Maximizing Ecosystem Services provided to the New Oil Crop *Brassica carinata* Through Landscape and Arthropod Diversity

Shane Stiles
*South Dakota State University*

Follow this and additional works at: [https://openprairie.sdstate.edu/etd](https://openprairie.sdstate.edu/etd)

Part of the [Agriculture Commons](https://openprairie.sdstate.edu/etd), [Ecology and Evolutionary Biology Commons](https://openprairie.sdstate.edu/etd), and the [Entomology Commons](https://openprairie.sdstate.edu/etd)

**Recommended Citation**


[https://openprairie.sdstate.edu/etd/3154](https://openprairie.sdstate.edu/etd/3154)
MAXIMIZING ECOSYSTEM SERVICES PROVIDED TO THE NEW OIL CROP

*Brassica carinata* THROUGH LANDSCAPE AND ARTHROPOD DIVERSITY

BY

SHANE STILES

A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Biological Sciences

Specialization in Biology

South Dakota State University

2019
MAXIMIZING ECOSYSTEM SERVICES PROVIDED TO THE NEW OIL CROP

Brassica carinata THROUGH LANDSCAPE AND ARTHROPOD DIVERSITY

SHANE STILES

This thesis is approved as a credible and independent investigation by a candidate for a

Master of Science in Biological Sciences and is acceptable for meeting the thesis

requirements for this degree. Acceptance of this thesis does not imply that conclusions

reached by the candidate are necessarily conclusions of the major department.

Charles Fenster, Ph.D.
Thesis Advisor

Date

Volker Brakel, Ph.D.
Head, Department of Biology

Date

Dean, Graduate School

Date
This thesis is dedicated to my parents, Dana and Jim, and to my brother and sister, Sean and Julie. Thank you for the constant encouragement and willingness to help me move far away.
ACKNOWLEDGEMENTS

I would like to extend my gratitude to my advisor Dr. Charles Fenster for his unwavering encouragement, motivation and support, Dr. Henning Nottebrock for his wealth of knowledge and his patience in teaching me analytical techniques, and my lab mate Isabela Vilella-Arnizaut for her support and feedback. I want to extend my gratitude to the undergraduate assistants, Nicholas Peterson, Jacob Gelderman, and Jacob Smithers for their persistence and hard work in the field. Lastly, I want to thank my committee Dr. Maribeth Latvis, Dr. Jon Lundgren, and Dr. Alan Davis for their guidance and feedback.

This research would not have been possible without funding from the North Central Sun Grant Initiative (USDA/DOE) SA1500640
## TABLE OF CONTENTS

**ABSTRACT** ........................................................................................................................... vii

**Literature Review** ................................................................................................................... 1

**INTRODUCTION** ................................................................................................................... 1

**STUDY CROP** ......................................................................................................................... 1

**LANDSCAPE HETEROGENEITY** .............................................................................................. 2

**POLLINATION AGRICULTURE** ................................................................................................. 4

**Introduction** ............................................................................................................................. 7

**Materials and Methods** ......................................................................................................... 10

**STUDY DESIGN** ....................................................................................................................... 10

**INSECT COLLECTIONS** .......................................................................................................... 11

**HARVEST** .................................................................................................................................. 12

**ANALYSES** ............................................................................................................................... 12

Yield Calculation .......................................................................................................................... 12

**Landscape Heterogeneity Quantification** .............................................................................. 13

**Insect and Pollinator Diversity Calculation** ........................................................................... 14

**Results** ..................................................................................................................................... 16

  Main effects of farming practices and insect diversity on yield .................................................. 16
  Two-way interactions of farming practices and insect diversity on yield .................................... 17
  Three-way interactions of farming practices and insect diversity on yield ................................... 17
  Main effects of farming practices and pollinator diversity on yield ............................................ 18
  Two-way interactions of farming practices and pollinator diversity on yield ............................ 18
  Three-way interactions of farming practices and pollinator diversity on yield ........................... 19

**Farming practices on insect and pollinator diversity** ............................................................... 19

  Main effects of farming practices and landscape heterogeneity on insect diversity .................. 19
  Two-way interactions of farming practices and landscape heterogeneity on insect diversity .......... 19
  Main effects of farming practices and landscape heterogeneity on pollinator diversity ............ 20
  Two-way interactions of farming practices and landscape heterogeneity on pollinator diversity ... 20
  Main effects of landscape heterogeneity and farming practices on yield ................................... 20
  Two-way interactions of landscape heterogeneity and farming practices on yield .................... 20

**Discussion** ............................................................................................................................... 20

  Main Effects of farming practices and insect/pollinator diversity on yield ............................... 21
  Two-way interactions of farming practices and insect/pollinator diversity on yield ................. 23
  Three-way interactions of farming practices and insect/pollinator diversity on yield ................ 25
  Main Effects of landscape heterogeneity and farming practices on insect diversity, pollinator diversity and yield ........................................... 26
  Two-way Interactions of landscape heterogeneity and farming practices on insect diversity, pollinator diversity and yield .......................... 27

**Conclusions** ............................................................................................................................ 28

**Figures** ..................................................................................................................................... 30
ABSTRACT

MAXIMIZING ECOSYSTEM SERVICES PROVIDED TO THE NEW OIL CROP

*B. carinata* THROUGH LANDSCAPE AND ARTHROPOD DIVERSITY

SHANE STILES

2019

Prairies, once spanning the Upper Midwest, have now largely been replaced by agriculture. The lack of resources available to pollinators in agricultural fields and the practices employed by farmers to maximize yield has led to a decline in insect and pollinator diversity. There is a need to better understand how ecosystem services provided by a diverse insect community scale to current farming practices as they relate to crop yield. We sought to explain how landscape heterogeneity relates to insect and pollinator diversity, as well as how insect diversity relates to crop yield across common farming practices. To evaluate how farming practices relate to yield and insect diversity, we planted 35 single acre sites of *B. carinata*, a generalist flower that might be capable of supporting a diverse insect community. We randomly assigned each site with a combination of three treatments: tilling (yes/no), added honey bee hives (yes/no), and treatment with systemic neonicotinoids (yes/no). The Shannon Index of insect diversity sampled within the site, and the surrounding landscape at multiple spatial scales were calculated. We observed a significant positive relationship between insect (and pollinator) diversity with yield in the absence of any farming practice (*p*=0.002 and *p*<0.0001, respectively). All farming practices will increase yield. However, farming practices alter the relationship between yield and diversity. The addition of seed
treatment or tillage negates the relationship between insect (and pollinator) diversity with yield. Seed treatment alone results in a flat relationship between diversity and yield for all insects and a negative relationship for pollinators. Increased landscape heterogeneity results in a positive relationship between insect diversity at the 1000m scale \((p=0.019)\) and pollinator diversity at the 3000m scale \((p<0.001)\), suggesting large-scale heterogeneity contributes to overall insect diversity. Lastly, there is a positive relationship between \(B.\ carinata\) yield and landscape diversity at the 3000m scale \((p<0.0001)\). Our results show that increasing large-scale landscape heterogeneity is a good way to increase diversity and that diversity can serve as a substitute for common farming practices such as application of pesticides, tilling, or added honey bee hives. Increased heterogeneity could save farmers from the input cost of treatment or tillage, by way of increased insect diversity, while still providing similar yields.
Literature Review

INTRODUCTION

Ecosystem services represent the benefits that human populations derive from ecosystem function (Costanza et al., 1997). Examples include extraction of lumber, fuel, the biological control of pests, and the pollination of crops. Ecosystem services are often increased by biodiversity (Chapin, Zavaleta, Eviner, Naylor, & al, 2000; Hooper et al., 2005). Many fruit and vegetable crops are pollinated by insects (Klein et al., 2007). The total value of pollinators was estimated at $173 billion globally, per year (Gallai, Salles, Settele, & Vaissière, 2009). Climate change is expected to affect the access, availability and prices of crops in the future (Schmidhuber & Tubiello, 2007). It is also predicted to increase arable land in the US by 40%, most of which will be in the northern regions of the country (Fischer, Shah, Tubiello, & van Velhuizen, 2005). These changes in climate could allow for the introduction of new crop species into areas in which they were previously not grown (Olesen & Bindi, 2002) with the caveat that producers accept the new crop. The goal of this literature review is to highlight ecological problems associated with the intensification of agriculture and its effects on ecosystem services in the form of crop yield.

STUDY CROP

*Brassica carinata* (Brassicaceae) is a relatively new crop to the U.S. that could provide multiple benefits to agroecosystems. *Brassica carinata*, (carinata, hereafter) is an oilseed mustard that grows up 280 cm tall and produces up to 200 flowers. Every fruit contains between 10-20 seeds and seeds are recognized to have a high oil content. Carinata on
average produces 2 tons of seed per hectare (Basili & Rossi, 2018), and has the potential to be used as a biofuel, livestock feed, in phytoremediation, and in suppressing soil borne crop diseases (Furlan et al., 2010)(Anjum et al., 2012; Cardone et al., 2003; Licata et al., 2018; Pane, Villecco, Pentangelo, Lahoz, & Zaccardelli, 2012). Carinata was chosen as a study system because of its generalist flowers, similar to other pollinating crops, and the lack of relevant literature about this crop. Carinata is native to Ethiopia and is well suited for cultivation anywhere with limited frost. Carinata is of interest to producers as a winter cover in the Southeast U.S. (Ringo, n.d.) and as an alternative to canola in the Upper Midwest U.S. (“Advancement of Brassica carinata - SOUTH DAKOTA STATE UNIVERSITY,” n.d.). This crop is attractive to native pollinators, as well as to managed honey bees (Apis mellifera) (personal observation), but there is limited literature on the pollinators of carinata following introduction to the US. Carinata was introduced in 1957 as a leafy vegetable (Stephens, n.d.). While there is no evidence that this plant will become invasive, the literature is not conclusive as to the ecological impacts that this crop could have on regions where it may be introduced.

LANDSCAPE HETEROGENEITY

The Upper Midwest once possessed large prairies that sustained many pollinators with its high levels of plant diversity. But with European settlement, the landscape has been converted to one comprised mostly of intensive agriculture. This change has led to the loss of numerous taxa (Benton, Vickery, & Wilson, 2003) and the ecosystem services they offer (Grab et al., 2019). Many agricultural crops in this region do not provide sufficient resources to sustain the once abundant and diverse community of pollinators
Agricultural intensification jeopardizes wild bee communities and the pollination services they offer to crops (Klein et al., 2007). Many species of bees have been extirpated due to the intensification of agriculture (Burkle, Marlin, & Knight, 2013). Changes in the landscape have led to a change in community function (Hoehn, Tscharntke, Tylianakis, & Steffan-Dewenter, 2008). More available habitat and foraging options could increase the diversity of pollinators (Grab, Blitzer, Danforth, Loeb, & Poveda, 2017), which is tied to the function of the system as well as maximum ecosystem services (Kremen, 2018). The island biogeography hypothesis (MacArthur & Wilson, 1967) in which the diversity of an island is related to its size and travel between two islands is often difficult and determined by distances between each. This idea has also been applied to fragmented natural areas, with an emphasis placed on connecting fragmentated habitats to preserve biodiversity (Taylor, Fahrig, Henein, & Merriam, 1993). Movement of species between fragmented habitats is considered dangerous and difficult, and habitat fragments can be considered “islands” surrounded by a hostile “sea” of human land use came into question (Haila, 2002). Proper agricultural management may help bridge these islands and thereby help conserve biodiversity (Kennedy et al., 2013; Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005) while ameliorating the negative impacts of agriculture such as the loss of wildlife habitat, nutrient runoff, and greenhouse gas emissions (Power, 2010). Increasing landscape heterogeneity (e.g., the amount of land cover types), not necessarily the amount of natural areas, could have positive benefits on biodiversity, allowing animals to forage in differing land types to meet differing needs (Benton et al., 2003; Fahrig et al., 2011). There is evidence that many common agricultural pollinators can forage over long
distances. Honey bees can forage up to 6 km (Beekman & Ratnieks, 2000) and bumble bees can travel up to 20 km (Morris, 1993) from their nests. As landscape heterogeneity increases, the abundance and diversity of invertebrate predators increases, which suppresses pest species (Bianchi, Booij, & Tscharntke, 2006; Chaplin-Kramer, O’Rourke, Blitzer, & Kremen, 2011; Veres, Petit, Conord, & Lavigne, 2013). Other studies show that natural areas in close proximity to crops are needed to maintain high species diversity and maximize ecosystem function (Isaacs, Tuell, Fiedler, Gardiner, & Landis, 2009; Ricketts et al., 2008; Veres et al., 2013). Lastly, others are finding that provision of mass flowering crops is important for maintaining insect diversity (Holzschuh, Dormann, Tscharntke, & Steffan-Dewenter, 2013; Thom et al., 2016) due to the large amounts of nectar and pollen that they offer. Currently, the literature is not clear as to which of the previously mentioned management styles (increased heterogeneity, presence of natural areas, or proportion of the landscape devoted to pollinator-attractive crops) would maximize insect biodiversity and related ecosystem services.

POLLINATION AGRICULTURE

Pollinator communities contribute to humans by providing ecosystem services in the form of pollination (Costanza et al., 1997; Kremen, 2005). The prairie ecosystem has been mostly eradicated from SD (Wright & Wimberly, 2013), agricultural intensification has been correlated with declines in insect abundance and diversity (Tscharntke et al., 2012). Biodiversity, allows functionally redundant species that respond differently to environmental fluctuations to ensure that niches are consistently occupied (M. Loreau, 2001). The addition of more resources for pollinators could increase pollinator diversity (Grab et al., 2017) and indirectly, the pollination of crop plants, however interpretation
differs on the diversity metric used. The literature is not clear as to the number of pollinators needed to maximize yields, but investigations have indicated native pollinators, in addition to managed pollinators, are crucial for increasing the yields of crops (Garibaldi et al., 2013; Lindström, Herbertsson, Rundlöf, Bommarco, & Smith, 2016; Mallinger & Gratton, 2015). Increasing pollinator species and genera diversity respectively, has been related to increases in yield of canola, a crop that is closely related carinata (Atmowidi, Buchori, Manuwoto, Suryobroto, & Hidayat, 2007; Perrot, Gaba, Roncoroni, Gautier, & Bretagnolle, 2018). Others have found that functional group diversity, as opposed to species diversity, is the most important factor for increasing yields (Hoehn et al., 2008). additionally, others have found that species richness of wild bees increased fruit set more than bee abundance (Mallinger & Gratton, 2015).

Factors such as plant height (Hoehn et al., 2008), plant diversity (Hoehn et al., 2008), and nutritional resources presented by the plant community (Nottebrock et al., 2017) all affect pollinator foraging strategies due to variations in pollinator preference, physiology, and life history. Farming practices like insecticide use (Rundlöf et al., 2015), relative abundances of domesticated honey bees (Kremen, 2018), and tillage of fields (McLaughlin & Mineau, 1995) also affect pollinator foraging and diversity. The addition of pesticides into agricultural systems can reduce pest populations (Elbert, Haas, Springer, Thielert, & Nauen, 2008), but it can also interfere with pollination processes. For example, sublethal doses of neonicotinoids can alter insect foraging behavior (Henry et al., 2012; Tomé, Martins, Lima, Campos, & Guedes, 2012; Williamson, Willis, & Wright, 2014) and increase insect preference for neonicotinoid laced resources (Arce et
Tilling fields reduces the abundance of eusocial bee species (Williams et al., 2010). It was hypothesized that because a single individual is responsible for repopulation after a disturbance event, eusocial species have a harder time coping with tilled soil (Kratschmer et al., 2018). There has been some speculation about the interaction between wild pollinators and the addition of nonnative honey bees. A review study that found an equal number of papers claiming there was and was not competition for resources between wild pollinators and honey bees in plant communities (Mallinger, Gaines-Day, & Gratton, 2017), however this study only focused on natural systems. Native bee and honey bee abundances increased the yield of sunflowers through differing methods of pollen dispersal (Greenleaf & Kremen, 2006), although 90% of all commercial pollination of sunflowers is performed by honey bees (Genersch, 2010). Agrobiont species, such as solitary bees adapted to living in agroecosystems, tend to dominate agricultural systems, creating a dependency on a few pollinating species within agricultural systems (Mogren, Rand, Fausti, & Lundgren, 2016).

Our study aims to investigate if changes to landscape heterogeneity results in declines in ecosystem services provided by diversity and if this holds across common farming practices such as pesticide treatment, tilling, and added honey bee hives. This thesis contains three main goals: 1) to evaluate the relationship between the diversity of all insects and yield of carinata, as well as the diversity of pollinating insects and carinata yield, 2) to determine the extent to which common farming practices such as tilling, use of neonicotinoids, and the addition of honey bee hives affects the yield benefits
contributed by insects and pollinators, and 3) to elucidate the effects of landscape heterogeneity at different spatial scales on insect/pollinator diversity.

**Introduction**

Intensive agriculture has replaced prairies as the primary land use within the Upper Midwest (McGregor, 1986). These lands, once rich in biodiversity, have been converted to landscapes dominated by corn and soybean, providing minimal floral forage to insects and pollinators (Smart et al., 2016). The lack of resources including nectar and pollen availability in agricultural fields and the practices employed by farmers to maximize yield such as tilling, pesticide treatment, and added honey bee hives, has led to a decline in insect and pollinator diversity (Kearns, Inouye, & Waser, 1998). Additionally, landscape heterogeneity or the diversity of land uses at the landscape scale has declined with agricultural intensification (Benton et al., 2003). These changes have altered ecosystem services provided by arthropods to humans. In order to quantify the ecosystem services that are provided by a diverse insect community, we need to scale the services against current farming practices as they relate to crop yield. Appropriate management of services can ameliorate many of the negative impacts of agriculture (Power, 2010).

Wild pollinators are sometimes found to contribute more to crop yield than domesticated honey bees (Garibaldi et al., 2013; Lindström et al., 2016; Mallinger & Gratton, 2015). However, land use change has had an impact on pollination services provided to crops by decreasing pollinator diversity (Grab et al., 2019). Additionally, there are instances of
agriculture favoring agrobiont species that compensate for the pollination services of the pollinators displaced with intensification (Mogren et al., 2016). Furthermore, common farming practices in the US, such as the use of neonicotinoid insecticides (Rundlöf et al., 2015), tillage (McLaughlin & Mineau, 1995), and added honey bees (Mallinger et al., 2017) can negatively affect wild pollinators. Agricultural intensification generally jeopardizes wild bee communities and hence the pollination services they offer to crops (Klein et al., 2007).

Common farming practices such as treatment with neonicotinoids, tillage, and added honey bee hives (henceforth referred to as common farming practices) are believed to increase crop yields. Tillage can have a positive overall effect on crop yield under some circumstances, but its benefits are crop and context dependent, for example it has a mild to negative effect on Brassica napus yields (Arvidsson, Etana, & Rydberg, 2014). Additionally, added honey bees do not always fully replace the yield benefits offered by native pollinators (Garibaldi et al., 2013) yet are used in 90% of all commercial pollination (Genersch, 2010). Neonicotinoids have been effective in controlling pests of differing crops, possibly leading to higher yields (Elbert et al., 2008; Lahiri, Roberts, & Toews, 2019; Perkins, Steckel, & Stewart, 2018). However, we have little understanding on how these common farming practices interact with insect diversity in terms of crop yield. Can, for example, producers increase yield by a combination of anthropogenic inputs and ecosystem services?
Increased landscape heterogeneity is thought to act as a preserver of biodiversity, and consequently ecosystem services (Michel Loreau, Mouquet, & Gonzalez, 2003; Tscharntke et al., 2005). Farming practices occur within a broader agricultural ecosystem that in turn influences insect diversity (Fahrig et al., 2011). As landscape heterogeneity increases, the abundance and diversity of natural enemies increases, stabilizing pest communities while increasing insect diversity (Bianchi et al., 2006; Chaplin-Kramer et al., 2011; Veres et al., 2013). Increasing insect diversity could both increase pollination services and mediate pest populations. Thus, to have a better understanding of how insect and pollinator diversity is related to crop yield we need to consider the landscape context in which farming inputs occur. Linking landscape heterogeneity and farming practices with insect/pollinator diversity and yield is an area in which more attention is required.

We use the oilseed mustard *Brassica carinata* (carinata, Brassicaceae) to examine the relationship between insect/pollinator diversity and yield within a broader agroecosystem landscape context. This crop was chosen because it has a generalist flower that is visited by many pollinating species and likely shares a similar pollination system with other flowering crops in the region, especially canola. There is also a need to study ecological properties of this crop as planting becomes more common. Carinata is currently being developed as a biofuel, for aid in phytoremediation, and as a feedstock (Anjum et al., 2012; Cardone et al., 2003; Licata et al., 2018). Cultivation of this crop could also have ecological benefits as a provider of resources to pollinators, similar to what is found with its relative *Brassica napus* (e.g., canola) (Holzschuh et al., 2013; Thom et al., 2016). Carinata grows to 280 cm tall and produces up to 200 flowers per season. Every
siliqueous fruit contains 10-20 seeds with a high protein and oil content (Basili & Rossi, 2018) and thus has the appearance of a robust canola plant.

Our study explicitly quantifies the effect of insect and pollinator diversity on yield across a range of common farming practices as well as landscape determinants of insect and pollinator diversity by addressing the following questions. First, is there a relationship between insect/pollinator diversity with carinata yield? Second, are insect/pollinator diversity yield effects modified by the common farming practices of tilling, seed treatment with neonicotinoids, and the addition of honey bee hives? Third, is there a relationship between landscape and insect/pollinator diversity found within our plots and if so, at what scale? Our overall goal is to evaluate farming practices and landscape heterogeneity to determine the strongest predictors of carinata yield and insect/pollinator diversity. Our questions become especially relevant in the context of global food security. Climate change is expected to impact the access, availability, and prices of crops in the future (Schmidhuber & Tubiello, 2007). Knowledge of these effects could be used for future prediction of yield under an altered climate.

**Materials and Methods**

**STUDY DESIGN**

In 2017 and 2018 we planted carinata in 19 × 1-acre sites and in 16 × 1-acre sites, in Brookings and Kingsbury Counties, South Dakota, respectively (appendix A). To measure how common farming practices might interact with insect diversity and carinata yield, we employed a 2 × 2 × 2 factorial design. Carinata of unknown variety, acquired
from Green Cover Seed in Bladen, NE, was planted in May-June of 2017 and May of 2018 with a grain seed drill. Seeding rate was 9 kg/ha (or 8 lbs./acre) and row spacing was 19 cm (7.5 in) apart. We chose sites surrounded by varying degrees of heterogeneity, ranging from many different land uses with an irregular distribution to few land uses with a more even distribution. All sites were randomly assigned a combination of three treatments: seeds treated with Poncho 600®, a systemic neonicotinoid containing 48% clothianidin (yes, no), four added honey bee hives (yes, no), and tilled (yes, no). Overall, 17 sites were treated with clothianidin, 18 sites had honey bee hives, and 22 sites were tilled. Honey bee hives were deployed soon after planting directly adjacent to the carinata fields. At deployment, hives had approximately 8 frames of bees, received no sugar supplemental feeds, and were actively managed over the season to facilitate hive growth. A table of all treatments received by each site can be found in appendix B. All sites were treated with Roundup® prior to carinata germination and 1 all sites were treated with a grass herbicide about one month post emergence, Medall II® in 2017, and Poast® in 2018.

INSECT COLLECTIONS

Sweep samples were used to quantify insect diversity. A 30 m transect was randomly established in each field on each sample date. We averaged 3 and 4 samples per site in 2017 and 2018, respectively. The net was 15 inches in diameter. Samples were collected parallel to the transect. Once insects were collected they were frozen until identification. Across both growing seasons, a total of 142 sweep samples were collected and identified. Insects were observed under an Olympus® microscope made by Diagnostic Instruments Inc and using GSQH10X/22 oculars. Insects were identified to family, then to
morphospecies within family for both years using Borror and Delong’s Study of Insects 7th edition, as well as bugguide.com. Pollinators were assigned according to a literature search of each family.

HARVEST

We harvested plants when the fruits were browned and took several measurements to determine plant development and yield. Five randomly selected carinata plants per 1 m² were cut at ground level and placed into individual paper bags. The remaining carinata plants in the quadrat were harvested and placed into a larger bag. All plants were dried in a drying oven until a consistent weight was reached. To perform yield estimation for each site, every random plant was weighed, the total fruits per random plant were counted, and five fruits from each random plant were selected. The seeds of each fruit were weighed and the number of viable and aborted seeds were counted to estimate yield per plant. Average weights and yields of each focal plant within a quadrat was used to estimate the yield of that quadrat based on its weight. To estimate site yield, we used a linear regression model described below.

ANALYSES

Yield Calculation

For all statistical analyses we used R version 3.5.1 (R Core Team 2018). Calculations of site yield included seed number and weight information of all harvested focal plant individuals per 1m² and site. Every site was used as an experimental unit. We performed a linear mixed effect model with R package lme4 using number of fruits as the response
variable and plant weight as the predictor variable. In addition, the average weight of an individual seed per site and the site itself were used as random effects to correct for differences between the sites and ripeness of the fruits. Model predictions were then used to calculate the seed weight per m² based on the biomass weight and yield of each focal plants for each quadrat. In other words, the yield of each quadrat was determined by the yields of each focal plant. Finally, the site yield was predicted by the mean yield of five quadrats per site and multiplied by 10,000 (the number of square meters in a hectare) to estimate the yield of each site in units of kg/ha. Yield calculations can be found in appendix C.

*Landscape Heterogeneity Quantification*

To estimate landscape heterogeneity, we used a Trimble GeoXH 2005 dGPS with up to 10 cm accuracy to record the center of each site as a data point. We then obtained a raster file (matrix of pixels organized into a grid in which each pixel contains a colored value representing a specific land use) of 2017 and 2018 USDA Cropscape data. Vector shapefiles were then created at three radii from each of our site points (500m, 1000m, 3000m). Vector files were created in QGIS version 2.18.9. The proportional land use indices were calculated by clipping the raster surrounding every individual site to its appropriate vector radii diameters, and then using the GRASS ‘r.report’ feature located inside QGIS to determine the number of pixels corresponding to each land use. Shannon diversity (H) of the landscape surrounding each site was calculated using the ‘vegan’ community ecology package (R package version 2.4-6). Landscape Quantification code can be found in appendix D.
Insect and Pollinator Diversity Calculation

The diversity of insects and pollinators were calculated using the Shannon index (appendix E) estimated with the ‘plyr’ package in R. The Shannon index is calculated using the following formula:

\[-(P_i * \ln(P_i))\]

where \(P_i\) is the sum of the proportions of each species, and \(\ln\) is the natural log.

Qualitatively similar results were observed for the relationship of landscape heterogeneity and yield with the separate components of the Shannon index.

Relationship between insect/pollinator diversity and carinata yield

To compare yield with insect and pollinator diversity we used linear mixed effect models with year as the random intercept effect. To meet assumptions of a normal distribution, for the analyses, yield was natural log +1 transformed. Our three farming practices and diversity metrics are fixed effects as shown by the following formula:

\[\ln (Yield+1) \sim (\text{Seed Treatment} \times \text{Honey Bee Hives} \times \text{Tillage} \times \text{Diversity Metric}) + (1 | \text{year})\]

The model includes all main and interactive effects. Our models were then simplified using stepwise-backward variable selection (Crawley, 2013). We tested for the inclusion of non-significant main and interaction effects using chi-square as a criterion for model assessment. The best overall model included all factors even though some factors were
not significant. All models can be found in appendix F. The main and interaction effects are summarized as model effect sizes. Each farming practice effect reflects its increase in yield, holding all other variables constant. Each farming practice effect reflects the absence of all other farming practices due to their categorical nature and holding constant the continuous diversity metrics. Interaction effects are added to the sum of the main effects that comprise the interaction. If an interaction effect is absent we must assume that the main effects are additive. To translate the effect size into increased yield in kg/ha raise $e$ to the effect size ($e^{\text{effect size}}$).

We did not include landscape heterogeneity into the model for two reasons. First, we expect landscape heterogeneity to affect yield through diversity and so we focus on the relationship between landscape heterogeneity and diversity. Furthermore, in the analyses presented below, we found no relationship between farming practices and diversity, suggesting that landscape heterogeneity is a major determinant of insect diversity in the carinata sites.

Relationship between insect/pollinator diversity and landscape heterogeneity

To compare insect diversity to landscape heterogeneity we used a model much like the previous model. The three landscape scales were multiplied by the three farming practices and again, simplified using stepwise backward variable selection. The diversity metric was natural log transformed. The formula is shown below:
$ln(shannon) - (500m_{landscape} + 1000m_{landscape} + 3000m_{landscape}) \times (\text{Seed Treatment} + \text{Honey Bee Hives} + \text{Tillage}) + (1|year)$

*Relationship between landscape heterogeneity and yield*

To compare the relationship between yield and landscape heterogeneity, yield was again natural log +1 transformed and compared to the three landscape scales and farming practices, using year as a random intercept effect as shown below:

$ln(Yield + 1) - (500m_{landscape} + 1000m_{landscape} + 3000m_{landscape}) \times (\text{Seed Treatment} + \text{Honey Bee Hives} + \text{Tillage}) + (1|year)$

*Results*

Because the analyses are conducted on yield data that have been natural log transformed, the results represented in figures are plotted on a $ln$ scale. To make the results more comprehensible, we provide estimated ranges of the yield in kg in the text presented below. The significant effects of main factors and their interactions are presented as effect sizes ($\pm$ one standard error) of yield (kg/ha). Insect and pollinator diversity are presented separately. For purposes of simplicity, only effect sizes of interactions are presented for all interactions. Yield is presented in tables 1 and 2.

*Main effects of farming practices and insect diversity on yield*

Seed treatment, added honey bee hives, tillage, and insect diversity have a significant positive effect on yield when all other variables are controlled for, however the
relationship between these factors and yield changed according to farming practices. Tillage has the strongest effect on yield, adding $23\pm1.94$ kg carinata seed/ha, while seed treatment has the weakest at $6.96\pm2.03$ kg/ha. Insect Shannon diversity and honey bee treatment have intermediate effects on yield; there were $9.8\pm1.06$ kg/ha for every unit increase in Shannon, and $10.17\pm2.09$ kg/ha when honey bee hives were adjacent to the carinata fields (Fig. 1, Table 1).

Two-way interactions of farming practices and insect diversity on yield

Added honey bee hives and tillage are the only farming practices that show a significant interaction on carinata yield independent of insect diversity. This interaction has a strong negative relationship with an effect of $-3.63\pm0.83$. That is, the combination of added hives and tilling is not additive, but results in a yield roughly the same as either of these factors did alone. Neither seed treatment $\times$ tillage nor seed treatment $\times$ added honey bee hives had interaction effects that were significant, but they were kept in the simplified model after performing a chi-square test that indicated better model performance with their inclusion. All three farming practices individually have a significant negative interaction with insect diversity on yield. Seed treatment has the smallest interaction with diversity and an effect size of $-1.87\pm0.72$ while tillage has the strongest interaction with diversity at $-2.71\pm0.76$. In other words, farming practices are not additive with insect diversity, resulting in yields that are not increased by increasing insect diversity in the presence of the three farming practices (Fig. 1, Table 1).

Three-way interactions of farming practices and insect diversity on yield
The interaction between seed treatment, tillage, and insect diversity is positive with an effect of 2.25±0.98. The interaction between seed treatment, added honey bee hives, and insect diversity is also positive (Fig. 1, Table 1). In other words, adding a second farming practice restores the relationship of insect diversity with yield.

Main effects of farming practices and pollinator diversity on yield

Seed treatment, added honey bee hives, tillage, and pollinator diversity all have a significant positive effect on yield when all other variables are controlled for, however the relationship between these factors and yield changes with the addition of new farming practices. Tillage has the strongest effect on yield with an effect of 2.39±0.48 (10.91±1.61 kg/ha), while pollinator diversity has the weakest at 1.10±0.21 (3±1.2 kg/ha). Seed treatment and added honey bee hive effects are of intermediate strength effect sizes of 1.64±0.5 (5.15±1.64 kg/ha) and 1.51±0.42 (4.52±1.52 kg/ha) respectively (Fig. 2, Table 2).

Two-way interactions of farming practices and pollinator diversity on yield

That all two-way interactions between farming practices and pollinators diversity on yield are negative translates to farming practices interfering in the relationship between pollinator diversity and yield. The interaction between seed treatment and added honey bee hives is not significant, but is withheld in the final model in accordance with the chi-square test. Seed treatment and tillage significantly interact with effect sizes of -1.69±0.62. Added honey bee hives and tillage also interact with an effect of -2.78±0.62. Seed treatment and pollinator diversity interacted with an effect of -1.83±0.56. Tillage
and pollinator diversity interact with an effect of -2.72±0.54. Again, these values indicate that the effect size is lower than the additive values of their main effects (Fig. 2, Table 2).

*Three-way interactions of farming practices and pollinator diversity on yield*

Seed treatment, tillage, and pollinator diversity interact with a strong effect of 2.91±0.78. Added honey bee hives, tillage, and pollinator diversity has an effect of 2.56±0.69 (Fig. 2, Table 2).

*Farming practices on insect and pollinator diversity*

Using insect and pollinator diversity as response variables and farming practices as predictor variables, we did not find significant evidence that any combination of farming practices within our one acre sites enhances or decreases insect or pollinator diversity.

*Main effects of farming practices and landscape heterogeneity on insect diversity*

There is a significant positive relationship between insect diversity and landscape heterogeneity (H) at the 1000m scale with an effect of 0.14±0.05 (Table 3).

*Two-way interactions of farming practices and landscape heterogeneity on insect diversity*

There is a significant positive interaction between landscape heterogeneity at the 500m scale and seed treatment with an effect of 0.15±0.07 (Table 3). There is also a significant negative interaction between landscape heterogeneity at the 1000m scale and tillage with an effect of -0.18±0.08 (Fig. 3, Table 3).
Main effects of farming practices and landscape heterogeneity on pollinator diversity

There is a significant positive relationship between landscape heterogeneity and pollinator diversity at the 3000m scale with an effect of 0.39±0.09 (Table 4).

Two-way interactions of farming practices and landscape heterogeneity on pollinator diversity

There is a significant negative interaction between landscape heterogeneity at the 3000m scale and tillage on pollinator diversity with an effect of -0.39±0.1 (Fig. 4, Table 4).

Main effects of landscape heterogeneity and farming practices on yield

There is a significant positive relationship between landscape heterogeneity at the 3000m scale and yield of carinata with an effect of 2.13±0.46 (adding 8.47±1.59 kg/ha for every unit increase of heterogeneity) (Fig. 6, Table 5).

Two-way interactions of landscape heterogeneity and farming practices on yield

There is a significant negative interaction between landscape heterogeneity at the 3000m scale and tillage with an effect of -1.85±0.5 (Fig. 6, Table 5).

Discussion

Few studies have evaluated the relationship between overall insect species diversity and yield in the context of farming practices (Letourneau & Bothwell, 2008; Lundgren &
Fausti, 2015) The approaches used here allow us to address the importance of three common farming practices and insect/pollinator diversity to yield, landscape heterogeneity to insect/pollinator diversity, and lastly, landscape heterogeneity to yield. Overall, we found that increased insect/pollinator diversity as well as all farming practices (added honey bee hives, tillage, neonicotinoid seed treatment) increase carinata yield. The common farming practices studied interfere with pollination and pest control services provided by wild insects, perhaps by deterring visitation, and killing insects present at the site. Additionally, we found that insect/pollinator diversity within our carinata sites is dependent on large-scale landscape heterogeneity and not on farming practices within our sites. Finally, we demonstrate that the largest scale of landscape heterogeneity (3000m) is positively related to carinata yield. Below we discuss the individual main effects and their interactions in turn.

*Main Effects of farming practices and insect/pollinator diversity on yield*

Biodiversity and ecosystem services are positively related (Chapin et al., 2000; Hooper et al., 2005). For example, higher levels of pollinator diversity is associated with increased yield (Atmowidi et al., 2007; Dainese et al., 2019; Greenleaf & Kremen, 2006; Hoehn et al., 2008; Mallinger & Gratton, 2015). Neonicotinoids (Elbert et al., 2008), tillage (Malhi & Lemke, 2007), and added honey bee hives (Sabbahi, DeOliveira, & Marceau, 2005), all of which can increase yields of canola, and these observations are corroborated by our results with carinata. A single unit increase of insect diversity had a stronger positive effect on yield than did treating crops with neonicotinoids. One unit increase of insect
diversity and the addition of honey bees had equal effects on carinata yield. More research is needed to determine the optimum population of honey bees to introduce into an agricultural field in our study areas. We found no direct influence on diversity from neonicotinoid treatment, honey bee hives, and tillage. This could be due to the small one-acre size of each of our sites. Mass flowering crops can increase the abundance of a wild bee species (Holzschuh et al., 2013), but the studied bee was a solitary species and might possibly not reflect the behavior of eusocial species. Mass flowering crops could be a way to sustain native pollinators without inflicting severe economic harm on producers. However, more research is needed to determine the relationship between farming practices in carinata sites of varying size and insect/pollinator diversity. It is possible that practices such as tilling and pesticide use upon the broader landscape mitigate any change to diversity by farming practices performed at our carinata sites (Tscharntke et al., 2005).

Insect diversity has a stronger effect (2.28) than pollinator diversity (1.10) on yield, indicating that insect diversity contributes more to a higher yield than does pollinator diversity alone. Insect diversity includes all pollinators collected, but it also accounts for non-pollinating insects including both pests and natural enemies. Biodiversity could favor suppression of pest populations and enhance the activity of natural enemies in agroecosystems (Landis, Wratten, & Gurr, 2000), especially if the measured biodiversity exists within a complex landscape (Bianchi et al., 2006). Therefore, many non-pollinating insects also contribute ecosystem services by suppressing pest populations. Our insect diversity measurement more strongly contributes to carinata yield due to the addition of both pollinators and natural enemies. We observed several known pests such as flea
beetles (*Phyllotreta spp*.), pollen beetles (Coleoptera: Nitidulidae), owlet moths (Lepidoptera: Noctuidae), and hemipteran pests in the genus *Lygus*, all of which are associated with yield loss in the closely related canola (Reddy, 2017).

**Two-way interactions of farming practices and insect/pollinator diversity on yield**

All two-way interactions included in the final models examining yield in relation to insect/pollinator diversity are negative, indicating that farming practices interfere with the positive effects on yield by insect diversity. Added honey bee hives and tilling did not have a perfectly additive effect on yield. Tilling almost completely negated the positive effect of insect or pollinator diversity on yield. These findings are consistent with previous studies demonstrating that eusocial bees are more sensitive to tilling regardless of nest location (Kratschmer et al., 2018; Williams et al., 2010). A single fertile female is responsible for eusocial bee reproduction, which could lead to greater difficulty in repopulation after disturbance compared to solitary species in which most females are reproductive (Kratschmer et al., 2018).

There is a significant negative interaction between seed treatment with insect/pollinator diversity in relation to yield, supporting previous studies that even sublethal doses of neonicotinoids negatively alter pollinator behavior (Henry et al., 2012; Rundlöf et al., 2015). This suggests that seed treatment decouples the relationship between insect/pollinator diversity and yield. There is also a significant interaction between added honey bee hives and insect diversity with yield, although not significant in the pollinator diversity model. Bees will avoid flowers containing predators and also flowers in which a
previous predation attempt occurred (Dukas, 2001). There is also a possibility that non-pollinating insects could consume floral resources, contributing to the negative interaction between insect diversity and honey bee hives. These could explain the negative interaction between insect diversity and added honey bee hives, however, more research is needed to determine the mechanisms underlying the relationship between honey bees and non-pollinating insects.

The lack of an interaction between pollinator diversity and added honey bee hives suggests that the effects of wild pollinators and honey bees are additive. The foraging behavior and size of the honey bees are unique among observed pollinators in the field, possibly filling a niche in carinata pollination requirements. Bee species often have differing forage heights, time of day, and behavior on the flower (Hoehn et al., 2008), suggesting that diverse preferences are the mechanism by which species diversity operates. Honey bees could therefore supplement yield provided by wild bees (Garibaldi et al., 2013) maximizing the yield of a site. This is especially important when considering recent declines in wild bee diversity and abundance (Burkle et al., 2013). Current research on competitive interactions between managed honey bees and native bees is mixed, with about half of studies finding negative interactions between managed and native bees (Mallinger et al., 2017). There is also evidence that variation in floral resources could influence managed pollinator and wild bee interactions (Nottebrock et al., 2017).
There is no interaction between added honey bee hives and seed treatment, possibly because the surrounding environment is inundated with pesticides, or because honey bees are better at detoxifying pesticides than wild bees (Rundlöf et al., 2015).

Our negative two-way interactions of farming practices with insect/pollinator diversity demonstrate that benefits provided by a diverse community can be decoupled by human modification of the landscape and that stakeholders should be cautious before intensive farming practices are implemented. We conclude that the farming practices manipulated in our study negatively alter the ecosystem services provided by insects; thus producing a cap on how much yield can be attained on a specific field.

*Three-way interactions of farming practices and insect/pollinator diversity on yield*

Four three-way interactions were observed within our models. Two occurred in our model relating to pollinators and yield while two occurred in our insect and yield model. All contain a positive interaction consisting of two farming practices and one diversity metric. It is possible that the yield is supplemented by the addition of a second farming practice to the negative two way interactions mentioned above. One farming practice might interact negatively with insect/pollinator diversity and require an additional farming practice to compensate for those losses in yield. The negative two way interaction between honey bees and insect diversity has a yield effect of -2.22. Consequently, the addition of a third interaction (seed treatment) to the honey bee-insect interaction almost exactly canceled the negative effect of the 2-way interaction with a yield effect of 2.17. The same compensation is observed in the pollinator model. The 2-
way interaction between tilling and pollinators has a yield effect of -2.7, but the addition of a third interaction (seed treatment) resulted in a yield effect of 2.92, again, canceling the negative effects of the 2-way interaction. Lastly, there is no interaction between all three farming practices with insect/pollinator diversity, suggesting that these relationships reach a threshold in which they are not altered any further.

Main Effects of landscape heterogeneity and farming practices on insect diversity, pollinator diversity and yield

Insect and pollinator diversity were positively related to landscape heterogeneity at the 1000m and 3000m scales, respectively. There was no effect of small-scale landscape heterogeneity (500m) on yield or insect diversity, demonstrating that large-scale land use (>500m) is important for insect/pollinator diversity and that biodiversity loss associated with land use change is not an issue that can be addressed by a single landowner. Honey bees forage up to 6 km (Beekman & Ratnieks, 2000) and bumble bees can fly up to 20 km (Morris, 1993). As landscape heterogeneity increases, the functional land uses available to insects will also increase, such as forage for resources, nesting, and mating grounds (Fahrig et al., 2011). Landscape heterogeneity at the 1000m scale was related to total insect diversity because many non-pollinating insects are not as strong of fliers and cannot travel the same distances as pollinators. Lastly, yield was positively associated with landscape heterogeneity at the 3000m scale. Because heterogeneity at the 3000m scale is positively related to pollinator diversity and yield, we conclude that pollinator diversity is enhanced by landscape heterogeneity, but other factors present in a more
heterogenous landscape, such as better farming practices and more edge areas could also increase yield.

*Two-way Interactions of landscape heterogeneity and farming practices on insect diversity, pollinator diversity and yield*

The significant positive interaction between small scale landscape heterogeneity and seed treatment on insect diversity could be related to the behavioral alterations of neonicotinoids on insect behavior (Tomé et al., 2012; Williamson et al., 2014) including a developed preference for neonicotinoid laced resources (Arce et al., 2018), meaning that a treated site could capture more species from the diverse local landscape.

The negative interaction between 1000m landscape heterogeneity and 3000m landscape heterogeneity with tilling in relation to insect and pollinator diversity may indicate that tillage practices destroy the habitat suitability for insects and pollinators (Nicholls & Altieri, 2013). Tilling at our carinata plots almost completely negated the positive effects of a heterogeneous landscape on insect/pollinator diversity. Increased heterogeneity provides a greater diversity of functional habitats for insects and pollinators, (Steffan-Dewenter, 2002; Tscharntke et al., 2005) many of which are ground nesting and would be destroyed by tillage (Kratschmer et al., 2018). This negative interaction was also reflected between tillage and 3000m heterogeneity in relation to yield.
Conclusions

What ecological relationships are investigated?
First, we evaluate the relationship between yield of carinata and the diversity of insects and pollinators present in the study sites. Second, we look at the relationship between three common farming practices and yields of the crop. Lastly, we compare landscape heterogeneity at three different scales to the diversity of insects and pollinators sampled within our plots.

What methods were applied?
We addressed our research questions by employing a 2 x 2 x 2 factorial design to measure the response to the three farming practices. Linear mixed-effect models were used to evaluate these relationships using year as a random effect. Models were simplified using a chi-square test.

What is the main result?
Increasing large-scale landscape heterogeneity is a good way to increase insect and pollinator diversity. Additionally, increased insect and pollinator diversity was correlated with higher yield. Common farming practices will also increase yields, however increasing insect or pollinator diversity in the presence of a common farming practice will diminish the relationship between diversity and yield.

What conclusion can be drawn?
Increased landscape heterogeneity could lead to higher crop yields and possibly replace some farming practices. It is important to maintain a high diversity of insects and pollinators at the landscape level to facilitate ecosystem function and ecosystem services. This reserve of diversity could prove useful for agriculture in the near future.

Carinata yield at our plots is increased by 1) common farming practices (neonicotinoid treatment, tillage, and added honey bee hives), 2) increasing diversity of pollinating insects, 3) increasing diversity of the entire insect community and 4) increasing landscape heterogeneity. There is, however, tension between many of the farming practices and insect/pollinator diversity. Many farming practices might ultimately increase yield, but they are not additive in that they decrease the insect/pollinator contribution to yield. Our findings suggest that increased landscape heterogeneity and insect/pollinator diversity increases yield, but these relationships are decoupled by common farming practices such as tilling, seed treatment, and added honey bee hives.

Human land use does not necessarily entail habitat destruction, and proper agricultural management can enhance biodiversity, in turn increasing ecosystem function and services (Tscharntke et al., 2005) (Fig. 9). Management tactics such as diversification of the
landscape, reduction in tilling, and reduction of pesticide use could all have positive impacts on the ecosystem services provided by pollinators. Increased landscape heterogeneity increases biodiversity and will therefore, act as biological insurance for ecosystem services (Michel Loreau et al., 2003). This study could have policy implications relating to the use of pesticides, tilling, and the diversification of the landscape. Policies that discourage the use of tilling and pesticides could be paired with incentives to diversify the landscape, maximizing pollinator health in an agricultural landscape. The warming of the global climate is predicted to increase arable land in North America by 40% (Fischer et al., 2005). By providing insects with a diverse and connected landscape we can invest in the future of agriculture in the US. Climate change in northern areas, such as the Upper Midwest, could allow for the introduction of new crop species (Olesen & Bindi, 2002). A diverse and healthy array of insects could be maintained in a heterogenous landscape, maximizing the benefits this climate change could bring. Our results demonstrate that landscape heterogeneity is an important factor in the enhancement of pollination services, that not only increase yield, but could allow us to accommodate crops suitable to the future climate of this region.
Figures

Yield and Insect Diversity Mediated by Tillage and Seed Treatment

<table>
<thead>
<tr>
<th>Till</th>
<th>Untreated Seeds</th>
<th>Treated Seeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-till</td>
<td>Untreated Seeds</td>
<td>Treated Seeds</td>
</tr>
<tr>
<td>Natural Log of Yield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insect Diversity</td>
<td>1.0  1.5  2.0  2.5</td>
<td>1.0  1.5  2.0  2.5</td>
</tr>
<tr>
<td>Yield (kg/ha)</td>
<td>22026  2981  403  55</td>
<td>22026  2981  403  55</td>
</tr>
</tbody>
</table>
FIGURE 1: Linear mixed effect analysis of main effects, 2-way, and 3-way interactions between tillage and seed treatment (first figure) and treatment and added honey bee hives (second figure), with insect diversity on *Brassica carinata* yield in eastern South Dakota, 2017-2018. Ticks on the x-axis represent insect diversity of each site.
FIGURE 2: Linear mixed effect analysis of main effects, 2-way, and 3-way interactions between tillage and seed treatment (first figure) and tillage and added honey bee hives (second figure), with pollinator diversity on *Brassica carinata* yield in eastern South Dakota, 2017-2018. Ticks on the x-axis represent pollinator diversity of each site.
FIGURE 3: Linear mixed effect analysis of interactions between tillage and landscape heterogeneity at a 1000m radius on insect diversity sampled within sites of *Brassica carinata* in eastern South Dakota, 2017-2018. Ticks on the x-axis represent measured individual site heterogeneity.
FIGURE 4: Linear mixed effect analysis of interactions between seed treatment and landscape heterogeneity at a 500m radius on insect diversity sampled within sites of *Brassica carinata* in eastern South Dakota, 2017-2018. Ticks on the x-axis represent measured individual site heterogeneity.
FIGURE 5: Linear mixed effect analysis of interactions between tillage and landscape heterogeneity at a 3000m radius on pollinator diversity sampled within sites of *Brassica carinata* in eastern South Dakota, 2017-2018. Ticks on the x-axis represent measured individual site heterogeneity.
FIGURE 6: Linear mixed effect analysis of interactions between tillage and landscape heterogeneity at a 3000m radius on the yield of *Brassica carinata* in eastern South Dakota, 2017-2018. Ticks on the x-axis represent measured individual site heterogeneity.
FIGURE 7: Insect diversity within sites of *Brassica carinata* plotted by log of the yield of each site. Every point indicates a single acre site in Eastern South Dakota between 2017-2018.
FIGURE 8: Large scale landscape heterogeneity within sites of *Brassica carinata* plotted by log of the yield of each site. Every point indicates a single acre site in Eastern South Dakota between 2017-2018.
FIGURE 9: Reciprocal relationship between ecosystem function and ecosystem services in the context of a heterogeneous landscape. Carinata enhances ecosystem function with the provision of nectar and pollen resources, while insect and pollinator diversity enhance ecosystem service by providing pollination and pest control. These relationships are optimized in the presence of a highly heterogeneous landscape.
### Tables

**TABLE 1**: Linear mixed effects analysis of farming practices, insect diversity, and interactions on the yield of *Brassica carinata*. $P < 0.05$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

<table>
<thead>
<tr>
<th>Effects</th>
<th>Effect Size</th>
<th>Standard Error</th>
<th>Degrees of Freedom</th>
<th>p-value</th>
<th>Estimated Increase in Yield (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>3.0624</td>
<td>0.6028</td>
<td>32</td>
<td>5.71e-05***</td>
<td>_________</td>
</tr>
<tr>
<td>Seed Treatment</td>
<td>1.9407</td>
<td>0.7120</td>
<td>31</td>
<td>0.013020*</td>
<td>6.96</td>
</tr>
<tr>
<td>Added Honey bees</td>
<td>2.3241</td>
<td>0.7499</td>
<td>30</td>
<td>0.005654**</td>
<td>10.22</td>
</tr>
<tr>
<td>Tillage</td>
<td>3.1495</td>
<td>0.6889</td>
<td>29</td>
<td>0.000185***</td>
<td>23.32</td>
</tr>
<tr>
<td>Insect Diversity^</td>
<td>2.2832</td>
<td>0.6450</td>
<td>28</td>
<td>0.002057**</td>
<td>9.8</td>
</tr>
<tr>
<td>Seed treatment x Added honey bees</td>
<td>-0.4480</td>
<td>0.7899</td>
<td>27</td>
<td>0.576897</td>
<td>_________</td>
</tr>
<tr>
<td>Seed treatment x Tillage</td>
<td>-1.0361</td>
<td>0.7848</td>
<td>26</td>
<td>0.201662</td>
<td>_________</td>
</tr>
<tr>
<td>Added honey bees x Tillage</td>
<td>-3.6303</td>
<td>0.8391</td>
<td>25</td>
<td>0.000328***</td>
<td>6.32</td>
</tr>
<tr>
<td>Seed Treatment x Insect Diversity^</td>
<td>-1.8775</td>
<td>0.7268</td>
<td>24</td>
<td>0.017756*</td>
<td>10.45</td>
</tr>
<tr>
<td>Added honey bees x Insect Diversity^</td>
<td>-2.2235</td>
<td>0.7642</td>
<td>23</td>
<td>0.008666**</td>
<td>10.8</td>
</tr>
<tr>
<td>Interaction</td>
<td>F Value</td>
<td>P Value</td>
<td>df</td>
<td>Additional Information</td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>---------</td>
<td>---------</td>
<td>-----</td>
<td>----------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Tillage x Insect Diversity</td>
<td>2.7138</td>
<td>0.001918**</td>
<td>22</td>
<td><strong>The model estimate of increased yield under insect diversity represents a single unit increase of diversity. Diversity ranges from 1-3, this model allows for a maximum of 2 unit increases in diversity. Estimated increase in yield was calculated by the addition of all main, preceding, and current interaction effect sizes taken to e^i.</strong></td>
<td></td>
</tr>
<tr>
<td>Seed Treatment x Added Honeybees x Insect Diversity</td>
<td>2.1729</td>
<td>0.029931*</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed Treatment x Tillage x Insect Diversity</td>
<td>2.2557</td>
<td>0.033771*</td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 2: Linear mixed effects analysis of farming practices, pollinator diversity, and interactions on the yield of *Brassica carinata*. $P < 0.05; * P < 0.05; ** P < 0.01; *** P < 0.001.$

<table>
<thead>
<tr>
<th>Effects</th>
<th>Effect Size</th>
<th>Standard Error</th>
<th>Degrees of Freedom</th>
<th>p-value</th>
<th>Estimated Increase in Yield (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>4.1753</td>
<td>0.4073</td>
<td>12.7618</td>
<td>1.59e-07 ***</td>
<td>_________</td>
</tr>
<tr>
<td>Seed Treatment</td>
<td>1.6420</td>
<td>0.5003</td>
<td>20.0677</td>
<td>0.003716 **</td>
<td>5.17</td>
</tr>
<tr>
<td>Added Honey bees</td>
<td>1.5147</td>
<td>0.4298</td>
<td>20.0004</td>
<td>0.002133 **</td>
<td>4.55</td>
</tr>
<tr>
<td>Tillage</td>
<td>2.3913</td>
<td>0.4897</td>
<td>20.0291</td>
<td>8.95e-05 ***</td>
<td>10.93</td>
</tr>
<tr>
<td>Pollinator Diversity^</td>
<td>1.1046</td>
<td>0.2128</td>
<td>20.9397</td>
<td>3.86e-05 ***</td>
<td>3.02</td>
</tr>
<tr>
<td>Seed treatment x Tillage</td>
<td>-1.6967</td>
<td>0.6288</td>
<td>20.0044</td>
<td>0.013830 *</td>
<td>10.35</td>
</tr>
<tr>
<td>Added honey bees x Tillage</td>
<td>-2.7867</td>
<td>0.6003</td>
<td>20.0786</td>
<td>0.000156 ***</td>
<td>3.06</td>
</tr>
<tr>
<td>Seed Treatment x Pollinator Diversity^</td>
<td>-1.8392</td>
<td>0.5626</td>
<td>20.1230</td>
<td>0.003818 **</td>
<td>2.48</td>
</tr>
<tr>
<td>Added honey bees x Pollinator Diversity^</td>
<td>-0.6318</td>
<td>0.4036</td>
<td>20.0932</td>
<td>0.133122</td>
<td>_________</td>
</tr>
<tr>
<td>Tillage x Pollinator Diversity^</td>
<td>-2.7270</td>
<td>0.5411</td>
<td>20.2327</td>
<td>6.07e-05 ***</td>
<td>2.16</td>
</tr>
<tr>
<td>Seed Treatment</td>
<td>2.9167</td>
<td>0.7811</td>
<td>20.0185</td>
<td>0.001307 **</td>
<td>6.0</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------</td>
<td>--------</td>
<td>---------</td>
<td>-------------</td>
<td>-----</td>
</tr>
<tr>
<td>Added Honey bees x Tillage x Pollinator Diversity^</td>
<td>2.5694</td>
<td>0.6925</td>
<td>20.5193</td>
<td>0.001337 **</td>
<td>4.20</td>
</tr>
</tbody>
</table>

^The model estimate of increased yield under pollinator diversity represents a single unit increase of diversity. Diversity ranges from 1-3, this model allows for a maximum of 2 unit increases in diversity. Estimated increase in yield was calculated by the addition of all main, preceding, and current interaction effect sizes taken to e^x.
TABLE 3: Linear mixed effects analysis of landscape heterogeneity, farming practices, and interactions on insect diversity sampled in sites of *Brassica carinata*. $P < 0.05$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

<table>
<thead>
<tr>
<th>Effects</th>
<th>Effect Size</th>
<th>Standard Error</th>
<th>Degrees of Freedom</th>
<th>p-value</th>
<th>Estimated Increase in Insect Diversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.59990</td>
<td>0.09565</td>
<td>2.67562</td>
<td>0.0114 *</td>
<td>_____</td>
</tr>
<tr>
<td>Heterogeneity 500m</td>
<td>-0.08282</td>
<td>0.05361</td>
<td>26.02034</td>
<td>0.1345</td>
<td>_____</td>
</tr>
<tr>
<td>Heterogeneity 1000m</td>
<td>0.14984</td>
<td>0.05992</td>
<td>26.01267</td>
<td>0.0190 *</td>
<td>1.16</td>
</tr>
<tr>
<td>Seed Treatment</td>
<td>0.05786</td>
<td>0.07415</td>
<td>26.00526</td>
<td>0.4422</td>
<td>_____</td>
</tr>
<tr>
<td>Tillage</td>
<td>0.02291</td>
<td>0.07934</td>
<td>26.01839</td>
<td>0.7751</td>
<td>_____</td>
</tr>
<tr>
<td>Heterogeneity 500m x Seed Treatment</td>
<td>0.15588</td>
<td>0.07481</td>
<td>26.13823</td>
<td>0.0471 *</td>
<td>1.14</td>
</tr>
<tr>
<td>Heterogeneity 1000m x Tillage</td>
<td>-0.18353</td>
<td>0.08001</td>
<td>26.14962</td>
<td>0.0301 *</td>
<td>0.99</td>
</tr>
</tbody>
</table>
TABLE 4: Linear mixed effects analysis of landscape heterogeneity, farming practices, and interactions on pollinator diversity sampled in sites of *Brassica carinata*. *P* < 0.05; *P* < 0.05; **P** < 0.01; ***P*** < 0.001.

<table>
<thead>
<tr>
<th>Effects</th>
<th>Effect Size</th>
<th>Standard Error</th>
<th>Degrees of Freedom</th>
<th>p-value</th>
<th>Estimated Increase in Pollinator Diversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.81041</td>
<td>0.07972</td>
<td>2.23576</td>
<td>0.006470 **</td>
<td>_______</td>
</tr>
<tr>
<td>Heterogeneity 3000m</td>
<td>0.39727</td>
<td>0.09855</td>
<td>29.36178</td>
<td>0.000361 ***</td>
<td>1.49</td>
</tr>
<tr>
<td>Tillage</td>
<td>-0.06618</td>
<td>0.07866</td>
<td>29.04183</td>
<td>0.407002</td>
<td>_______</td>
</tr>
<tr>
<td>Heterogeneity 3000m</td>
<td>-0.39671</td>
<td>0.10669</td>
<td>29.06970</td>
<td>0.000852 ***</td>
<td>0.94</td>
</tr>
</tbody>
</table>
TABLE 5: Linear mixed effects analysis of landscape heterogeneity, farming practices, and interactions on yield of *Brassica carinata*. $P < 0.05$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

<table>
<thead>
<tr>
<th>Effects</th>
<th>Effect Size</th>
<th>Standard Error</th>
<th>Degrees of Freedom</th>
<th>p-value</th>
<th>Increase in Yield (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>5.6471</td>
<td>0.2866</td>
<td>29.0000</td>
<td>$&lt; 2e-16$ ***</td>
<td>______</td>
</tr>
<tr>
<td>Heterogeneity 3000m</td>
<td>2.1365</td>
<td>0.4634</td>
<td>29.0000</td>
<td>7.49e-05 ***</td>
<td>8.47</td>
</tr>
<tr>
<td>Tillage</td>
<td>0.6068</td>
<td>0.3767</td>
<td>29.0000</td>
<td>0.11803</td>
<td>______</td>
</tr>
<tr>
<td>Heterogeneity 3000m x Tillage</td>
<td>-1.8509</td>
<td>0.5064</td>
<td>29.0000</td>
<td>0.00101 **</td>
<td>2.44</td>
</tr>
</tbody>
</table>
Appendices

APPENDIX A

This table outlines the name, coordinates, nearest city, yield, large-scale landscape heterogeneity and year of study for each of our sites.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Site Coordinates</th>
<th>Nearest City</th>
<th>Landscape Heterogeneity (3000m)</th>
<th>Yield (kg/ha)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volga</td>
<td>44°18'4.04&quot;N and 96°55'24.34&quot;W</td>
<td>Volga, SD</td>
<td>1.68</td>
<td>120.58</td>
<td>2017</td>
</tr>
<tr>
<td>Aurora</td>
<td>44°18'32.33&quot;N and 96°40'16.42&quot;W</td>
<td>Aurora, SD</td>
<td>1.52</td>
<td>104.08</td>
<td>2017</td>
</tr>
<tr>
<td>Pathology</td>
<td>44°19'15.72&quot;N and 96°46'20.03&quot;W</td>
<td>Brookings, SD</td>
<td>2.12</td>
<td>1691.46</td>
<td>2017</td>
</tr>
<tr>
<td>Felt</td>
<td>44°22'9.14&quot;N and 96°47'27.25&quot;W</td>
<td>Brookings, SD</td>
<td>1.57</td>
<td>730.43</td>
<td>2017</td>
</tr>
<tr>
<td>Bruce 2</td>
<td>44°25'37.22&quot;N and 96°53'9.30&quot;W</td>
<td>Bruce, SD</td>
<td>1.65</td>
<td>958.60</td>
<td>2017</td>
</tr>
<tr>
<td>Bruce 3</td>
<td>44°25'37.65&quot;N</td>
<td>Bruce, SD</td>
<td>1.61</td>
<td>2308.38</td>
<td>2017</td>
</tr>
<tr>
<td></td>
<td>Latitude</td>
<td>Longitude</td>
<td>Town</td>
<td>Distance</td>
<td>Price</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>------------</td>
<td>----------</td>
<td>--------</td>
</tr>
<tr>
<td>Bruce 4</td>
<td>44°30'23.57&quot;N</td>
<td>96°52'43.39&quot;W</td>
<td>Bruce, SD</td>
<td>1.64</td>
<td>919.62</td>
</tr>
<tr>
<td>Bruce 5</td>
<td>44°30'6.56&quot;N</td>
<td>96°53'14.99&quot;W</td>
<td>Bruce, SD</td>
<td>1.60</td>
<td>1704.12</td>
</tr>
<tr>
<td>Bruce 6</td>
<td>44°30'2.05&quot;N</td>
<td>96°52'19.17&quot;W</td>
<td>Bruce, SD</td>
<td>1.62</td>
<td>228.01</td>
</tr>
<tr>
<td>Jesse 1</td>
<td>44°25'0.19&quot;N</td>
<td>97°11'18.83&quot;W</td>
<td>Arlington, SD</td>
<td>1.35</td>
<td>0.609</td>
</tr>
<tr>
<td>Jesse 2</td>
<td>44°30'35.18&quot;N</td>
<td>97°11'18.83&quot;W</td>
<td>Arlington, SD</td>
<td>1.69</td>
<td>1966.77</td>
</tr>
<tr>
<td>Jesse 3</td>
<td>44°29'7.65&quot;N</td>
<td>97°11'18.83&quot;W</td>
<td>Arlington, SD</td>
<td>1.61</td>
<td>189.95</td>
</tr>
<tr>
<td>Jesse 4</td>
<td>44°29'25.66&quot;N</td>
<td>97°11'18.83&quot;W</td>
<td>Arlington, SD</td>
<td>1.64</td>
<td>801.15</td>
</tr>
<tr>
<td>Location</td>
<td>Latitude</td>
<td>Longitude</td>
<td>City/State</td>
<td>Distance</td>
<td>Angle</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------</td>
<td>------------------</td>
<td>------------</td>
<td>----------</td>
<td>-------</td>
</tr>
<tr>
<td>Oak 1</td>
<td>44°30'27.59&quot;N</td>
<td>96°31'42.93&quot;W</td>
<td>White, SD</td>
<td>1.61</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>44°29'59.55&quot;N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oak 2</td>
<td>44°31'41.77&quot;W</td>
<td>96°31'42.93&quot;W</td>
<td>White, SD</td>
<td>1.50</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>44°34'23.89&quot;N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roger 1</td>
<td>44°34'23.89&quot;N</td>
<td>96°47'56.93&quot;W</td>
<td>Estelline, SD</td>
<td>1.71</td>
<td>249.67</td>
</tr>
<tr>
<td></td>
<td>44°34'37.64&quot;N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roger 2</td>
<td>44°35'28.16&quot;N</td>
<td>96°48'16.48&quot;W</td>
<td>Estelline, SD</td>
<td>1.69</td>
<td>453.53</td>
</tr>
<tr>
<td></td>
<td>44°35'44.96&quot;N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roger 3</td>
<td>44°34'44.96&quot;N</td>
<td>96°47'7.43&quot;W</td>
<td>Estelline, SD</td>
<td>1.76</td>
<td>652.33</td>
</tr>
<tr>
<td></td>
<td>44°18'31.65&quot;N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aurora 1</td>
<td>44°18'34.26&quot;N</td>
<td>96°40'28.50&quot;W</td>
<td>Aurora, SD</td>
<td>1.55</td>
<td>297.15</td>
</tr>
<tr>
<td></td>
<td>44°18'31.65&quot;N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Latitude</td>
<td>Longitude</td>
<td>Distance (m)</td>
<td>Year</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-------------------</td>
<td>--------------------</td>
<td>--------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>Volga 1</td>
<td>44°17'54.63&quot;N</td>
<td>96°40'4.06&quot;W</td>
<td>1.93</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>Volga 2</td>
<td>44°19'31.13&quot;N</td>
<td>96°55'14.67&quot;W</td>
<td>1.85</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>Pathology 1</td>
<td>44°19'11.00&quot;N</td>
<td>96°46'18.00&quot;W</td>
<td>2.17</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>Pathology 2</td>
<td>44°22'8.75&quot;N</td>
<td>96°47'31.03&quot;W</td>
<td>1.60</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>Felt 1</td>
<td>44°21'59.20&quot;N</td>
<td>96°47'44.60&quot;W</td>
<td>1.62</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>Felt 2</td>
<td>44°29'59.55&quot;N</td>
<td>96°31'42.93&quot;W</td>
<td>1.53</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>Oak 11</td>
<td>44°30'27.59&quot;N</td>
<td>96°31'42.93&quot;W</td>
<td>1.65</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td>Oak 22</td>
<td>44°30'27.59&quot;N</td>
<td>96°31'42.93&quot;W</td>
<td>1.53</td>
<td>2018</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and</td>
<td>and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>------------------------------------------</td>
<td>------------------------------------------</td>
<td>------------------</td>
<td>-----</td>
<td>------------------</td>
</tr>
<tr>
<td>Roger 11</td>
<td>44°35'4.47&quot;N and 96°31'41.77&quot;W</td>
<td>Estelline, SD</td>
<td>1.67</td>
<td>673.52</td>
<td></td>
</tr>
<tr>
<td>Roger 22</td>
<td>44°34'46.96&quot;N and 96°48'15.10&quot;W</td>
<td>Estelline, SD</td>
<td>1.67</td>
<td>169.96</td>
<td></td>
</tr>
<tr>
<td>Roger 33</td>
<td>44°34'22.75&quot;N and 96°48'15.79&quot;W</td>
<td>Estelline, SD</td>
<td>1.79</td>
<td>657.79</td>
<td></td>
</tr>
<tr>
<td>Roger 44</td>
<td>44°34'22.45&quot;N and 96°47'44.09&quot;W</td>
<td>Estelline, SD</td>
<td>1.83</td>
<td>124.48</td>
<td></td>
</tr>
<tr>
<td>Scott 1</td>
<td>44°24'9.70&quot;N and 96°47'35.85&quot;W</td>
<td>Toronto, SD</td>
<td>1.48</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Scott 2</td>
<td>44°24'26.21&quot;N and 96°33'25.12&quot;W</td>
<td>Toronto, SD</td>
<td>1.50</td>
<td>572.68</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX B

This table highlights each of the three treatments each site received over each study year.
Average density is the average number of carinata plants counted in a randomly placed square meter for each site, counts were performed 5 times at each site.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Seed Treatment</th>
<th>Added Hives</th>
<th>Till/No-till</th>
<th>Average Density (m²)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurora 1</td>
<td>Treated</td>
<td>Yes</td>
<td>Till</td>
<td>37.6</td>
<td>2018</td>
</tr>
<tr>
<td>Aurora 2</td>
<td>Non-treated</td>
<td>Yes</td>
<td>Till</td>
<td>38.2</td>
<td>2018</td>
</tr>
<tr>
<td>Pathology 1</td>
<td>Treated</td>
<td>No</td>
<td>Till</td>
<td>66.0</td>
<td>2018</td>
</tr>
<tr>
<td>Pathology 2</td>
<td>Non-treated</td>
<td>No</td>
<td>Till</td>
<td>41.6</td>
<td>2018</td>
</tr>
<tr>
<td>Felt1</td>
<td>Treated</td>
<td>No</td>
<td>Till</td>
<td>33.8</td>
<td>2018</td>
</tr>
<tr>
<td>Felt 2</td>
<td>Non-treated</td>
<td>Yes</td>
<td>Till</td>
<td>36.8</td>
<td>2018</td>
</tr>
<tr>
<td>Volga 1</td>
<td>Treated</td>
<td>Yes</td>
<td>Till</td>
<td>52.6</td>
<td>2018</td>
</tr>
<tr>
<td>Volga 2</td>
<td>Non-treated</td>
<td>No</td>
<td>Till</td>
<td>55.4</td>
<td>2018</td>
</tr>
<tr>
<td>Scott 1</td>
<td>Non-treated</td>
<td>Yes</td>
<td>Till</td>
<td>36.4</td>
<td>2018</td>
</tr>
<tr>
<td>Scott 2</td>
<td>Treated</td>
<td>No</td>
<td>Till</td>
<td>44.0</td>
<td>2018</td>
</tr>
<tr>
<td>Oak 11</td>
<td>Non-treated</td>
<td>Yes</td>
<td>No-till</td>
<td>27.1</td>
<td>2018</td>
</tr>
<tr>
<td>Oak 22</td>
<td>Treated</td>
<td>No</td>
<td>No-till</td>
<td>59.6</td>
<td>2018</td>
</tr>
<tr>
<td>Roger 11</td>
<td>Non-treated</td>
<td>Yes</td>
<td>No-till</td>
<td>55.6</td>
<td>2018</td>
</tr>
<tr>
<td>Roger 22</td>
<td>Non-treated</td>
<td>No</td>
<td>No-till</td>
<td>22.0</td>
<td>2018</td>
</tr>
<tr>
<td>Roger 33</td>
<td>Treated</td>
<td>Yes</td>
<td>No-till</td>
<td>51.2</td>
<td>2018</td>
</tr>
<tr>
<td>Dataset</td>
<td>Treated</td>
<td>Yes/No</td>
<td>Till/No-till</td>
<td>Year</td>
<td>Value</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>--------</td>
<td>--------------</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>Roger 44</td>
<td>Treated</td>
<td>No</td>
<td>No-till</td>
<td>2018</td>
<td>51.0</td>
</tr>
<tr>
<td>Aurora</td>
<td>Treated</td>
<td>Yes</td>
<td>Till</td>
<td>2017</td>
<td>161.2</td>
</tr>
<tr>
<td>Volga</td>
<td>Non-treated</td>
<td>Yes</td>
<td>Till</td>
<td>2017</td>
<td>103.8</td>
</tr>
<tr>
<td>Felt</td>
<td>Non-treated</td>
<td>No</td>
<td>Till</td>
<td>2017</td>
<td>104.2</td>
</tr>
<tr>
<td>Pathology</td>
<td>Treated</td>
<td>No</td>
<td>Till</td>
<td>2017</td>
<td>123.4</td>
</tr>
<tr>
<td>Roger 3</td>
<td>Treated</td>
<td>No</td>
<td>No-till</td>
<td>2017</td>
<td>96.6</td>
</tr>
<tr>
<td>Roger 2</td>
<td>Non-treated</td>
<td>No</td>
<td>No-till</td>
<td>2017</td>
<td>104.8</td>
</tr>
<tr>
<td>Roger 1</td>
<td>Non-treated</td>
<td>Yes</td>
<td>No-till</td>
<td>2017</td>
<td>120.4</td>
</tr>
<tr>
<td>Roger 4</td>
<td>Treated</td>
<td>Yes</td>
<td>No-till</td>
<td>2017</td>
<td>122.0</td>
</tr>
<tr>
<td>Bruce 6</td>
<td>Treated</td>
<td>Yes</td>
<td>Till</td>
<td>2017</td>
<td>27.0</td>
</tr>
<tr>
<td>Bruce 5</td>
<td>Treated</td>
<td>No</td>
<td>Till</td>
<td>2017</td>
<td>38.8</td>
</tr>
<tr>
<td>Bruce 4</td>
<td>Treated</td>
<td>No</td>
<td>Till</td>
<td>2017</td>
<td>97.8</td>
</tr>
<tr>
<td>Bruce 2</td>
<td>Non-treated</td>
<td>No</td>
<td>Till</td>
<td>2017</td>
<td>85.6</td>
</tr>
<tr>
<td>Bruce 3</td>
<td>Non-treated</td>
<td>No</td>
<td>Till</td>
<td>2017</td>
<td>105.2</td>
</tr>
<tr>
<td>Oak 1</td>
<td>Non-treated</td>
<td>Yes</td>
<td>Till</td>
<td>2017</td>
<td>20.0</td>
</tr>
<tr>
<td>Oak 2</td>
<td>Non-treated</td>
<td>No</td>
<td>Till</td>
<td>2017</td>
<td>10.2</td>
</tr>
<tr>
<td>Jesse 1</td>
<td>Non-treated</td>
<td>No</td>
<td>No-till</td>
<td>2017</td>
<td>40.6</td>
</tr>
<tr>
<td>Jesse 2</td>
<td>Treated</td>
<td>Yes</td>
<td>No-till</td>
<td>2017</td>
<td>55.8</td>
</tr>
<tr>
<td>Jesse 3</td>
<td>Non-treated</td>
<td>Yes</td>
<td>No-till</td>
<td>2017</td>
<td>18.0</td>
</tr>
<tr>
<td>Jesse 4</td>
<td>Treated</td>
<td>No</td>
<td>No-till</td>
<td>2017</td>
<td>31.2</td>
</tr>
</tbody>
</table>
APPENDIX C
This code highlights how yield was predicted. Number of fruits per square was predicted by using the weight of the plant as a fixed effect, mean weight of the seeds per fruit as a random slope effect, and site id as a random intercept effect. Mean weight of seeds per square was determined by aggregating estimated seed number per square and multiplying by average weight per individual seed of the square. The mean of all five squares was multiplied by 4047, the number of square meters in an acre or by 10,000 the number of square meters in a hectare.

```r
#rm(list=ls())
#gc()
focal_yield <- read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/final_yield.csv", header = TRUE,
stringsAsFactor=F, na.strings = c("na","NA")
) sq <- read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/final_density.csv", header = TRUE,
stringsAsFactor=F, na.strings = c("na","NA")
) wt <- read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/final_sq.csv",header = TRUE,
stringsAsFactor=F, na.strings = c("na","NA")
)

focal_yield$plant_weight<- (focal_yield$bag_w-59.8) #weight of small bags
wt$sq_wt<- (wt$sq_wt-251) #weight of large square bags
focal_yield<- focal_yield[which(focal_yield$plant_weight<=180),]
focal_yield<- focal_yield[which(focal_yield$plant_weight>=0),]

#fertile seeds (yield)
focal_yield$seed_set_mean<-rowMeans(focal_yield[,c(6,9,12,15,18)], na.rm = TRUE)
#focal_yield$seed_set_plant<-focal_yield$seed_set_mean*focal_yield$no_fr

#aborted seeds
focal_yield$abort_mean<-rowMeans(focal_yield[,c(7,10,13,16,19)], na.rm = TRUE)
#focal_yield$abort_plant<-focal_yield$abort_mean*focal_yield$no_fr

###
focal_yield$seed_number_plant<-focal_yield$seed_set_plant+focal_yield$abort_plant
focal_yield$seed_number_plant[is.na(focal_yield$seed_number_plant)] <- 0

#CREATE SEED MASS PER PLANT
focal_yield$mass_mean<-rowMeans(focal_yield[,c(8,11,14,17,20)], na.rm = TRUE)

focal_yield$mass_sum<-rowSums(focal_yield[,c(8,11,14,17,20)], na.rm = TRUE)
#focal_yield$seed_sum<-rowSums(focal_yield[,c(6,7,9,10,12,13,15,16,18,19)], na.rm = TRUE)
focal_yield$seed_per_fruit<-rowSums(focal_yield[,c(6,7,9,10,12,13,15,16,18,19)]/5, na.rm = TRUE)
#mean mass of each individual seed per plant
focal_yield$mass_mean_seed<-focal_yield$mass_mean/(focal_yield$seed_set_mean+focal_yield$abort_mean)
```

#avg_seed_wt_sq<aggregate(yield_data$seed_wt,list(yield_data$square_id), mean, na.rm = TRUE)
# mean mass of seeds per plant
# focal_yield$plant_seed_mass <- focal_yield$seed_number_plant*focal_yield$mass_mean_seed

p1 <- 'x'
dat_yield1 <- subset(focal_yield, !grepl(p1, fo_id))
dat_yield_ex <- subset(focal_yield, grepl(p1, fo_id))
# focal_yield <- focal_yield[which(focal_yield$plant_weight>0),]

library(lme4)
model_n <- lmer(no_fr~plant_weight+(mass_mean|site_id), data=dat_yield1)
summary(model_n)
# fruits_per_square <- coefficients(model_n)
# calculated fruits per square using each of the coefficients by hand
# mean mass of seeds per square

plot(dat_yield1$no_fr~dat_yield1$plant_weight)# fresh, aborted, total yield
summary(focal_yield)
sq$square_id <- paste(sq$site_id, sq$sq_id, sep='_')
wt$square_id <- paste(wt$site_id, wt$sq_id, sep='_')
focal_yield$square_id <- paste(focal_yield$site_id, focal_yield$sq_id, sep='_')

sq_foc <- merge(x=wt, y=sq, by='square_id', all.x=T, all.y=T, suffixes = c('', ''), # warning is ok
    yield_data <- merge(x=sq_foc, y=focal_yield, by='square_id', all.x=T, all.y=F, suffixes = c('', ''), # warning is ok
    yield_data <- yield_data[!duplicated(yield_data$square_id),]

# yield_data$seed_mass_sq <- aggregate(yield_data$plant_seed_mass, list(yield_data$square_id), mean, na.rm = TRUE)

yield_data$seed_per_square <- yield_data$fruits_per_sq*yield_data$seed_per_fruit
# maybe delete yield_data$yield_per_square <- aggregate(yield_data$seed_per_square, list(yield_data$square_id), mean, na.rm = TRUE)

# mean number of seeds per square for each site
mean_seed_per_square <- aggregate(yield_data$seed_per_square, list(yield_data$site_id), mean, na.rm = TRUE)
colnames(mean_seed_per_square) <- c("site_id", "mean_seed_per_square")
mean_seed_per_square$seeds_per_site <- (mean_seed_per_square$mean_seed_per_square)*4047
# mean_seed_per_square$yield_per_site <- mean_seed_per_square$seeds_per_site*

# average individual seed mass per square
avg_seed_wt_sq <- aggregate(yield_data$mass_mean_seed, list(yield_data$square_id), mean, na.rm = TRUE)
colnames(avg_seed_wt_sq) <- c("square_id", "avg_seed_wt_sq")
library(tidyr)
avg_seed_wt_sq <- separate(data = avg_seed_wt_sq, col = square_id, into = c("site_id", "id"), sep = "_")

# the average weight of a single seed at each site
avg_seed_wt_site <- aggregate(avg_seed_wt_sq$avg_seed_wt_sq, list(avg_seed_wt_sq$site_id), mean, na.rm = TRUE)
colnames(avg_seed_wt_site) <- c("site_id", "avg_seed_wt_site")

# final data set
final_yield <- merge(x = avg_seed_wt_site, y = mean_seed_per_square, by = 'site_id', all.x = T, all.y = T, suffixes = c('m', 'n'))
final_yield$yield_kg <- (final_yield$avg_seed_wt_site * final_yield$seeds_per_site) / 1000
# write.csv(final_yield, file = ('final carinata yield'))

APPENDIX D

The class of pixels and total number of pixels per class for the buffers representing each landscape scale was converted into an csv file. Using the vegan package Shannon diversity of the landscape (landscape heterogeneity) was calculated at three spatial scales 500m, 1000m, and 3000m.

mbuf_3000 <- read.csv('/Users/shanestiles/Desktop/Carinata Data/Finals/all site diversity 3000.csv', header = TRUE)
mbuf_3000 <- mbuf_3000[, c(1:3)]
mbuf_3000$class <- as.factor(mbuf_3000$class)
library(reshape2)
datbuf_3000 <- dcast(mbuf_3000, site_id ~ class, value.var = "pix_no", fun.aggregate = sum, na.rm = TRUE, header = T)
datbuf_3000 <- datbuf_3000[-1]
site_id <- datbuf_3000$site_id[1]
datbuf_3000[is.na(datbuf_3000)] <- 0
datbuf_3000$site_id <- NULL
library(vegan)
mbuf_3000_shan <- diversity(datbuf_3000, index = "shannon")
mbuf_3000_simp <- diversity(datbuf_3000, index = "simpson")

#########################################################################
#1000m buffer
mbuf_1000 <- read.csv('/Users/shanestiles/Desktop/Carinata Data/Finals/all site diversity 1000.csv', header = TRUE)
mbuf_1000 <- mbuf_1000[, c(1:3)]
mbuf_1000$class <- as.factor(mbuf_1000$class)
library(reshape2)
datbuf_1000 <- dcast(mbuf_1000, site_id ~ class, value.var = "pix_no", fun.aggregate = sum, na.rm = TRUE, header = T)
datbuf_1000 <- datbuf_1000[-1]
datbuf_1000[is.na(datbuf_1000)] <- 0
datbuf_1000$site_id <- NULL
mbuf_1000_shan <- diversity(datbuf_1000, index = "shannon")
mbuf_1000_simp<- diversity(datbuf_1000, index = "simpson")

#500m buffer
mbuf_500<- read.csv('Users/shanestiles/Desktop/Carinata Data/Finals/All site diversity 500.csv',header=TRUE)
mbuf_500<- mbuf_500[,c(1:3)]
mbuf_500$class<- as.factor(mbuf_500$class)
library(reshape2)
datbuf_500<- dcast(mbuf_500,site_id~class,value.var="pix_no", fun.aggregate = sum, na.rm = TRUE, header=T)
datbuf_500[is.na(datbuf_500)] <- 0
datbuf_500$site_id<-NULL
mbuf_500_simp<- diversity(datbuf_500, index = "simpson")
dat_diversity<-(cbind.data.frame(site_id, mbuf_500_simp, mbuf_500_simp, mbuf_1000_simp, mbuf_1000_simp, mbuf_3000_simp, mbuf_3000_simp))

APPENDIX E

The insect/pollinator shannon (and simpson) diversity, abundance, and evenness is calculated. Diversity metrices, yield, and landscape metrices are combined into a single data frame.

fin_trans <- read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/final_transect.csv", header= TRUE)
#only pollinators included in the data set
#fin_trans<-fin_trans[which(fin_trans$Pollinator==c('y')),]

#pollinators and non-pest insects included in the data set
#fin_trans<-fin_trans[which(fin_trans$Pollinator==c('y','l')),]

#only pest insects included in the data set
#fin_trans<-fin_trans[which(fin_trans$Pollinator==c('n')),]
fin_trans$spp <- paste(fin_trans$family_id, fin_trans$species_id, sep="_")
morphospecies<-aggregate(fin_trans$sno_ind, list(fin_trans$spp), sum)
fin_trans$transect_id <- paste(fin_trans$site_id, fin_trans$transect_no, fin_trans$time, sep = "_")
#dens<-read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/final_density.csv", header = T)
#mean_dens<-aggregate(dens$density, list(dens$site_id), mean)
#colnames(mean_dens) <- c("site_id","density")
trtmt<-read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/final_carinata_design.csv",header = T)
# total number of insect samples and insect samples per site
tran_no <- aggregate(fin_trans$transect_id, list(fin_trans$site_id), count)

# reshape data frame with species as columns and sites (transects) as rows
library(reshape2)
dat <- dcast(fin_trans, site_id ~ spp, value.var='no_ind', fun.aggregate = sum)
summary(dat)

# calculate different diversity indices
library(plyr)
library(permute)
library(lattice)
library(vegan)
library(MASS)
library(effects)
library(lmerTest)
library(lme4)
library(agricolae)
library(ggplot2)
dat1 <- ddply(dat,~site_id,function(x) {
  data.frame(richness=sum(x[-1]>0))
})
dat2 <- ddply(dat,~site_id,function(x) {
  data.frame(abundance=sum(x[-1]))
})
dat3 <- ddply(dat,~site_id,function(x) {
  data.frame(rarefy=rarefy(x[-1], sample=10, MARGIN=1))
})
dat4 <- ddply(dat,~site_id,function(x) {
  data.frame(shannon=diversity(x[-1], index="shannon"))
})
# dat4 <- dat4[,c(1),]
brillouin <- function(x) {
  N <- sum(x)
  (log(factorial(N)) - sum(log(factorial(x))))/N
}
dat5 <- ddply(dat,~site_id,function(x) {
  data.frame(brillouin=brillouin(x[-1]))
})
dat6 <- ddply(dat,~site_id,function(x) {
  data.frame(simpson=diversity(x[-1], index="simpson"))
})
dat7 <- ddply(dat,~site_id,function(x) {
  data.frame(eveness=exp(diversity(x[-1], index="simpson"))/sum(x[-1]>0))
})
dat8 <- ddply(dat,~site_id,function(x) {
data.frame(true_shannon=exp(diversity(x[-1], index="shannon")))
}

fin_div <- Reduce(function(x, y) merge(x, y, all=TRUE), list(dat1, dat2, dat4, dat5, dat6, dat7, dat8))
#write.csv(fin_div, file = "final_trans_div")
site_div <- read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/all_site_diversity.csv",header = T)
site_trt <- merge(trtmt,fin_div, by='site_id', all.x=T, all.y=F, sort= FALSE, suffixes = c("",""), na.strings = c("na","NA"))
#site_trt2 <-merge(site_trt,mean_dens, by='site_id', all.x=T, all.y=F, sort= FALSE, suffixes = c("",""), na.strings = c("na","NA"))
site_trt3<-merge(site_trt,site_div, by='site_id', all.x=T, all.y=F, sort= FALSE, suffixes = c("",""), na.strings = c("na","NA"))
yield<-read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/final carinata yield", header = T)

site_trt4<-merge(site_trt3, yield, by='site_id', all.x=T, all.y=F, sort= FALSE, suffixes = c("",""), na.strings = c("na","NA"))
as.character(site_trt4$year)
#site_trt4<-site_trt4[-c(35,36),] #delete oak 1 and bruce 1, due to lack of data

#changes units of yield to kilograms per hectare
site_trt4$yield_kg_ha<-site_trt4$yield_kg*2.47105

APPENDIX F

Relationships between yield, farming practices, and diversity metrics was calculated using linear mixed-effects models with year as a random effect. Farming practices and diversity metrics were fixed effects.

a<-read.csv("/Users/shanestiles/Desktop/Carinata Data/Finals/all_site_variables_poll:ins.csv", header = T)
library(effects)
library(MASS)
library(lme4)

#shannon ~ farming practices
lmes<-lmer(log(shannon)~(seed_treatment*hb_treatment*farming_p)+(1|year), data=a)
summary(lmes)
dropterm(lmes, test='Chisq')
lmes1<-update(lmes, .~-seed_treatment:hb_treatment:farming_p)
dropterm(lmes1, test='Chisq')
lmes2<-update(lmes1, .~-seed_treatment:farming_p)
dropterm(lmes2, test='Chisq')
lmes3<-update(lmes2, .~-hb_treatment:farming_p)
dropterm(lmes3, test='Chisq')
lmes4<-update(lmes3, .~-farming_p)
dropterm(lmes4, test='Chisq')
lmes5<-update(lmes4, .~-seed_treatment:hb_treatment)
dropterm(lmes5, test='Chisq')
# pollinators ~ farming practices

```r
lmesp <- lmer(log(pollinator_shannon) ~ (seed_treatment*hb_treatment*farming_p) + (1|year), data=a)
summary(lmesp)
dropterm(lmesp, test='ChiSq')
```

# yield ~ farming practices * all insects

```r
lmeys <- lmer(log(yield_kg_ha+1) ~ (seed_treatment*hb_treatment*farming_p)*scale(shannon)+(1|year),
data=a)
summary(lmeys)
dropterm(lmeys, test='ChiSq')
```

# yield ~ farming practices * pollinators

```r
lmeyps <- lmer(log(yield_kg_ha+1) ~ (seed_treatment*hb_treatment*farming_p)*scale(pollinator_shannon)+(1|year),
data=a)
summary(lmeyps)
dropterm(lmeyps, test='ChiSq')
```
summary(lmeyps4)
plot(allEffects(lmeyps4), ask=F, xlab= "Pollinator Diversity", ylab = "Log of Yield", main = "Yield and Pollinator Diversity Mediated by Farming Practices")
plot(effect("seed_treatment:farming_p:scale(pollinator_shannon)",lmeyps4))
plot(effect("hb_treatment:farming_p:scale(pollinator_shannon)",lmeyps4))

#all insects ~ heterogeneity * farming practices
lme_het<-
lmer(log(shannon)~(scale(mbuf_500_shan)+scale(mbuf_1000_shan)+scale(mbuf_3000_shan))*(seed_treatment+hb_treatment+farming_p)+(1|year), data = a)
summary(lme_het)
dropterm(lme_het, test='Chisq')
lme_het1<-
update(lme_het, .~. - scale(mbuf_3000_shan):farming_p)
dropterm(lme_het1, test='Chisq')
lme_het2<-
update(lme_het1, .~. - scale(mbuf_3000_shan):hb_treatment)
dropterm(lme_het2, test='Chisq')
lme_het3<-
update(lme_het2, .~. - scale(mbuf_500_shan):hb_treatment)
dropterm(lme_het3, test='Chisq')
lme_het4<-
update(lme_het3, .~. - scale(mbuf_1000_shan):hb_treatment)
dropterm(lme_het4, test='Chisq')
lme_het5<-
update(lme_het4, .~. - scale(mbuf_500_shan):farming_p)
dropterm(lme_het5, test='Chisq')
lme_het6<-
update(lme_het5, .~. - hb_treatment)
dropterm(lme_het6, test='Chisq')
lme_het7<-
update(lme_het6, .~. - seed_treatment)
dropterm(lme_het7, test='Chisq')
lme_het8<-
update(lme_het7, .~. - mbuf_1000_shan)
dropterm(lme_het8, test='Chisq')
lme_het9<-
update(lme_het8, .~. - scale(mbuf_3000_shan):seed_treatment)
dropterm(lme_het9, test='Chisq')
summary(lme_het9)

r.squaredLR(lme_het9)
plot(allEffects(lme_het9), ask=F, xlab= "insect shannon", ylab = "site heterogeneity", main = "shannon ~ heterogeneity")
plot(effect("scale(mbuf_1000_shan):farming_p",lme_het9))
plot(effect("scale(mbuf_500_shan):seed_treatment",lme_het9))

#pollinators ~ heterogeneity * farming practices
lmep_het<-
lmer(log(pollinator_shannon)~(scale(mbuf_500_shan)+scale(mbuf_1000_shan)+scale(mbuf_3000_shan))*(seed_treatment+hb_treatment+farming_p)+(1|year), data = a)
summary(lmep_het)
dropterm(lmep_het, test='Chisq')
lmep_het1<-
update(lmep_het, .~. - scale(mbuf_500_shan):hb_treatment)
dropterm(lmep_het1, test='Chisq')
lmep_het2<-
update(lmep_het1, .~. - scale(mbuf_3000_shan):hb_treatment)
dropterm(lmep_het2, test='Chisq')
lmep_het3<-
update(lmep_het2, .~. - scale(mbuf_3000_shan):seed_treatment)
dropterm(lmep_het3, test='Chisq')
lmep_het4<-
update(lmep_het3, .~. - scale(mbuf_1000_shan):seed_treatment)
dropterm(lmep_het4, test='Chisq')
lmep_het5<-
update(lmep_het4, .~. - scale(mbuf_1000_shan):hb_treatment)
dropterm(lmep_het5, test='Chisq')
lmep_het6<-
update(lmep_het5, .~. - hb_treatment)
dropterm(lmep_het6, test='Chisq')
lmep_het7<-
update(lmep_het6, .~. - scale(mbuf_1000_shan):farming_p)
dropterm(lmep_het7, test='Chisq')
lmep_het8<- update(lmep_het7, .~. - scale(mbuf_500_shan):seed_treatment)
dropterm(lmep_het8, test='Chisq')
lmep_het9<- update(lmep_het8, .~. - seed_treatment)
dropterm(lmep_het9, test='Chisq')
lmep_het10<- update(lmep_het9, .~. - scale(mbuf_1000_shan))
dropterm(lmep_het10, test='Chisq')
lmep_het11<- update(lmep_het10, .~. - scale(mbuf_500_shan):farming_p)
dropterm(lmep_het11, test='Chisq')
lmep_het12<- update(lmep_het11, .~. - scale(mbuf_500_shan))
dropterm(lmep_het12, test='Chisq')
summary(lmep_het12)
plot(allEffects(lmep_het12), ask=F, xlab= "pollinator shannon", ylab = "site heterogeneity", main = "shannon ~ heterogeneity")
plot(effect("scale(mbuf_3000_shan):farming_p", lmep_het12))

#yield ~ heterogeneity * farming practices
lmey_het<- lmer(log(yield_kg_ha+1)-(scale(mbuf_500_shan)+scale(mbuf_1000_shan)+scale(mbuf_3000_shan))*(see d_treatment+hb_treatment+farming_p)+(1|year), data = a)
summary(lmey_het)
dropterm(lmey_het, test='Chisq')
lmey_het1<- update(lmey_het, .~. - scale(mbuf_500_shan):farming_p)
dropterm(lmey_het1, test='Chisq')
lmey_het2<- update(lmey_het1, .~. - scale(mbuf_1000_shan):farming_p)
dropterm(lmey_het2, test='Chisq')
lmey_het3<- update(lmey_het2, .~. - scale(mbuf_1000_shan):seed_treatment)
dropterm(lmey_het3, test='Chisq')
lmey_het4<- update(lmey_het3, .~. - scale(mbuf_500_shan):seed_treatment)
dropterm(lmey_het4, test='Chisq')
lmey_het5<- update(lmey_het4, .~. - scale(mbuf_3000_shan):seed_treatment)
dropterm(lmey_het5, test='Chisq')
lmey_het6<- update(lmey_het5, .~. - seed_treatment)
dropterm(lmey_het6, test='Chisq')
lmey_het7<- update(lmey_het6, .~. - scale(mbuf_3000_shan):hb_treatment)
dropterm(lmey_het7, test='Chisq')
lmey_het8<- update(lmey_het7, .~. - scale(mbuf_500_shan):hb_treatment)
dropterm(lmey_het8, test='Chisq')
lmey_het9<- update(lmey_het8, .~. - scale(mbuf_500_shan))
dropterm(lmey_het9, test='Chisq')
lmey_het10<- update(lmey_het9, .~. - scale(mbuf_1000_shan):hb_treatment)
dropterm(lmey_het10, test='Chisq')
lmey_het11<- update(lmey_het10, .~. - scale(mbuf_1000_shan))
dropterm(lmey_het11, test='Chisq')
lmey_het12<- update(lmey_het11, .~. - hb_treatment)
dropterm(lmey_het12, test='Chisq')
summary(lmey_het12)
plot(allEffects(lmey_het12), ask=F, xlab= "heterogeneity 3000", ylab = "Log of Yield", main = "yield ~ heterogeneity")
Bibliography


Industrial Crops and Products, 117, 140–148. doi: 10.1016/j.indcrop.2018.02.032


influences the motor function of adult worker honeybees. *Ecotoxicology*, 23(8), 1409–1418. doi: 10.1007/s10646-014-1283-x

**Glossary of Terms**

**Carinata** – The crop *Brassica carinata* in the Brassicaceae family, many species rely to some extent, on pollination services.

**Neonicotinoid**- A systemic pesticide that disrupts the nervous system of many insects.

**Landscape Heterogeneity**- The Shannon diversity of all pixels corresponding to land uses within a given radius (500m, 1000m, and 3000m).

**Ecosystem Function**- The physical and biological processes that occur within the ecosystem, such as growth, reproduction, and nutrient cycling.

**Ecosystem Service**- Benefits that humans derive from nature, such as pest control, pollination services, or recreational benefits.

**Biodiversity**- The variety of arthropod life within a habitat or ecosystem.