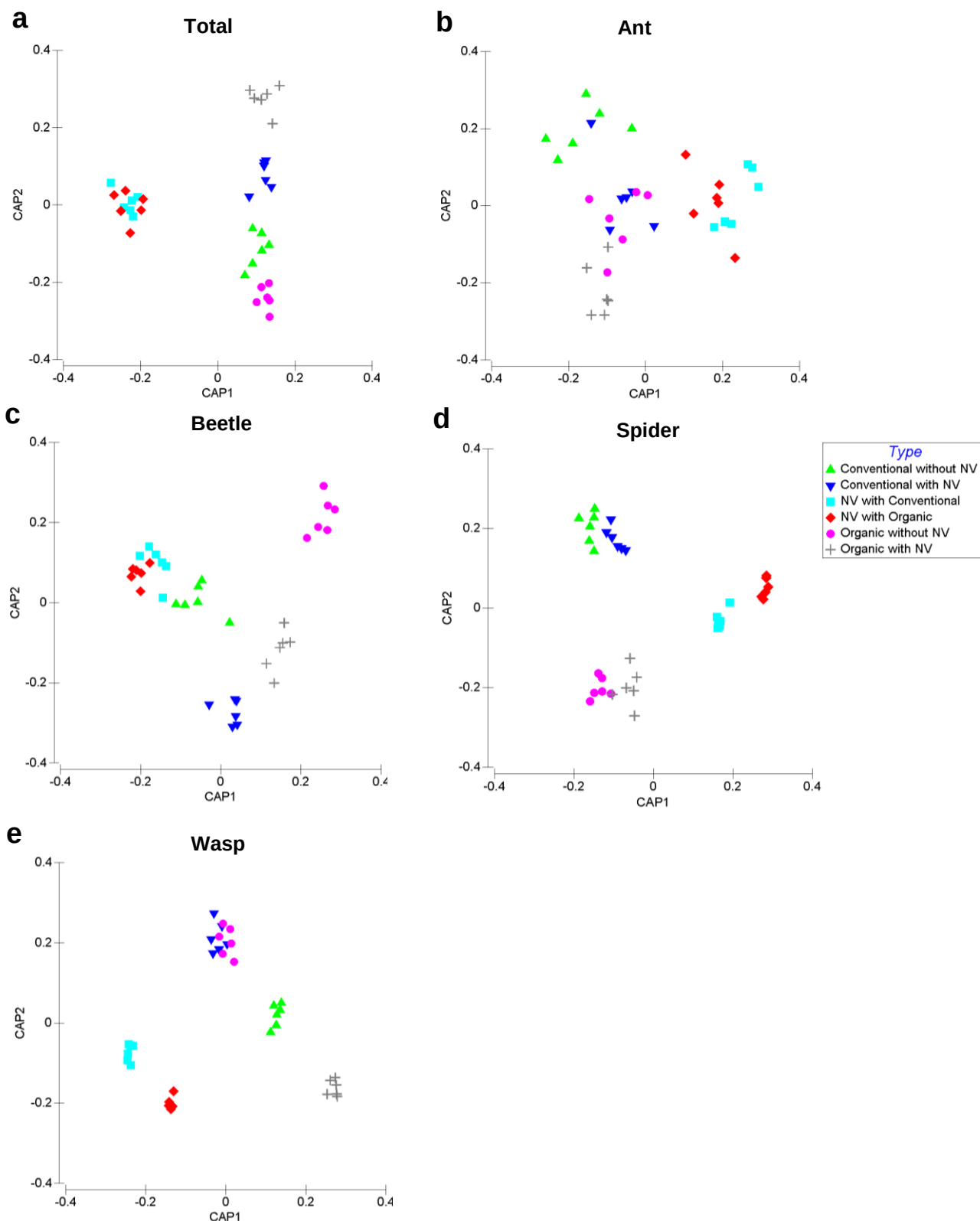


Figure 2.6 – Canonical Analysis of Principal Coordinates (CAP) results for (a) total, (b) ant, (c) beetle, (d) spider and (e) wasp composition differences between treatment types (conventional orchards without natural vegetation; conventional orchards with natural vegetation; natural vegetation neighbouring conventional orchards; natural vegetation neighbouring organic orchards; organic orchards without natural vegetation; organic orchards with natural vegetation).

2.3.2.1 Environmental variables associated with predator species richness, abundance and SID patterns

Environmental variables were found to have a varying association with species richness, abundance and SID for the total and major predator groupings. Average plant height (1 m²), average % cover grass (5 m²), average % cover herb (5 m²) and average leaf litter depth (5 m²) dominated the total predator grouping (Table 2.3). When significant, average plant height (1 m²) was consistently associated with increased total species richness and abundance (Table 2.3). Average % cover grass (5 m²) and herb (5 m²) were mostly associated with significantly increased total species richness (Table 2.3). Average leaf litter depth (5 m²), however, was associated with significantly increased total species richness but mostly significantly decreased abundance (Table 2.3).

Table 2.3 – Linear mixed model (LMM) results of environmental variables associated with total species richness (SppR), abundance (Abun.) and Simpsons' Index of Diversity (SID) between the combination of management type and biotope, and management type and biotope separately. Significant chi-square results are indicated using a (*), *p < 0.05, **p < 0.01, ***p < 0.001. (+) or (–) indicates the direction of the relationship between the response and environmental variable based on Spearman rank-order correlations.

Landscape factor		Response variable	Environmental variables
Combination		SppR	(+) APH 1: 6.44*, (+) ALLD 5: 5.04*
		Abun.	(+) APH 1: 5.24*, (–) ACL 5: 6.48*
		SID	(+) ACL 5: 6.35*
Management type	Org	SppR	(–) ACL 5: 7.79**, (+) ALLD 5: 10.36**
		Abun.	(–) ACL 5: 15.07***, (–) ALLD 5: 10.49**
		SID	-
	Conv	SppR	(+) APH 1: 8.01**, (+) TFP 5: 4.34*, (+) ACH 5: 14.14***
		Abun.	-
		SID	-
	OrchNV	SppR	(+) APH 1: 5.95*, (+) ACH 5: 5.93*
		Abun.	(+) PSA 1: 12.28***
		SID	(–) PSA 1: 9.13**
Biotope	Orch	SppR	(+ Org, – Conv) MNG: 9.97**, (+) ACG 5: 8.24**
		Abun.	(+) ALLD 5: 21.12***
		SID	(– Org, + Conv) MNG: 7.89**
	NV	SppR	(+) TFP 5: 4.52*, (+) ACG 5: 7.63**
		Abun.	(–) ALLD 5: 8.22**
		SID	(+) ALLD 5: 7.89**

Org = organic, Conv = conventional, OrchNV = orchard with natural vegetation, Orch = orchard without natural vegetation, NV = natural vegetation neighbouring orchards, PSA 1 = plant species richness (1 m²), PSA 5 = plant species richness (5 m²), TFP 5 = total flowering plants (5 m²), APH 5 = average plant height (5 m²), ACG 5 = average % cover grass (5 m²), ACH 5 = average % cover herb (5 m²), ACL 5 = average % cover litter (5 m²), ALLD 5 = average leaf litter depth (5 m²), MNG = Management type

Ant species richness was significantly associated with increased plant species richness (5 m²) and mostly by average % cover grass (5 m²) (Table 2.4). Plant species abundance (1 m²) and average plant height (1 m²) were significantly associated with increased ant abundance (Table 2.4). Conversely, average % cover litter (5 m²) and average leaf litter depth (5m) (except orchards with natural vegetation biotope) were significantly associated with decreased ant abundance (Table 2.4). Plant species richness (5 m²) was significantly associated with decreased beetle species richness and abundance (Table 2.4). Conversely, the plant canopy cover variables, average % cover grass (5 m²) and herb (5 m²), and average leaf litter depth (5 m²), were found to be significantly associated with increased beetle species richness, abundance and SID consistently (Table 2.4). Spider species richness, abundance and SID were significantly associated with increased average plant height (1 m²) total flowering plants (5 m²), average % cover grass (5 m²) and average leaf litter depth (5 m²) (Table 2.5). Average plant height (1 m²) and average % cover herb (5 m²) were both found to be significantly associated with increased wasp species richness, abundance and SID consistently (Table 2.5).

Table 2.4 – Linear mixed model (LMM) results of environmental variables associated with ant and beetle species richness (SppR), abundance (Abun.) and Simpsons' Index of Diversity (SID) between the combination of management type and biotope, and management type and biotope separately. Significant chi-square results are indicated using a (*), *p < 0.05, **p < 0.01, ***p < 0.001. (+) or (–) indicates the direction of the relationship between the response and environmental variable based on Spearman rank-order correlations.

Predator grouping	Landscape factor	Response variable	Environmental variables
Ant	Combined	SppR	(+) PSR 5: 7.21**, (+) ACL 5: 4.62*, (+) ALLD 5: 4.39*
		Abun.	(+) APH 1: 6.99**
		SID	-
	Management type	SppR	(+) PSR 5: 9.58**
		Abun.	(–) ACL 5: 9.56**, (–) ALLD 5: 6.94**
		SID	(+) ACL 5: 12.94***
	Conv	SppR	(–) APH 5: 21.70***, (–) ACG 5: 9.83**, (+) TFP 5: 6.80**
		Abun.	-
		SID	-
	OrchNV	SppR	(–) TFP 5: 5.24*, (–) APH 5: 4.63*
		Abun.	(+) PSA 1: 16.97***, (–) ACL 5: 8.33**
		SID	-
	Biotope	SppR	(+) ACG 5: 9.73**, (–) ACL 5: 3.85*
		Abun.	(+) ALLD 5: 15.12***
		SID	(–) ALLD 5: 8.14**
	NV	SppR	(+) ACG 5: 12.73***
		Abun.	(–) ALLD 5: 8.66**
		SID	(+) ACL 5: 8.72**
Beetle	Combined	SppR	(–) PSR 5: 40.13***, (+) ALLD 5: 23.32***
		Abun.	(–) PSR 5: 39.47***, (+) ALLD 5: 20.79***
		SID	(+) ACG 5: 10.80**
	Management type	SppR	(+) ACH 5: 7.47**, (–) ACL 5: 3.89*, (+) ALLD 5: 12.41***
		Abun.	(–) PSR 5: 27.61***
		SID	(+) ALLD 5: 8.53**
	Conv	SppR	(+) APH 5: 7.70**, (+) ACH 5: 9.61**
		Abun.	(+) PSA 1: 5.28*, (+) APH 5: 16.70***, (+) ACH 5: 10.25**
		SID	(+) ACH 5: 9.03**
	OrchNV	SppR	(+) PSR 1: 15.29***, (–) APH 5: 10.53***, (+) ACH 5: 24.13***
		Abun.	(+ Org, – Conv) MNG: 4.13*
		SID	-
	Biotope	SppR	(+) ALLD 5: 9.65**
		Abun.	(–) ACL 5: 11.99***, (+) ALLD 5: 26.23***
		SID	-
	NV	SppR	(+) APH 5: 5.04*
		Abun.	(–) ACG 5: 7.07**
		SID	-

Org = organic, Conv = conventional, OrchNV = orchard with natural vegetation, Orch = orchard without natural vegetation, NV = natural vegetation neighbouring orchards, PSR 1 = plant species richness (1 m²), PSA 1 = plant species abundance (1 m²), APH 1 = average plant height (1 m²), PSR 5 = plant species richness (5 m²), TFP 5 = total flowering plants (5 m²), APH 5 = average plant height (5 m²), ACG 5 = average % cover grass (5 m²), ACH 5 = average % cover herb (5 m²), ACL 5 = average % cover litter (5 m²), ALLD 5 = average leaf litter depth (5 m²), MNG = Management type

Table 2.5 – Linear mixed model (LMM) results of environmental variables associated with spider and wasp species richness (SppR), abundance (Abun.) and Simpsons' Index of Diversity (SID) between the combination of management type and biotope, and management type and biotope separately. Significant chi-square results are indicated using a (*), *p < 0.05, **p < 0.01, ***p < 0.001. (+) or (–) indicates the direction of the relationship between the response and environmental variable based on Spearman rank-order correlations.

Predator grouping	Landscape factor		Response variable	Environmental variables
Spider	Combined		SppR	(+) TFP 5: 4.33*, (+) ALLD 5: 8.70**
			Abun.	(+) ALLD 5: 14.83***
			SID	(+) ALLD 5: 8.39**
	Management type	Org	SppR	(–) PSA 1: 5.81*
			Abun.	(–) ACL 5: 6.67**
			SID	(+) ALLD 5: 11.87***
		Conv	SppR	(+) APH 1: 8.37**, (+) TFP 5: 15.69***, (–) ACG 5: 6.05*, (+) ACH 5: 4.84*
			Abun.	-
			SID	(+) APH 1: 15.30***
	Biotope	OrchNV	SppR	(–) PSR 1: 13.56***, (+) PSA 1: 7.06**
			Abun.	(+) ALLD 5: 10.26**
			SID	-
		Orch	SppR	(+) TFP 5: 20.91***
			Abun.	(+) TFP 5: 12.18***
			SID	(+ Org, – Conv) MNG: 16.66***
		NV	SppR	(+) PSA 1: 6.68**, (+) TFP 5: 10.83***, (+) ACG 5: 9.71**
			Abun.	(–) ALLD 5: 6.69**
			SID	(+) ALLD 5: 5.61*
Wasp	Combined		SppR	(+) APH 1: 9.24**
			Abun.	(+) PSA 1: 4.31*, (+) APH 1: 7.80**, (+) ACH 5: 5.88*
			SID	(+) APH 1: 15.02***
	Management type	Org	SppR	(–) PSR 5: 13.71***, (+) ACH 5: 5.37*
			Abun.	(–) PSR 5: 21.26***, (+) ACH 5: 10.97***
			SID	-
		Conv	SppR	(+) APH 1: 11.50***, (+) ACH 5: 12.31***
			Abun.	(+) APH 1: 13.09***, (+) ACH 5: 20.65***
			SID	-
	Biotope	OrchNV	SppR	(+) APH 1: 14.75***
			Abun.	(+) APH 1: 6.71**
			SID	-
		Orch	SppR	(+ Org, – Conv) MNG: 9.16**
			Abun.	(+) APH 1: 13.77***
			SID	(+) APH 1: 13.10***
		NV	SppR	(–) ALLD 5: 6.10*
			Abun.	-
			SID	-

Org = organic, Conv = conventional, OrchNV = orchard with natural vegetation, Orch = orchard without natural vegetation, NV = natural vegetation neighbouring orchards, PSR 1 = plant species richness (1 m²), PSA 1 = plant species abundance (1 m²), APH 1 = average plant height (1 m²), PSR 5 = plant species richness (5 m²), TFP 5 = total flowering plants (5 m²), APH 5 = average plant height (5 m²), ACG 5 = average % cover grass (5 m²), ACH 5 = average % cover herb (5 m²), ACL 5 = average % cover litter (5 m²), ALLD 5 = average leaf litter depth (5 m²), MNG = Management type

2.3.2.2 Environmental variables influencing predator assemblage composition

The environmental variables driving differences in predator assemblage composition across landscape contexts were dominated by average plant height (1 m²), plant species richness (5 m²) and average leaf litter depth (5 m²) (Table 2.6). Plant species richness (5 m²) was associated with significant differences in predator assemblage composition for the combination of management and biotope types across all predator groupings (Table 2.6). It also was associated with significant differences in beetle and spider assemblage composition for organic management as well as total and wasp assemblage composition for both management types (Table 2.6). Total assemblage composition for the orchard with natural vegetation biotope, and spider assemblage composition for the two orchard biotopes, differed with management type (Table 2.6). Significant differences in ant, beetle and wasp assemblage composition for the orchard without natural vegetation biotope were associated with average leaf litter depth (5 m²) (Table 2.6). Average plant height (1 m²) dominated the orchard without natural vegetation biotope by associating with significant differences in total, ant, beetle and wasp assemblage composition (Table 2.6). Significant differences in total, ant and spider assemblage composition for the natural vegetation neighbouring orchards biotope were driven by average % litter cover (5 m²) (Table 2.6).

Table 2.6 – Distance based linear modelling (DistLM) results based on Bray-Curtis similarity for each predator grouping in each landscape context (Org – organic, Conv – conventional, OrchNV – orchard with natural vegetation, Orch – orchard without natural vegetation, NV – natural vegetation neighbouring orchards). Only the environmental variables selected by DistLM sequential tests are shown. Significant Pseudo-F results are indicated using a (*), *p < 0.05, **p < 0.01, ***p < 0.001.

Predator grouping	Landscape factor		Environmental variables	Cum. % Var.
Total	Combination		PSR 5: 4.78***; APH 1: 3.30***	20.29
	Management type	Org	PSR 5: 3.71***	18.83
		Conv	PSR 5: 3.55***	18.17
	Biotope	OrchNV	MNG: 2.02**	16.77
		Orch	APH 1: 3.87***	27.92
		NV	ACL 5: 1.41**	12.38
Ant	Combination		PSR 5: 3.72***; APH 1: 4.43***	20.51
	Management type	Org	ALLD 5: 3.56***	18.22
		Conv	APH 1: 3.74***	18.93
	Biotope	OrchNV	ALLD 5: 2.63*	20.80
		Orch	APH 1: 6.79***	40.44
		NV	ACL 5: 2.30**	18.69
Beetle	Combination		PSR 5: 4.88***; ALLD 5: 3.84***	21.68
	Management type	Org	PSR 5: 5.35***	25.04
		Conv	APH 5: 2.90***	15.54
	Biotope	OrchNV	ALLD 5: 1.96*	16.39
		Orch	APH 1: 3.88***	27.94
		NV	ACG 5: 1.77	15.04
Spider	Combination		PSR 5: 3.90***; APH 1: 3.73***	19.40
	Management type	Org	PSR 5: 3.25***	16.86
		Conv	TFP 5: 4.42***	21.62
	Biotope	OrchNV	MNG: 2.42**	19.51
		Orch	MNG: 4.68**	31.89
		NV	ACL 5: 2.01**	16.73
Wasp	Combination		PSR 5: 3.14***	8.47
	Management type	Org	PSR 5: 2.32***	12.68
		Conv	PSR 5: 2.27***	12.44
	Biotope	OrchNV	ALLD 5: 1.66**	14.24
		Orch	APH 1: 1.47*	12.84
		NV	ACG 5: 1.35	11.9

Cum. % Var. = cumulative percentage variation explained by environmental variables, Org = organic, Conv = conventional, OrchNV = orchard with natural vegetation, Orch = orchard without natural vegetation, NV = natural vegetation neighbouring orchards, PSR 1 = plant species richness (1 m²), PSA 1 = plant species abundance (1 m²), APH 1 = average plant height (1 m²), PSR 5 = plant species richness (5 m²), TFP 5 = total flowering plants (5 m²), APH 5 = average plant height (5 m²), ACG 5 = average % cover grass (5 m²), ACH 5 = average % cover herb (5 m²), ACL 5 = average % cover litter (5 m²), ALLD 5 = average leaf litter depth (5 m²), MNG = Management type

2.4 Discussion

This study contributes to the growing body of literature worldwide on the impact of local and landscape factors on the arthropod predator complex (Bengtsson et al. 2005, Tscharntke et al. 2005, Chaplin-Kramer et al. 2011, Tuck et al. 2014, Gurr et al. 2017, Lichtenberg et al. 2017). It shows that using predator-friendly farming practices and conserving natural vegetation in the agricultural landscape can significantly improve predator species richness and abundance in cropland, specifically orchards. Organic management consistently improved predator species richness and abundance relative to conventional management. Additionally, the presence of neighbouring natural vegetation was associated with a great improvement in predator species richness in conventional orchards. The degree of environmental heterogeneity was significantly associated with the predator patterns seen in each of the landscape contexts. Increased environmental heterogeneity was generally associated with improved predator species richness and abundance.

When viewed at the local scale, management had a large influence on predator species richness, abundance and assemblage composition. Organic management was consistently associated with significantly greater total, beetle, spider and wasp species richness and abundance, and had a significantly different predator assemblage composition to conventional management. This concurs with a number of studies that found an increase in a diverse array of predators on organic versus conventional farms (Mäder et al. 2002, Bengtsson et al. 2005, Hole et al. 2005, Schmidt et al. 2005, Birkhofer et al. 2008, Batáry et al. 2012, Inclán et al. 2015, Lichtenberg et al. 2017, Djoudi et al. 2019). Predators are better able to survive in cropland when the environmental conditions are best suited for their survival and fecundity (Landis et al. 2000). An increase in environmental heterogeneity of the understorey and soil habitat was positively associated with predator species richness and abundance, and was the main difference between the organic and conventional farms. The presence of ground cover, floral resources, leaf litter and healthy, organic-rich soil benefits predators through the provision of crucial habitat and resources throughout their lifecycles (Altieri and Schmidt 1986, Landis et al. 2000, Pfiffner and Luka 2003, Fuller et al. 2005, Birkhofer et al. 2008, Silva et al. 2010, Ramsden et al. 2015).

The presence of natural vegetation in relation to orchards led to an array of different responses by the predator groupings. Ant species richness was significantly greater in natural vegetation than orchards and was also significantly different in assemblage composition between these biotopes. The presence of natural vegetation is therefore important for conserving ant species that are habitat specialists and unable to tolerate agricultural disturbances (Hoffmann and Andersen 2003, Andersen and Majer 2004). The presence of undisturbed natural vegetation neighbouring orchards could potentially aid in suppressing

certain ant species from dominating in orchards. The high variability in ant abundance across some natural vegetation sites could be as a result of a few ant species dominating disturbed natural vegetation sites that had less understorey plant and litter cover (Hoffmann and Andersen 2003, Andersen and Majer 2004). Natural vegetation neighbouring orchards therefore needs to be protected from disturbances, such as over-browsing, in order to prevent disturbance-adapted ant species (for example: the large pugnacious ant – *Anoplolepis custodiens*) from dominating and potentially spilling over into orchards (Hoffmann and Andersen 2003). Although beetle species richness, abundance and diversity were significantly lower in natural vegetation, orchards with natural vegetation had consistently greater species richness than orchards without. Natural vegetation could potentially serve as a refuge and stable overwintering habitat for sensitive predaceous beetles that are then strongly attracted to the neighbouring productive cropland habitat during the warmer seasons (Holland and Luff 2000). Wasp species richness and abundance in orchards with natural vegetation was shown to be significantly greater than in orchards without natural vegetation and natural vegetation itself. The recorded benefits of non-crop habitat for wasp species have been supported in literature as it can provide wasps with a stable environment and valuable food resources from which to disperse into cropland (Landis et al. 2000, Bianchi et al. 2006, 2008, Thomson and Hoffmann 2009, 2010).

At the landscape scale, predator species richness, abundance and diversity differed depending on the combination of orchard management type and biotope used. Conventional orchards with neighbouring natural vegetation were shown to generally have significantly greater predator species richness when compared to conventional orchards without natural vegetation. These orchards were associated with predator spillover from natural vegetation which provides the environmental heterogeneity and resources needed by a diverse array of predators for survival and population growth (Tscharntke et al. 2005, Thomson and Hoffmann 2009, Henri et al. 2015). In comparison, organic orchards with neighbouring natural vegetation generally had equal predator species richness, abundance and diversity than organic orchards without neighbouring natural vegetation. This disproves our original hypothesis that organic farming in combination with neighbouring natural vegetation would have the highest predator diversity and abundance. The increase in environmental heterogeneity provided by neighbouring natural vegetation did not have a major impact on predators due to the already high-level of environmental heterogeneity present on organic farms (Tscharntke et al. 2005). Due to the higher simplicity of the landscape, organic orchards without natural vegetation consistently had significantly greater predator species richness, abundance and diversity than conventional orchards without natural vegetation. The influence of the high levels of organic environmental heterogeneity in a relatively simple landscape led to the drastic differences

encountered (Tscharntke et al. 2005, Tuck et al. 2014). Predators with high dispersal abilities (for example: certain ballooning spider species), combined with a diverse organic cropland habitat, can allow for high predator species richness and abundance away from areas of natural vegetation (Schmidt et al. 2005). There were no significant differences in predator species richness, abundance and diversity between the conventional and organic orchards with neighbouring natural vegetation which is supported by previous research that shows high biodiversity is supported in complex landscapes compared to simple landscapes (Schmidt et al. 2005, Tscharntke et al. 2005, Chaplin-Kramer et al. 2011). Complex landscapes, with significant areas of non-crop habitat, result in a high influx of predators into nearby orchards, with management type having a minor influence (Purtauf et al. 2005, Tscharntke et al. 2005, Bianchi et al. 2006). This study therefore supports the intermediate landscape-complexity hypothesis that the greatest impact of local management practices will be in simpler landscapes and not complex landscapes (Tscharntke et al. 2005, 2012).

This study was unfortunately limited by time constraints and therefore could not investigate the herbivore complex within the same study sites. Further research into the dynamics of the herbivore complex across similar landscape contexts would improve the understanding of the impact of the predator assemblage and environmental drivers on the herbivore assemblage and the relationships within.

2.5 Management recommendations and conclusions

Depending on their landscape context, farmers looking to improve their predator complex should aim to increase heterogeneity in their cropland and in the landscape. Cropland heterogeneity can be increased through cover cropping, mulching and the use of organic compost and manure. This will provide predators with habitat and resources needed to survive and increase their population sizes within cropland. This strategy will be particularly effective in cropland that is located within a transformed agricultural matrix. By conserving and restoring remnant natural vegetation in the landscape, farmers will benefit from a rich and abundant predator assemblage that will be more resilient to agricultural and environmental disturbances. Restoring natural vegetation corridors along orchard boundaries, fence lines and roads can be one method used by farmers to enhance the movement of biodiversity into the agricultural landscape (Figure 2.7). In conclusion, wise research, planning and implementation can create agricultural landscapes that can feed the ever-growing human population, have substantially reduced impacts on the environment and maximise resilience of native biodiversity and agriculture to future climate change effects (Kremen and Merenlender 2018).



Figure 2.7 – An example of natural vegetation (right) conserved along a farm fence line in the Sundays River Valley, South Africa.

2.6 References

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Chapter 3

Arthropod predator edge effects between orchards and neighbouring natural vegetation

ABSTRACT

Edges between agricultural and native ecosystems are becoming more abundant as agriculture expands to keep up with the growing human population. Predators in natural ecosystems (for example: ants, predaceous beetles, spiders and wasps) assert top-down control on herbivore species, including agricultural pests, and therefore knowledge of how the edge environment affects the predator assemblage is crucial. Parasitoids were included in the term predator within this study. This study investigated the change in predator species richness, abundance, diversity and assemblage composition between natural vegetation (thicket) and citrus orchards (conventional and organic) in the Sundays River Valley, Eastern Cape, South Africa. Predators were sampled from an edge along a transect into neighbouring natural vegetation and citrus orchards respectively, using a vacuum sampler and pitfall traps. Greater total, ant and wasp species richness, abundance and diversity were recorded at the natural vegetation-orchard edge regardless of orchard management type. Orchards had greater beetle species richness, abundance and diversity than natural vegetation. In contrast, spider species richness, abundance and diversity was similar across the two neighbouring habitats. Organic orchards had greater total, ant, beetle and spider species richness and abundance than conventional orchards. Low similarity between predator assemblages in native and orchard habitats suggested little spillover between habitats. Beta diversity was greater in natural vegetation than orchards for most predator groups. This study found that natural vegetation was associated with greater predator species richness, abundance and diversity in nearby orchards but varies greatly between predator groupings. Orchards were also associated with greater predator species richness, abundance and diversity in nearby natural vegetation which can impact on native species survival and movement. It is therefore recommended that, in combination with organic management techniques, natural vegetation should be maintained and restored in the agricultural landscape to promote predator diversity in orchards through spillover from natural vegetation. Conserving and restoring natural vegetation also allows for connectivity between natural habitats and native species survival in these modified landscapes.

Keywords: citrus, conventional, edges, natural vegetation, orchards, organic, predators, South Africa, thicket

3.1 Introduction

Globally, natural habitats are under ever-increasing pressure as the human population, and its negative environmental impacts, continue to grow (Tilman 1999, Tilman et al. 2001). Human-dominated landscapes, such as agricultural landscapes, are increasingly expanding and replacing native biotopes, resulting in wide-ranging habitat destruction and fragmentation (Tilman 1999, Tilman et al. 2001, Foley et al. 2005). Biodiversity in remnant natural vegetation in agricultural landscapes is greatly influenced by neighbouring cropland due to the novel edge environments created between these biotopes (Ewers and Didham 2006, Campbell et al. 2011). These can either aid, hinder or have no effect on assemblage structure and species movement between biotopes (Ries et al. 2004, Tscharntke et al. 2012).

Movement of species between crop and non-crop habitat is often affected by the condition of edge environments, the ecotones, in terms of biotope contrast and edge size (Collinge and Palmer 2002, Dauber and Wolters 2004, Campbell et al. 2011). Edges have varying impacts on biodiversity in neighbouring patches due to the different dispersal responses of individual species across the ecotone (Duelli and Obrist 2003, Tscharntke et al. 2005, Rand et al. 2006). Stenotopic species, specialists, are strongly adapted to non-crop habitat and usually do not disperse into cropland whilst, conversely, cultural species are strongly adapted to the crop habitat and rarely found in non-crop habitats (Duelli and Obrist 2003, Tscharntke et al. 2005). Species in-between these two extremes, are either dispersers or ecotone species (Duelli and Obrist 2003). Dispersers colonise the crop from the non-crop habitat, with decreasing abundance as distance from the non-crop habitat increases (Duelli and Obrist 2003, Tscharntke et al. 2005). Similarly, ecotone species have a strong preference for the ecotone environment and are strongly prevalent in the ecotone between the non-crop and crop habitats (Duelli and Obrist 2003, Tscharntke et al. 2005). The final group of species are ubiquitists, which have no habitat preference and are evenly spread between the two neighbouring habitats (Duelli and Obrist 2003, Tscharntke et al. 2005).

The benefit of non-crop habitat for increasing arthropod predators in neighbouring cropland is increasingly supported by a growing body of literature (Altieri and Schmidt 1986, Miliczky and Horton 2005, Sackett et al. 2009, Thomson and Hoffmann 2009, Macfadyen et al. 2015, Šálek et al. 2018, Boetzi et al. 2019). The term predator used within this study included parasitoids. Non-crop habitats can provide predators with vital food resources and refuge from agricultural and environmental disturbances, potentially resulting in increased survival, population sizes and lifecycle completion (Landis et al. 2000). A diverse array of predators can then spillover into neighbouring cropland from non-crop habitats (Altieri and Schmidt 1986, Landis et al. 2000, Thomson and Hoffmann 2009, Boetzi et al. 2019). This spillover of predators depends heavily on the contrast between neighbouring habitat types,

with lower habitat contrast assisting predator dispersal and greater habitat contrast hindering predator dispersal (Collinge and Palmer 2002, Campbell et al. 2011, Gaigher et al. 2015).

An often understudied aspect of edge effects on predator assemblages is the influence of cropland on neighbouring non-crop habitat (Blitzer et al. 2012). As species are known to potentially disperse from higher-productive habitats to lower-productive habitats, edges can allow for the dispersal of predators or pests into non-crop habitat (Tscharntke et al. 2005, 2016, Rand et al. 2006, Frost et al. 2015, Moxley et al. 2017). This has numerous potential environmental impacts as cropland subsidised predators can cause increased non-crop native herbivore predation and parasitism, and competition with native predator specialists (Tscharntke et al. 2005, Rand et al. 2006, Blitzer et al. 2012, Frost et al. 2015). Alternatively, spillover of pests into natural habitat can increase competition with native herbivore species for resources, influence native plant fitness or increase predation on native species through apparent competition (Carvalho et al. 2008, Van Veen et al. 2008).

Predators in cropland can be promoted by organic farming, which excludes the use of chemical pesticides and fertilisers (Altieri and Schmidt 1986, Birkhofer et al. 2008, Lichtenberg et al. 2017, Djoudi et al. 2019). Organic farming increases environmental heterogeneity in cropland through either cover cropping, mulching, manure, compost applications or combination thereof, which provides habitat, shelter and food resources to predators (Altieri and Schmidt 1986, Pfiffner and Luka 2003, Fuller et al. 2005, Birkhofer et al. 2008, Norton et al. 2009, Silva et al. 2010, Ramsden et al. 2015). Farmers will be informed by this study as to the possible value of organic farming techniques, while conserving natural vegetation next to orchards, in order to maximise the presence of predators in cropland.

This study aims to investigate whether the presence of natural vegetation bordering alongside citrus orchards (conventional and organic) has an influence on predator species richness, abundance, diversity and assemblage composition across the natural vegetation-orchard edge. The study objectives are:

1. To determine if there are differences in predator species richness, abundance and diversity across the natural vegetation-orchard edge.
2. To determine whether predator and environmental variable edge patterns differ between different orchard management types (conventional and organic).
3. To determine if there are differences in predator assemblage composition and beta diversity across the natural vegetation-orchard edge for each management type.

It is expected that the highest predator species richness, abundance and diversity will be at the natural vegetation-orchard edge. The greater environmental heterogeneity in organic orchards, associated with a diverse and dense orchard cover crop and no orchard pesticide

applications, is expected to result in greater predator species richness, abundance, diversity and assemblage composition similarity to natural vegetation than that of conventional orchards.

3.2 Methods

3.2.1 Study area and sites

The 12 natural vegetation-orchard study sites were spread across six citrus farms within the Sundays River Valley, Eastern Cape, South Africa ($33^{\circ}27'08.7''$ S, $25^{\circ}31'30.6''$ E, Figure 3.1). Albany Alluvial Vegetation, Sundays Noorsveld and Sundays Thicket are the main natural vegetation types that occur in the study area (Hoare et al. 2006). Due to the high plant species endemism in the study area, it falls within the Albany Centre of Floristic Endemism (Victor and Dold 2003). Additionally, the study area also falls within the Maputaland-Pondoland-Albany Biodiversity Hotspot as a result of this high endemism in combination with high levels of habitat destruction and degradation (Steenkamp et al. 2004). Conventional citrus farms with similar pesticide regimes were chosen for this study. Study site selection was limited by the number of organic citrus farms available with neighbouring natural vegetation. Predominantly Navel citrus orchards (either conventional or organic) with neighbouring remnant natural vegetation were chosen as study sites. Fieldwork was conducted in early spring (September 2017) and late summer (February 2018).

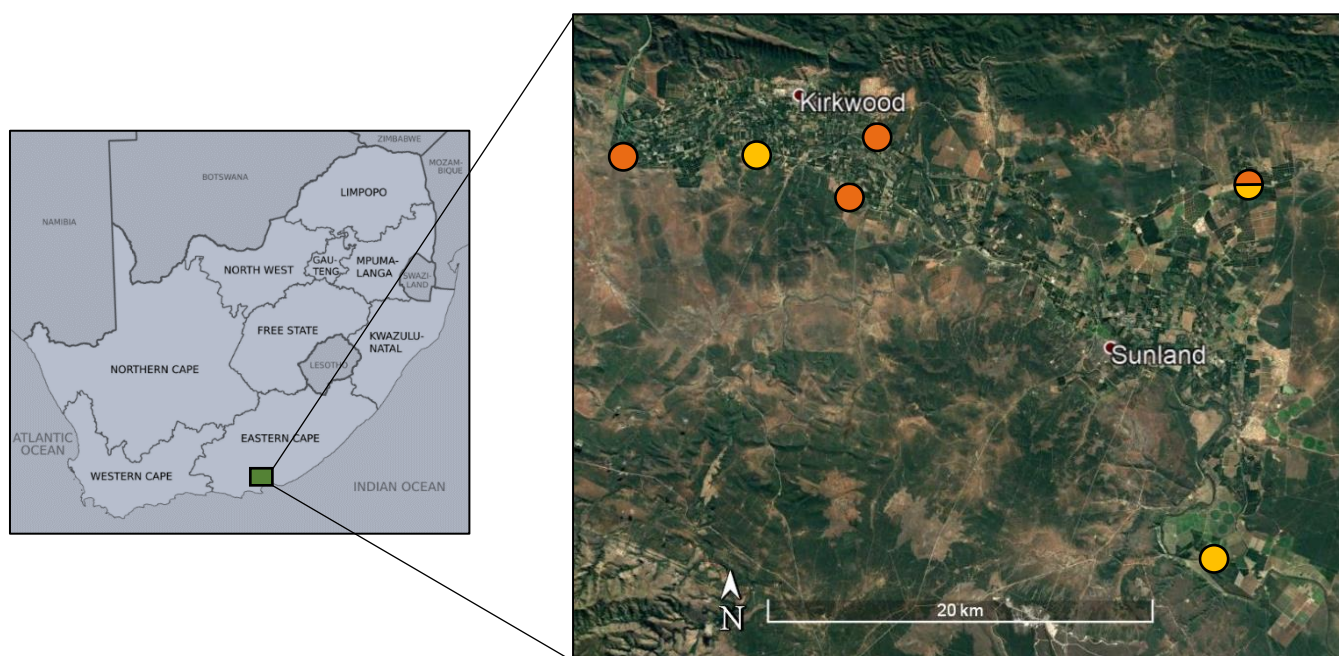


Figure 3.1 – The six citrus farms containing 12 study sites in the Sundays River Valley, Eastern Cape, South Africa. Orange – conventional farm, yellow – organic farm. Satellite image: Google Earth, 2018.

3.2.2 Arthropod predator sampling

Three natural vegetation-orchard treatments were included in this study, namely: a combination of both conventional and organic orchard management types; conventional orchard management type only; organic orchard management type only. Arthropods were sampled in each of the three treatments (combined, conventional and organic orchards with neighbouring natural vegetation). A total of 12 sites were used for the combined treatment, and six sites were used for each of the conventional and organic treatments. A minimum of 150 m separated study sites that occurred on the same farm. To sample the natural vegetation-orchard gradient, sampling of predators occurred along a transect at 10 m, 20 m, 30 m, 40 m and 50 m intervals into the orchard and natural vegetation study sites respectively (Figure 3.2).

A vacuum sampler (Stihl SH 86), which captures arthropods in a fine mesh bag attached to its nozzle, was used to sample canopy-dwelling predators at each study site (Southwood and Henderson 2000, Gaigher et al. 2015). A standard 100 insertions with the vacuum sampler was performed at each sampling point, with 50 insertions in the lower canopy (below 50 cm) and 50 insertions in the upper canopy (above 50 cm). Each vacuum insertion lasted approximately one second. The 100 insertions were sampled along a perpendicular 50 m walk away and back towards the sampling start point, with lower canopy insertions occurring along the walk away and upper canopy insertions occurring on the return walk (Figure 3.2). Due to the thickness of the natural vegetation, the 50 lower and upper canopy insertions were performed as close to 50 m from the starting point as was possible. Insertions performed in the orchards were placed between 0 m and 2 m from the citrus tree bases. After each insertion walk, the vacuum samples were transferred to plastic resealable bags in order to be frozen and preserved for later identification.

Pitfall traps were installed at paired sampling points, separated by 5 m, to sample ground-dwelling predators (Southwood and Henderson 2000, Magoba and Samways 2012). To prevent damage or disturbance to the pitfall traps from vehicles or people, they were placed underneath the orchard rows between 0 m and 1 m from the citrus tree bases (depending on the irrigation sprayer locations). Paired sampling points were located at each transect locality, resulting in 20 pitfalls per treatment transect (Figure 3.2). An ethylene glycol solution (50% ethylene glycol, 50% water and a drop of detergent to break the surface tension) was used to half-fill the pitfall traps (6.5 cm diameter, 9 cm deep). After being installed and left in the field for a week, they were then retrieved and the contents transferred to a 96% ethanol solution to be preserved for laboratory analysis.

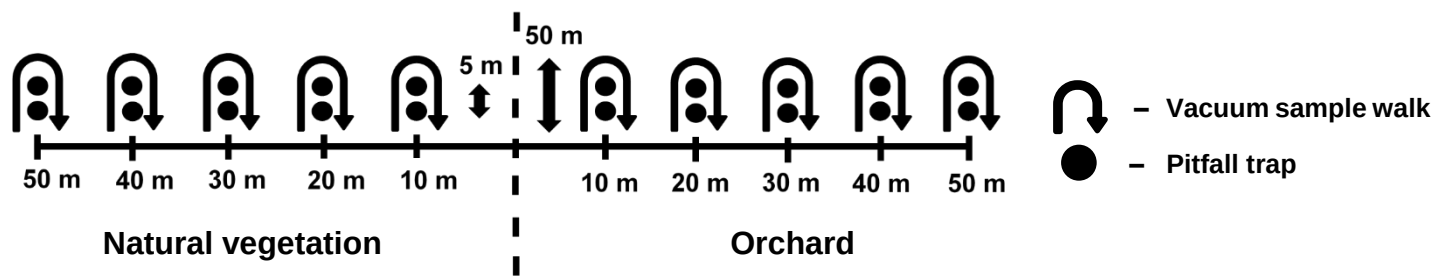


Figure 3.2 – Vacuum sampling and pitfall trapping transect design used to sample canopy and ground-dwelling predators respectively at each natural vegetation-orchard site. Dashed vertical line represents the edge between natural vegetation and orchards.

The sampled arthropods were sorted into morphospecies (from this point onwards referred to as species) and their abundance counted. Due to time constraints preventing finer taxonomic identification, as well as lack of taxonomic resolution for many taxa in this biodiversity hotspot, the sampled arthropods were identified to either class, order or family level (Picker et al. 2004). The following predator taxa were recorded: Araneae, predaceous Coleoptera, Chilopoda, Formicidae, Hymenoptera (wasps), Mantodea, Neuroptera, Odonata, Opiliones, Orthoptera, Pseudoscorpiones, Scorpiones and Solifugae (Appendix A).

3.2.3 Environmental variable sampling

Using a 1 m² quadrat (lower canopy – below 50 cm height) and a 5 m² quadrat (upper canopy – above 50 cm height), the following environmental variables were sampled at each study site: plant species richness and abundance, number of flowering plants, average plant height, percentage vegetation cover of different growth forms (grass, herb and woody) and ground cover (litter, bare ground and rockiness), as well as average leaf litter depth. Each quadrat type was replicated at each transect locality. In order to incorporate greater potential environmental variance, percentage grass and herb cover, ground cover and average leaf litter depth were included in the 5 m² quadrat recordings. Orchard quadrats were placed 1 m away from citrus tree bases. Using relevant field guides, plant species in each quadrat were identified to species as far as possible and their abundance counted (Appendix B) (Bromilow 2010, Vlok and Schutte-Vlok 2010, Manning 2013).

3.2.4 Data analysis

Data analyses were conducted for the entire dataset, and also separately for each of the four major predator groups (ants, beetles, spiders and wasps). Arthropod predator data between different sampling methods (vacuum sampling and pitfall trapping methods) and seasons (spring and summer) were pooled for each transect locality. Additionally, environmental data

(except plant species richness and abundance) were recorded across both seasons and averaged. Plant species richness and abundance data were only recorded in spring.

The combination of biotope (natural vegetation and orchard) and locality (10 m, 20 m, 30 m, 40 m and 50 m) was used as the fixed explanatory variable in the following analyses. Differences in predator species richness, abundance and Simpson's Index of Diversity (first and second objectives) were calculated between biotope localities of each treatment (combined, conventional and organic management) using Linear mixed models (LMMs). Residual distributions were tested for normality using the Shapiro-Wilks test. Over-dispersed data were either log or square root transformed. LMMs with Gaussian distributions were analysed in R (version 3.5.1) (R Core Team 2018) using the R *lme4* package (Bolker et al. 2009, Bates et al. 2016). The R *vegan* package (Oksanen et al. 2018) was used to calculate Simpson's Index of Diversity (1-D value), a value between 0 and 1 that represents greater diversity as the value increases. To reduce possible bias from spatial nestedness, a random variable (distinct geographic regions of study sites in the Sundays River Valley) was included in analyses. These regions were selected based on study sites that were near to one another in clearly separate geographic areas of the Sundays River Valley.

Differences in predator assemblage composition between biotope localities of each treatment (combined, conventional and organic management) were tested using Permutational Multivariate Analysis of Variance (PERMANOVA) tests. The random variable, geographic region, was included in the PERMANOVA tests. Differences between management types (conventional and organic) within orchard localities were also tested. Primer 6 (version 6.1.13) and the PERMANOVA+ add-on (version 1.0.3) (PRIMER-E 2008) were used to investigate differences in predator assemblage patterns. In order to reduce the influence of study sites with very high abundances, fourth root transformation was performed on the entire data set and the ant abundance data. Similarity between biotope location assemblages for each treatment was firstly calculated by performing the Bray-Curtis similarity function (Anderson et al. 2008). Significant differences ($p < 0.05$) in biotope locality assemblage similarity for each treatment were calculated using a PERMANOVA main test. PERMANOVA pairwise-tests were used to follow up significant differences to determine which biotope locality assemblages differed significantly from one another for each treatment. Multidimensional scaling (MDS) plots were performed to visualise the predator assemblage differences between biotope localities of the combined treatment. Finally, Permutational analysis of multivariate dispersions (PERMDISP) tests, based on distances from a centroid, were used to calculate beta diversity differences between biotope localities of each treatment.

3.3 Results

Overall, 1 318 predator species and 117 917 individuals were sampled during this study. The predator assemblage sampled consisted of Araneae (167 spp., 3741 individuals), predaceous Coleoptera (98 spp., 2439 individuals), Chilopoda (8 spp., 136 individuals), Formicidae (77 spp., 105 768 individuals), Hymenoptera – wasps (732 spp., 4436 individuals), Mantodea (8 spp., 54 individuals), Neuroptera (9 spp., 119 individuals), Odonata (2 spp., 2 individuals), Opiliones (3 spp., 13 individuals), Orthoptera (2 spp., 3 individuals), Pseudoscorpiones (5 spp., 1183 individuals), Scorpiones (3 spp., 4 individuals) and Solifugae (4 spp., 19 individuals). Hymenoptera – wasps (56% spp., 4% individuals), Araneae (28% spp., 3% individuals), predaceous Coleoptera (7% spp., 2% individuals) and Formicidae (6% spp., 90% individuals) dominated the predator assemblage.

3.3.1 Patterns of predator species richness, abundance and Simpson's Index of Diversity (SID) across biotope localities

Total species richness was significantly different between biotope localities of the combined and organic treatments, with greater total species richness in combined and organic orchard locations near the edge (Figure 3.3a; Table 3.1). For the combined, conventional and organic treatments, total species richness increased towards the edge in both natural vegetation and orchards (Figure 3.3a). Although total abundance between locations was similar to one another, there was an increase in total abundance at the natural vegetation closest to the edge across treatments (Figure 3.3b). Similarly, there was no trend in total SID between biotope locations of each treatment, however there was a decrease in total SID at the natural vegetation location closest to combined and conventional edge (Figure 3.3c). Total species richness and SID were greater in organic orchard localities than conventional orchard localities (Figure 3.3a & b).

Table 3.1 – Linear mixed model (LMM) results of predator species richness, abundance and Simpsons' Index of Diversity differences between biotope localities of each treatment (combined, conventional and organic management). Significant chi-square results are indicated using a (*), *p < 0.05, **p < 0.01, ***p < 0.001.

Predator grouping	Treatment type	Species richness	Abundance	Simpson's Index of Diversity
		Main test	Main test	Main test
Total	Combination	56.29***	1.84	7.03
	Conventional	13.31	10.51	11.33
	Organic	57.88***	0.92	6.57
Ant	Combination	59.67***	6.85	3.50
	Conventional	55.31***	21.25*	7.68
	Organic	18.65*	2.46	4.98
Beetle	Combination	162.24***	118.33***	99.89***
	Conventional	69.00***	45.78***	57.26***
	Organic	109.12***	95.11***	50.12***
Spider	Combination	13.55	10.80	2.80
	Conventional	15.26	3.61	23.03**
	Organic	8.11	15.31	4.89
Wasp	Combination	61.17***	52.96***	25.01**
	Conventional	23.21**	21.55*	10.54
	Organic	49.81***	44.41***	24.20**

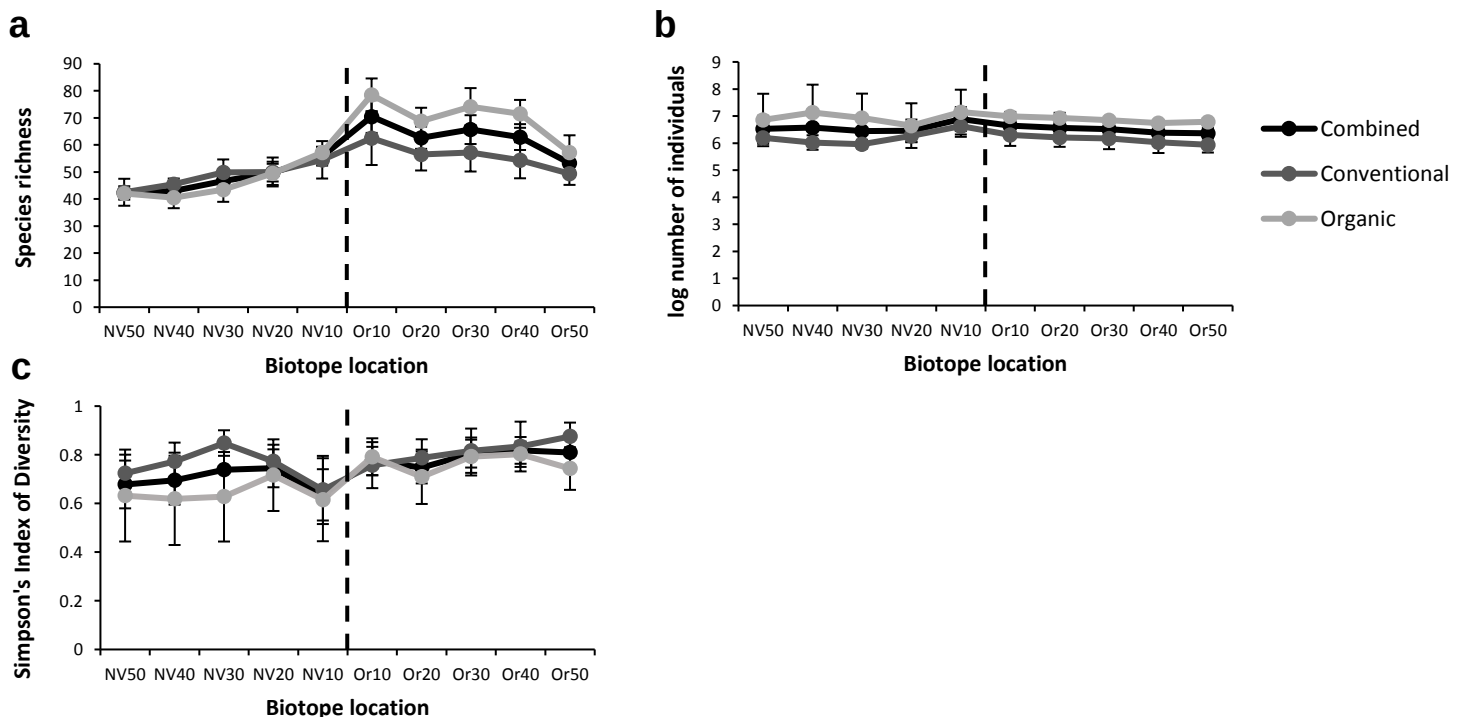


Figure 3.3 – Patterns of total (a) species richness, (b) abundance and (c) Simpson's Index of Diversity (mean $\pm$ SE) across biotope localities for each treatment (combined, conventional and organic management). X-axis labels indicate distance from the natural vegetation (NV) and orchard (Or) edge, for example: NV 50 = 50 m into natural vegetation from the edge. Dashed vertical line represents the edge between natural vegetation and orchards.

Ant species richness changed significantly with biotope location across treatments (Table 3.1). Ant species richness across treatments was lower in orchards than natural vegetation, and decreased in the orchard as the distance from the edge increased (Figure 3.4a). Ant abundance also significantly differed between conventional biotope locations, with conventional orchards having lower ant abundance than natural vegetation (Figure 3.4b; Table 3.1;). The natural vegetation location closest to edge had the greatest ant abundance across treatments (Figure 3.4b). Within orchards themselves, ant abundance hardly differed, although in conventional orchards there was a decline in ant abundance with distance from the edge (Figure 3.4b). Although ant SID was similar across most combined and conventional locations, it did decrease at the natural vegetation location nearest to the edge and two orchard locations nearest to the edge (Figure 3.4c). In contrast, ant SID was similar across most organic locations but decreased at the two orchard locations furthest from the edge (Figure 3.4c). Ant species richness and abundance were both greater in organic than conventional orchards (Figure 3.4a & b).

Beetle species richness, abundance and SID all differed significantly between combined, conventional and organic locations (Table 3.1). Orchard beetle species richness, abundance and SID increased sharply across the edge and was always greater than in the natural vegetation (Figure 3.4d, e & f). In combined and organic treatments, beetle species richness increased in the natural vegetation locations closest to the edge and decreased in the orchard location furthest from the edge (Figure 3.4d). Beetle abundance between locations within each respective biotope (natural vegetation and orchard) was similar across treatments (Figure 3.4e). Although beetle SID was similar between orchard locations across treatments, it increased in natural vegetation locations near the edge (Figure 3.4f). Organic orchard localities had greater beetle species richness and abundance than conventional orchard localities (Figure 3.4d & e).

Spider species richness increased towards the combined, conventional and organic natural vegetation-orchard edge (Figure 3.5a). Spider abundance showed a decreasing trend in conventional orchards as distance from the edge increased, whilst it showed a decreasing trend in natural vegetation for the organic treatment as distance from the edge increased (Figure 3.5b). Spider SID differed significantly between conventional locations, with greater spider SID in natural vegetation than conventional orchards (Figure 3.5c; Table 3.1). Spider SID was similar across combined locations (Figure 3.5c). Although spider SID at organic natural vegetation locations experienced large variation, organic orchard spider SID increased towards the mid-orchard location (Figure 3.5c). Spider species richness and abundance were greater in organic orchard localities than conventional orchard localities (Figure 3.5a & b).

Wasp species richness and abundance differed significantly between biotope locations across treatments, with a declining trend away from the natural vegetation-orchard edge (Figure 3.5d & e; Table 3.1). Wasp species richness and abundance increased towards the combined and conventional edge locations (Figure 3.5d & e). There was greater wasp species richness and abundance at the organic natural vegetation location nearest to the edge (when compared to other natural vegetation locations) whilst it was lower in the organic orchard locations 20 m and 50 m from the edge (Figure 3.5d & e). Wasp SID significantly differed between combined and organic treatments, with lower wasp SID in natural vegetation and a decreasing trend in natural vegetation locations as distance from the edge increased (Figure 3.5f; Table 3.1). Wasp species richness and abundance was greater in the mid-orchard localities of organic orchards than conventional orchards (Figure 3.5d & e).

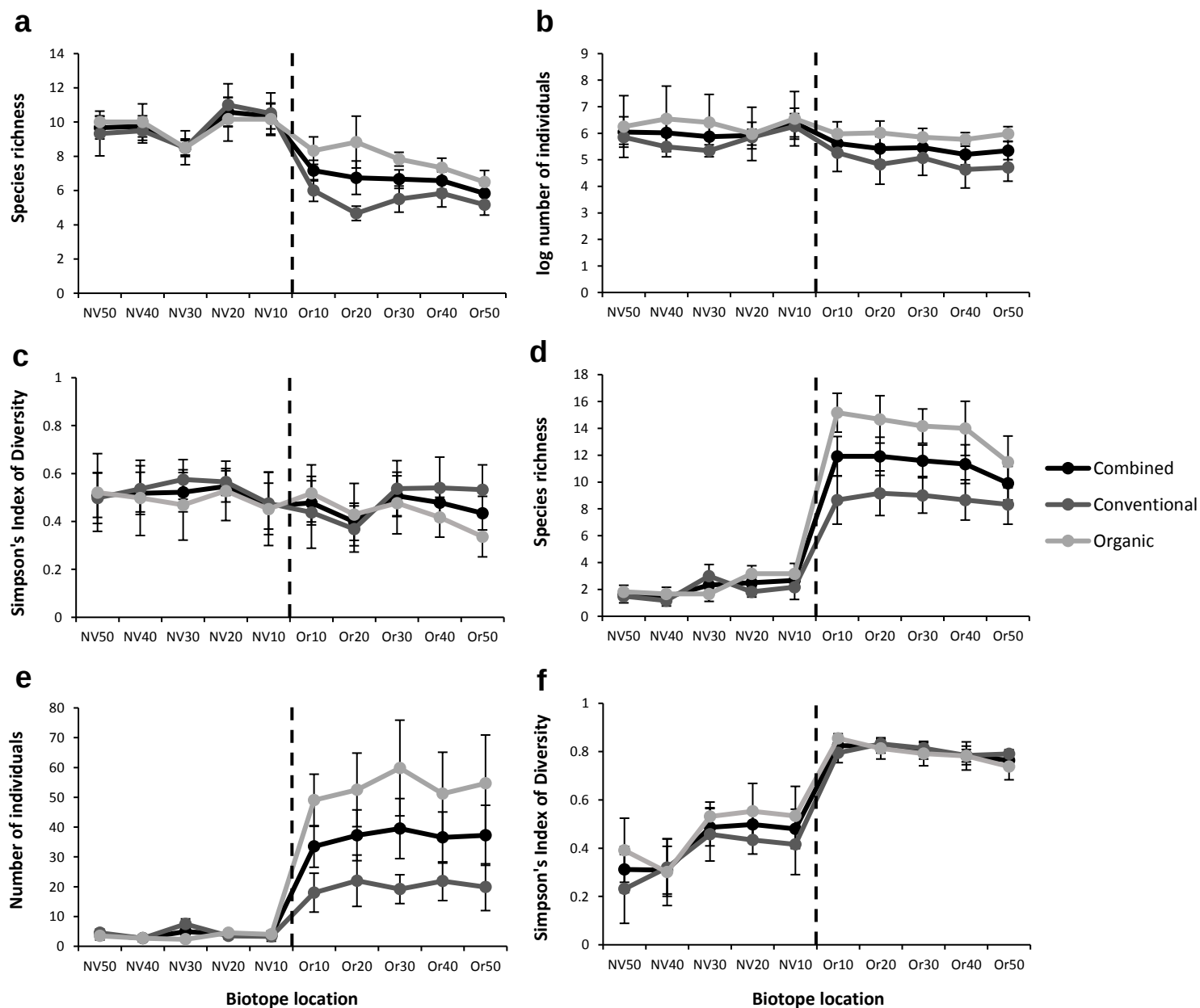


Figure 3.4 – Patterns of ant (a) species richness, (b) abundance and (c) Simpson's Index of Diversity, beetle (d) species richness, (e) abundance and (f) Simpson's Index of Diversity (mean $\pm$ SE) across biotope localities for each treatment (combined, conventional and organic management). X-axis labels indicate distance from the natural vegetation (NV) and orchard (Or) edge, for example: NV 50 = 50 m into natural vegetation from the edge. Dashed vertical line represents the edge between natural vegetation and orchards.

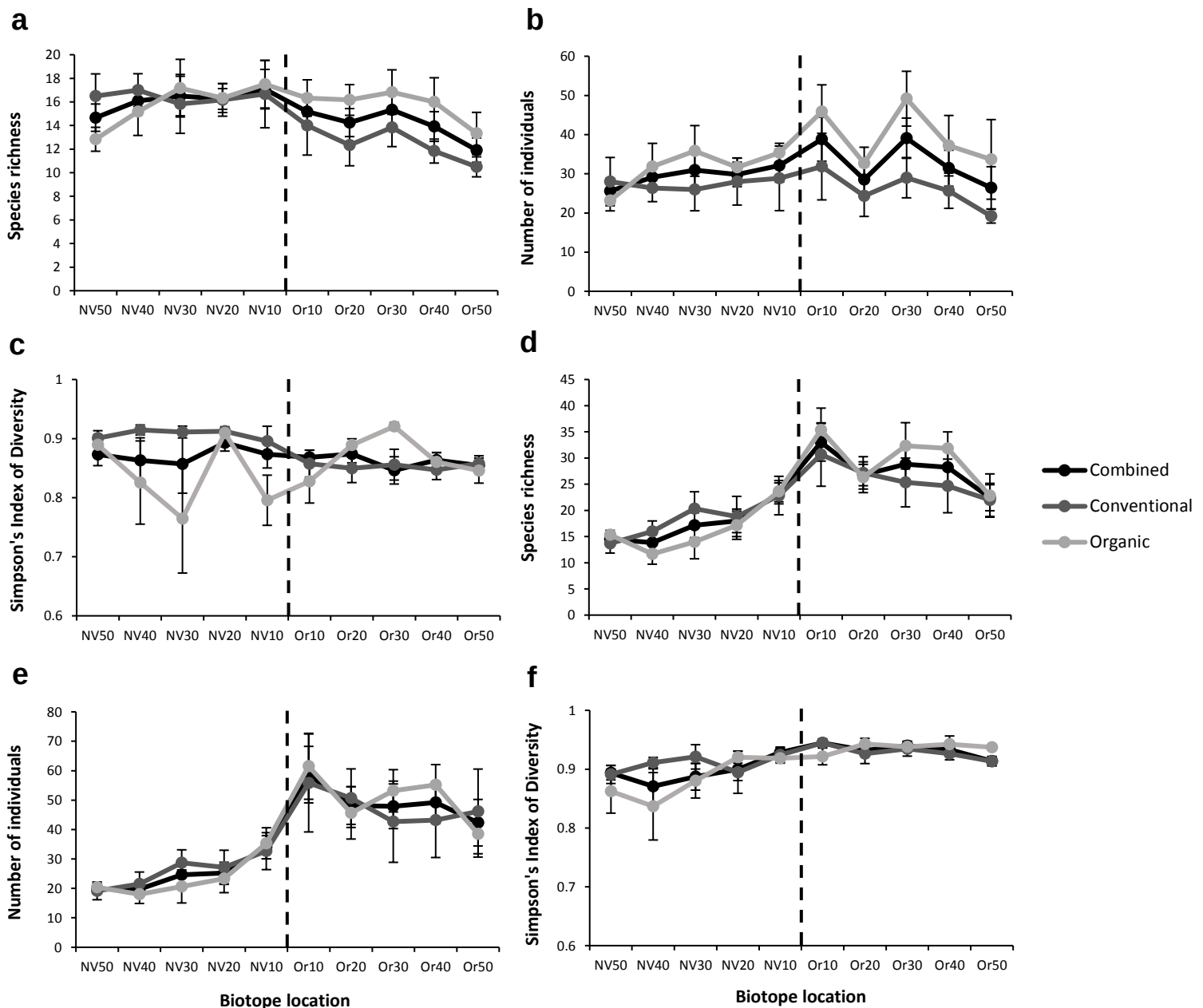


Figure 3.5 – Patterns of spider (a) species richness, (b) abundance and (c) Simpson's Index of Diversity, wasp (d) species richness, (e) abundance and (f) Simpson's Index of Diversity (mean $\pm$ SE) across biotope localities for each treatment (combined, conventional and organic management). X-axis labels indicate distance from the natural vegetation (NV) and orchard (Or) edge, for example: NV 50 = 50 m into natural vegetation from the edge. Dashed vertical line represents the edge between natural vegetation and orchards.

The four major environmental variables, average percentage grass (5 m) and herb (5 m) cover, average plant height (1 m) and average leaf litter depth (5 m), varied in their response to transect locality across treatments. Whilst there was a gradual increase in percentage grass and herb cover across the combined and conventional edge, the increase in percentage grass and herb cover across the organic edge was rapid (Figure 3.6a, d & g). Average plant height (cm) was similar across combined and organic locations whereas it decreased from the natural vegetation to conventional orchards (Figure 3.6b, e & h). In contrast, average leaf litter depth (cm) gradually increased from the natural vegetation to combined and organic orchards whilst it was similar between conventional locations (Figure 3.6c, f & i).

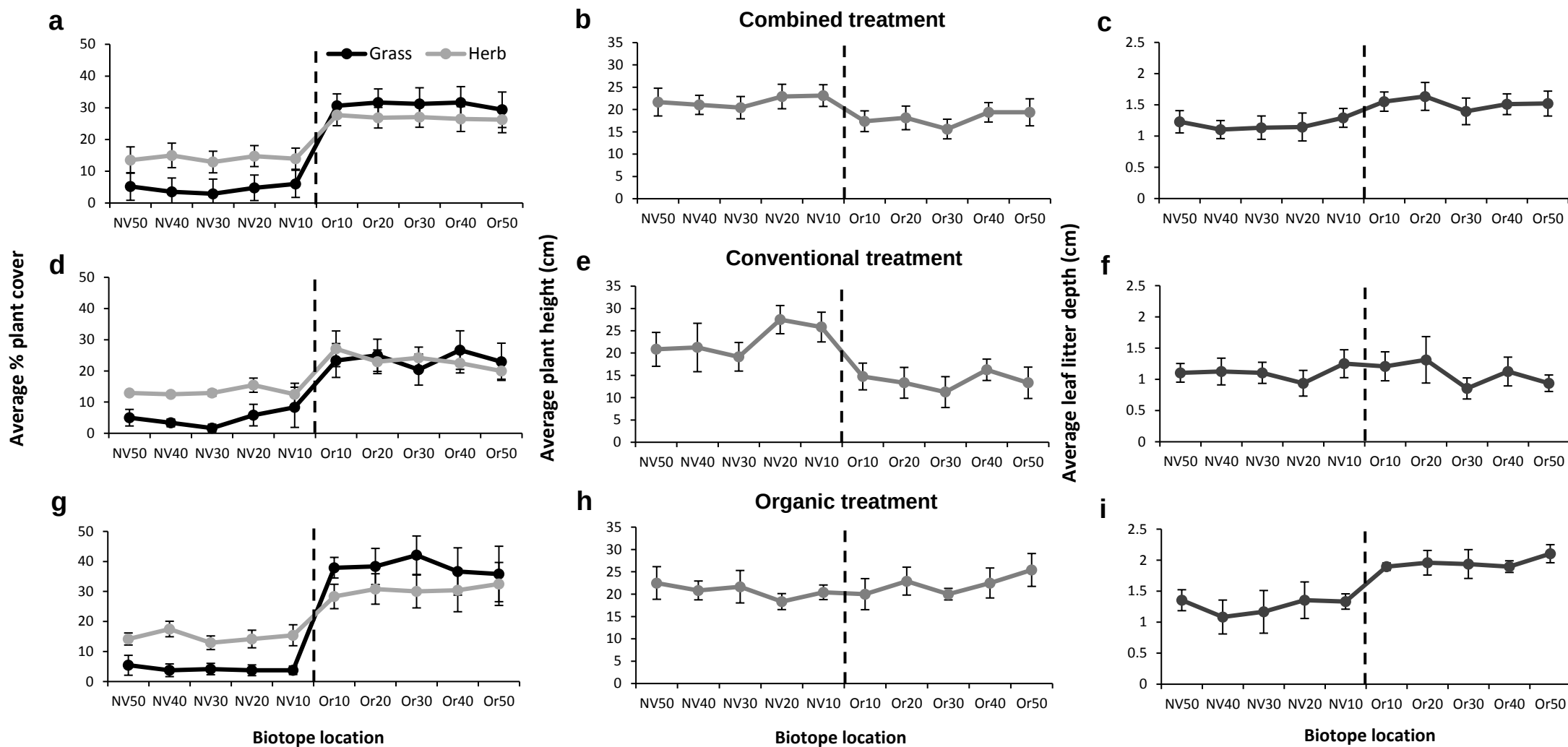


Figure 3.6 – The influence of biotope locality on environmental variables in the combined treatment (a) average percentage cover grass (5 m) and herb (5 m), (b) average plant height (1 m) and (c) average leaf litter depth (5 m); conventional treatment (d) average percentage cover grass (5 m) and herb (5 m), (e) average plant height (1 m) and (f) average leaf litter depth (5 m); organic treatment (g) average percentage cover grass (5 m) and herb (5 m), (h) average plant height (1 m) and (i) average leaf litter depth (5 m) (mean $\pm$ SE). X-axis labels indicate distance from the natural vegetation (NV) and orchard (Or) edge, for example: NV 50 = 50 m into natural vegetation from the edge. Dashed vertical line represents the edge between natural vegetation and orchards.

3.3.2 Patterns of predator assemblage composition and beta diversity across biotope localities

With the exception of beetles, predator assemblages differed significantly between natural vegetation and orchards (Table 3.2). Whilst beetle species assemblage composition differed significantly between the combined and organic biotope locations, it did not differ significantly between the conventional biotope locations (Table 3.2). Predator assemblage composition differed between conventional and organic orchard localities for all predator groupings (Table 3.2).

Table 3.2 – Permutational Multivariate Analysis of Variance (PERMANOVA) main test results on predator assemblage relationships between biotope localities of each treatment (combined, conventional and organic management) and orchard management types (conventional and organic). Significant Pseudo-F results from PERMANOVA main tests are indicated using a (*), *p < 0.05, **p < 0.01, ***p < 0.001.

Predator grouping	Total	Ant	Beetle	Spider	Wasp
Treatment type					
Combination	2.21***	1.69***	2.18***	1.81***	1.57***
Conventional	1.72***	1.70***	1.25	1.52***	1.27***
Organic	1.77***	1.35*	1.99***	1.74***	1.34***
Orchard management type					
Conventional - Organic	4.77***	5.91***	5.88***	4.60***	3.12***

Total, spider and wasp assemblage composition differed significantly between the natural vegetation and orchard locations of the combined and conventional treatments (Figure 3.7; Table 3.3). Natural vegetation and orchard locations for the organic treatment also differed significantly in total assemblage composition (Table 3.3). Ant assemblage composition differed significantly between the natural vegetation and orchard locations of the combined treatment type (Figure 3.7; Table 3.3). In contrast, conventional treatment locations differed significantly in ant assemblage composition between the natural vegetation (10 m, 20 m, 30 m, 40 m and 50 m) and orchard (10 m, 20 m) locations, natural vegetation (10 m and 20 m) and orchard (40 m and 50 m) locations, and natural vegetation (10 m) and orchard (30 m) locations (Table 3.3). Similarly, organic treatment locations were only significantly different in ant assemblage composition between natural vegetation (10 m, 40 m and 50 m) and orchard (40 m and 50 m) locations, and natural vegetation (50 m) and orchard (20 m and 30 m) locations (Table 3.3). Beetle species assemblage composition differed significantly between the natural vegetation and orchard locations of the combined and organic treatments (Figure 3.7; Table 3.3). Organic treatment locations differed significantly in spider assemblage composition between the natural vegetation and orchards whilst the two organic orchard (10 m and 20 m) locations also differed significantly to one another (Table 3.3). Across treatment

types, wasp assemblage composition differed significantly between the natural vegetation and orchard locations except for the natural vegetation (10 m) and orchard (20 m) locations of the organic treatment (Figure 3.7; Table 3.3).

Table 3.3 – Permutational Multivariate Analysis of Variance (PERMANOVA) pairwise test results on predator assemblage relationships between biotope localities of each treatment (combined, conventional and organic management). ≠ indicates significant differences based on PERMANOVA pairwise tests.

Predator grouping	Treatment type	Pairwise test
Total	Combination	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
	Conventional	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
	Organic	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
Ant	Combination	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
	Conventional	NV10, NV20, NV40, NV50 ≠ Or10, Or20; NV10, NV20 ≠ Or40, Or50; NV10 ≠ Or30
	Organic	NV10, NV40, NV50 ≠ Or40, Or50; NV50 ≠ Or20, Or30
Beetle	Combination	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
	Conventional	-
	Organic	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
Spider	Combination	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
	Conventional	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
	Organic	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50; Or10 ≠ Or20
Wasp	Combination	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
	Conventional	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or20, Or30, Or40, Or50
	Organic	NV10, NV20, NV30, NV40, NV50 ≠ Or10, Or30, Or40, Or50; NV20, NV30, NV40, NV50 ≠ Or20

NV10 = natural vegetation 10 m, NV20 = natural vegetation 20 m, NV30 = natural vegetation 30 m, NV40 = natural vegetation 40 m, NV50 = natural vegetation 50 m, Or10 = Orchard 10 m, Or20 = Orchard 20 m, Or30 = Orchard 30 m, Or40 = Orchard 40 m, Or50 = Orchard 50 m.

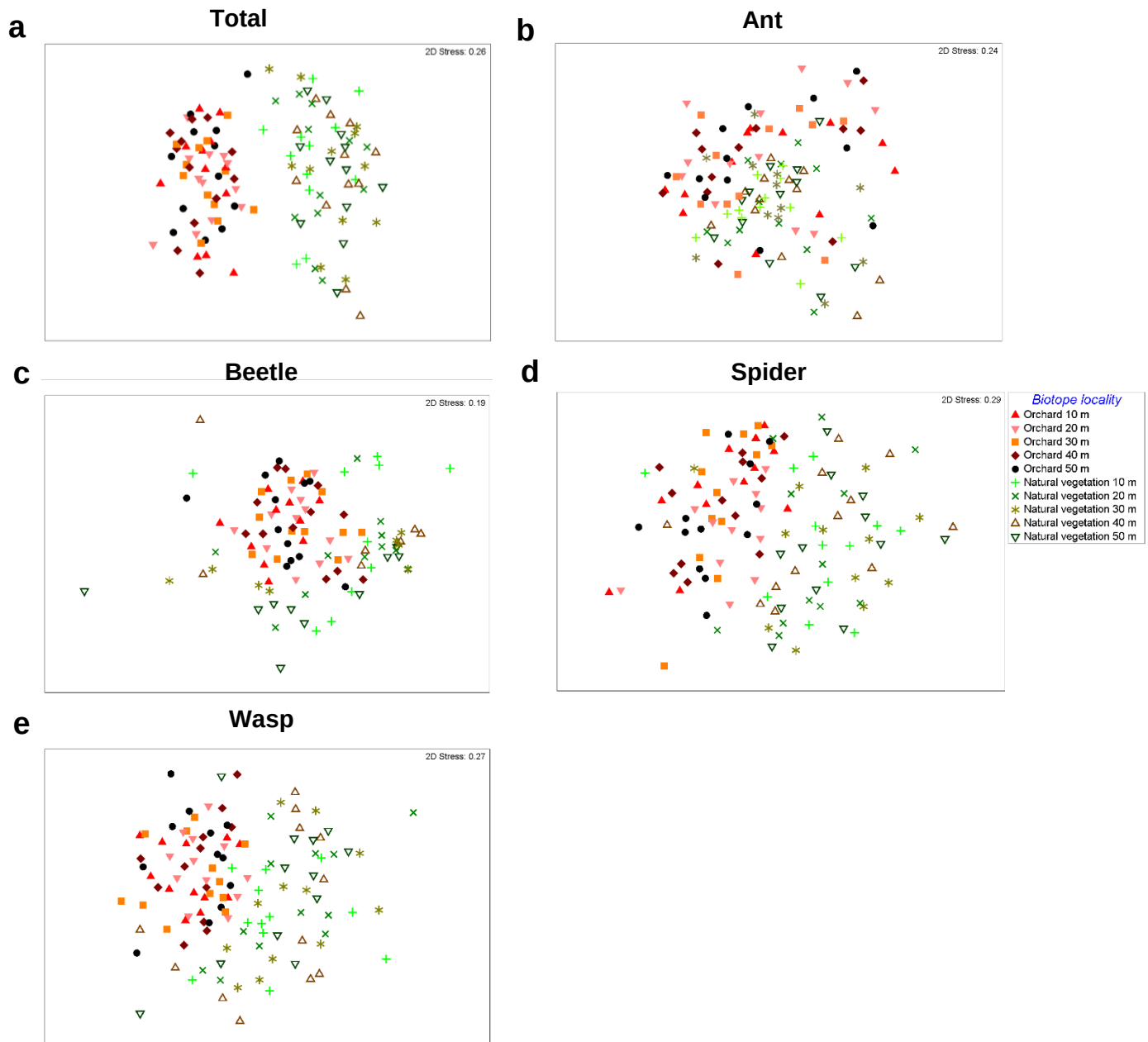


Figure 3.7 – Multidimensional scaling (MDS) results for (a) total, (b) ant, (c) beetle, (d) spider and (e) wasp composition differences between biotope locations of the combined treatment (10 m, 20 m, 30 m, 40 m and 50 m into the orchard and natural vegetation respectively).

Generally, predator beta diversity was significantly greater in natural vegetation locations than the orchard locations, the exception being ant beta diversity in combined and conventional orchards (Figure 3.8). Combined orchards had similar predator beta diversity between locations whereas conventional and organic orchard beta diversity varied between predator groups (Figure 3.8). Total, beetle and spider beta diversity was greater in conventional orchard locations that were closer to the natural vegetation edge (Figure 3.8a, h & k). In contrast, total, beetle and spider beta diversity was found to be greater in organic orchard locations that were further from the natural vegetation edge (Figure 3.8c, i & l).

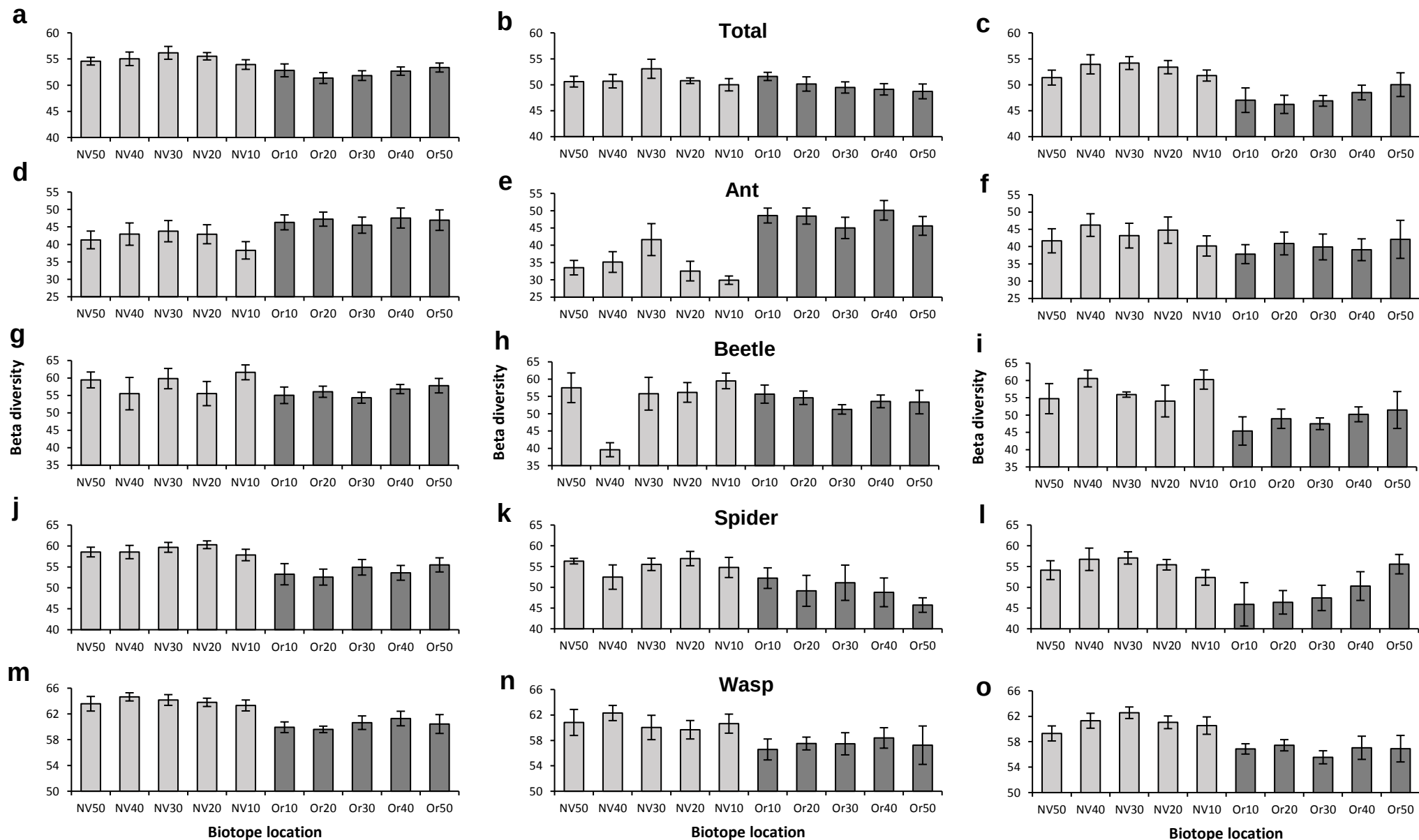


Figure 3.8 – Permutational analysis of multivariate dispersions (PERMDISP) results for the total (a) combined, (b) conventional and (c) organic treatment; ant (d) combined, (e) conventional and (f) organic treatment; beetle (g) combined, (h) conventional and (i) organic treatment; spider (j) combined, (k) conventional and (l) organic treatment; wasp (m) combined, (n) conventional and (o) organic treatment. X-axis labels indicate distance from the natural vegetation (NV) and orchard (Or) edge, for example: NV 50 = 50 m into natural vegetation from the edge.

3.4 Discussion

This study shows that predator species richness, abundance, diversity and assemblage composition changes across the edge between non-crop and crop habitats. There was large response variation by the predator groupings to edges, emphasising how various taxa respond to the landscape differently (Ingham and Samways 1996, Duelli and Obrist 2003, Ries and Sisk 2004, Ries et al. 2004, Rand et al. 2006). An improvement in the total, ant and wasp species complex in orchards was associated with neighbouring natural vegetation, which highlights the importance of nearby natural vegetation for cropland predators (Altieri and Schmidt 1986, Sackett et al. 2009, Thomson and Hoffmann 2009). Organic orchards generally had greater predator species richness and abundance relative to conventional orchards. Orchards were also associated with a greater total, ant, beetle and wasp species complex in natural vegetation near edges, demonstrating that edges between natural vegetation and orchards can potentially have both beneficial effects for agriculture and detrimental effects for native biodiversity conservation (Tscharntke et al. 2005).

Total species richness in both habitats increased towards the edge for all treatments. The positive edge response in both habitats suggests the presence of ecotone species that either take advantage of resources available in both neighbouring habitats or rely on resources available at edges and not in biotope interiors (Duelli and Obrist 2003, Ries and Sisk 2004, Ries et al. 2004, Rand et al. 2006, van Halder et al. 2011). Similarly, the increase in ant species richness and abundance at the combined and conventional natural vegetation-orchard edge illustrates the positive edge response experienced in both habitats (Rand et al. 2006). This is also potentially an indication of certain ecotone ant species being present that can either make use of complementary resources available in both habitats or edge enhanced resources not equally available in biotope interiors (Duelli and Obrist 2003, Ries and Sisk 2004, Ries et al. 2004, Rand et al. 2006, van Halder et al. 2011). The greater ant species richness and abundance in natural vegetation indicates that there is a diverse array of stenotopic ant species that cannot survive in the agricultural matrix (Duelli and Obrist 2003, Andersen and Majer 2004, Ries et al. 2004). Across treatments, orchards had greater levels of beetle species richness, abundance and SID. Orchards in the Sundays River Valley are irrigated, fertilised (either conventionally or organically) and generally have greater grass and herb cover than natural vegetation, resulting in a productive perennial habitat favoured by beetles in comparison to the poor soils and arid conditions of remnant natural vegetation areas (Tscharntke et al. 2016). Therefore, the majority of these beetles are potentially cultural species that are strongly adapted to the orchard environment and do not rely heavily on non-crop habitat for resources (at least during the warmer months of the year) (Duelli and Obrist 2003, Rand et al. 2006). With the exception of beetle abundance and the conventional

treatment's beetle species richness, beetle species richness and SID increased at the natural vegetation edge locations. This positive response in the natural vegetation indicates that certain generalist beetle species spillover from the orchards into natural vegetation to make use of available complementary resources, such as alternate prey sources (Ries et al. 2004, Rand et al. 2006).

Spider species richness, abundance and diversity mostly had a neutral edge response across treatments (Ries et al. 2004). This could be caused by the high dispersal ability of certain spider species (for example: ballooning spiders), in combination with the generalist predatory behaviour of spiders, resulting in no observable differences at the local scale (Tscharntke et al. 2005). Combined and conventional wasp species richness, abundance and SID increased in both habitats towards the edge. This positive response in both habitats indicates that there are ecotone wasp species that either make use of complementary resources available in both habitats or rely on edge enhanced resources (Duelli and Obrist 2003, Ries and Sisk 2004, Ries et al. 2004, Rand et al. 2006, van Halder et al. 2011). In the organic treatment, there was only an increase in wasp species richness, abundance and SID in the natural vegetation locations near the edge. The positive response experienced could be caused by the passive spillover of generalist, disperser wasp species from the productive orchards into the less-productive natural vegetation (Duelli and Obrist 2003, Rand et al. 2006).

Predator species richness, abundance and assemblage composition was greatly influenced by management type in orchards. Total, ant, beetle and spider species richness and abundance were consistently greater in organic orchards than conventional orchards. This finding is supported by a number of studies that also found an increase in predators on organic versus conventional farms (Mäder et al. 2002, Bengtsson et al. 2005, Hole et al. 2005, Schmidt et al. 2005, Birkhofer et al. 2008, Batáry et al. 2012, Inclán et al. 2015, Lichtenberg et al. 2017, Djoudi et al. 2019). This could be associated with the increased environmental heterogeneity of the orchard understorey and soil surface that was recorded in organic orchards relative to conventional orchards. Predator survival and persistence in cropland is increased when environmental conditions provide vital food resources, shelter and habitat to predators (Landis et al. 2000). The environmental conditions that benefit predators include ground cover, floral resources and organic-rich soil with a surface layer of mulch (Altieri and Schmidt 1986, Landis et al. 2000, Pfiffner and Luka 2003, Fuller et al. 2005, Birkhofer et al. 2008, Silva et al. 2010, Ramsden et al. 2015).

Predator assemblage composition was greatly influenced by the edge between the non-crop and crop habitats. There was little overlap in total, spider and wasp species assemblage composition between the natural vegetation and orchards. This suggests that the

agricultural matrix is a substantial barrier to movement for most high trophic native taxa, even when the matrix was softened by organic farming practices (Gaigher et al. 2015). This is concerning for native biodiversity conservation which requires connectivity between native communities to allow for recolonization following local disturbance events and shifting species distributions in response to climate change (Bengtsson et al. 2003, Bennett 2003). Whereas combined and organic beetle assemblage composition also differed between the two habitats, conventional beetle assemblage composition was similar between habitats. This could be due to the similarity in environmental conditions (lower grass and herb cover, and similar leaf litter depth) and therefore lower contrast between habitats which allowed for greater exchange of beetle species across the natural vegetation-orchard edge (Collinge and Palmer 2002, Campbell et al. 2011). Of all the predator groupings, ant species assemblage composition was most similar between the two habitats. Nevertheless, ant assemblage composition at the natural vegetation-conventional orchard edges differed from the interior locations for both habitats. It may be that these edge locations are dominated by disturbance-adapted ant species that thrive in the novel edge environment whereas the interior locations are dominated by disturbance-sensitive ant species (Hoffmann and Andersen 2003, Dauber and Wolters 2004). In contrast, ant assemblage composition at the natural vegetation-organic orchard edges were similar, although these assemblages did differ at locations away from the edge. The natural vegetation and orchard interior ant species are likely stenotopic and cultural species respectively whilst ant species at the edge locations could be ecotone generalist species that use complementary resources available in both habitats (Duelli and Obrist 2003, Ries et al. 2004, Rand et al. 2006).

Greater beta diversity was found in natural vegetation across most treatments and predator groups. This indicates that the greater heterogeneity in environmental conditions in natural vegetation resulted in a greater turnover of species (Tylianakis et al. 2005, Tscharrntke et al. 2007). This emphasises the importance of natural vegetation for maintaining a diverse assemblage of predator species within the entire landscape (Tylianakis et al. 2005, Tscharrntke et al. 2007). The lower beta diversity in orchards is probably due to greater environmental consistency experienced in cropland which results in less species turnover (Tscharrntke et al. 2007). Human activities, agriculture included, can cause ecological homogenisation, with many rarer, specialist species being replaced by a smaller amount of widespread species that can survive in human-dominated ecosystems (McKinney and Lockwood 1999, Socolar et al. 2016). Interestingly, there was greater total, beetle and spider beta diversity near the conventional orchard edge in contrast to lower total, beetle and spider beta diversity near the organic orchard edge. The spillover of diverse total, beetle and spider species from the natural vegetation across the edge into the conventional orchards could

explain this pattern of conventional beta diversity (Clough et al. 2007, Tschardt et al. 2007). The pattern in organic beta diversity could instead be as a result of a few common total, beetle and spider species dominating the orchard edge environment.

Natural vegetation was associated with greater total and wasp species richness and abundance, and ant species richness in neighbouring orchards. This concurs with a number of studies that found non-crop habitats can provide predators with essential resources and protection from disturbances, resulting in greater predator species richness and abundance in nearby cropland (Altieri and Schmidt 1986, Landis et al. 2000, Miliczky and Horton 2005, Sackett et al. 2009, Thomson and Hoffmann 2009, Macfadyen et al. 2015, Boetzi et al. 2019). The relatively high levels of spider species richness, abundance and SID across treatment locations is supported by Schmidt et al. (2005) that high amounts of non-crop habitat improve spider diversity in the landscape. Non-crop habitat is therefore emphasised as an important source of spider diversity to nearby cropland (Schmidt et al. 2005). The presence of orchards neighbouring natural vegetation led to greater total, ant, beetle and wasp species richness, ant and wasp abundance, and beetle and wasp diversity in natural vegetation near the natural vegetation-orchard edge. This could negatively impact on native herbivores in these edge areas and potentially also hinder their dispersal between non-crop habitat patches (Tschardt et al. 2005, Rand et al. 2006, Blitzer et al. 2012, Frost et al. 2015). This edge impact however did not penetrate deep into the natural vegetation, suggesting that agricultural impacts will not impact greatly on core native biodiversity provided natural vegetation patches are large enough, have a low perimeter-area ratio and are well connected to one another (Bennett 2003).

The low similarity in predator assemblage composition between natural vegetation and orchards emphasises the importance of natural vegetation connectivity through the agricultural landscape to allow for native species dispersal and long-term survival (Bennett 2003, Gaigher et al. 2015, Henri et al. 2015). The usage of native plants as cover crops, that are adapted to the local environmental conditions and provide ample floral nectar and pollen resources during citrus growing seasons, could aid native species dispersal across the agricultural matrix (Isaacs et al. 2009).

Due to time constraints, this study was limited to the predator complex and could not investigate the herbivore complex. Knowledge of herbivore diversity and community patterns across the natural vegetation-orchard edge would aid the understanding on how predator and herbivore species interact with one another and whether natural vegetation is a source, sink or barrier for herbivore species in the landscape. Research into the use of native plant species for citrus orchard cover cropping would be an exciting avenue to pursue as it will

contribute to softening of the agricultural matrix for native species and prevent the prevalence and spread of invasive plant species in cropland.

3.5 Management recommendations and conclusions

Natural vegetation in the landscape was associated with an improvement in the predator complex in nearby orchards. Farmers should aim to conserve natural vegetation on their farms to serve as a source of diverse and abundant predators which will be resilient to agricultural and climatic disturbances. The negative edge effect of the agricultural matrix on natural vegetation and the barrier it poses to specialist native species movement emphasises the need for wide corridors connecting patches of natural vegetation in the agricultural landscape. This study suggests that natural vegetation patches and corridors that are narrower than 40 m will be influenced by edge effects (20 m deep), thus negatively effecting specialist native species that rely on core habitat for survival. Natural vegetation in the agricultural landscape will need to be protected from disturbances such as pesticide applications and over-grazing in order to prevent loss of specialist species diversity and dominance of generalist, disturbance-adapted species (for example: the large pugnacious ant – *Anoplolepis custodiens*, which has been shown to respond to disturbance in both croplands and village habitats; Mauda et al. 2018). Organic farm conditions were also associated with an increase in predator species richness and abundance in orchards. Cover cropping, mulching and using organic compost and manure can be methods to increase environmental heterogeneity in cropland. In conclusion, organic management techniques and conserving neighbouring natural vegetation can be used to increase predators in orchards. This strategy will contribute to biodiversity conservation in the agricultural landscape of the Sundays River Valley.

3.6 References

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Chapter 4

Conclusion and recommendations

4.1 General discussion

Although there have been a fair number of studies on biodiversity, particularly of predators, in agricultural systems, to date the vast majority have been conducted in highly transformed, low-diversity, developed countries (Tuck et al. 2014, Katayama et al. 2019). Parasitoids were included in the term predator within this study. A heavy reliance on agriculture by developing countries, combined with their situation in subtropical and tropical regions, makes these countries vulnerable to future climate change impacts (Roschewitz et al. 2005, Schmidhuber and Tubiello 2007). These factors together emphasise the need for research into sustainable farm and landscape management in developing countries to safeguard future food production and biodiversity conservation. Furthermore, most of this work has focused on annual crops (Tuck et al. 2014). Perennial cropland experiences less disturbance and greater resource availability throughout the year relative to annual crops (Altieri 1999). This thesis therefore aimed to investigate how local and landscape factors influence predator species in the agricultural landscape of the Sundays River Valley, Eastern Cape, South Africa.

The first data chapter, chapter two, investigated whether, and to what extent, different citrus management practices (conventional and organic) within different landscape contexts (with and without natural vegetation neighbouring orchards) influence predator species richness, abundance, diversity and assemblage composition. The environmental variables (plant species richness and abundance, number of flowering plants, average plant height, percentage vegetation cover in three categories [grass, herb, woody] and ground cover [litter, bare ground and rockiness], as well as average leaf litter depth) that drive these predator patterns were also investigated. The influence that the natural vegetation-orchard edge had on predator species in the neighbouring biotopes was the focus of chapter three. This chapter investigated whether, and how, predator species richness, abundance, diversity and assemblage composition changed across the edge between natural vegetation and orchards, again taking into consideration management practices (namely: combined, conventional and organic).

Chapter two found that local and landscape factors can significantly influence the predator complex in cropland. Organic farm management was associated with greater total, beetle, spider and wasp species richness and abundance, and ant abundance in comparison with conventional farm management. This study concurs with a large body of literature

showing that organic farming can benefit predators in comparison with conventional farming (Mäder et al. 2002, Bengtsson et al. 2005, Hole et al. 2005, Schmidt et al. 2005, Birkhofer et al. 2008, Batáry et al. 2012, Inclán et al. 2015, Lichtenberg et al. 2017, Djoudi et al. 2019). The benefit of organic farming for predators may be primarily driven by environmental heterogeneity, provided by the cover crop and soil surface conditions in organic orchards. These cover and soil conditions provide predators with essential food resources and habitat for increased survival and fecundity (Altieri and Schmidt 1986, Pfiffner and Luka 2003, Fuller et al. 2005, Birkhofer et al. 2008, Norton et al. 2009, Silva et al. 2010, Ramsden et al. 2015). Intriguingly, this positive influence of organic farming relative to conventional farming, was only recorded in landscape contexts where nearby natural vegetation was absent, suggesting that neighbouring natural vegetation compensates for the negative impacts of conventional farming on predators. The original hypothesis was that a combination of natural vegetation and organic farming would be the most beneficial to the predator complex, showing that organic farming improves cropland biodiversity in areas without natural vegetation. This study therefore supports the intermediate landscape-complexity hypothesis that states that complex landscapes will support high levels of biodiversity in comparison to simpler landscapes and local management will have a minor influence on biodiversity in complex landscapes (Purtauf et al. 2005, Tscharntke et al. 2005a, Bianchi et al. 2006). This suggests that in simpler systems, land-sharing approaches, such as organic citrus farming, can make a relatively large contribution to predator conservation in areas where there is less natural vegetation remaining in the landscape. Conventional farms, in contrast to organic farms, greatly benefitted from the associated increase in environmental heterogeneity provided by nearby natural vegetation. Predator species richness within conventional farms neighbouring natural vegetation was greater than that for conventional farms without neighbouring natural vegetation. The high environmental heterogeneity provided by the natural vegetation likely did not influence the predator complex on organic farms because environmental heterogeneity present on organic farms is already high (Tscharntke et al. 2005a). These results emphasise the landscape-scale influence of thicket conservation in areas where farming intensity is higher.

In chapter three, it was found that orchard predators were influenced by management type and that habitat edges influenced predators in both natural vegetation and orchards. Similar to chapter two, predator species richness and abundance were greater in organic than conventional orchards, illustrating that in-field management practices can still influence predators in complex landscapes. Total, ant and wasp species richness, and wasp abundance increased towards the natural vegetation-orchard edge. The species that drove this trend were likely ecotone-adapted species that can make use of complementary resources available in the neighbouring habitats (Duelli and Obrist 2003, Rand et al. 2006).

The natural vegetation-orchard edge can be beneficial for orchard predators, but at the same time detrimental to native biodiversity in natural vegetation (Tscharntke et al. 2005b). These edge effects did not, however, penetrate deeply into the natural vegetation. The agricultural impacts on core native biodiversity can consequently be reduced by ensuring natural vegetation patches are large enough, have a low perimeter-area ratio and are well-connected to one another (Bennett 2003). The need for natural vegetation connectivity was emphasised by the low predator assemblage composition similarity between natural vegetation and orchards. Natural vegetation corridors, a potential method to increase connectivity, could allow native, specialist species to disperse through the agricultural landscape and improve long-term species survival (Bennett 2003).

Only one other study was found that investigated arthropod diversity in the Thicket biome (Fabricius et al. 2003). Fabricius et al. (2003) found that natural vegetation hosted a diverse array of stenotopic arthropods that did not spillover into surrounding agricultural areas, in this case, commercial livestock farms. The presence of unique, stenotopic predator species and high beta diversity recorded in chapter three therefore supports their finding and stresses the importance of thicket conservation to conserve native biodiversity in the landscape. Elsewhere, in the Cape Floristic Region of South Africa, unique arthropod biodiversity has also been recorded in natural vegetation (fynbos), highlighting the importance of natural vegetation conservation in agricultural landscapes for biodiversity conservation (Gaigher and Samways 2010, Kehinde and Samways 2014).

Farmers with thicket remaining on private land within and surrounding the Sundays River Valley could enter into stewardship agreements to conserve thicket and receive governmental incentives in return (Barendse et al. 2016). Although there are fewer stewardship programmes in the Eastern Cape than some other provinces (for example: Western Cape and KwaZulu-Natal), stewardship is being increasingly adopted and implemented, with a new agreement, the Indalo Game Reserves Protected Environment, being recently signed in 2018 under the Eastern Cape Biodiversity Stewardship Programme (Barendse et al. 2016).

In summary, both local and landscape factors significantly influenced the predator assemblage. These can be managed to promote predator species richness, abundance and diversity within the agricultural landscape. If natural vegetation in the landscape is managed correctly, the orchard predator complex can improve whilst minimising the detrimental edge effects on native biodiversity.

4.2 Study limitations and future research needs

Due to time constraints, this thesis was unable to investigate the arthropod herbivore complex present within the same local and landscape contexts. Research into the herbivore complex would provide valuable knowledge on which local and landscape factors drive arthropod herbivore patterns in cropland (Chaplin-Kramer et al. 2011). It would provide insight into how the predator and herbivore complexes interact and whether the relationship between these two groups is directly or inversely proportional or neutral (Tscharntke et al. 2005b, Bianchi et al. 2006, Chaplin-Kramer et al. 2011). Natural vegetation can vary in its importance to different invertebrate species, temporally, as well as spatially (Simba et al. 2018). The role of natural vegetation may vary over time, and surveys completed over a full year or more would establish whether, and to what extent natural vegetation, or neighbouring crops, serve as sources or sinks of herbivore and predator species (Tylianakis et al. 2005, Moxley et al. 2017). The importance of natural vegetation as either a source, sink or barrier to herbivore species would be valuable for pest control management in the landscape (Tscharntke et al. 2005b).

Differentiation of responses by arthropod predator generalists and specialists to landscape complexity unfortunately could not be undertaken as a result of time limitations in arthropod predator identification. As Chaplin-Kramer et al. (2011) found that predator specialists have a stronger response to landscape complexity at smaller scales, it would be interesting to investigate if there were differences in landscape complexity response by predator generalists and specialists in this particular study area.

Research into the selection and use of native plants as cover crops in cropland would be of great value as this could contribute to the softening the agricultural matrix, aid dispersal of native species across cropland and provide maximum floral resources to predators – provided no pesticides harmful to predators are applied (Isaacs et al. 2009). Perennial native plant species with the following characteristics would hold the most potential for success: resistance to herbivory and disease; high floral area and narrow flower corollas; provision of high amounts of floral nectar and pollen during the growing and harvesting seasons of the year (Fiedler and Landis 2007, Isaacs et al. 2009). The current proliferation and spread of invasive alien plants in the cover crop would also be limited as a result.

4.3 Recommendations

4.3.1 Farm management

Environmental heterogeneity is crucial for predator species richness, abundance and diversity at both a local and landscape scale. In simpler landscapes, organic management techniques

such as cover cropping, mulching, and using organic compost and manure are methods that conventional farmers can use to improve environmental heterogeneity in cropland and the predator complex. Additionally, the use of selective pesticides with low toxicity to predators (particularly those without organo-phosphates, carbamates and synthetic pyrethroids) can increase predator survival and persistence in cropland (Theiling and Croft 1988). Orchards, particularly those under organic management, were able to support high levels of predator species richness, abundance and diversity, providing evidence that perennial cropland can maintain a diverse predator complex in contrast with frequently-disturbed, annual cropland. This study illustrates that there are methods to soften the agricultural matrix and increase biodiversity in cropland, which will mostly include cultural and ubiquitous species but also potentially stenotopic species moving between natural vegetation patches (Donald and Evans 2006, Driscoll et al. 2013). This emphasises that the agricultural matrix is also an important component for biodiversity conservation in the landscape mosaic and needs to be managed correctly to fully benefit long-term biodiversity conservation (Donald and Evans 2006, Driscoll et al. 2013, Kremen and Merenlender 2018).

Natural vegetation in the agricultural landscape should be conserved and restored to increase landscape complexity and therefore promote a rich, abundant and resilient predator assemblage. Orchards benefit directly from natural vegetation through elevated levels of predator species richness and abundance associated with neighbouring natural vegetation, with orchard areas near natural vegetation benefiting the most. Landscape complexity can be increased in the agricultural landscape through natural vegetation corridors that connect natural vegetation patches to one another. These corridors could be created or restored along orchard boundaries, fence lines and roads.

4.3.2 Conservation management

Although natural vegetation improved the predator complex in nearby cropland, cropland in turn was associated with a detrimental edge effect in neighbouring natural vegetation. The increased predator species richness, abundance and diversity in natural vegetation near edges could negatively impact on native herbivore and specialist predators, including their movement across natural vegetation-cropland boundaries (Tscharntke et al. 2005b, Rand et al. 2006, Blitzer et al. 2012, Frost et al. 2015). Natural vegetation should therefore be conserved so as to ensure sufficient core habitat exists for native species long-term survival and persistence (Bennett 2003). Based on the general edge effect on predators that was recorded in natural vegetation, natural vegetation patches and corridors narrower than 40 m will be influenced by edge effects (20 m deep). The low similarity in predator assemblages between natural vegetation and orchards emphasises the need for natural vegetation corridors connecting these patches. This will increase connectivity between natural vegetation patches

and therefore allow native biodiversity to disperse through the agricultural landscape (Bennett 2003). Additionally, natural vegetation in the agricultural landscape should be protected from disturbances such as over-grazing and pesticide applications in order to prevent disturbance-adapted species (for example: the large pugnacious ant – *Anoplolepis custodiens*) from dominating and excluding disturbance-sensitive native species. Invasive alien plant removal, such as *Opuntia ficus-indica* (prickley pear), *Opuntia aurantiaca* (jointed prickley pear) and *Ricinus communis* (castor-oil plant), is also recommended to conserve high quality habitat for native species and reduce potential hosts for pest species, such as false codling moth (Kirkman and Moore 2007).

4.4 References

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Appendix A – List of arthropod predator morphospecies recorded in each landscape context of this study (C – conventional orchards without neighbouring natural vegetation, CNV – conventional orchards with neighbouring natural vegetation, NVC – natural vegetation neighbouring conventional orchards, NVO – natural vegetation neighbouring organic orchards, O – organic orchards without neighbouring natural vegetation, ONV – organic orchards with neighbouring natural vegetation).

Class/order/family	Common name	Morphospecies	Landscape context
Araneae	Spider	S1	C, CNV, NVC, NVO, O, ONV
		S13	CNV, O, ONV
		S14	O, ONV
		S15	CNV, NVC, NVO, O, ONV
		S40	O
		S41	NVC, O
		S46	CNV, O, ONV
		S50	C, CNV, NVC, NVO, O, ONV
		S53	C, CNV, NVC, NVO, O, ONV
		S55	C, CNV, NVC, NVO, O, ONV
		S60	C, NVC, NVO, O
		S63	C, NVC, O
		S64	O
		S68	ONV
		S71	O
		S72	O
		S76	C, CNV, NVC, NVO, O, ONV
		S83	CNV, NVC, NVO, O, ONV
		S90	CNV, NVC, NVO, O, ONV
		S93	O
		S120	C, CNV, NVC, NVO, O, ONV
		S129	O, ONV
		S138	C, CNV, NVC, O, ONV
		S151	C, CNV, NVC, NVO, O, ONV
		S159	CNV, NVC, NVO, O
		S160	O
		S164	CNV, NVC, NVO, O, ONV
		S167	CNV, NVC, NVO, O
		S172	C, CNV, NVC, NVO, O, ONV
		S185	CNV, NVO, O
		S192	C
		S207	C, CNV, NVC, NVO, O, ONV
		S247	C, CNV, NVC
		S249	C
		S250	C
		S261	NVO
		S274	NVO
		S279	NVC, NVO
		S286	NVO
		S298	CNV, NVC, NVO, ONV
		S304	NVO
		S309	NVC, NVO

S315	NVC, NVO, ONV
S319	NVO
S324	NVO
S335	NVC, NVO, ONV
S336	NVO
S343	NVO
S345	CNV, NVC, NVO
S346	NVC, NVO
S347	NVO
S349	NVO
S352	NVO
S354	CNV, NVC, NVO, O
S363	C, CNV, NVO
S367	NVO, ONV
S372	NVC, NVO, O
S378	CNV, NVC, NVO, ONV
S385	NVC, NVO
S386	NVO
S393	NVC, NVO, O, ONV
S394	NVC, NVO
S407	CNV, NVC, NVO, ONV
S412	NVC, NVO
S428	NVC, ONV
S429	CNV, NVC, ONV
S432	NVC
S438	NVC
S440	NVC
S444	NVC, NVO, O
S453	CNV, NVC, NVO, ONV
S470	NVC, ONV
S472	NVC
S484	CNV, NVC
S490	NVC, ONV
S491	CNV, NVC, ONV
S492	NVC
S493	NVC
S506	NVC
S517	NVC
S528	CNV
S529	CNV, ONV
S570	CNV
S590	CNV, ONV
S612	CNV
S614	CNV
S629	CNV
S665	ONV
S689	ONV
S694	ONV
S701	ONV

S703	ONV
S704	ONV
S716	ONV
S726	CNV, O, ONV
S738	CNV, O, ONV
S739	O, ONV
S744	C
S751	C, CNV, NVC, O
S755	CNV, O, ONV
S756	CNV
S758	CNV, NVC
S760	CNV, NVC
S784	CNV, NVO, ONV
S785	CNV, O, ONV
S790	CNV, ONV
S800	CNV
S809	CNV, O
S811	C, CNV, NVO, O, ONV
S812	C, CNV
S821	CNV
S829	CNV, O
S836	CNV, NVC, O, ONV
S844	CNV, NVC, ONV
S847	CNV
S851	CNV
S852	CNV
S855	CNV
S856	CNV
S860	CNV, NVC, ONV
S863	CNV
S864	NVC
S865	NVC, ONV
S866	NVC
S867	NVC
S869	NVC
S871	NVC
S873	NVC
S874	CNV, NVC, NVO, O
S875	NVC, O, ONV
S878	NVC, NVO
S879	C, CNV, NVC, NVO, ONV
S883	NVC
S885	NVC
S887	NVC
S888	NVC
S891	NVC
S892	NVC, NVO
S892	NVO
S893	CNV, NVC, NVO, ONV

S894	CNV, NVC, O
S895	CNV, NVC, NVO, O
S896	NVC
S899	NVC, NVO
S904	CNV, NVC, NVO, O, ONV
S905	NVC
S907	NVC
S910	C, CNV, NVC, NVO, O, ONV
S912	NVC
S914	NVC, O, ONV
S921	NVC
S922	CNV, NVC, ONV
S925	NVC
S929	NVC
S930	NVC
S934	C, CNV, NVC, NVO, O, ONV
S935	CNV, NVC, NVO, ONV
S939	C, CNV, NVC, NVO, O, ONV
S940	NVC
S941	NVC
S942	NVC, NVO
S946	C, NVC, NVO
S948	NVC
S949	NVC, NVO
S957	NVC
S958	C, NVC, NVO
S959	NVC
S966	NVC, ONV
S970	NVC, NVO
S971	NVC, NVO
S972	NVC
S973	NVC
S974	CNV, NVC, NVO, O, ONV
S975	NVC
S984	NVC
S985	NVC, NVO
S988	CNV, NVC, NVO, O, ONV
S991	NVO
S995	NVO, O
S1000	NVO
S1001	NVC
S1001	NVO
S1002	NVO
S1005	NVC
S1005	NVO
S1008	NVC, NVO
S1009	NVO
S1011	NVO
S1014	CNV, NVC, NVO, ONV

S1017	C, CNV, NVC, NVO, O, ONV
S1034	CNV, NVC, NVO
S1037	NVO
S1038	NVO
S1042	NVO
S1049	NVO
S1051	CNV, NVO
S1052	NVO
S1053	NVO
S1057	NVO, O
S1058	CNV, NVO, O
S1060	NVC, NVO
S1061	NVC, NVO, O
S1062	C, NVC, NVO, O
S1063	NVO
S1064	NVO
S1066	NVO
S1067	NVO
S1068	NVC, NVO, O
S1071	NVO
S1072	NVC, NVO
S1073	NVC, NVO
S1074	C, CNV, NVC, NVO
S1076	NVO
S1082	NVC, NVO, ONV
S1083	NVC, NVO
S1084	NVO
S1089	NVC, NVO
S1091	NVC, O, ONV
S1092	NVC, NVO, O
S1093	NVO, O
S1094	O
S1095	O
S1097	O
S1103	O
S1107	O, ONV
S1108	O
S1109	O
S1114	CNV, O, ONV
S1115	O
S1116	O, ONV
S1120	CNV, NVO, O
S1123	O
S1124	O
S1125	O
S1130	O
S1132	O
S1133	O
S1134	O

S1135	O, ONV
S1141	O
S1143	O
S1144	O
S1145	O
S1146	O
S1147	CNV, NVC, O, ONV
S1148	CNV, O, ONV
S1155	O
S1156	O
S1157	O
S1158	O
S1159	O
S1160	O
S1161	O
S1167	ONV
S1168	ONV
S1184	ONV
S1188	O, ONV
S1191	ONV
S1203	ONV
S1208	ONV
S1211	ONV
S1212	CNV, O, ONV
S1216	ONV
S1217	CNV
S1218	NVC, ONV
S1223	CNV, O, ONV
S1227	ONV
S1228	C, ONV
S1239	ONV
S1242	O, ONV
S1251	NVC, ONV
S1252	C, ONV
S1253	ONV
S1259	NVC, NVO, O
S1259	ONV
S1266	ONV
S1272	CNV, NVC, O, ONV
S1273	CNV, ONV
S1274	NVC, ONV
S1275	NVO, ONV
S1280	NVO, ONV
S1281	C, CNV, NVO, ONV
S1295	NVO, O, ONV
S1304	NVC, NVO, O, ONV
S1310	C, CNV, O, ONV
S1315	CNV, NVO, O, ONV
S1319	C, ONV

S1326	ONV
S1327	ONV
S1328	ONV
S1329	CNV, ONV
S1331	NVC, NVO, O, ONV
S1332	ONV
S1334	ONV
S1335	ONV
S1336	CNV
S1339	ONV
S1342	ONV
S1361	ONV
S1362	ONV
S1363	O
S1363	ONV
S1364	CNV, NVC, NVO, O, ONV
S1369	ONV
S1370	CNV, NVC, NVO, O, ONV
S1374	NVC, NVO, ONV
S1381	NVC, ONV
S1397	NVC
S1403	NVC
S1406	CNV, NVC, NVO
S1407	NVC
S1408	CNV, NVC, NVO
S1414	CNV, NVC, NVO
S1416	NVC, NVO
S1424	NVC
S1428	C, NVC
S1430	NVC, NVO
S1440	CNV, NVO, ONV
S1442	CNV
S1443	C, CNV
S1449	CNV
S1451	CNV
S1456	CNV, NVO
S1457	C, CNV
S1458	CNV
S1459	CNV
S1460	C, CNV, O
S1462	CNV, NVO, O
S1463	CNV
S1471	O
S1482	O
S1485	O
S1486	O
S1498	C
S1503	C
S1506	C, NVO

S1510	NVO
S1512	NVO
S1517	NVO
S1520	NVO
S1521	NVO
S1523	NVO
S1528	NVO
S1530	NVO
S1532	NVO
S1533	NVO
S1535	NVO
S1536	NVO
S1537	NVO
S1540	NVC, NVO
S1549	NVO
S1551	NVO
S1552	NVO
S1555	NVO
S1556	NVO
S1571	C, CNV
S1572	C
S1573	C, CNV
S1574	C
S1583	CNV, NVC, NVO, O, ONV
S1599	CNV, O
S1600	CNV
S1601	CNV
S1603	CNV, NVC, O
S1604	CNV, ONV
S1613	CNV, NVO, ONV
S1620	CNV
S1624	O
S1630	O
S1633	NVO, O, ONV
S1634	O
S1640	O, ONV
S1641	O
S1642	O
S1643	O
S1644	NVC, NVO, O, ONV
S1646	O
S1651	NVC, O, ONV
S1652	O
S1655	NVC, NVO, O, ONV
S1656	O, ONV
S1657	NVO, O, ONV
S1669	O
S1670	O, ONV
S1671	O

S1675	O, ONV
S1680	O, ONV
S1683	O
S1686	O, ONV
S1690	O
S1691	O
S1692	O
S1694	O, ONV
S1699	CNV
S1704	CNV
S1708	ONV
S1724	ONV
S1725	NVO, ONV
S1739	ONV
S1740	ONV
S1744	ONV
S1751	ONV
S1762	NVC, NVO, ONV
S1765	ONV
S1766	ONV
S1772	ONV
S1777	NVO
S1778	NVO
S1780	NVO
S1787	NVC, NVO
S1788	NVC, NVO
S1790	NVO
S1791	NVO
S1795	NVC, NVO
S1797	NVO
S1799	NVC, NVO
S1803	NVO
S1812	NVO
S1817	NVO
S1820	NVO
S1822	NVC, NVO
S1823	NVO
S1824	NVO
S1826	NVO
S1829	NVC, NVO
S1830	NVC, NVO
S1832	NVO
S1834	NVO
S1837	NVO
S1839	NVO
S1841	NVO
S1845	NVO
S1857	NVO
S1858	NVO

		S1861	NVC, NVO
		S1865	NVC, NVO
		S1866	NVO
		S1877	NVC
		S1882	NVC
		S1884	NVC
		S1887	NVC
		S1890	NVC
		S1891	NVC
		S1896	NVC
		S1897	NVC
		S1899	NVC
		S1913	NVC
		S1915	NVC
		S1916	NVC
		S1926	NVC
		S1937	NVC
		S1939	NVC
		S1940	NVC
		S1941	NVC
		S1948	NVC
		S1951	NVC
		S1958	NVC
		S1959	NVC
		S1966	NVC
Coleoptera	Beetle	S6	O
		S9	C, CNV, O, ONV
		S26	O
		S27	O
		S33	C, CNV, NVC, NVO, O, ONV
		S35	C, CNV, NVC, NVO, O, ONV
		S39	CNV, O, ONV
		S48	C, CNV, O, ONV
		S57	CNV, O, ONV
		S68	C, CNV, NVO, O, ONV
		S91	CNV, O, ONV
		S98	O, ONV
		S108	O
		S128	CNV, NVC, O, ONV
		S135	O, ONV
		S140	CNV, O, ONV
		S170	O
		S186	C, CNV, NVC, NVO, O, ONV
		S194	C, CNV, NVO, ONV
		S284	NVO
		S305	NVO
		S329	NVO
		S330	NVO
		S338	NVO

S341	NVO
S355	NVO
S390	NVO
S399	NVC, NVO, ONV
S435	NVC, NVO
S454	NVC, ONV
S456	NVC
S460	CNV, NVC, O, ONV
S462	CNV, NVC, NVO, ONV
S489	C, NVC, O
S496	CNV, NVC, O, ONV
S500	CNV, NVC, ONV
S504	NVC
S526	CNV
S527	CNV
S537	C, CNV, NVO, O
S540	C, CNV, ONV
S563	CNV, ONV
S567	CNV
S573	C, CNV
S580	C, CNV, O
S588	CNV, ONV
S611	CNV
S645	ONV
S646	ONV
S652	CNV, O, ONV
S683	ONV
S698	ONV
S706	ONV
S725	CNV, O, ONV
S743	ONV
S761	CNV, O, ONV
S802	C, CNV, NVC, NVO, O, ONV
S805	CNV, ONV
S813	CNV, NVC, O, ONV
S835	CNV
S843	CNV
S861	C, CNV, NVC, O, ONV
S987	NVO
S1090	O
S1102	CNV, O
S1113	O
S1118	O
S1119	O
S1128	C, CNV, NVC, NVO, O, ONV
S1129	O
S1142	O
S1163	O, ONV
S1166	ONV

Chilopoda

Centipede

S1180	CNV, ONV
S1201	O, ONV
S1210	O, ONV
S1221	O, ONV
S1232	CNV, O, ONV
S1240	ONV
S1250	CNV, O, ONV
S1258	NVC, ONV
S1262	ONV
S1264	ONV
S1271	ONV
S1279	CNV, NVC, NVO, O, ONV
S1290	ONV
S1297	ONV
S1301	CNV, NVC, NVO, O, ONV
S1308	C, CNV, O, ONV
S1309	CNV, NVC, NVO, O, ONV
S1320	CNV, ONV
S1333	O, ONV
S1343	CNV, NVO, ONV
S1345	ONV
S1348	ONV
S1368	C, CNV, NVC, NVO, ONV
S1410	NVC
S1423	NVC
S1427	NVC, NVO
S1431	NVC
S1469	O
S1483	O
S1499	C
S1500	C
S1519	NVO
S1534	NVO
S1569	C, CNV
S1570	C
S1592	CNV, NVO, O, ONV
S1688	O
S1713	ONV
S1754	ONV
S1802	NVO
S1821	NVO
S1938	NVC
S1954	NVC
S85	C, CNV, NVC, NVO, O, ONV
S410	NVO
S749	C
S750	C, ONV
S815	CNV
S1338	NVC, NVO, ONV

Formicidae	Ant	S1346	NVO, ONV
		S1373	C, CNV, NVO, O, ONV
		S1420	NVC
		S1564	C
		S2	C, CNV, NVC, NVO, O, ONV
		S144	O
		S145	O, ONV
		S146	C, CNV, NVC, NVO, O, ONV
		S176	CNV, NVC, NVO, O, ONV
		S187	C, NVC, NVO, O, ONV
		S193	C, NVO
		S198	C, CNV, NVC, NVO, O, ONV
		S199	C, CNV, NVC, NVO, O, ONV
		S202	C, CNV, NVC, NVO, O, ONV
		S211	C, CNV, NVC, NVO, O, ONV
		S218	C, CNV, NVC, NVO, O, ONV
		S248	C, ONV
		S255	NVC, NVO
		S270	C, CNV, NVC, NVO, O, ONV
		S273	NVC, NVO, ONV
		S291	NVO
		S292	C, CNV, NVC, NVO, ONV
		S300	C, CNV, NVO, ONV
		S323	C, CNV, NVC, NVO, O, ONV
		S360	CNV, NVC, NVO, ONV
		S373	C, CNV, NVO, ONV
		S391	NVC, NVO, O, ONV
		S403	NVC, NVO, O
		S408	C, NVC, NVO
		S409	NVC, NVO, O
		S414	NVC, NVO, ONV
		S420	NVO
		S448	CNV, NVC, NVO
		S452	NVC
		S455	NVC
		S476	NVC, NVO
		S478	CNV, NVC, O, ONV
		S568	CNV, ONV
		S593	C, CNV, NVC, NVO, ONV
		S672	NVO, ONV
		S702	ONV
		S711	ONV
		S80	C, CNV, NVC, NVO, O, ONV
		S969	C, CNV, NVC, NVO, O, ONV
		S980	NVC, NVO, O, ONV
		S1010	C, NVC, NVO, O
		S1035	NVC, NVO
		S1065	NVO
		S1081	NVO

S1111	O
S1112	O
S1131	C, NVC, O
S1238	C, CNV, NVC, NVO, O, ONV
S1255	CNV, NVC, NVO, ONV
S1283	ONV
S1324	CNV, NVC, ONV
S1344	NVC, ONV
S1352	ONV
S1359	ONV
S1378	NVC, NVO, ONV
S1395	NVC
S1400	NVC, NVO
S1417	C
S1417	CNV, NVC, NVO, O
S1433	NVC
S1435	NVC
S1436	CNV, O
S1439	CNV, O
S1441	CNV
S1446	CNV
S1454	CNV
S1464	NVO, O
S1474	NVC, NVO, O, ONV
S1484	O
S1491	O
S1492	O
S1495	C
S1505	C
S1522	NVO
S1527	NVO
S1542	NVO
S1550	NVO
S1554	NVO
S1562	C, CNV
S1563	C, O
S1568	C
S1578	C
S1581	C, NVC
S1584	CNV, NVO, O, ONV
S1587	CNV, NVC, O, ONV
S1702	CNV, ONV
S1705	NVC, ONV
S1706	NVC, NVO, ONV
S1707	ONV
S1789	NVC, NVO
S1828	NVO
S1929	NVC
S1935	NVC

Hymenoptera	Wasp	S4	C, CNV, NVC, NVO, ONV
		S12	CNV, O, ONV
		S43	C, CNV, NVC, NVO, ONV
		S75	C, CNV, NVC, O, ONV
		S84	C, CNV, NVC, NVO, O, ONV
		S88	C, CNV, O, ONV
		S94	O, ONV
		S131	CNV, NVC, NVO, O, ONV
		S143	CNV, O, ONV
		S149	NVC, NVO, O, ONV
		S155	CNV, O, ONV
		S162	O, ONV
		S174	C, CNV, NVO, O, ONV
		S175	NVC, NVO, O, ONV
		S190	CNV, NVC, O, ONV
		S196	C, CNV, NVC, NVO, O, ONV
		S221	C, CNV, O, ONV
		S223	CNV
		S233	C
		S234	C, NVC, NVO, O, ONV
		S241	C, CNV, NVC, NVO
		S257	NVC, NVO, O, ONV
		S258	NVC, NVO, O
		S264	CNV, NVC, NVO, ONV
		S266	NVO
		S267	CNV, NVC, NVO
		S282	CNV, NVC, NVO
		S287	NVO
		S294	CNV, NVC, NVO, ONV
		S295	NVO
		S297	CNV, NVC, NVO
		S299	NVO
		S300	NVC, NVO
		S301	NVO, ONV
		S310	NVO
		S311	NVC, NVO, O, ONV
		S312	NVO
		S316	NVO
		S317	CNV, NVC, NVO
		S320	CNV, NVO
		S326	NVO
		S329	CNV, O
		S331	NVO
		S332	C, CNV, NVC, NVO, O, ONV
		S334	NVO
		S337	NVO
		S342	CNV, NVC, NVO, O, ONV
		S350	CNV, NVO
		S353	C, CNV, NVC, NVO, ONV

S356	NVO
S361	CNV, NVC, NVO, ONV
S362	CNV, NVO
S365	NVO
S369	NVO
S371	CNV, NVC, NVO, ONV
S374	NVC, NVO
S375	NVC, NVO
S380	NVO
S392	NVO
S395	NVC, NVO
S396	NVO
S405	NVO
S413	NVC, NVO, O, ONV
S415	NVO
S42	CNV, O, ONV
S421	NVO
S424	CNV, NVC, ONV
S425	NVC
S433	NVC
S434	NVC, NVO
S443	NVC
S445	CNV, NVC
S446	NVC, ONV
S450	NVC
S469	NVC
S474	NVC
S475	NVC
S481	NVC
S497	CNV, NVC, ONV
S498	CNV, NVC
S502	NVC
S507	NVC
S513	NVC
S514	NVC, NVO
S515	NVC
S520	NVC
S521	C, CNV, NVC, NVO, O, ONV
S522	CNV, ONV
S525	CNV, NVC, ONV
S531	CNV
S534	CNV
S535	C, CNV, ONV
S536	CNV, NVC, O, ONV
S539	CNV, ONV
S543	CNV, O, ONV
S546	CNV, ONV
S547	C, CNV, O, ONV
S548	CNV, ONV

S551	CNV, ONV
S552	CNV
S553	CNV, ONV
S557	CNV
S558	CNV, ONV
S559	CNV, O, ONV
S564	CNV
S565	CNV, O, ONV
S571	CNV, NVO, O
S576	CNV, NVC
S578	CNV
S581	CNV
S582	CNV
S585	CNV
S586	CNV
S587	CNV
S589	CNV
S592	CNV, ONV
S602	CNV
S605	NVO
S608	CNV, ONV
S609	C, CNV, NVO, ONV
S613	CNV
S616	CNV, NVC, O, ONV
S617	CNV, O
S618	CNV
S620	CNV, NVO
S622	CNV, NVO
S623	CNV
S626	CNV
S627	CNV, O, ONV
S636	CNV
S638	C, CNV, O, ONV
S639	C, CNV, NVC, O, ONV
S648	ONV
S649	C, CNV, O, ONV
S650	C, CNV, NVC, NVO, O, ONV
S654	ONV
S655	ONV
S657	ONV
S660	ONV
S661	CNV, NVC, O, ONV
S662	C, CNV, O, ONV
S663	ONV
S666	ONV
S668	ONV
S670	ONV
S671	CNV, NVC, ONV
S673	C, O, ONV

S680	ONV
S682	NVO, O, ONV
S687	ONV
S688	ONV
S700	ONV
S710	ONV
S714	ONV
S728	C, CNV, NVC, NVO, O, ONV
S729	ONV
S730	ONV
S732	ONV
S733	ONV
S735	ONV
S736	CNV, NVC, NVO, O, ONV
S740	ONV
S745	C, CNV, NVO
S746	C
S747	C, CNV, NVC, NVO, O, ONV
S748	C, O, ONV
S752	C
S753	C, ONV
S754	C
S757	CNV, O
S759	CNV, NVC, NVO
S762	CNV
S763	CNV, ONV
S764	CNV
S765	CNV
S766	CNV
S767	CNV
S768	CNV, ONV
S769	C, CNV, NVO, O
S770	CNV, NVC, O, ONV
S771	CNV, NVC, NVO, O, ONV
S772	CNV, ONV
S773	C, CNV, NVC, O, ONV
S774	CNV, ONV
S775	CNV
S776	CNV
S777	CNV
S778	C, CNV, NVC, NVO, O, ONV
S779	CNV
S780	CNV, NVC
S781	CNV, ONV
S782	CNV, NVO
S783	C, CNV, NVC, O, ONV
S787	CNV
S788	CNV, ONV
S789	CNV

S791	CNV
S793	CNV
S794	C, CNV, NVC, NVO, O, ONV
S795	CNV, ONV
S796	CNV, O
S797	CNV, ONV
S798	CNV
S799	CNV
S801	CNV
S804	CNV
S806	CNV
S807	CNV
S808	CNV
S810	CNV, NVC, ONV
S814	CNV, O, ONV
S816	CNV
S817	CNV
S818	CNV, NVC
S819	CNV, ONV
S820	CNV
S822	CNV
S823	CNV, O
S824	CNV, O, ONV
S825	CNV
S826	C, CNV, NVO, O, ONV
S827	CNV, ONV
S828	CNV, NVO, ONV
S830	CNV
S831	CNV
S832	CNV
S833	CNV
S834	CNV, ONV
S837	CNV, ONV
S838	CNV
S839	CNV
S840	CNV, NVO
S841	CNV, ONV
S842	CNV
S845	CNV, O
S846	CNV, ONV
S848	CNV, ONV
S849	CNV, O, ONV
S850	CNV
S853	CNV, NVO, ONV
S854	CNV, NVC, O
S857	CNV, ONV
S858	CNV
S859	CNV, NVC, ONV
S868	NVC, NVO, ONV

S870	NVC
S872	NVC
S876	CNV, NVC, NVO
S877	CNV, NVC, NVO, O
S880	CNV, NVC, NVO, O, ONV
S881	NVC
S882	CNV, NVC, O
S884	NVC
S886	NVC, NVO
S889	C, CNV, NVC, NVO, O, ONV
S890	C, CNV, NVC, NVO, O, ONV
S897	NVC
S898	CNV, NVC, ONV
S900	CNV, NVC
S901	NVC
S902	C, NVC, O
S903	CNV, NVC, O, ONV
S906	CNV, NVC
S908	NVC, NVO, O, ONV
S909	NVC
S911	NVC
S913	CNV, NVC, NVO, ONV
S915	NVC
S916	CNV, NVC, ONV
S917	CNV, NVC, NVO, O, ONV
S918	NVC, NVO
S919	NVC
S920	NVC
S923	NVC
S924	NVC
S926	NVC
S927	NVC
S928	NVC
S931	NVC
S932	NVC
S933	NVC
S936	NVC
S937	NVC
S943	NVC, NVO
S944	NVC
S945	NVC
S947	NVC
S950	NVC, NVO
S951	NVC
S952	NVC
S953	NVC
S954	NVC, NVO, O, ONV
S955	NVC
S956	NVC

S960	NVC
S961	CNV, NVC, ONV
S962	NVC, ONV
S963	NVC, NVO
S964	NVC, NVO, O
S965	NVC, NVO
S967	NVC, NVO
S968	CNV, NVC, ONV
S976	CNV, NVC, O, ONV
S977	C, CNV, NVC, NVO, O, ONV
S978	CNV, NVC
S979	NVC
S981	NVC
S982	NVC, NVO
S983	NVC
S989	CNV, NVC, NVO, O, ONV
S992	NVO
S993	NVO, ONV
S994	NVO
S996	CNV, NVC, NVO
S997	NVO
S998	CNV, NVC, NVO, ONV
S999	NVO
S1003	NVC, NVO
S1004	NVO
S1006	CNV, NVC, NVO, ONV
S1007	C, CNV, NVC, NVO, ONV
S1012	CNV, NVO, O
S1013	NVO, ONV
S1015	NVO
S1016	NVC, NVO, ONV
S1018	CNV, NVO
S1019	CNV, NVO, O, ONV
S1020	NVC, NVO, O
S1021	NVO
S1022	NVO
S1023	NVO, ONV
S1024	CNV, NVO
S1025	CNV, NVO, ONV
S1026	NVC, NVO
S1027	NVC, NVO
S1028	CNV, NVC, NVO, ONV
S1029	NVO
S1030	NVO, ONV
S1031	NVO
S1032	NVC, NVO, ONV
S1033	NVO, ONV
S1036	CNV, NVC, NVO, O
S1039	NVO

S1040	NVC, NVO, O, ONV
S1041	NVO
S1043	NVO
S1044	CNV, NVO
S1045	NVO
S1046	CNV, NVO
S1047	NVO
S1048	C, CNV, NVC, NVO, O, ONV
S1050	NVC, NVO
S1054	CNV, NVC, NVO, ONV
S1055	NVO
S1056	NVO, O
S1059	NVO
S1069	CNV, NVC, NVO, O
S1070	NVC, NVO
S1077	NVO
S1078	NVC, NVO, ONV
S1079	NVO
S1080	NVO
S1085	NVO
S1086	NVO
S1087	NVC, NVO, O, ONV
S1098	NVC, NVO, O, ONV
S1099	NVO, O
S1100	O
S1101	O
S1104	O, ONV
S1105	O, ONV
S1106	O
S1110	O
S1117	O
S1121	O
S1122	O
S1126	C, CNV, O, ONV
S1127	O
S1136	NVO, O
S1137	O
S1138	O
S1139	O
S1140	C, CNV, O, ONV
S1149	O, ONV
S1150	CNV, O
S1151	O, ONV
S1152	O
S1153	O
S1154	O
S1162	O
S1164	O
S1165	O

S1169	ONV
S1170	ONV
S1171	ONV
S1172	CNV, ONV
S1173	ONV
S1174	NVC, NVO, ONV
S1175	NVO, ONV
S1176	ONV
S1177	C, CNV, ONV
S1178	ONV
S1179	ONV
S1181	O, ONV
S1182	ONV
S1183	NVO, ONV
S1185	ONV
S1186	ONV
S1187	ONV
S1189	ONV
S1190	CNV, ONV
S1192	O, ONV
S1193	CNV, ONV
S1194	CNV, NVO, ONV
S1195	C, CNV, NVC, NVO, O, ONV
S1196	CNV, ONV
S1197	CNV, NVO, O, ONV
S1198	CNV, O, ONV
S1199	ONV
S1200	O, ONV
S1202	CNV, NVO, ONV
S1204	ONV
S1205	ONV
S1206	C, NVO, ONV
S1207	NVC, ONV
S1209	ONV
S1213	ONV
S1214	ONV
S1215	ONV
S1219	O, ONV
S1220	O, ONV
S1224	CNV, NVC, ONV
S1225	CNV, ONV
S1226	ONV
S1229	CNV, O, ONV
S1230	NVC, NVO, O, ONV
S1231	CNV, NVC, O, ONV
S1233	ONV
S1234	ONV
S1235	CNV, ONV
S1236	ONV

S1237	NVC, ONV
S1241	ONV
S1243	CNV, O, ONV
S1244	CNV, ONV
S1245	ONV
S1246	ONV
S1247	C, O, ONV
S1248	ONV
S1249	ONV
S1254	NVO, O, ONV
S1256	NVC, O, ONV
S1257	ONV
S1261	CNV, ONV
S1263	ONV
S1265	ONV
S1267	ONV
S1268	CNV, NVC, ONV
S1269	C, NVO, ONV
S1270	CNV, NVC, NVO, ONV
S1276	CNV, ONV
S1277	ONV
S1278	CNV, O, ONV
S1282	C, CNV, NVC, NVO, ONV
S1284	ONV
S1285	C, O, ONV
S1286	ONV
S1287	CNV, O, ONV
S1288	ONV
S1289	NVC, ONV
S1292	ONV
S1293	CNV, NVC, NVO, O, ONV
S1294	CNV, NVC, NVO, ONV
S1296	ONV
S1298	ONV
S1299	C, CNV, NVC, O, ONV
S1300	ONV
S1302	ONV
S1303	ONV
S1305	C, CNV, NVC, NVO, O, ONV
S1306	C, CNV, NVC, NVO, O, ONV
S1307	C, CNV, NVC, O, ONV
S1311	C, CNV, NVO, O, ONV
S1312	C, NVO, ONV
S1313	CNV, O, ONV
S1314	CNV, O, ONV
S1316	CNV, NVC, NVO, O, ONV
S1317	CNV, NVC, NVO, ONV
S1318	C, CNV, NVC, NVO, O, ONV
S1321	NVO, O, ONV

S1322	CNV, NVC, NVO, ONV
S1323	CNV, NVC, ONV
S1325	CNV, O, ONV
S1330	ONV
S1337	NVC, ONV
S1340	ONV
S1341	CNV, O, ONV
S1347	ONV
S1349	O, ONV
S1350	NVC, NVO, ONV
S1351	ONV
S1353	NVC, ONV
S1354	ONV
S1355	ONV
S1356	C, NVC, ONV
S1357	ONV
S1358	NVC, ONV
S1360	CNV, NVO, ONV
S1365	NVC, ONV
S1366	C, NVO, ONV
S1367	ONV
S1371	NVC, ONV
S1372	CNV, O, ONV
S1375	NVC, NVO, O, ONV
S1376	NVC, NVO, ONV
S1377	NVC, NVO, ONV
S1379	NVC, ONV
S1380	NVO, ONV
S1382	NVC, ONV
S1383	ONV
S1384	ONV
S1385	C, CNV, NVC, NVO
S1387	NVC
S1388	NVC, NVO
S1389	NVC, NVO
S1390	NVC
S1391	C, NVC
S1392	CNV, NVC, NVO, O
S1393	NVC
S1394	NVC
S1396	NVC
S1398	NVC, NVO
S1399	NVC
S1401	NVC, NVO
S1404	NVC
S1405	CNV, NVC
S1409	NVC
S1411	CNV, NVC, ONV
S1412	NVC

S1413	NVC, NVO
S1415	NVC, NVO
S1418	NVC
S1421	NVC, NVO
S1422	NVC
S1425	CNV, NVC
S1426	NVC
S1429	C, CNV, NVC, O
S1432	C, CNV, NVC, O
S1434	NVC
S1437	CNV
S1438	CNV, NVO
S1444	C, CNV, NVO, O
S1445	CNV, O
S1447	CNV
S1450	CNV
S1452	CNV
S1453	CNV, ONV
S1455	C, CNV
S1461	CNV
S1465	O
S1466	O
S1467	O
S1468	O
S1470	O
S1472	O, ONV
S1473	O
S1476	O
S1477	O
S1478	O
S1479	O
S1480	O
S1481	O
S1487	O
S1488	O
S1489	O
S1490	O
S1494	C
S1496	C
S1497	C
S1501	C
S1502	C
S1504	C
S1507	NVO
S1508	NVO
S1509	NVO, ONV
S1511	NVO
S1513	NVO
S1514	CNV, NVO

S1515	NVO
S1516	NVO
S1518	NVO
S1524	NVO
S1525	NVO
S1526	NVO
S1529	NVO
S1538	NVO
S1539	CNV, NVC, NVO, O, ONV
S1541	NVO
S1543	NVO
S1544	NVO
S1545	NVO
S1546	NVO
S1547	NVO
S1553	NVO
S1557	NVO
S1558	NVO
S1559	NVO
S1560	C, CNV, O
S1561	C
S1565	C, NVO
S1566	C, CNV
S1567	C, CNV, O
S1575	C
S1576	C, CNV, NVC, NVO, O, ONV
S1577	C, CNV, ONV
S1579	C, CNV, ONV
S1580	C, CNV, NVC, NVO, O, ONV
S1582	C, CNV, O, ONV
S1585	CNV, ONV
S1586	CNV, NVC, NVO, O, ONV
S1589	CNV, O, ONV
S1590	CNV, O
S1591	CNV, O, ONV
S1593	CNV, O, ONV
S1594	CNV, O, ONV
S1595	CNV
S1596	CNV, NVO, O, ONV
S1597	CNV, NVC, NVO, O, ONV
S1598	CNV, O, ONV
S1602	CNV, O
S1605	CNV, ONV
S1606	CNV, O
S1607	CNV
S1608	CNV, NVC, NVO, O
S1609	CNV, O, ONV
S1610	CNV
S1611	CNV

S1612	CNV, ONV
S1614	CNV, ONV
S1615	CNV
S1616	CNV
S1617	CNV, ONV
S1618	CNV, O
S1619	CNV, NVO
S1622	CNV, O, ONV
S1623	CNV
S1625	NVC, NVO, O, ONV
S1626	O
S1627	O
S1628	O
S1629	O
S1631	O
S1632	O
S1635	O, ONV
S1636	O, ONV
S1637	O
S1638	O
S1639	O
S1645	O, ONV
S1647	O
S1648	O
S1649	O
S1650	O
S1653	O
S1654	O
S1658	O, ONV
S1659	NVC, O, ONV
S1660	O
S1661	O, ONV
S1662	O
S1663	O
S1664	O
S1665	O, ONV
S1666	O
S1667	O
S1668	O
S1672	O
S1673	O
S1674	O
S1676	O
S1677	NVC, O
S1678	O
S1679	O
S1681	O
S1682	O, ONV
S1684	O

S1685	O
S1687	O
S1693	O, ONV
S1695	O
S1696	O
S1697	NVC, O
S1698	CNV, NVC
S1700	CNV
S1701	CNV
S1703	CNV
S1709	ONV
S1710	ONV
S1711	ONV
S1712	ONV
S1714	ONV
S1715	ONV
S1716	ONV
S1717	NVO, ONV
S1718	ONV
S1719	ONV
S1720	ONV
S1721	NVO, ONV
S1722	ONV
S1723	ONV
S1726	ONV
S1727	NVC, ONV
S1728	ONV
S1729	ONV
S1730	ONV
S1731	ONV
S1732	NVC, ONV
S1733	ONV
S1734	NVC, NVO
S1734	ONV
S1735	ONV
S1736	ONV
S1737	ONV
S1738	ONV
S1741	ONV
S1742	ONV
S1743	ONV
S1745	ONV
S1746	ONV
S1747	ONV
S1748	ONV
S1749	NVO, ONV
S1750	ONV
S1753	ONV
S1756	ONV

S1757	NVC, NVO, ONV
S1758	NVO, ONV
S1759	ONV
S1760	ONV
S1761	ONV
S1763	ONV
S1764	ONV
S1767	NVO, ONV
S1768	NVC, ONV
S1769	ONV
S1770	ONV
S1773	ONV
S1774	ONV
S1775	ONV
S1776	NVO
S1779	NVO
S1781	NVC, NVO
S1782	NVC, NVO
S1783	NVC, NVO
S1784	NVO
S1785	NVO
S1786	NVO
S1792	NVO
S1793	NVO
S1794	NVO
S1796	NVC, NVO
S1798	NVC
S1798	NVO
S1800	NVC, NVO
S1801	NVO
S1804	NVO
S1805	NVC, NVO
S1806	NVO
S1807	NVO
S1808	NVO
S1809	NVO
S1810	NVO
S1811	NVO
S1813	NVC, NVO
S1814	NVO
S1815	NVO
S1816	NVO
S1819	NVC, NVO
S1825	NVO
S1827	NVO
S1831	NVO
S1833	NVO
S1835	NVO
S1836	NVO

S1838	NVO
S1840	NVO
S1842	NVO
S1843	NVO
S1844	NVO
S1846	NVO
S1847	NVC, NVO
S1848	NVO
S1849	NVO
S1850	NVO
S1851	NVC, NVO
S1852	NVC, NVO
S1853	NVO
S1855	NVC, NVO
S1856	NVO
S1859	NVC, NVO
S1860	NVO
S1862	NVO
S1863	NVC, NVO
S1864	NVO
S1867	NVO
S1868	NVO
S1869	NVC, NVO
S1870	NVO
S1871	NVC, NVO
S1872	NVO
S1873	NVO
S1874	NVO
S1875	NVC
S1878	NVC
S1879	NVC
S1880	NVC
S1881	NVC
S1883	NVC
S1885	NVC
S1886	NVC
S1888	NVC
S1889	NVC
S1892	NVC
S1893	NVC
S1894	NVC
S1895	NVC
S1898	NVC
S1900	NVC
S1901	NVC
S1902	NVC
S1903	NVC
S1904	NVC
S1905	NVC

		S1906	NVC
		S1907	NVC
		S1908	NVC
		S1909	NVC
		S1910	NVC
		S1911	NVC
		S1912	NVC
		S1914	NVC
		S1917	NVC
		S1918	NVC
		S1919	NVC
		S1920	NVC
		S1921	NVC
		S1922	NVC
		S1923	NVC
		S1924	NVC
		S1925	NVC
		S1927	NVC
		S1928	NVC
		S1930	NVC
		S1931	NVC
		S1932	NVC
		S1933	NVC
		S1934	NVC
		S1936	NVC
		S1942	NVC
		S1943	NVC
		S1945	NVC
		S1946	NVC
		S1947	NVC
		S1949	NVC
		S1950	NVC
		S1952	NVC
		S1953	NVC
		S1955	NVC
		S1956	NVC
		S1957	NVC
		S1960	NVC
		S1961	NVC
		S1963	NVC
		S1967	NVC
		S1968	NVC
Mantodea	Mantis	S792	CNV, ONV
		S803	C, CNV, NVC, NVO, O, ONV
		S990	CNV, NVC, NVO, O, ONV
		S1222	CNV, O, ONV
		S1531	NVO
		S1588	CNV, NVC, O, ONV
		S1621	CNV

		S1876	NVC
		S1944	NVC
Neuroptera	Lacewing	S86	ONV
		S125	O
		S604	C, CNV, NVC, O, ONV
		S786	CNV
		S862	C, CNV, O, ONV
		S1260	ONV
		S1689	O
		S1755	ONV
		S1771	ONV
		S1818	NVO
		S1964	NVC
Odonata	Damselfly	S1962	NVC
		S1965	NVC
Opiliones	Harvestmen	S136	CNV, NVC, O, ONV
		S516	NVC, NVO
		S574	CNV
		S1096	O
Orthoptera	Cricket	S519	NVC
		S1493	C, NVO
Pseudoscorpiones	False scorpion	S47	C, CNV, NVC, NVO, O, ONV
		S222	C, CNV, NVC, NVO, ONV
		S327	NVC, NVO, ONV
		S426	NVC, NVO
		S1088	NVO, O, ONV
Scorpiones	Scorpion	S384	NVO
		S461	NVC
		S466	NVC
		S1419	NVC, NVO
Solifugae	Solifuge	S1386	CNV, NVC, NVO, O
		S1402	NVC, NVO
		S1448	CNV
		S1548	NVO

Appendix B – List of plant species recorded in each landscape context of this study (C – conventional orchards without neighbouring natural vegetation, CNV – conventional orchards with neighbouring natural vegetation, NVC – natural vegetation neighbouring conventional orchards, NVO – natural vegetation neighbouring organic orchards, O – organic orchards without neighbouring natural vegetation, ONV – organic orchards with neighbouring natural vegetation).

Plant species	Landscape context
<i>Aizoan rigidum</i>	CNV, NVC, ONV
<i>Albuca</i> species	NVO
<i>Aloe africana</i>	NVC, NVO
<i>Aloe speciosa</i>	NVC, NVO
<i>Aloe striata</i>	NVO
<i>Aptenia haeckeliana</i>	NVO, ONV
<i>Arctotheca calendula</i>	O
<i>Asparagus asparagoides</i>	NVC, NVO
<i>Azima tetracantha</i>	CNV, NVC, NVO
<i>Bidens pilosa</i>	CNV, O, ONV
<i>Blepharis capensis</i>	NVO
<i>Boscia oleoides</i>	NVC
<i>Bromus catharticus</i>	C, CNV, NVO, O, ONV
<i>Bulbine frutescens</i>	NVO
<i>Bulbine latifolia</i>	NVO
<i>Cadaba aphylla</i>	NVO
<i>Capperis sepiaria</i>	NVC, NVO
<i>Capsella bursa-pastoris</i>	C
<i>Chenopodium album</i>	CNV, ONV
<i>Cirsium vulgare</i>	ONV
<i>Citrus</i> species	C, CNV, O, ONV
<i>Commelina</i> species	NVC, NVO
<i>Cotyledon</i> species	NVC, NVO
<i>Cotyledon velutina</i>	NVC, NVO
<i>Crassula expansa</i>	NVO
<i>Crassula muscosa</i>	NVO
<i>Crassula ovata</i>	NVC
<i>Crassula perforata</i>	NVC, NVO
<i>Crassula subaphylla</i>	NVC

<i>Delosperma</i> species	NVC
<i>Drosanthemum hispidum</i>	NVC, NVO
<i>Emex australis</i>	CNV, ONV
<i>Erodium moschatum</i>	CNV, ONV
<i>Euclea undulata</i>	NVC, NVO
<i>Euphorbia ledienii</i>	NVC, NVO
<i>Euphorbia mauritanica</i>	NVC, NVO
<i>Galium spurium</i>	O
<i>Gasteria bicolor</i>	NVO
<i>Grewia robusta</i>	NVC, NVO
<i>Haemanthus albiflos</i>	NVO
<i>Hermannia althaeoides</i>	NVO
<i>Hypoestes</i> species	NVC, NVO, ONV
<i>Ledebouria ensifolia</i>	NVO
<i>Lycium ferocissimum</i>	NVC, NVO
<i>Malva parviflora</i>	C, ONV
<i>Malvastrum coromandelianum</i>	C
<i>Medicago polymorpha</i>	C, CNV, O, ONV
<i>Nemesia fruticans</i>	CNV
<i>Olea europaea</i> subsp. <i>africana</i>	NVO
<i>Opuntia aurantiaca</i>	NVC, NVO
<i>Opuntia ficus-indica</i>	NVC, NVO
<i>Oxalis corniculata</i>	C, NVO, O, ONV
<i>Panicum maximum</i>	CNV, NVC, NVO, ONV
<i>Pappea capensis</i>	NVC, NVO
<i>Pelargonium odoratissimum</i>	NVC
<i>Pelargonium peltatum</i>	NVC, NVO
<i>Pentzia incana</i>	NVO
<i>Picris echioides</i>	CNV, O, ONV
<i>Plantago lanceolata</i>	C, O, ONV
<i>Plumbago auriculata</i>	NVC
<i>Portulacaria afra</i>	NVC, NVO
<i>Protasparagus</i> species 1	NVC, NVO, ONV
<i>Protasparagus</i> species 2	NVC, NVO

<i>Psilocaulon pageae</i>	NVC
<i>Rhigozum obovatum</i>	NVC, NVO, ONV
<i>Ricinus communis</i>	NVC
<i>Sansevieria hyacinthoides</i>	NVC, NVO
<i>Sarcostemma viminale</i>	NVC, NVO
<i>Schotia afra</i>	NVC, NVO
<i>Searsia longispina</i>	NVC, NVO
<i>Searsia pterota</i>	NVO
<i>Selago decipiens</i>	NVC, NVO
<i>Senecio pterophorus</i>	CNV, O
<i>Senecio radicans</i>	NVC, NVO
<i>Sideroxylon inerme</i>	NVO
<i>Sisymbrium</i> species 1	C, O, ONV
<i>Sisymbrium</i> species 2	CNV, ONV
<i>Solanum</i> species 1	CNV
<i>Solanum</i> species 2	ONV
<i>Solanum tomentosum</i>	ONV
<i>Sonchus oleraceus</i>	C, CNV, O, ONV
<i>Sphalmanthus plenifolius</i>	NVC, NVO
<i>Stachys aethiopica</i>	NVC
<i>Stellaria media</i>	C, CNV, O, ONV
<i>Sutera microphylla</i>	NVO
Unidentified grass species 1	ONV
Unidentified grass species 2	ONV
Unidentified grass species 3	O
Unidentified grass species 4	C
Unidentified grass species 5	O
Unidentified grass species 6	NVC
Unidentified grass species 7	ONV
Unidentified species 1	CNV, NVO, ONV
Unidentified species 2	CNV
Unidentified species 3	C, NVO, ONV
Unidentified species 4	C
Unidentified species 5	CNV, O

Unidentified species 6	NVO
Unidentified species 7	C, O
Unidentified species 8	NVC
Unidentified species 9	C, CNV, O
Unidentified species 10	CNV, O
Unidentified species 11	O, ONV
Unidentified species 12	NVO
Unidentified species 13	NVO
<i>Vachellia karroo</i>	NVC, NVO, ONV
<i>Veronica persica</i>	C, O, ONV
<i>Zygophyllum foetida</i>	NVC, NVO

Appendix C – Spearman rank-order correlations ($-0.6 < r > 0.6$) recorded across sample sites (organic and conventional citrus orchards with and without neighbouring natural vegetation, and within natural vegetation itself). Bold correlation values indicate highly correlated variables that were selected for refinement.

Spearman Rank Correlation		
Variable 1	r	Variable 2
Plant species abundance (1 m ²)	0.63	Total flowering grasses (1 m ²)
Plant species abundance (1 m ²)	0.64	Total flowering other (1 m ²)
Plant species abundance (1 m ²)	0.67	Average % cover grass (1 m ²)
Plant species abundance (1 m ²)	0.65	Average % cover herb (1 m ²)
Total flowering grasses (1 m ²)	0.68	Total flowering other (1 m ²)
Total flowering grasses (1 m ²)	0.84	Average % cover grass (1 m ²)
Total flowering grasses (1 m ²)	0.66	Average % cover grass (5 m ²)
Total flowering grasses (1 m ²)	-0.66	Average % cover litter (5 m ²)
Total flowering other (1 m ²)	0.60	Average % cover grass (1 m ²)
Total flowering other (1 m ²)	0.69	Average % cover herb (1 m ²)
Total flowering other (1 m ²)	0.62	Average % cover grass (5 m ²)
Total flowering other (1 m ²)	-0.72	Average % cover litter (5 m ²)
Average plant height (1 m ²)	0.61	Average % cover herb (1 m ²)
Average plant height (1 m ²)	-0.74	Average % cover bare ground (1 m ²)
Average plant height (1 m ²)	-0.62	Average % cover bare ground (5 m ²)
Average plant height (1 m ²)	0.60	Average leaf litter depth (5 m ²)
Average % cover grass (1 m ²)	-0.60	Average % cover litter (1 m ²)
Average % cover grass (1 m ²)	-0.63	Average % cover bare ground (1 m ²)
Average % cover grass (1 m ²)	0.80	Average % cover grass (5 m ²)
Average % cover grass (1 m ²)	-0.70	Average % cover litter (5 m ²)
Average % cover grass (1 m ²)	-0.65	Average % cover bare ground (5 m ²)
Average % cover grass (1 m ²)	0.64	Average leaf litter depth (5 m ²)
Average % cover herb (1 m ²)	-0.66	Average % cover bare ground (1 m ²)
Average % cover herb (1 m ²)	0.71	Average % cover herb (5 m ²)
Average % cover herb (1 m ²)	-0.69	Average % cover bare ground (5 m ²)
Average % cover woody (1 m ²)	0.64	Average % cover rockiness (1 m ²)
Average % cover woody (1 m ²)	0.92	Plant species richness (5 m ²)
Average % cover woody (1 m ²)	0.82	Plant species abundance (5 m ²)
Average % cover woody (1 m ²)	-0.70	Average plant height (5 m ²)
Average % cover woody (1 m ²)	-0.74	Average % cover grass (5 m ²)
Average % cover woody (1 m ²)	0.79	Average % cover woody (5 m ²)

Average % cover woody (1 m ²)	0.72	Average % cover rockiness (5 m ²)
Average % cover litter (1 m ²)	0.76	Average % cover litter (5 m ²)
Average % cover bare ground (1 m ²)	-0.87	Average leaf litter depth (1 m ²)
Average % cover bare ground (1 m ²)	0.81	Average % cover bare ground (5 m ²)
Average % cover bare ground (1 m ²)	-0.91	Average leaf litter depth (5 m ²)
Average % cover rockiness (1 m ²)	0.63	Plant species richness (5 m ²)
Average % cover rockiness (1 m ²)	-0.64	Average % cover grass (5 m ²)
Average % cover rockiness (1 m ²)	0.94	Average % cover rockiness (5 m ²)
Average leaf litter depth (1 m ²)	-0.67	Average % cover bare ground (5 m ²)
Average leaf litter depth (1 m ²)	0.92	Average leaf litter depth (5 m ²)
Plant species richness (5 m ²)	0.88	Plant species abundance (5 m ²)
Plant species richness (5 m ²)	-0.67	Average plant height (5 m ²)
Plant species richness (5 m ²)	-0.72	Average % cover grass (5 m ²)
Plant species richness (5 m ²)	0.80	Average % cover woody (5 m ²)
Plant species richness (5 m ²)	0.68	Average % cover litter (5 m ²)
Plant species richness (5 m ²)	0.73	Average % cover rockiness (5 m ²)
Plant species abundance (5 m ²)	0.81	Average % cover woody (5 m ²)
Plant species abundance (5 m ²)	0.60	Average % cover rockiness (5 m ²)
Total flowering other (5 m ²)	-0.65	Average plant height (5 m ²)
Average % cover grass (5 m ²)	-0.73	Average % cover woody (5 m ²)
Average % cover grass (5 m ²)	-0.79	Average % cover litter (5 m ²)
Average % cover grass (5 m ²)	-0.63	Average % cover rockiness (5 m ²)
Average % cover woody (5 m ²)	0.67	Average % cover litter (5 m ²)
Average % cover bare ground (5 m ²)	-0.76	Average leaf litter depth (5 m ²)

Appendix D – Mean ($\pm$ SD) results of predator species richness, abundance and Simpsons' Index of Diversity for each management type and biotope.

Predator grouping	Response variable	Management type			Biotope	
		Conv	Org	OrchNV	Orch	NV
Total	Species richness	89.33 $\pm$ 30.2	124.9 $\pm$ 33.39	121.3 $\pm$ 25.37	101.92 $\pm$ 54.47	98.08 $\pm$ 14.73
	Abundance	582.9 $\pm$ 490.26	4 123 $\pm$ 8156.71	894 $\pm$ 625.9	1 647.8 $\pm$ 1 289.31	4 516.8 $\pm$ 10 169.14
	Simpson's Index of Diversity	0.79 $\pm$ 0.2	0.59 $\pm$ 0.32	0.8 $\pm$ 0.2	0.59 $\pm$ 0.25	0.71 $\pm$ 0.39
Ant	Species richness	12.39 $\pm$ 4.45	14.06 $\pm$ 3.62	11.25 $\pm$ 3.2	11.83 $\pm$ 3.74	16.58 $\pm$ 3.2
	Abundance	370.61 $\pm$ 428.74	3 715.7 $\pm$ 8 215.39	469.2 $\pm$ 558.18	1 305.1 $\pm$ 1 132.24	4 355.2 $\pm$ 10 150.1
	Simpson's Index of Diversity	0.51 $\pm$ 0.26	0.32 $\pm$ 0.31	0.47 $\pm$ 0.28	0.23 $\pm$ 0.24	0.55 $\pm$ 0.3
Beetle	Species richness	9.83 $\pm$ 6.17	15.94 $\pm$ 9.92	19.67 $\pm$ 6.14	14.92 $\pm$ 7.89	4.08 $\pm$ 1.51
	Abundance	41.44 $\pm$ 46.44	105.1 $\pm$ 118.88	127.4 $\pm$ 131.28	83.33 $\pm$ 58.47	9 $\pm$ 4.02
	Simpson's Index of Diversity	0.7 $\pm$ 0.18	0.73 $\pm$ 0.2	0.82 $\pm$ 0.14	0.76 $\pm$ 0.12	0.57 $\pm$ 0.21
Spider	Species richness	25.89 $\pm$ 10.87	36.44 $\pm$ 11.8	28 $\pm$ 6.25	30.33 $\pm$ 19.92	35.17 $\pm$ 4.9
	Abundance	77.39 $\pm$ 22.65	127.11 $\pm$ 74.39	94.58 $\pm$ 40.03	125.92 $\pm$ 90.12	86.25 $\pm$ 26.26
	Simpson's Index of Diversity	0.88 $\pm$ 0.08	0.89 $\pm$ 0.11	0.89 $\pm$ 0.04	0.87 $\pm$ 0.09	0.89 $\pm$ 0.14
Wasp	Species richness	36.5 $\pm$ 18.51	53.22 $\pm$ 18.73	57.33 $\pm$ 16.6	39.92 $\pm$ 26	37.33 $\pm$ 9.51
	Abundance	76.89 $\pm$ 61.41	109.17 $\pm$ 57.22	137.5 $\pm$ 62.53	83.5 $\pm$ 63.12	58.08 $\pm$ 16.08
	Simpson's Index of Diversity	0.91 $\pm$ 0.07	0.95 $\pm$ 0.04	0.95 $\pm$ 0.02	0.9 $\pm$ 0.09	0.94 $\pm$ 0.05

Conv = conventional, Org = organic, OrchNV = orchard with natural vegetation, Orch = orchard without natural vegetation, NV = natural vegetation neighbouring orchards

Appendix E – Mean ($\pm$ SD) results of predator species richness, abundance and Simpsons' Index of Diversity for each treatment type.

Predator grouping	Response variable	Treatment type					
		C	CNV	NVC	O	ONV	NVO
Total	Species richness	54.17 $\pm$ 14.18	109 $\pm$ 20.47	104.83 $\pm$ 15.65	149.7 $\pm$ 29.23	133.7 $\pm$ 25.13	91.33 $\pm$ 11.09
	Abundance	513.8 $\pm$ 354.78	652.5 $\pm$ 740.87	582.5 $\pm$ 361.83	2 782 $\pm$ 667.04	1 135.5 $\pm$ 415.92	8 451.2 $\pm$ 13 792.84
	Simpson's Index of Diversity	0.72 $\pm$ 0.24	0.86 $\pm$ 0.21	0.78 $\pm$ 0.16	0.39 $\pm$ 0.11	0.75 $\pm$ 0.18	0.63 $\pm$ 0.46
Ant	Species richness	9.83 $\pm$ 2.14	10.5 $\pm$ 3.83	16.83 $\pm$ 3.49	13.83 $\pm$ 4.07	12 $\pm$ 2.53	16.33 $\pm$ 3.2
	Abundance	340.5 $\pm$ 323.7	357.7 $\pm$ 636.3	413.7 $\pm$ 334.37	2270 $\pm$ 694.65	580.8 $\pm$ 500.69	8 296.7 $\pm$ 13 757.08
	Simpson's Index of Diversity	0.39 $\pm$ 0.26	0.59 $\pm$ 0.31	0.56 $\pm$ 0.19	0.08 $\pm$ 0.03	0.36 $\pm$ 0.21	0.53 $\pm$ 0.4
Beetle	Species richness	8.83 $\pm$ 2.64	16.67 $\pm$ 4.63	4 $\pm$ 1.67	21 $\pm$ 6.42	22.67 $\pm$ 6.31	4.17 $\pm$ 1.47
	Abundance	50.67 $\pm$ 54.28	63.83 $\pm$ 49.64	9.83 $\pm$ 4.4	116 $\pm$ 44.86	191 $\pm$ 160.47	8.17 $\pm$ 3.82
	Simpson's Index of Diversity	0.7 $\pm$ 0.12	0.86 $\pm$ 0.04	0.55 $\pm$ 0.2	0.82 $\pm$ 0.08	0.77 $\pm$ 0.2	0.59 $\pm$ 0.24
Spider	Species richness	13.83 $\pm$ 2.71	25.83 $\pm$ 5.64	38 $\pm$ 3.46	46.83 $\pm$ 14.55	30.17 $\pm$ 6.55	32.33 $\pm$ 4.63
	Abundance	71.67 $\pm$ 23.75	75 $\pm$ 18.84	85.5 $\pm$ 26.46	180.2 $\pm$ 101.2	114.17 $\pm$ 47.43	87 $\pm$ 28.56
	Simpson's Index of Diversity	0.8 $\pm$ 0.06	0.89 $\pm$ 0.04	0.95 $\pm$ 0.02	0.94 $\pm$ 0.02	0.89 $\pm$ 0.05	0.83 $\pm$ 0.18
Wasp	Species richness	17.67 $\pm$ 11.54	50.83 $\pm$ 14.78	41 $\pm$ 10.81	62.17 $\pm$ 12.89	63.83 $\pm$ 16.92	33.67 $\pm$ 7.06
	Abundance	35 $\pm$ 26.89	131.5 $\pm$ 76.47	64.17 $\pm$ 19.25	132 $\pm$ 48.95	143.5 $\pm$ 51.63	52 $\pm$ 10.47
	Simpson's Index of Diversity	0.84 $\pm$ 0.09	0.95 $\pm$ 0.03	0.95 $\pm$ 0.02	0.97 $\pm$ 0.01	0.95 $\pm$ 0.01	0.92 $\pm$ 0.07

C = conventional orchards without natural vegetation, CNV = conventional orchards with natural vegetation, NVC = natural vegetation neighbouring conventional orchards, NVO = natural vegetation neighbouring organic orchards, O = organic orchards without natural vegetation, ONV = organic orchards with natural vegetation