Butterflies, Tallgrass Prairie, and Green Roofs

by

Pamela Blackmore

B.L.A., Utah State University, 2013

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF LANDSCAPE ARCHITECTURE

Department of Landscape Architecture and Regional & Community Planning
College of Architecture, Planning & Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2019

Approved by:

Major Professor
Lee R. Skabelund

Copyright

Abstract

As pollinators continue to decrease across the United States, it is becoming more important to understand how this trend can be reversed. Cities, which have typically eliminated and fragmented pollinator habitat, may be able to utilize rooftops for the benefit of pollinators. The Memorial Stadium green roofs at Kansas State University are rooftops previously used as stadium seating, portions of which have recently been converted to native prairie vegetation. I evaluated the effectiveness of these green roofs as pollinator habitat in an urban context by comparing butterfly communities of the green roofs to those in an urban native prairie at Warner Park in Manhattan, Kansas, and a protected tallgrass prairie at the Konza Prairie Biological Station, approximately 10 km south of Manhattan, Kansas. I assessed the influence of on-site vegetation composition on butterfly species richness, distribution, behavior, and abundance. I employed a modified Pollard walk, plant composition sampling, and mapping of spatial distribution of vegetation used by individual butterflies with a GPS unit.

Initial findings suggest that green roofs can provide urban habitat for butterflies. Indeed, butterfly abundance and mean species richness were greater at the Memorial Stadium than at either native prairie. However, while the green roofs support many species of butterflies, tallgrass prairie specialist species that were seen in the native prairie sites, such as the regal fritillary, were not observed using the green roofs. Butterfly behavior also varied between sites: butterflies using the stadium were predominately foraging, whereas butterflies at native prairie sites were flying through and not interacting with the plants. While plant species interactions with butterflies and links per species were greatest at Memorial Stadium, nestedness was lowest at this site. This study not only suggests that green roofs can compensate for lost pollinator habitat in urban areas, but by examining the effects of vegetation composition and structure as

well as local land cover on butterfly abundance and behavior, it has important implications for the design and management of green roofs as urban butterfly habitat.

Table of Contents

List of Figures

List of Tables

Acknowledgments

I have been extremely fortunate to have the help of many people and funding sources: Katie Mahlmeister, Chad Dykstra, and Marcos Aleman all assisted with field work. Allyssa Decker assisted with statistical analyses. Thanks also to my committee members: Jeff Taylor helped with field work, data management, plant identification, grant and scholarship applications, and statistical analyses. Lee Skabelund, Dave Haukos, PhD, and Brent Chamberlain, PhD, provided mentoring, and assisted with grant and scholarship applications, materials, research protocols, and continued support.

John Briggs, PhD, and John Blair, PhD, provided equipment and access to the Konza Prairie Biological Station. Ellen Welti provided supplies. Amanda Kuhl connected me with LTER technicians and provided equipment. Eva Horne helped me get started at Konza Prairie and introduced me to the research and site management team. Rory O'Connor helped with statistics. Wyatt Thompson and Casey Smithson allowed me to conduct my study at Warner Park. Joseph Myers and Mark Fronce with K-State Facilities constantly coordinated with me and provided me materials and access to the Memorial Stadium green roofs.

Thanks to the many organizations that helped partially cover my research and education costs. Funding and in-kind support has been provided by the K-State Mary K. Jarvis Fellowship in Landscape Architecture, the Konza Prairie Biological Station, the Pollinator Partnership, the Garden Club of America, the National Garden Clubs, the Kansas Garden Club, the Grassland Heritage Foundation, and the K-State Graduate Student Council.

Dedication

For my four-year-old nephew, Max, who shares my love of butterflies, and for two of my sisters, Janette and Joan, who gave me unrelenting support that helped get me through these last couple years.

Chapter 1 - Introduction

With increasing urbanization and development, undeveloped areas such as native grasslands in the United States are continually diminishing. These areas support many species of native fauna; encroachment of undeveloped area negatively affects habitats for many species. It has become apparent that some species dependent on undeveloped areas are at risk of extinction, with habitat destruction being identified as the leading cause (Pimm & Raven, 2000). Pollinators are those animals that transfer pollen from the anther of a flower to the conspecific stigma of another plant (Willmer, 2011). Worldwide, there have been significant reductions in pollinators, particularly Europe and North America (Potts et al., 2010). These losses are frequently attributed to many human-caused factors, some of which include habitat loss and fragmentation, introduction of non-native plants and animals, pesticide application, and climate change (Potts et al., 2010).

Recent studies suggest that urban areas may partially compensate for lost pollinator habitat, even for species of conservation significance (Bates, Sadler, & Mackay, 2013; Williams, Lundholm, & Macivor, 2014). Some authors suggest that of the limited available space in cities, rooftops stand uniquely positioned to reduce the inhospitality of cities (Benvenuti, 2014; Madre, Vergnes, Machon, & Clergeau, 2014) for reasons such as sunlight availability (Matteson & Langellotto, 2010) and underutilized space (Madre et al., 2014). However, some argue that the quality of pollinator habitat provided by green roofs is uncertain (Bates et al., 2013; Sutton, 2015), even though many designers and green roof advocates profess biodiversity to be among the landscape performance benefits commonly provided by green roofs (Williams et al., 2014). This project examines the extent to which a native plant green roof supports butterfly communities in Manhattan, Kansas, in comparison with nearby native prairie, and how on-site vegetation composition influences butterfly species richness, distribution, behavior, and abundance.

I focused specifically on butterflies in the order Lepidoptera for four main reasons. First, butterflies are charismatic flagship species (Guiney & Oberhauser, 2008; U.S. Forest Service, 2000). While the general public may view insects as pests, butterflies are an exception and serve as a desirable conservation icon. If green roofs assist in their survival, they may garner public support for green roofs and other urban green infrastructure. Second, some butterflies, such as monarch butterflies (*Danaus plexippus*), have experienced steep population declines over the past few decades. Declines have been so dramatic that the U.S. Fish and Wildlife Service is currently determining whether to list the monarch under the 1973 Endangered Species Act (Federal Register, 2014; Pleasants & Oberhauser, 2013; U.S. Fish and Wildlife Service, 2017). It is important to know whether green roofs might assist in recovery of this species and others like it. Third, pollinators, such as bees, wasps, beetles, butterflies, flies, and other arthropods, play a critical role in ecosystem function (Didham, Ghazoul, Stork, & Davis, 1996), particularly in grasslands (Summerville & Crist, 2001). They provide vital pollination services for plants (Meffe et al., 1998). Butterflies are indicators of quality pollinator habitat (Shepherd & Debinski, 2005), so evaluating their response to urban green roofs should give insights into potential use of green infrastructure by the broader pollinator community.

Fourth, butterflies are dependent on native plant diversity for larval hosts and nectaring (Myers, Hoksch, & Mason, 2012; Shepherd & Debinski, 2005). All butterflies were at one time herbivorous caterpillars, acquiring their energy to survive by eating plants (Willmer, 2011). Many butterfly larvae will only eat particular plants termed larval hosts, host plants, or food-plants (Brues, 1920). A well-known example is the monarch butterfly larvae, which will only eat milkweed (*Asclepias* spp.; Urquhart, 1960). The regal fritillary (*Speyeria idalia)* butterfly larvae, a tallgrass prairie specialist, will only eat certain violets (*Viola* spp.; Debinski & Kelly, 1998). After larvae metamorphosize and become adult butterflies, they become liquid feeders and mainly feed on flower nectar (Willmer, 2011). They may prefer some flowers due to volume and quality of the nectar and morphology of the flower (e.g., some butterflies prefer landing areas and most nectar at flowers that are suitable for their proboscis length), among other reasons (Willmer, 2011). This feeding specialization, or flower constancy, benefits flowers because it increases the chance that the butterfly will take pollen from one plant to a conspecific plant and permit sexual reproduction for that plant (Willmer, 2011). The phenology (or timing of life cycles) of butterflies and flowers is also extremely important for butterfly nectaring. For a butterfly to obtain food from a flower and the flower to have its pollen redistributed by a butterfly, the plant and flower must co-occur in space and time (Bartomeus et al., 2013). If a flower blooms only in the spring, it can provide no nectar to a butterfly that flies only in the summer. The likelihood that this mutualistic interaction will occur increases with greater plant richness (Bartomeus et al., 2013).

To better understand the extent to which green roofs support butterfly communities in an urban area, I completed a comparative analysis of two adjacent green roofs, the Memorial Stadium east and west green roofs (hereafter Memorial Stadium) at Kansas State University (Figure 1.1); two watersheds at the Konza Prairie Biological Station (hereafter native prairie); and a remnant urban prairie at Warner Park, all within or nearby Manhattan, Kansas. I did this by assessing vegetation composition using plant species coverage, richness, diversity, forbs blooming, litter depth, visual obstruction, and a blossom index. I assessed the butterfly community using butterfly species richness, abundance, behavior, and spatial distribution along two transects for each of these sites in relation to vegetation composition. I hypothesized that butterfly abundance, behavior, and distribution at the Memorial Stadium would be comparable to the native prairie sites, but that diversity and richness would be less, particularly that I would not find the tallgrass prairie specialist species at the Memorial Stadium that were present on native prairie. In addition, I thought that butterfly richness would increase with increased plant richness, larval host coverage, and forbs blooming.

My results indicate that an urban green roof can be found and used by many species of butterflies in high abundance relative to native prairie. Mean species richness (i.e., average number of species found each sampling session) of butterflies was greatest at the Memorial Stadium, while the native prairie had the greatest overall species richness (i.e., total number of species found). The native prairie had the greatest butterfly diversity. In addition, species composition of butterflies using the roof differed from native prairie: tallgrass prairie habitat specialist species present at prairie sites were not present at the green roofs. Predictors of butterfly abundance, richness, and diversity varied with season.

I anticipate this study will improve decision making for landscape architects, urban designers, and others attempting to support urban biodiversity through design interventions and management of green roofs. Based on my findings, I identify potential design implications to improve green roof butterfly communities. Many studies have indicated a need for this research, particularly in coordination with ecologists, because green roofs are becoming more common and some cities, such as London, UK, are creating policy requiring development of green roofs for enhancing biodiversity, among other benefits (Miller, 2008; Williams et al., 2014).

1.1 Study Sites

The three study sites, 1) the Memorial Stadium, 2) Warner Park urban prairie, and 3) two native prairie sites at Konza Prairie – were located within or near Manhattan, Kansas, in the tallgrass prairie of the Flint Hills (Figure 1.2). The tallgrass prairie is temperate grassland that receives a moderate amount of precipitation with extreme interannual climatic variability (Knapp & Seastedt, 1998). Study sites for comparison to the Memorial Stadium were selected based on how vegetation was managed at each site. Vegetation management regimes are critical since they influence and can dramatically alter plant composition in the tallgrass prairie (Collins & Calabrese, 2011). Vegetation on the two Memorial Stadium green roofs are cut back and fertilized with an organic fertilizer once in early spring and not burned due to the damage that might occur to the green roof components and building structure. For comparison sites, I identified the pros and cons of studying butterfly use on prairies managed with various vegetation management, such as burned/unburned, mowed/unmowed, and grazed/ungrazed by cattle and bison. Because annual cutting back of the green roof vegetation is expected, both mowed and grazed prairie were considered for comparison sites. Grazed sites were not selected given concerns about the need for efficient site access every two weeks, need to ensure researcher safety, and the fact that butterflies respond differently to grazing and mowing (Smith & Cherry, 2014), and these green roofs are managed via weed-whacking. Sites burned during the study were not considered because their vegetation community structure would be substantially different than the Memorial Stadium. Annually mowed sites and sites with infrequent burning are most like the Memorial Stadium and were thus deemed to be the best comparison sites.

1.1.1 Study Site 1: East and West Memorial Stadium Green Roofs

The Memorial Stadium green roofs (Figure 1.3 and Figure 1.4) are located on the Kansas State University (K-State) campus in Manhattan, Kansas (Figure 1.1). These two green roofs were added to the stadium bleachers to reduce the number of people able to occupy the bleachers at one time. The west green roof was installed in early summer 2015; the east was installed in early spring 2016. Between the green roofs is an artificial turf field. Because of safety concerns associated with the structural integrity of the architectural support system beneath the aging Memorial Stadium seating, the green roofs were constructed on top of a portion of the seating (concrete risers filled in with lightweight insultation and waterproofed) to limit the number of people that can occupy the stadium; thereby, reducing the weight placed on these two structures. In addition to limiting the weight on the stadium structure, other stated design objectives for the green roofs were to provide stop-over sites for prairie birds and pollinators, manage stormwater, provide an aesthetically pleasing setting for the K-State Alumni Center and other events, and to demonstrate K-State’s commitment to sustainability (Van Der Merwe, Skabelund, Sharda, Blackmore, & Bremer, 2017).

The substrate depth varies between 12 cm and 15 cm on each green roof. The types of substrates on each roof differed as expanded shale was added to lighten the structural load on the east Memorial Stadium. An assortment of native and non-native vegetation were planted via seed and live plants; however, most of the plants were native and planted to reflect the Flint Hills Ecoregion. Vegetation observed on each roof, though planted with similar species with plants and seeds supplied by a native plant nursery in eastern Kansas, was substantially different with the east green roof having more non-native grasses and forbs (Skabelund, Decker, Moore, Shrestha, & Bruce, 2017; Van Der Merwe et al., 2017).

These two green roofs were jointly managed by Blueville Nursery and K-State Facility staff during this study with volunteer assistance from K-State faculty and students. The vegetation was regularly watered during the growing season with an automated irrigation system, except after sufficient rainfall when the irrigation system was turned off, which was the case several times during 2017 and 2018. In combination, the steep slopes and 12-15 cm substrate depths, necessitate supplemental irrigation during prolonged dry spells to keep green roof plants alive and relatively healthy. Vegetation was cut back in the spring and fertilized with an organic fertilizer 2017 and 2018. In addition, woody species (ruderal species brought by birds, wind, or other mechanisms) were removed intermittently during each growing season, and other species considered undesirable were occasionally removed on select areas of the green roofs. I established a transect for the vegetation and butterfly study that encompassed the entire length of each green roof (approximately 127 m) and was 10 m wide, covering almost the entire 12-m wide green roofs. The east Memorial Stadium green roof is pictured in Figure 1.3. The west Memorial Stadium green roof is pictured in Figure 1.4.

1.1.2 Study Site 2: Konza Prairie Biological Station Watershed R20A and R20B

The Konza Prairie Biological Station (Figure 1.5) is located on a native, tallgrass prairie reserve approximately 10 km south of Manhattan, Kansas. The 3,487-ha research station is jointly owned by The Nature Conservancy and K-State and managed by the K-State Division of Biology. Located in the Flint Hills, the majority of Konza Prairie has not been plowed, but is still native tallgrass prairie. Konza Prairie is included in the National Science Foundation Long-Term Ecological Research network, which focuses on research that spans many temporal and spatial scales, as well as ecological levels (Kansas State University, 2019).

Konza Prairie’s basic research units are watersheds with various combinations of fire and grazing treatments applied to each. Watersheds are separated by mowed fireguards and fences depending on the requirements of the experimental treatment. Because the management of the Memorial Stadium does not involve grazing or burning, it was necessary to select comparable watersheds at Konza Prairie that would not be burned or grazed during 2017 and 2018. There were only two watersheds at Konza Prairie that met study criteria for both 2017 and 2018: R20A and R20B (Figure 1.5).

Both watersheds were on the southernmost portion of Konza Prairie. These watersheds were originally burned annually up until and including the year 2000. However, in 2001, these watersheds were not burned and they began a new burn interval of every 20 years. In 2008, R20A was unintentionally burned by a wildfire, so to maintain consistency, R20B was also burned the same year. Then again in 2011, the eastern half of R20B was burned in a wildfire. Thus, the last time these watersheds burned were either in 2008 or 2011. Because the majority of Konza Prairie is an active site for researchers from around the world, it was required that the study sites for this butterfly study not interfere with other researchers’ work. In addition, because these watersheds have not been burned in recent years, woody encroachment is occurring, and effort was taken to locate vegetation transects where there was minimal woody vegetation.

1.1.3 Study Site 3: Warner Park Urban Prairie

Warner Park urban prairie (Figure 1.6) is in southwestern Manhattan, Kansas, and was established in 1956. The majority of the park is undeveloped, with some trails, one covered structure, and a disk golf course in portions of the 33-ha park. Vegetation is a mixture of native open prairie, which is typically hayed annually in July or August, and surrounded at the periphery with wooded areas. Other sections of the park are regularly mowed prairie. Unlike the other study sites, no known vegetation studies were conducted at the urban prairie prior to this study.

The location used for this study was the southwestern, open, upland native prairie area of the park. The two transects at the site were located to maintain a maximum distance from the wooded areas because the wooded areas may be habitat for other species of butterflies, while still being in vegetation that was not regularly mowed. During the first field season, 2017, at the urban prairie, vegetation around the transects was cut down at the end of August prior to the completion of sampling. In addition, four vegetation monitoring plots were accidentally mowed on the west transect at the same time. The effect of the mowing was to concentrate butterfly activity along the unmowed portions of the transects, which skewed the data. During the second field season, 2018, transects were mowed over entirely and vegetation plot markers were removed at the start of August. Other than these mowings, this area did not experience any other vegetation treatments such as burning or grazing. Because transects at the urban prairie were removed, results have been separated into early season and late season data.

1.2 Figures

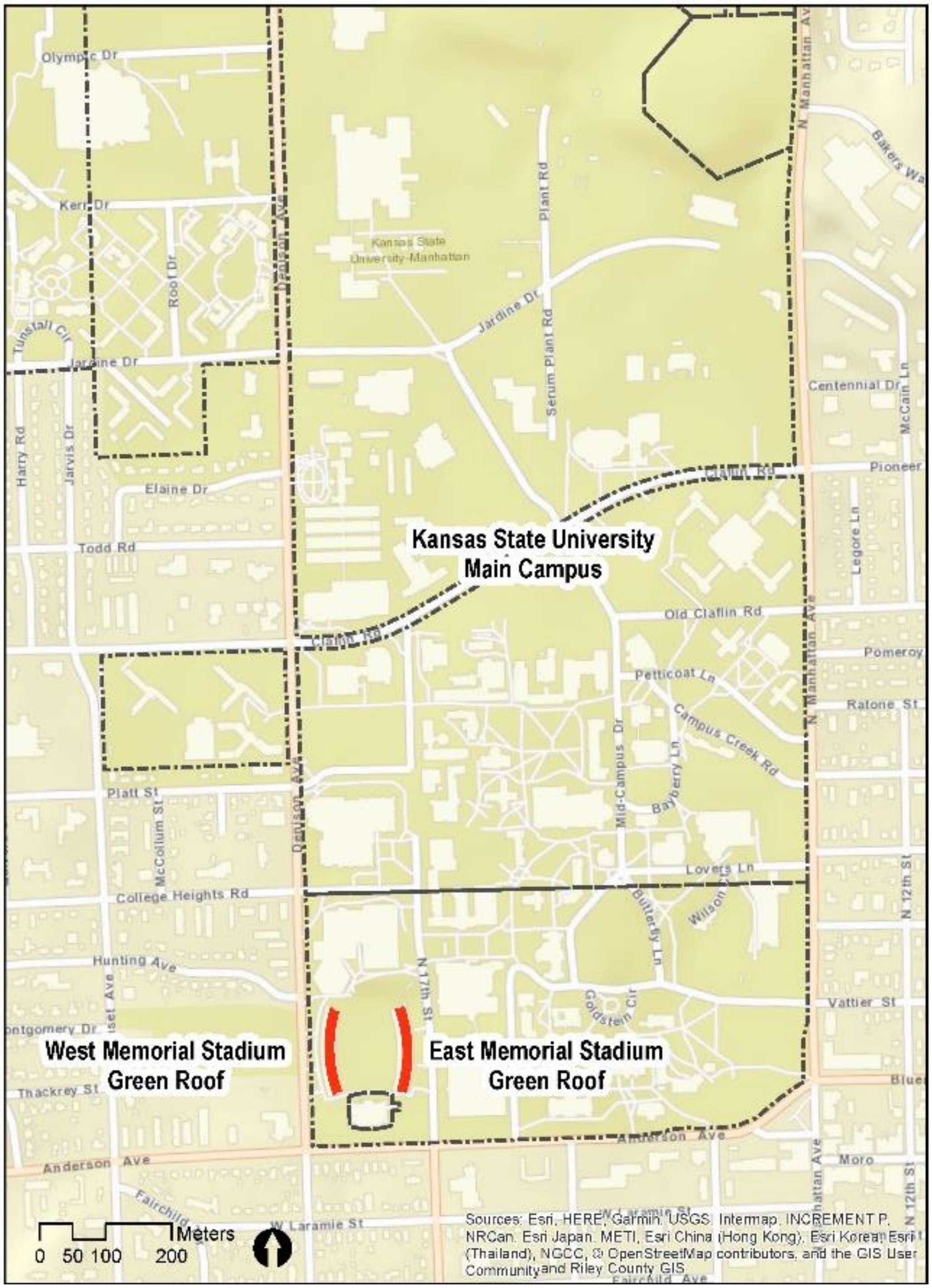

Figure 1.1. Map depicting the Memorial Stadium green roof locations in red on K-State's main campus in Manhattan, Kansas, 2018.

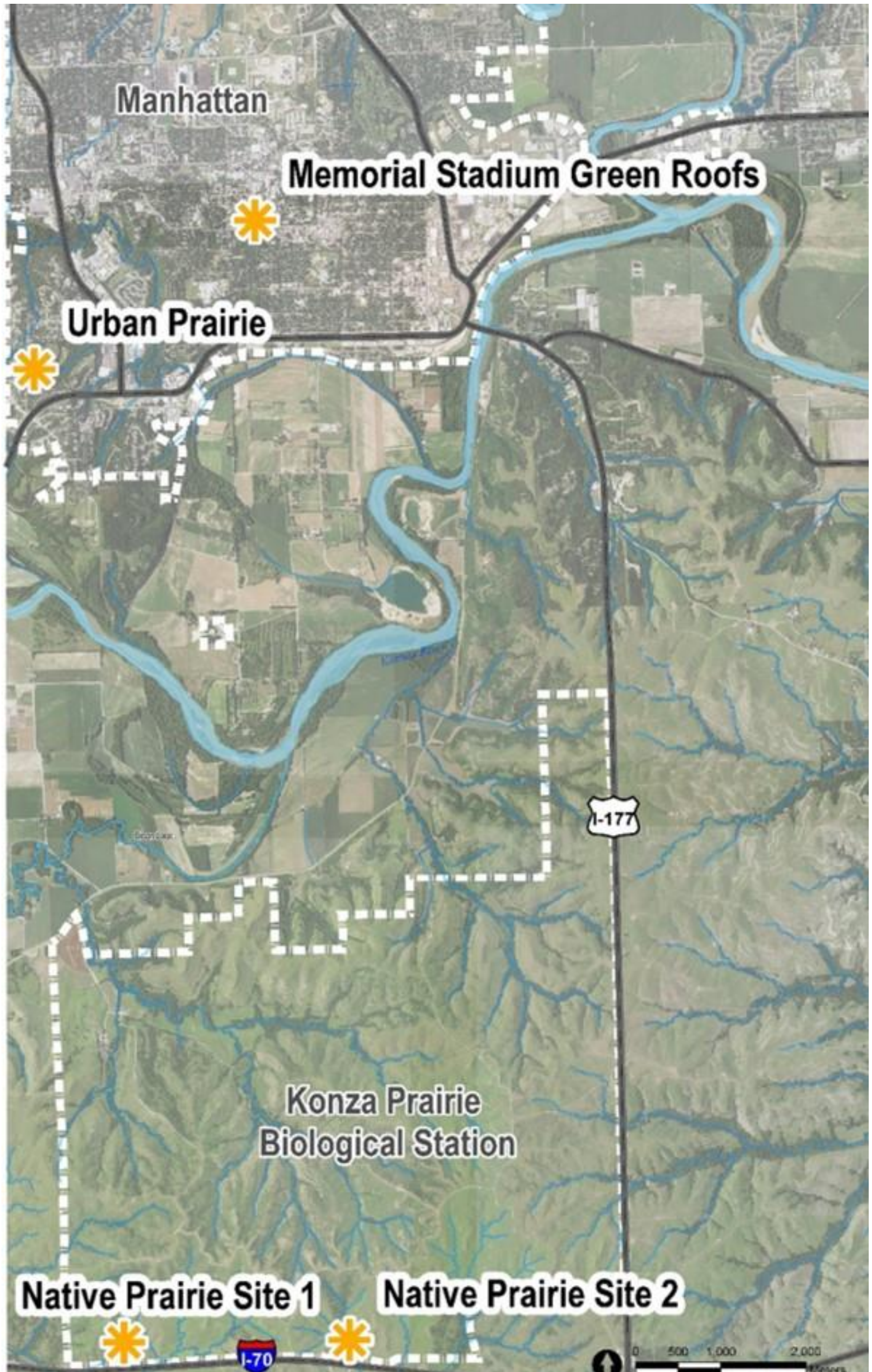

Figure 1.2. Map of the three study sites: the Memorial Stadium green roofs, Warner Park urban prairie, and native prairie within two watersheds at the Konza Prairie Biological Station, 2018.

Figure 1.3. East Memorial Stadium green roof pictured in September 2018. Photo taken by Lee R. Skabelund. Used with permission.

Figure 1.4. West Memorial Stadium green roof pictured in September 2018. Photo by Lee R. Skabelund. Used with permission.

Figure 1.5. Native prairie site pictured in 2017

Figure 1.6. Urban prairie site pictured in 2017.

Chapter 2 - Vegetation

2.1 Introduction

The tallgrass prairie is one of the most productive grasslands in North America (Knapp, Briggs, Hartnett, & Collins, 1998). There are numerous native grasses dominating plant communities in the Kansas tallgrass prairie. At Konza Prairie Biological Station, it is estimated that grasses *Andropogon gerardii*, *Sorghastrum nutans,* and *Schizachyrium scoparium* comprise 70% of total plant cover, with a diverse plant community of forbs and other graminoids (Blair, Nippert, & Briggs, 2014). Up to 99% of the native tallgrass prairie in North America has been lost to agricultural use and urbanization (Blair et al., 2014). However, Konza Prairie is an anomaly in that it is a protected tallgrass prairie site. Extensive loss of native tallgrass prairie results in reductions of ecosystem services that the plant community helps provide, including pollinator and other wildlife habitat.

The World War I Memorial Stadium is home to two recently constructed green roofs on the K-State campus in Manhattan, Kansas. One of the goals of the Memorial Stadium development was to mitigate losses of tallgrass prairie vegetation by providing native plants in an urban setting to support pollinator and bird habitat (Skabelund, 2016). In addition, green roofs can provide ecosystem services in urban areas such as reduction of stormwater peak discharge, reduction of urban heat effects, and better regulation of building temperatures (Oberndorfer et al., 2007). This, in essence, helps to reverse some of the ecosystem service losses that have resulted from urbanization's removal of native tallgrass prairie vegetation.

Some studies suggest that urban areas can foster habitat for a diverse range of wildlife (Angold et al., 2006). With the lack of available space in industrialized cities for green space, green roofs can offer an ecological niche for urban flora and fauna (Benvenuti, 2014). *Sedum* species have been the traditional plants of choice on green roofs in the past, but native vegetation, though sometimes more difficult to establish and maintain, can be used to increase wildlife biodiversity, particularly insects (Benvenuti, 2014). Development of green roofs as novel urban ecosystems is a form of reconciliation ecology, or the creation of habitat for wildlife (Kowarik, 2011; Rosenzweig, 2003). While green roofs may not be able to compensate entirely for landscape-scale habitat losses, they may contribute to urban biodiversity (Kowarik, 2011; Sutton, 2015). However, shallow substrate depths and vertical distance of green roofs from ground level can create urban niches, restricting some taxa from using the green roof (Sutton, 2015). Even though there are reduced numbers of pollinators on green roofs when compared to ground level, pollinators may still be able to provide sufficient pollination services to meet the needs of native vegetation (Ksiazek, Fant, & Skogen, 2012).

Almost every animal on earth relies on the ability of plants to complete the process of photosynthesis for their survival (Tallamy, 2007). Even strictly carnivorous animals rely on producers to convert energy from the sun into food for herbivores, such as insects, so that carnivores can in turn gain sustenance from the herbivores (Tallamy, 2007). Insects, then, are extremely important to other animals in higher trophic levels because of their ability to turn plants into food for birds and other organisms (Tallamy, 2007). Many butterflies require particular plants to serve as host plants for their larvae. Therefore, vegetation we plant in our gardens and greenspaces may limit which butterflies will be able to complete their life history processes in a given area (Tallamy, 2007). Exotic plants may have a negative effect on some butterflies. For example, in California three butterflies have been known to lay their eggs on exotic plants that are toxic to their larvae (Graves & Shapiro, 2003).

The plant community, then, may be highly influential in determining which butterfly species are attracted to and able to survive in a location. The Memorial Stadium green roofs were planted with 30 species, most of which were native (Van Der Merwe et al., 2017). This is a very small number compared to the more than700 native and non-native vascular plant taxa that have been recorded at Konza Prairie (Taylor, Mayfield, & Breckon, 2018). No known plant studies had been conducted at the urban prairie prior to this study. My objective was to conduct a thorough inventory of the plant community along transects at each of these three sites and compare each vegetation inventory to the butterfly communities at each transect.

2.2 Methods

2.2.1 Plant Composition Sampling Protocol

Vegetation composition sampling occurred along 127-m transects at each site, which were generally located with the start of each transect to the south. I established 21 plots, one every 6 m, which were offset by 1 m on either side of the transect centerline. At the initial sampling session, a coin was flipped to determine whether each of the 21 plots were located on the right or the left side of the transect. Plot locations were staked with posts and for each session of sampling the same locations were used (Figure 2.1). Sampling occurred every 3 weeks in 2017 and every 2 weeks in 2018 beginning in May and ending in September, coinciding with each session of butterfly sampling. One entire round of vegetation sampling and butterfly sampling at all transects constituted a "session." Five sessions were completed in 2017 and 10 sessions were completed in 2018. As previously mentioned, the transects were mowed down at the urban prairie, causing the data to be split between early and late seasons. Sampling sessions 6, 13, 14, 15, and 16 were included in the late season for only native prairie, while sessions 2, 3, 4, 5, 7, 8, 9, 10, 11, and 12 are included in the early season results for all three sites. There were six parts to the vegetation sampling:

1) I estimated cover classes of all plant species in a 0.5 X 0.5-m Daubenmire frame placed at each of the 21 posts on each transect (Daubenmire, 1959) with the help of Jeffrey Taylor, botanist at the Konza Prairie Biological Station. Seven cover classes were used (Table 2.1) following existing protocol at Konza Prairie Biological Station. Each species received a cover value that corresponds to the midpoint of the range that its assigned cover class spans as shown in the last column of Table 2.1. Overlapping canopy cover was included for all species, thus total canopy cover frequently exceeded 100%. Larval host coverage was calculated using plants in 6.2.

2) I counted the number of stems of flowering forbs in the Daubenmire frame (Myers et al., 2012) and created a blossom index. This index was calculated using the following formula:

$$x_{plot} = \sum \frac{b}{b_{max}}$$

Where *x*=blossom index, *b*=species blossom count, and b_{max}=yearly maximum species blossom count

3) I took four Robel pole measurements at each cardinal direction for visual obstruction in the center of each Daubenmire frame (Robel, Briggs, Dayton, & Hulbert, 1970).

4) I measured litter depth in each corner of the Daubenmire frame.

5) I inventoried land cover using GIS aerial interpretation in ArcMap 10.4 of all land within 500 m of each transect. Land cover was categorized as impervious surfaces; native grasses, forbs, and shrubs; standing water; and other landscape cover. Percent cover was determined for each category. These land cover types were digitized at a scale of 1:500 using imagery taken in 2017 as provided by the City of Manhattan with a spatial resolution of 0.07 m. Konza Prairie imagery was taken in 2012, had 1-m spatial resolution and was downloaded from

the National Agriculture Imagery Program with the U.S. Department of Agriculture Farm Service Agency. No statistical analysis was completed with these data.

6) I counted all species of forbs blooming within each transect.

All response and predictor variables are listed in Appendix B: Response and Predictor Variables.

2.2.2 Statistical Analyses

Plant data from 2017 and 2018 field surveys for plots at all sites were compiled and vegetation data from each plot were averaged across each transect. Plant data was organized by day of year to examine seasonal progression. It was also categorized as early season (sessions 2, 3 ,4, 5, 7, 8, 9, 10, 11, and 12) and late season (sessions 6, 13, 14, 15, and 16). Using the early and late season categorization, one-way analysis of variance (ANOVA) was then computed in R version 3.4.3. Variables analyzed include plant richness, evenness, Shannon diversity index (Spellerberg & Fedor, 2003), coverage, forbs blooming, blossom index, litter depth, and visual obstruction. My independent variable was site for each season.

2.3 Results

2.3.1 Plant Composition Sampling

2.3.1.1 General Results Across Time for All Sites

Nearly all vegetation variables increased over the season except litter depth and plant richness, which decreased, while Shannon diversity index remained relatively constant (Figure 2.2 and Figure 2.3). Total plant coverage increased the most throughout the season, followed by larval host plant cover.

2.3.1.2 Plant Variables By Site

This section examines results by site of each variable tracked during plant field surveying.

2.3.1.2.1 Plant Richness and Species Composition

I identified 182 plant species in plots at site transects. The native prairie site had the greatest overall plant species richness, with 108 observed, while the urban prairie had 88, and Memorial Stadium had 79, the lowest overall plant species richness. However, while I found the most species at the native prairie, the urban prairie had the highest average richness in each plot for early season (Figure 2.4). Early and late season plant richness were not different at the native prairie and Memorial Stadium.

I found many more species of plants at the Memorial Stadium than the 30 species planted there. I obviously did not find nearly as many of the more than700 taxa present at Konza Prairie on the native prairie transects given the relatively small area sampled of only a single vegetation management regime (i.e., unburned, ungrazed prairie). A complete list of all plants found at each site is in Appendix A: Plants at Each Study Site.

The most common functional group of plants across all sites was forbs and the least common functional group was woody vegetation (Figure 2.5). Total plant coverage, however, varied among sites. Graminoids dominated at the urban prairie site, while forbs dominated at Memorial Stadium, and the native prairie site had a more even mix of growth forms. Memorial Stadium had the greatest number of exotic species and the native prairie site had the least number. Memorial Stadium also had the greatest coverage of exotic species, while the urban prairie had the least coverage of exotic species. The majority of plants at all sites were perennial, but Memorial Stadium had the greatest number of species and coverage of biennial and annual plants. The native prairie had the greatest coverage of perennial plants.

2.3.1.2.2 Plant Evenness

The native prairie site had the lowest evenness, while Memorial Stadium and urban prairie sites had greater evenness (Figure 2.6) for early season. For late season, the native prairie and Memorial Stadium evenness were not different.

2.3.1.2.3 Plant Shannon Diversity Index

The urban prairie had greater early season diversity than both the native prairie and Memorial Stadium (Figure 2.7). Diversity was not different for late season between Memorial Stadium and native prairie.

2.3.1.2.4 Plant Coverage

For early season, the urban prairie had the greatest total coverage, Memorial Stadium had the lowest coverage (Figure 2.8). The largest percentage of total coverage (of the woody, forb, and graminoid coverage) for both the urban prairie and native prairie was graminoids. However, at Memorial Stadium, the largest percentage of coverage was forbs. The native prairie site had the greatest coverage of larval host plants and woody vegetation, whereas Memorial Stadium had the least coverage of larval host plants and woody vegetation. Late season plant coverage for Memorial Stadium and native prairie increased from the early season.

2.3.1.2.5 Forbs Blooming

Memorial Stadium had the greatest number of species of forbs blooming, while the native prairie had the least in the early season (Figure 2.9). By late season, the number of species of forbs blooming at Memorial Stadium was not different from the native prairie.

2.3.1.2.6 Blossom Index

The native prairie site had the lowest blossom index in the early season and Memorial Stadium had the greatest (Figure 2.10). By late season, however, the native prairie increased so that there was no difference between sites.

2.3.1.2.7 Litter Depth

Early and late season litter depth was greatest at the native prairie site and lowest at Memorial Stadium (Figure 2.11).

2.3.1.2.8 Visual Obstruction

Early season visual obstruction was greatest at the native prairie and urban prairie sites and lowest at Memorial Stadium (Figure 2.12). Late season visual obstruction was greater at the native prairie than at Memorial Stadium.

2.3.2 Land Cover Analysis

Land cover types and area within 500 m of each transect differed among study sites (Figure 2.13, Figure 2.14, Figure 2.15, and Figure 2.16; Table 2.2). Transects at the native prairie site had the least impervious surfaces (e.g., roads and buildings) of any of the sites whereas Memorial Stadium had the greatest area of impervious surfaces within 500 m of each transect. The urban prairie had the greatest amount of other landscape cover (e.g., traditional landscaped areas and road right of ways) within 500 m of each transect; native prairie had the least. Native prairie had the greatest area of native vegetation within 500 m and Memorial Stadium had the least native vegetation. The urban prairie was the only site with standing water within 500 m of each transect.

2.4 Discussion

I set out to understand how on-site vegetation composition influenced butterflies using a green roof. This section compares vegetation communities of the Memorial Stadium to the urban and rural native prairie sites by examining consistencies and differences among sites, while looking at the mechanisms behind those characteristics and how they might affect the butterfly community. It is hoped that through this thorough understanding of site-specific factors driving the plant community, combined with the direct influence of vegetation on butterfly communities (discussed in the next two chapters), it will be more apparent how to improve management of the plants on the green roofs for improved butterfly biodiversity and thereby inform Chapter 5- Green Roof Planning, Design, Construction, and Management Implications.

2.4.1 Patterns Consistent Among Sites

In general, plant coverage slightly increased throughout the season as vegetation matured. Plant richness slightly decreased as some species died off or senesced during the summer. Combining this with the minor increase of evenness as these species disappeared, diversity remained relatively constant throughout the season. Litter depth decreased likely due to the settling of vegetation from fragmentation, wind, decomposition, trampling, and other factors. Forb blossoming peaked at the end of the sampling period.

The majority of plant coverage at all sites was native and perennial. At Memorial Stadium this occurred because the landscape architect specified mostly native perennial vegetation in the planting plan. The green roof has been managed to promote native perennial vegetation since installation. At the native prairie sites, the vegetation was native and perennial because I purposefully selected comparison sites that had minimal human impact on the plant community.

Native perennial vegetation can influence the butterfly community that uses a site. In remnant prairies, it tends to support greater butterfly diversity and abundance than reconstructed prairie (Shepherd & Debinski, 2005). One study found a positive correlation between butterfly abundance and native plant diversity (Burghardt, Tallamy, & Shriver, 2009). Many annual plants do not provide resources for butterflies, so perennial plants can be more valuable to butterflies (Willmer, 2011). Invasive plants can negatively affect pollination of native plants (Bezemer, Harvey, & Cronin, 2014) and may outcompete native host plants and nectar sources that butterfly larvae and adults need (Moron et al., 2009; Schultz & Dlugosch, 1999) or reduce visitation rates of pollinators to native plants (Bezemer et al., 2014). Invasive plants may also negatively affect butterfly species diversity (Moron et al., 2009). However, some invasive plants have been found to increase pollination and seed set of native plants (Mckinney & Goodell, 2011).

Most interactions between plants and pollinators are generalized (Mckinney & Goodell, 2011) and exotic plants may increase the richness of generalist butterflies (Swengel, 1998). Some interactions, though, are specialized interactions between coevolved plants and their pollinators (Gilbert, 1980). For example, plants and pollinators may exhibit covariation in a geographical area such that proboscis length covaries with flower corolla tube length (Anderson & Johnson, 2008; Nilsson, 1988). Therefore, native perennial vegetation may promote specialist butterflies that require quality habitat to survive and study sites with the most native perennial vegetation and least invasives could support butterfly communities with specialist butterflies.

Non-native plants can adversely affect butterfly larvae. Because many butterfly larvae have a specific preference for a food plant due to ecological, chemical, or mechanical factors (Ehrlich & Raven, 1964), non-native plants can be undesirable or toxic to native pollinator larvae or may alter their development (Graves & Shapiro, 2003; Knerl & Bowers, 2013). In contrast, though, some native insects can adapt to invasives and alter their use of preferred host plants (Bezemer et al., 2014). Because native plants dominate each of the sites, negative affects of invasive species on butterfly larvae are minimal but may increase if the proportion of natives to nonnatives decreases.

2.4.2 Patterns That Differed Among Sites

Despite the commonalities in the progression of the plant community, there were several differences in the vegetation composition and structure among sites. This section discusses some of the greatest differences, mechanisms that may be causing them, and how those differences may affect the butterfly community. In general, the Memorial Stadium plant community was mostly forbs, had less richness than the urban prairie, had more forbs blooming and a greater blossom index than the other sites, less litter, lower visual obstruction, and less woody plant coverage than the other sites.

While the majority of plant coverage at Memorial Stadium consisted of forbs, the dominant vegetation at native and urban prairie sites was graminoids. Greater coverage of forbs occurred at Memorial Stadium because the plants specified in the planting plan survived and propogated on the roof. On the east Memorial Stadium green roof, the specified native grass seed was not included in the hydroseed mix, so the majority of grass growing on the east roof and new species on both roofs were likely planted as live plants, seeds in the seedbank of the substrate, or migrated to the roof via other dispersal methods.

Native tallgrass prairie is usually dominated by a few grass species and a variety of forb species (Mccain, Baer, Blair, & Wilson, 2010). Many grass skippers’ larval hostplants are grasses (Brock, Kaufman, Bowers, Bowers, & Hassler, 2003), so a plant community dominated by graminoids could increase abundance of these butterflies. However, this has not been the case in other butterfly studies (Swengel, 1996). Most butterflies rely on flowering forbs for nectar (Willmer, 2011), so dominance of forbs at the Memorial Stadium should increase abundance of butterflies at that site.

Memorial Stadium and the native prairie did not have different plant richness and Shannon Diversity, but the urban prairie had much greater plant richness. The native prairie likely had low richness because of how it is managed without grazing. Without grazers keeping dominant graminoids in check, forbs struggle to compete for light and resources with the grasses, which reduces plant richness and diversity (Hartnett, Hickman, & Walter, 1996; Knapp et al., 1999). Mowing has been identified as a potential mechanism that maintains species richness (Collins, Knapp, Briggs, Blair, & Steinauer, 1998), which is how the urban prairie is managed. Because Memorial Stadium vegetation is cut back annually, this may improve the richness of the plant community over time. Other variables such as season of mowing and whether cut plant material is left in place or baled may also play a role in species richness differences among sites.

The low richness at Memorial Stadium could be due to the limited species planted there, its relatively isolated setting where seed dispersal is limited, its young age, or nutrient inputs. For example, a restoration experiment at Konza Prairie showed that nitrogen inputs reduced species diversity and richness of restored prairie (Baer, Blair, Collins, & Knapp, 2004). Restored prairie vegetation, such as Memorial Stadium, does not have the richness and diversity of native tallgrass prairie. A study in the tallgrass prairie of Texas found that remnant prairies at three different scales all had more diverse and richer plant communities than restored prairie (Polley, Derner, & Wilsey, 2005). Because the availability of larval hostplants influences butterflies using a site (Schultz & Dlugosch, 1999), the low richness and diversity of Memorial Stadium could reduce richness and diversity of the butterfly community.

Evenness at Memorial Stadium and the urban prairie were not different in the early season, while the native prairie had the least even plant community. By late season, however, Memorial Stadium and the native prairie evenness were not different. This occurred at Memorial Stadium because some plants became more dominant in the late season, whereas evenness at the native prairie stayed consistent. While native and urban prairie sites had a dense mat of vegetation and litter at the surface of the ground, there was considerable bare ground at Memorial Stadium as the vegetation is still maturing, perhaps providing greater potential space for growth. How this dominance of particular species of plants affects the butterfly community depends on the plants that are dominating the plant community. Because forbs were dominant at Memorial Stadium, this could help meet the food and larval host requirements to attract butterflies to the green roofs.

Memorial Stadium had the most forb species blooming and largest blossom index in the early season, but by late season, Memorial Stadium and native prairie sites were not different. This occurred because the June to mid-August 2018 drought reduced plant reproduction at the native and urban prairie sites, whereas Memorial Stadium was irrigated during this period. When rain came towards the end of summer, more forbs started blooming at the native prairie. More forbs blooming at the two green roofs provided more nectar for butterflies at Memorial Stadium.

Litter depth and visual obstruction were greatest at the native and urban prairie sites and lowest at the Memorial Stadium for both seasons. Differences in litter depth among sites likely occurred because of age, context, location, and management of the sites. None of my sites were burned or grazed, which allowed litter to accumulate. When the plant material is cut back in the spring at the Memorial Stadium, the vegetation is left on the roof, so litter could accumulate over time. A deep litter layer may increase productivity during times of drought when water is limited

(Knapp & Seastedt, 1986). Undisturbed prairie may intercept 40% of rainfall, but prairie without litter can only intercept about 20% (Knapp & Seastedt, 1986). Therefore, accumulation of litter could indirectly benefit butterflies at the Memorial Stadium because a deeper litter layer may increase its ability to capture and store rainfall, reduce the amount of irrigation needed to maintain the vegetation that the butterflies rely upon, and reduce plant stress when there are issues with the irrigation system, especially given the steep slopes of the roofs that shed water relatively quickly. Greater visual obstruction increases litter depth over time as plants senesce. Additionally, aboveground biomass has been linked to butterfly diversity (Bergman et al., 2008). A direct benefit of litter is that some butterfly larvae overwinter in the litter layer (Davis, Debinski, & Danielson, 2007), so some species could find Memorial Stadium more attractive if a deeper litter layer was present.

While woody plant coverage was consistently the lowest coverage by functional group across sites, the native prairie had the greatest average woody coverage. At Memorial Stadium woody coverage was low because it is managed to remove those plants that could negatively affect the waterproofing membrane, such as woody dicots. There were few woody plants with mostly grasses and forbs at the native prairie and urban prairie sites because the urban prairie is hayed and the native prairie was, up until the last several years, burned annually. However, there is evidence of woody encroachment at the native prairie. Because increased woody plant coverage decreases biodiversity of plants and animals (Blair et al., 2014), the reduced biodiversity could make it more difficult for butterflies to meet their needs of forb diversity for nectar sources and larval hostplants. However, woody plant coverage may change the species composition of the butterfly community because some butterfly larval hosts are woody plants (Lotts & Naberhaus, 2017). Therefore, woody vegetation at the native prairie site may attract woodland butterfly species, but biodiversity may decrease. Continuing to manage Memorial Stadium to reduce woody plant coverage should help to maintain biodiversity and the current butterfly species composition.

The majority of the land cover surrounding Memorial Stadium was impervious surfaces such as rooftops, roads, and parking lots, while the other sites had much more native vegetation and other vegetated landscape cover. The Memorial Stadium was the most isolated of the sites on a university campus in a city, while the native prairie was the least isolated site within the largest area of native vegetation at a rural biological research station, and the urban prairie was at a park in a residential area surrounded in remnant native vegetation (Table 2.2).

Site area is important for butterfly species diversity and composition. A study of various grassland habitat sizes in Germany found that habitat area was correlated with butterfly diversity. Additionally, as habitat area increased, generalist butterflies decreased and specialist butterflies increased (Steffan-Dewenter & Tscharntke, 2000). Because Memorial Stadium has little surrounding native vegetated area, this could negatively affect the butterfly abundance of specialists, but increase abundance of generalists.

Results from many of the vegetation variables tracked indicate that Memorial Stadium should support an abundance and diversity of butterflies. There was a dominance of perennial native plants, particularly forbs, as well as plant mean richness, blossoms, and evenness comparable to or greater than native prairie. However, surrounding land cover, shallow litter depth, and low visual obstruction could negatively affect the abundance and diversity of the butterfly community at Memorial Stadium.

2.5 Tables

Table 2.1. Cover classes and midpoint of range for measuring plant community composition species canopy cover using the Daubenmire method

Cover Class	Range of Coverage (Percentage)	Midpoint of Range (Percentage)
1	0–1	0.5
2	1–5	2.5
3	5–25	15.0
4	25–50	37.5
5	50–75	62.5
6	75–95	85.0
7	95–100	97.5

Note. Table adapted from National Oceanic and Atmospheric Administration, 2003

Table 2.2. Average percent land cover within 500 meters of transects at the Memorial Stadium, native prairie, and urban prairie digitized using aerial imagery from 2017 for Memorial Stadium and urban prairie, and imagery from 2012 for the native prairie.

	Percentage of Land Cover within 500 meters of each transect			
	Impervious Surfaces	**Native Vegetation**	**Standing Water**	**Other Landscape Cover**
Memorial Stadium	61%	<1%	0%	39%
Native Prairie	3%	91%	0%	6%
Urban Prairie	28%	12%	<1%	60%

2.6 Figures

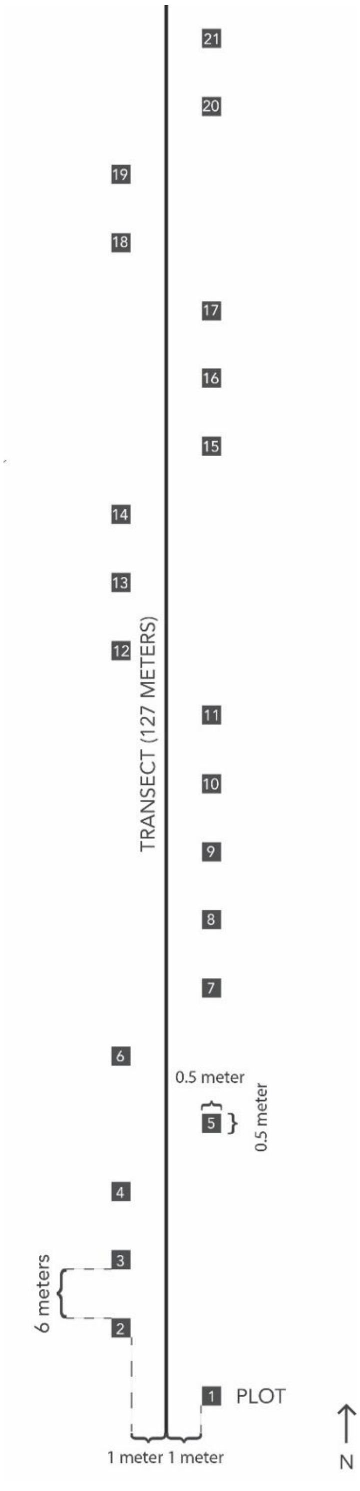

Figure 2.1. Diagram of plant composition sampling transect layout used at all sites. Plots are shown in grey, spaced 6 meters apart, and offset 1 meter from the transect center line.

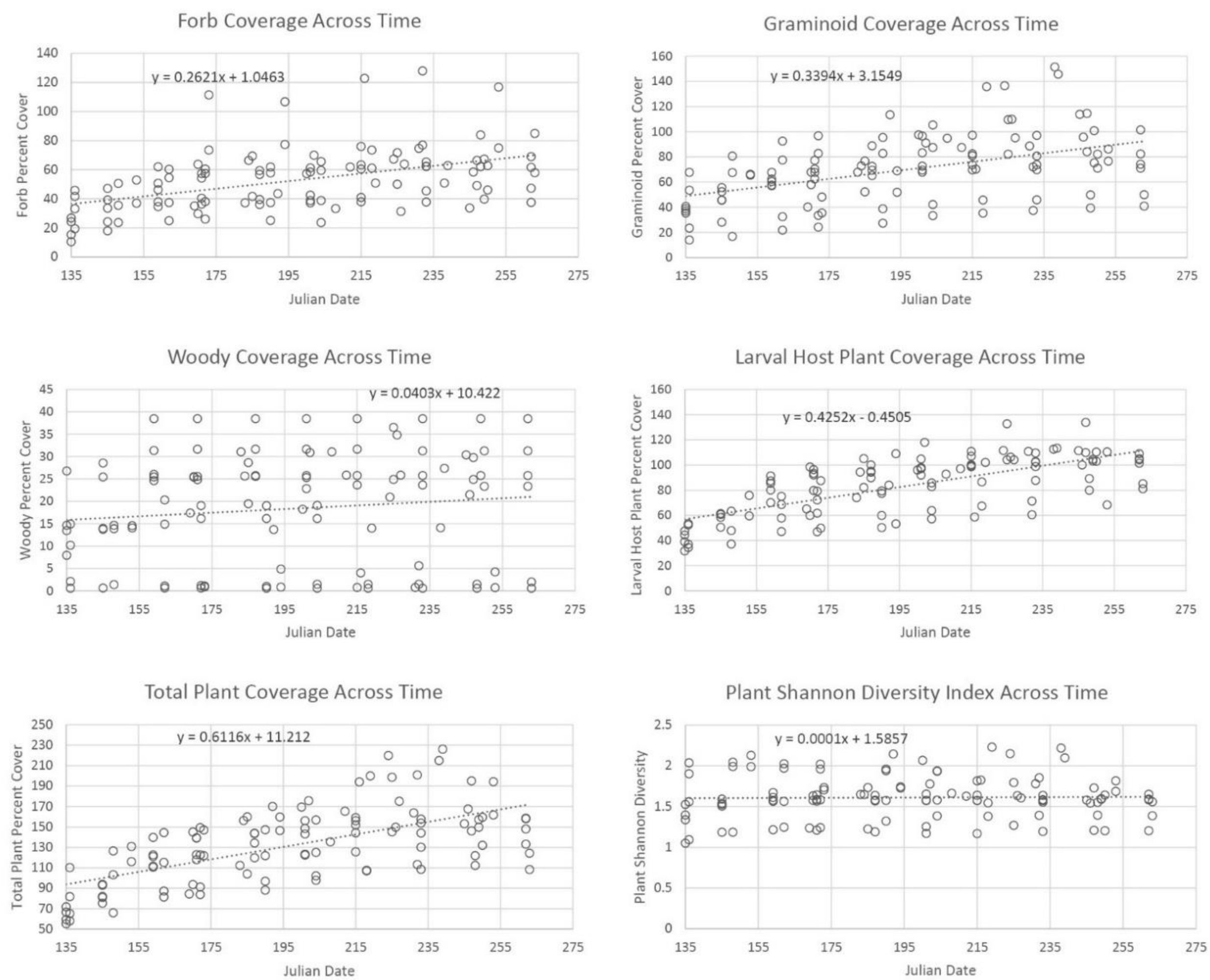

Figure 2.2. Seasonal progression of percent forb coverage, graminoid coverage, woody coverage, larval host plant coverage, total plant coverage, and plant Shannon diversity index at Memorial Stadium, native prairie, and urban prairie combined May through September.

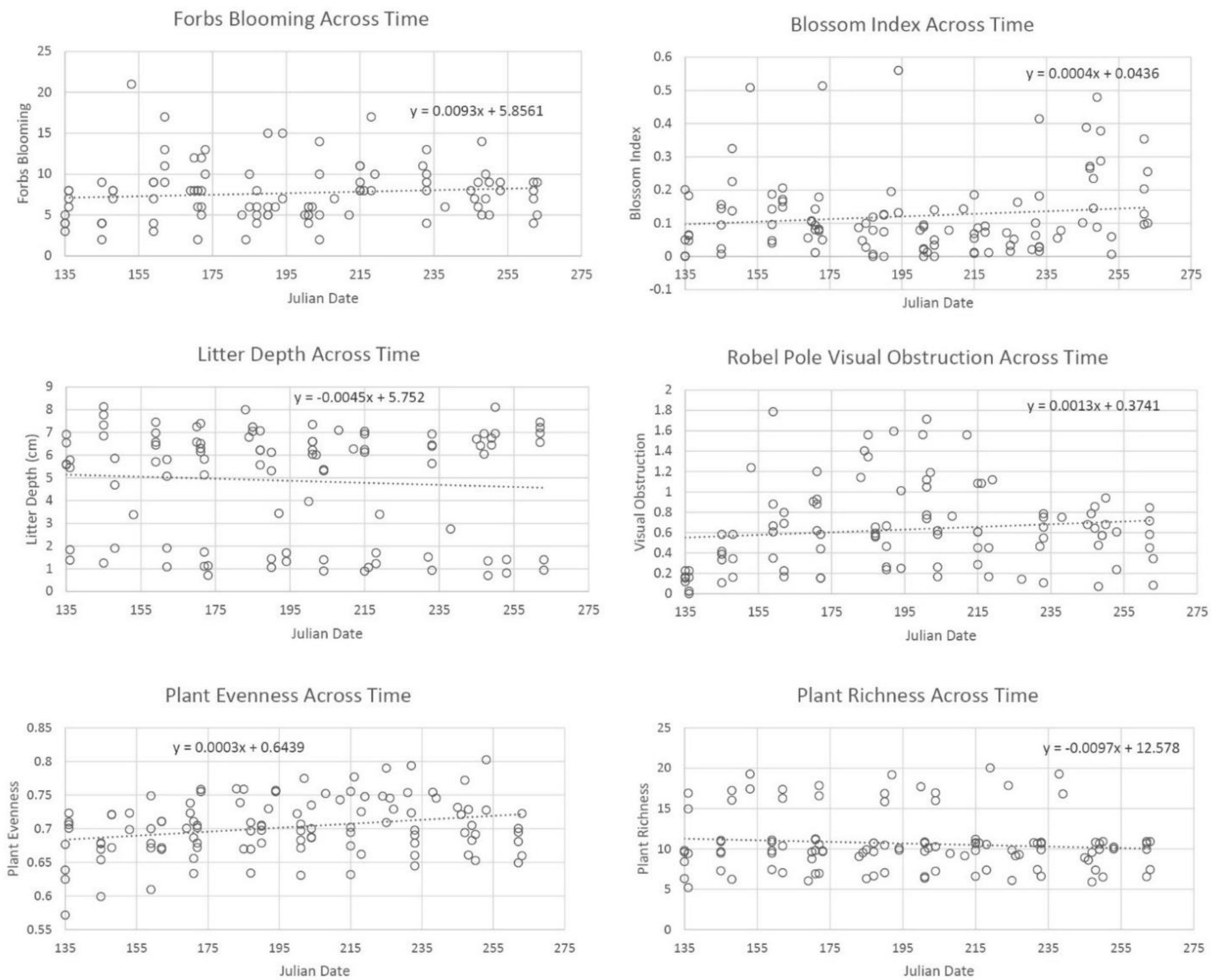

Figure 2.3. Seasonal progression of forbs blooming, blossom index, litter depth, visual obstruction, plant evenness, and plant richness at Memorial Stadium, native prairie, and urban prairie combined May through September 2017 and 2018. Shown by day of year.

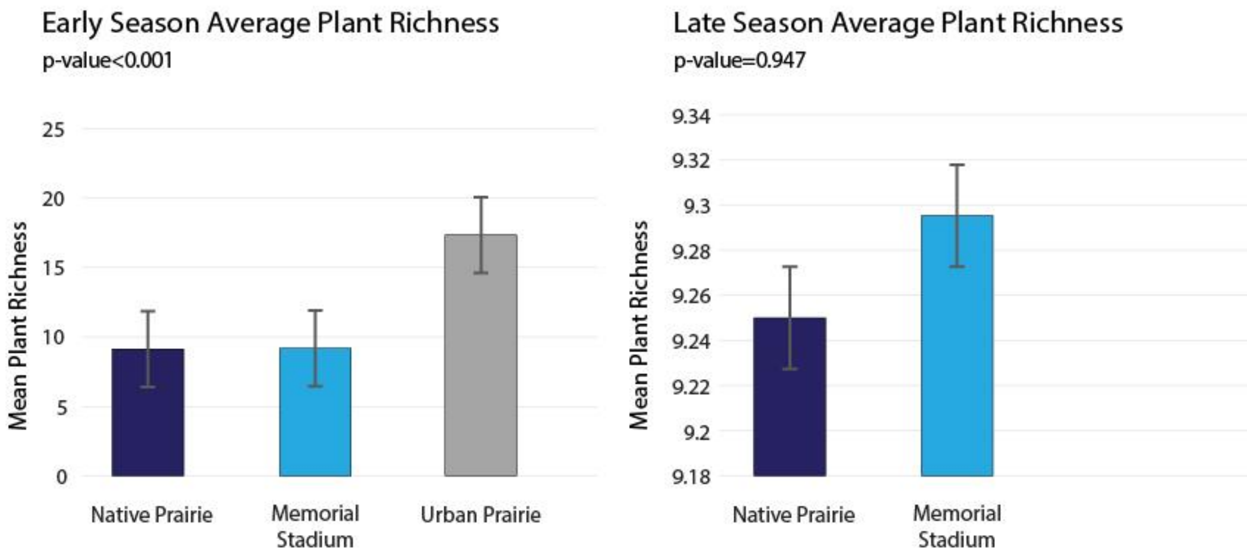

Figure 2.4. Early and late season average plant richness at the native prairie, Memorial Stadium, and urban prairie sites from data gathered in 2017 and 2018 with ANOVA P-values and standard error bars.

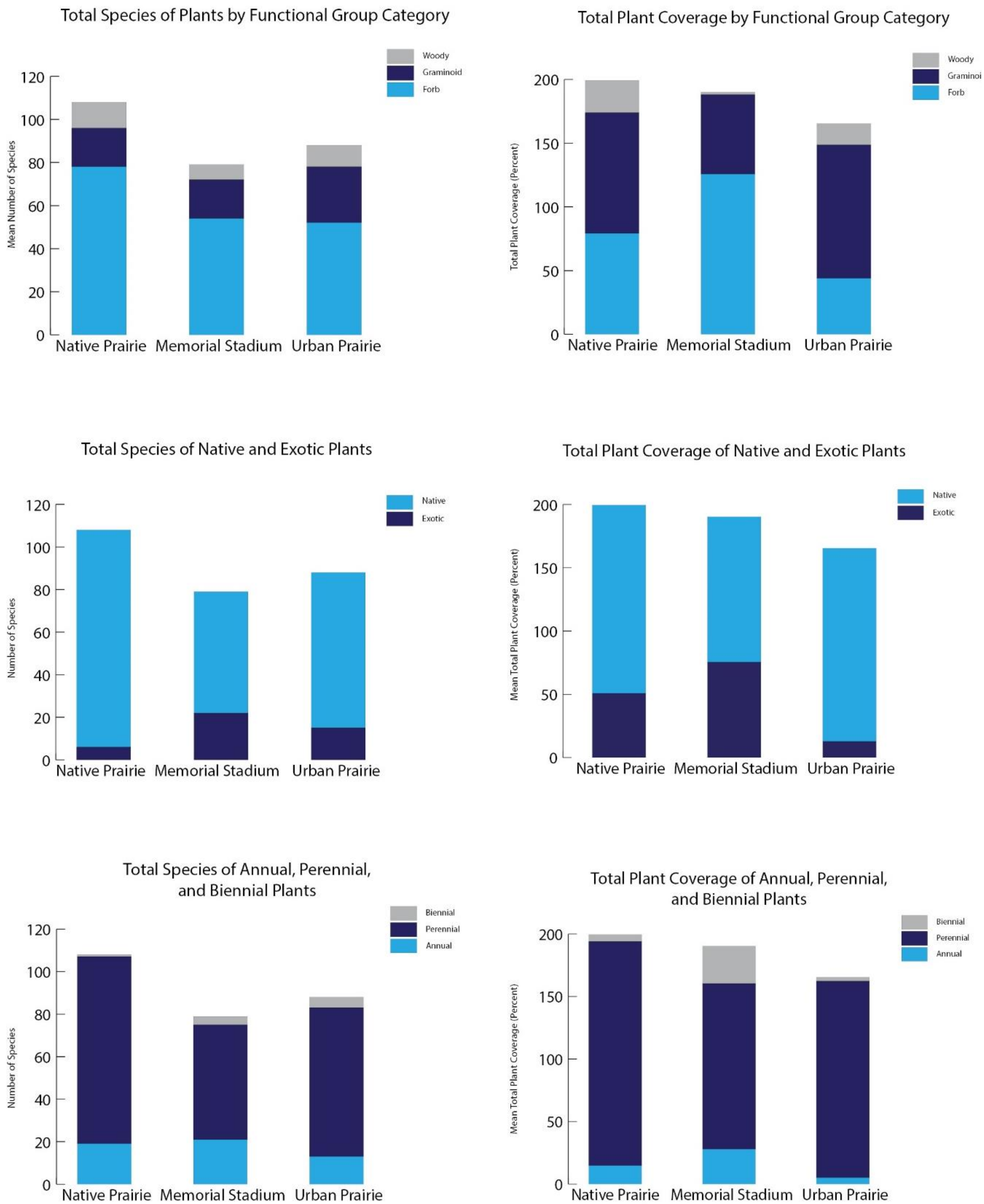

Figure 2.5. Native prairie, Memorial Stadium, and urban prairie plant community composition functional groups, native and exotic plants, and annual, perennial, and biennial plants from data gathered in 2017 and 2018.

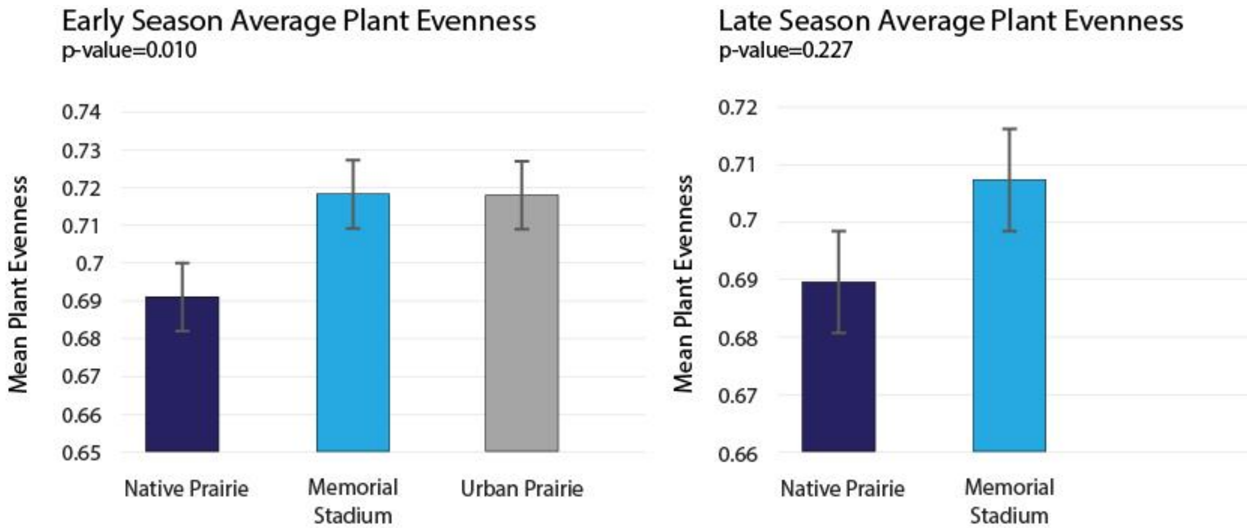

Figure 2.6. Early and late season average plant evenness at the native prairie, Memorial Stadium, and urban prairie sites from data gathered in 2017 and 2018 with ANOVA P-values and standard error bars.

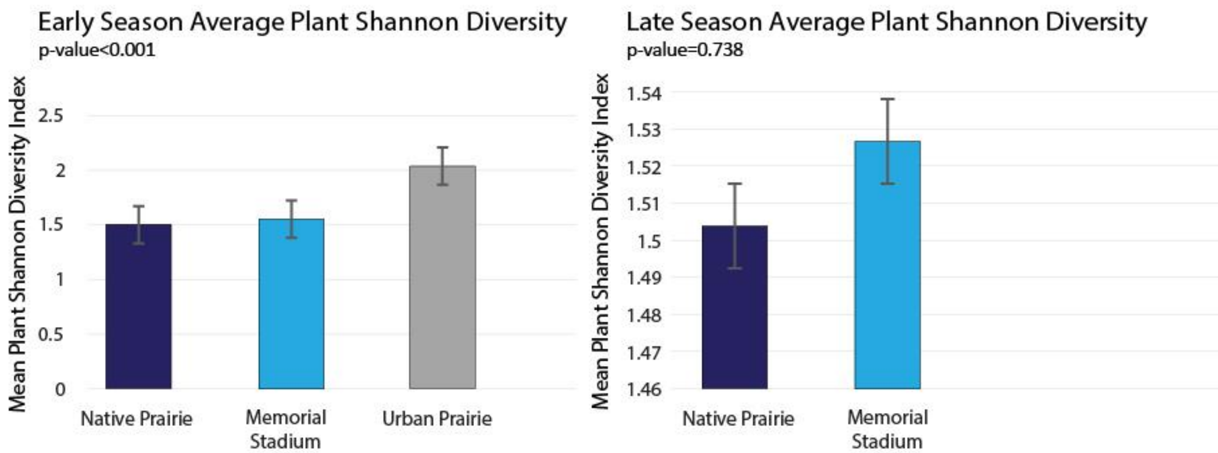

Figure 2.7. Early and late season average plant Shannon diversity at the native prairie, Memorial Stadium, and urban prairie sites from data gathered in 2017 and 2018 with ANOVA P-values and and error bars.

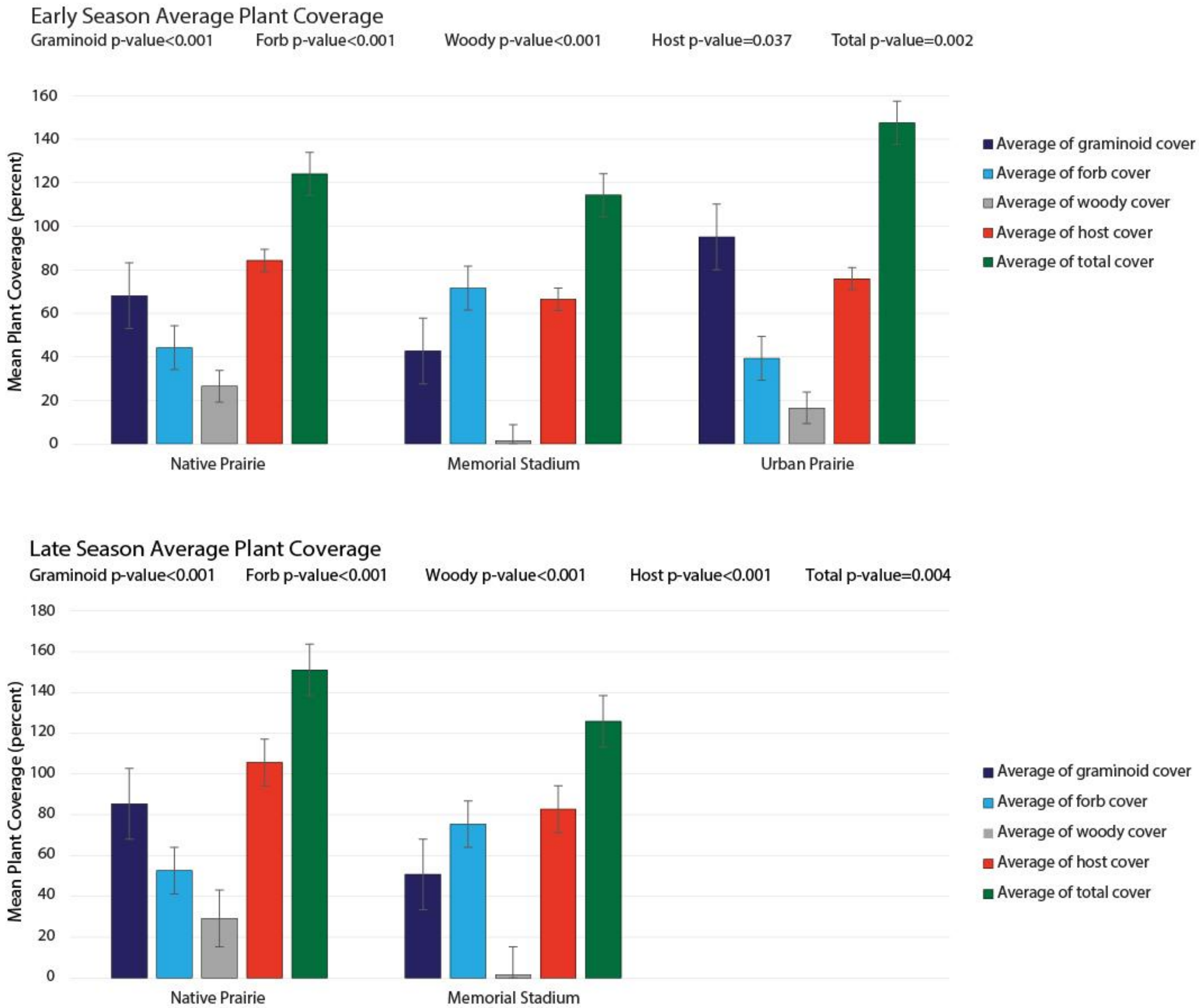

Figure 2.8. Early and late season average plant coverage at the native prairie, Memorial Stadium, and urban prairie sites from data gathered in 2017 and 2018 with ANOVA P-values and error bars.

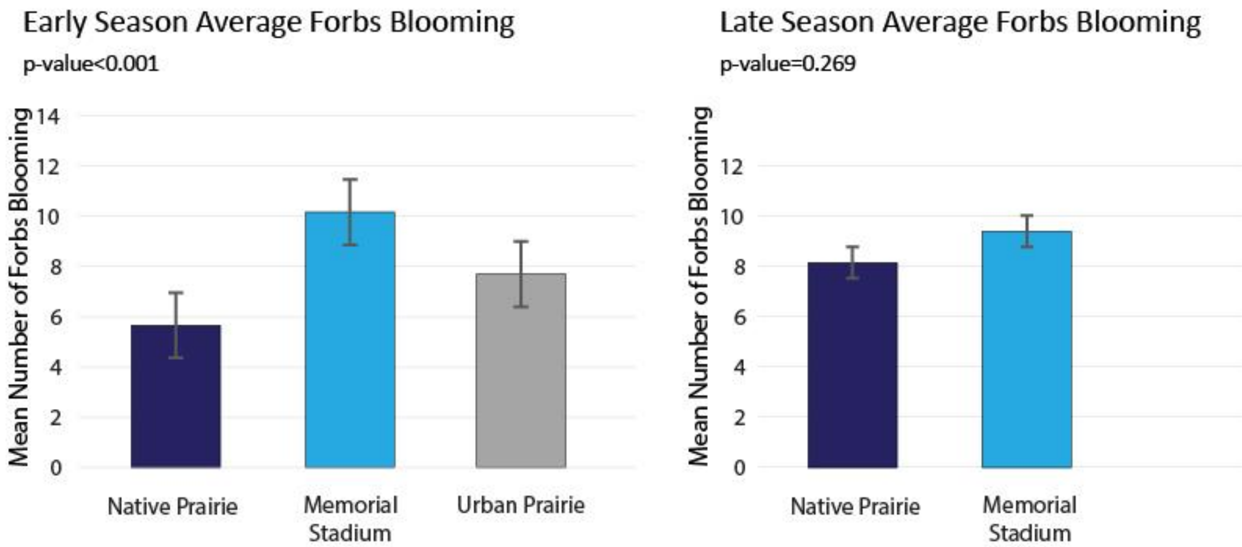

Figure 2.9. Early and late season average number of forb species blooming at the native prairie, Memorial Stadium, and urban prairie sites from data gathered in 2017 and 2018 with ANOVA P-values and standard error bars.

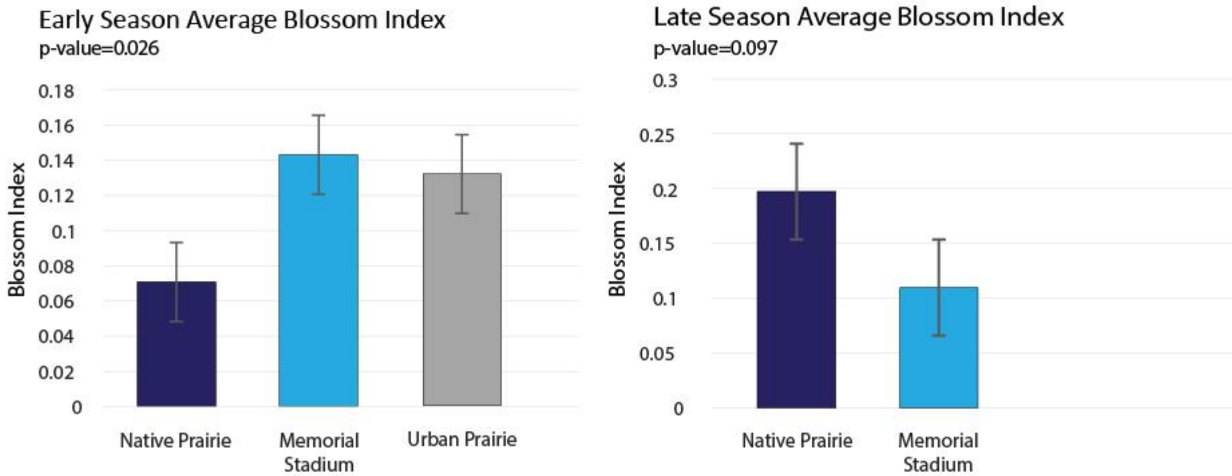

Figure 2.10. Early and late season average blossom index at the native prairie, Memorial Stadium, and urban prairie sites from data gathered in 2017 and 2018 with ANOVA P-values and standard error bars. This index was calculated using a count of blossoms.

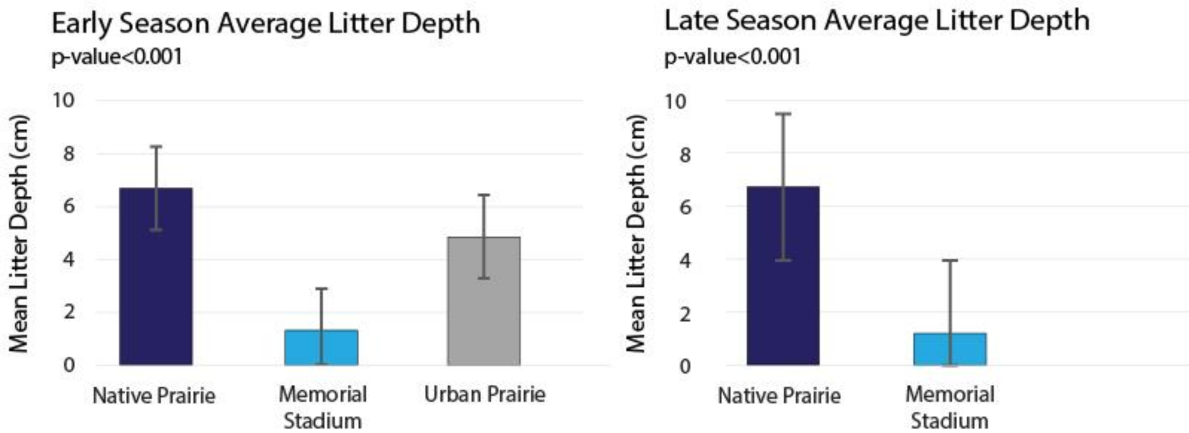

Figure 2.11. Early and late season average litter depth at the native prairie, Memorial Stadium, and urban prairie sites from data gathered in 2017 and 2018 with ANOVA P-values and standard error bars.

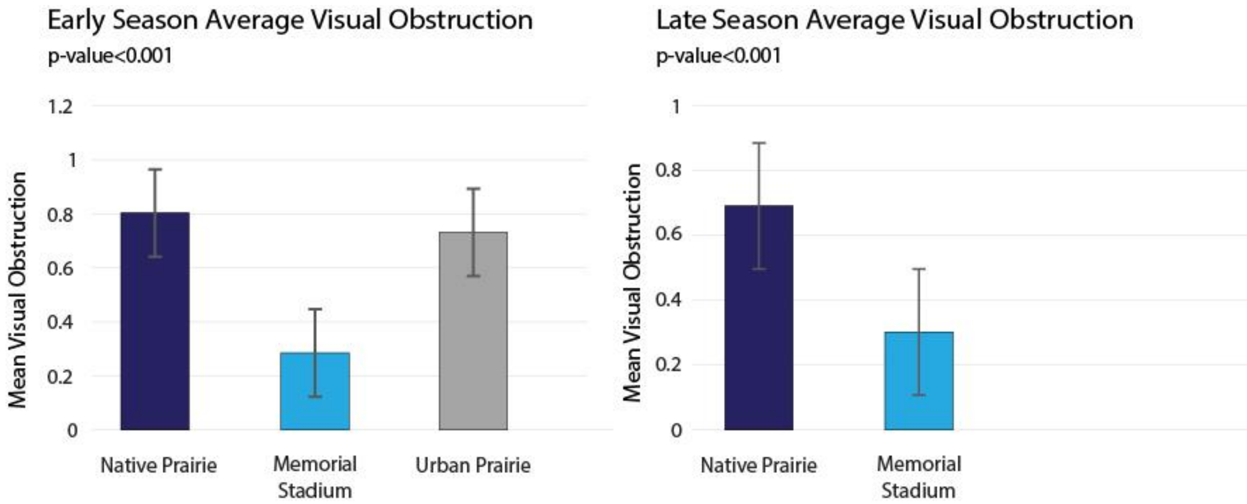

Figure 2.12. Early and late season average visual obstruction at the native prairie, Memorial Stadium, and urban prairie sites from data gathered in 2017 and 2018 with ANOVA P-values and standard error bars.

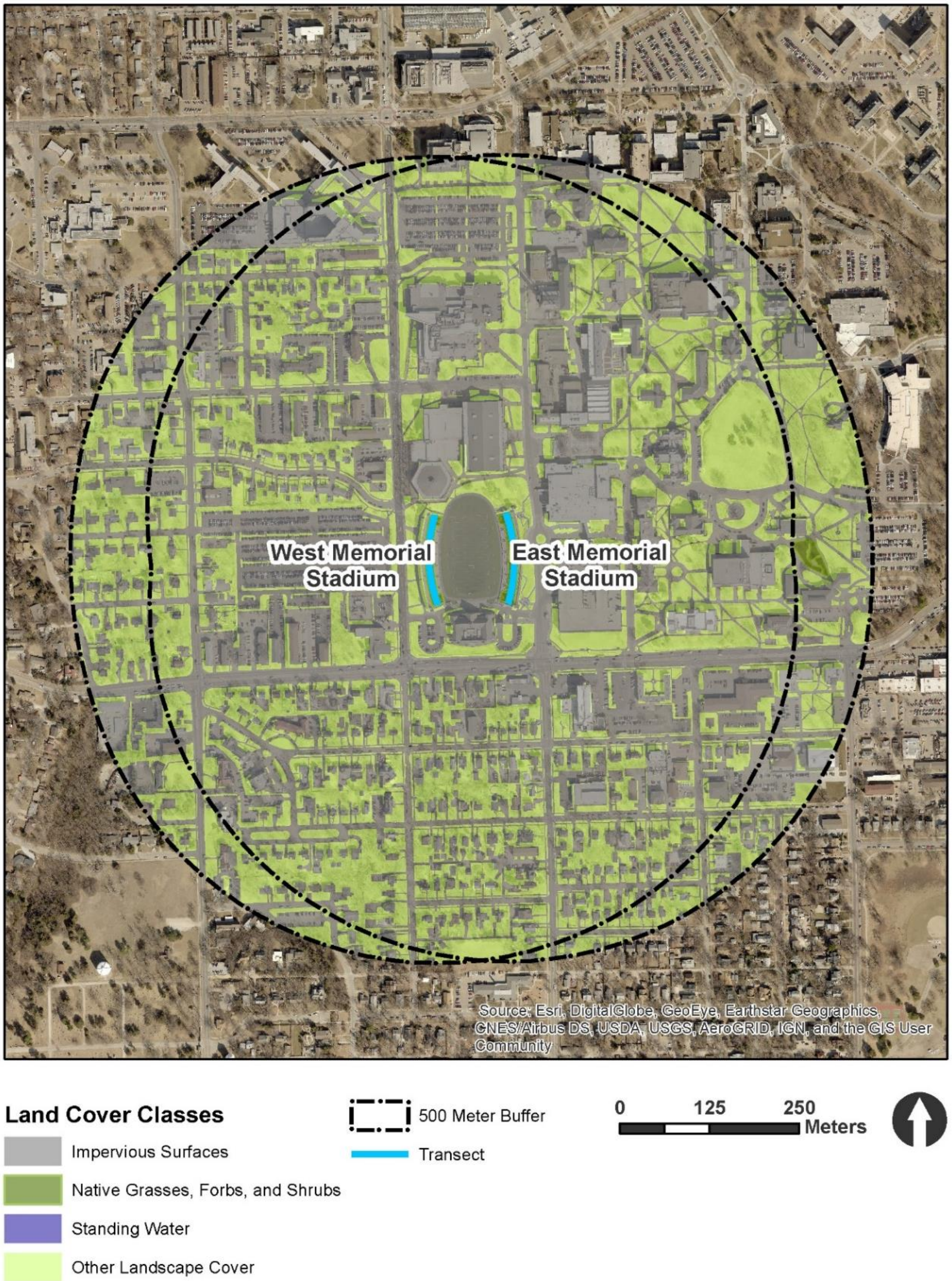

Figure 2.13. Land cover within 500 meters of the Memorial Stadium transects in Manhattan, Kansas, digitized in 2018 using aerial imagery taken in 2017.

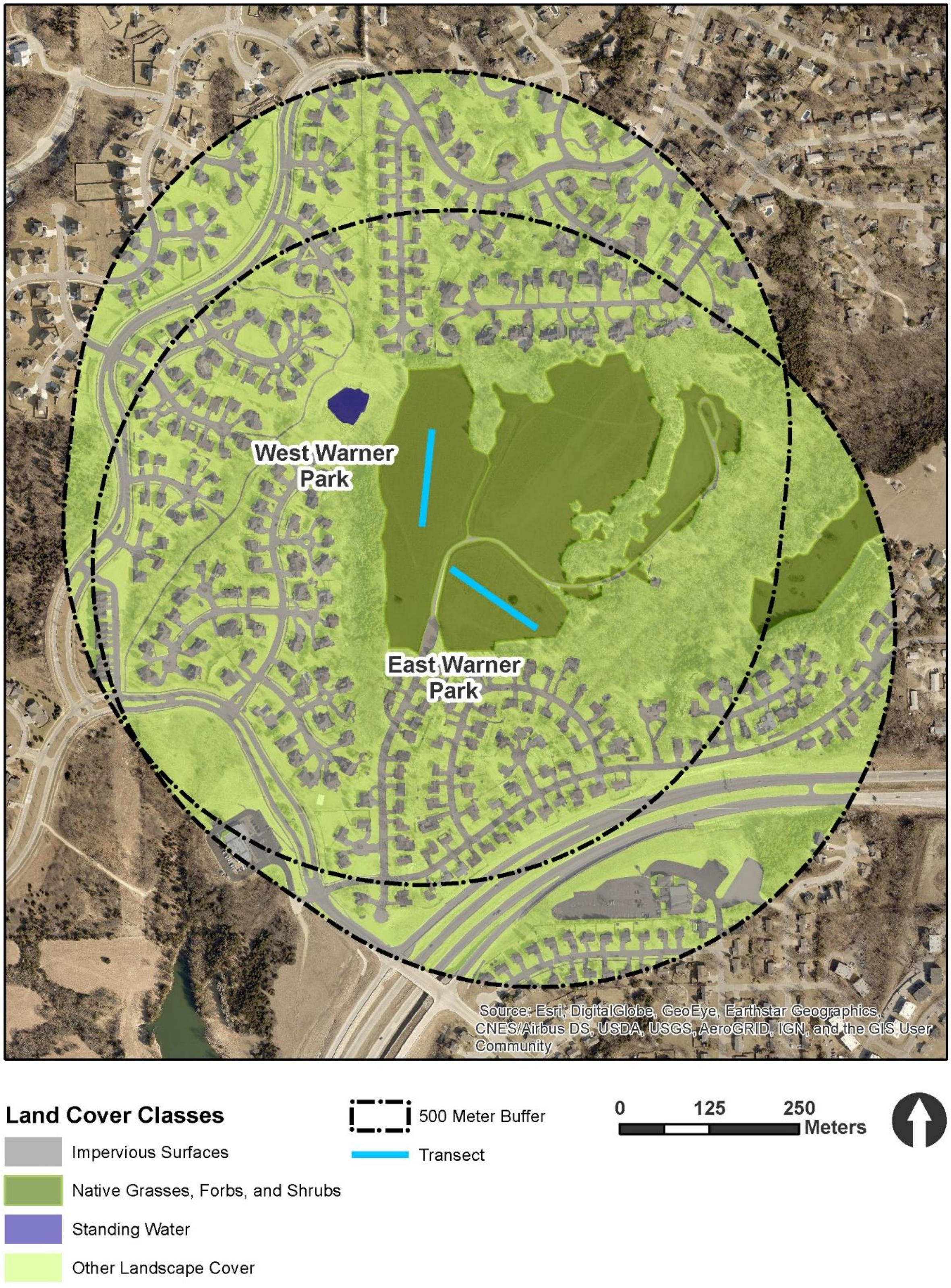

Figure 2.14. Land cover within 500 meters of the Warner Park urban prairie transects in Manhattan, Kansas, digitized in 2018 using aerial imagery taken in 2017.

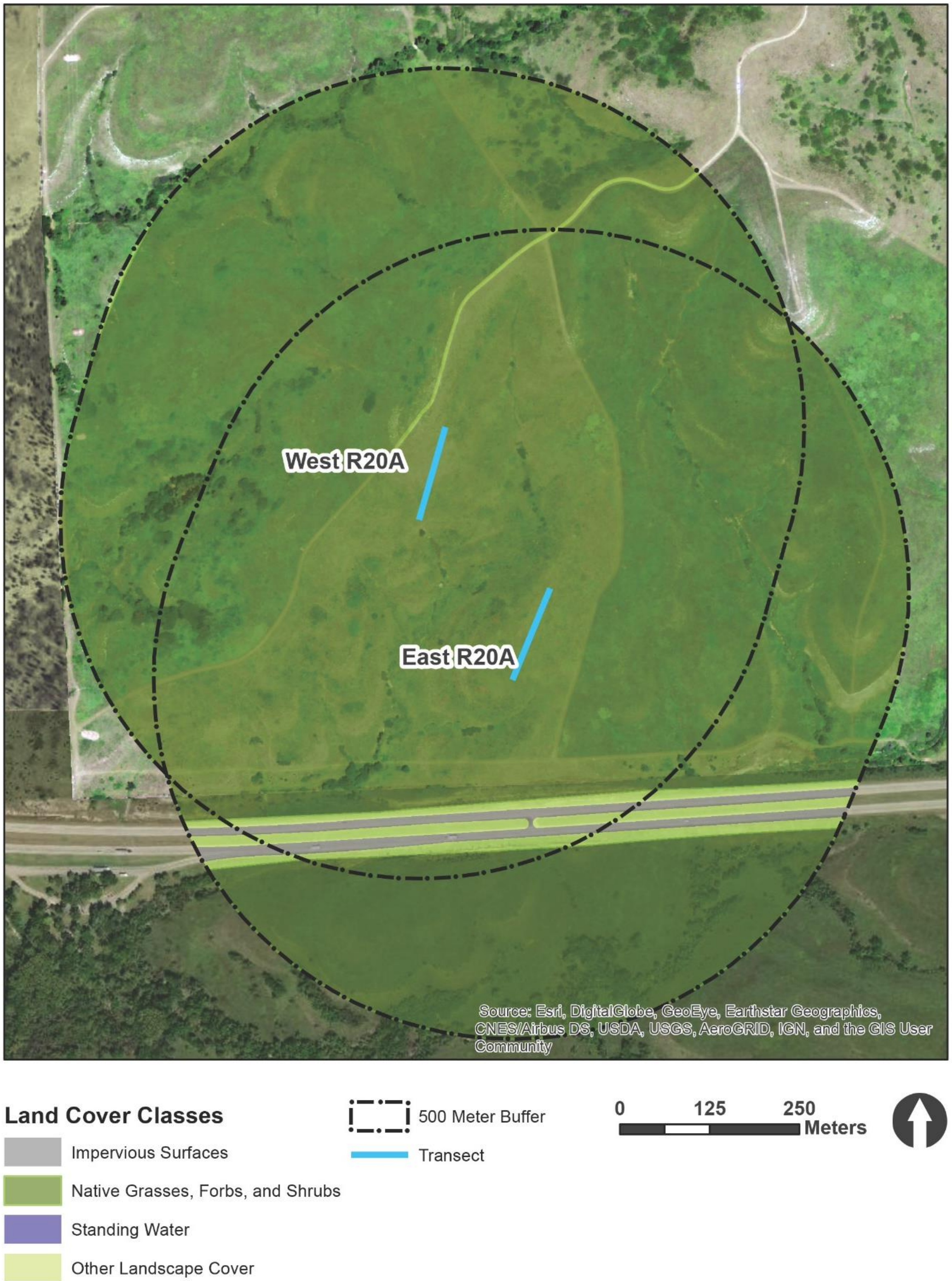

Figure 2.15. Land cover within 500 meters of the R20A Transects at Konza Prairie native prairie transects south of Manhattan, Kansas, digitized in 2018 using aerial imagery taken in 2012.

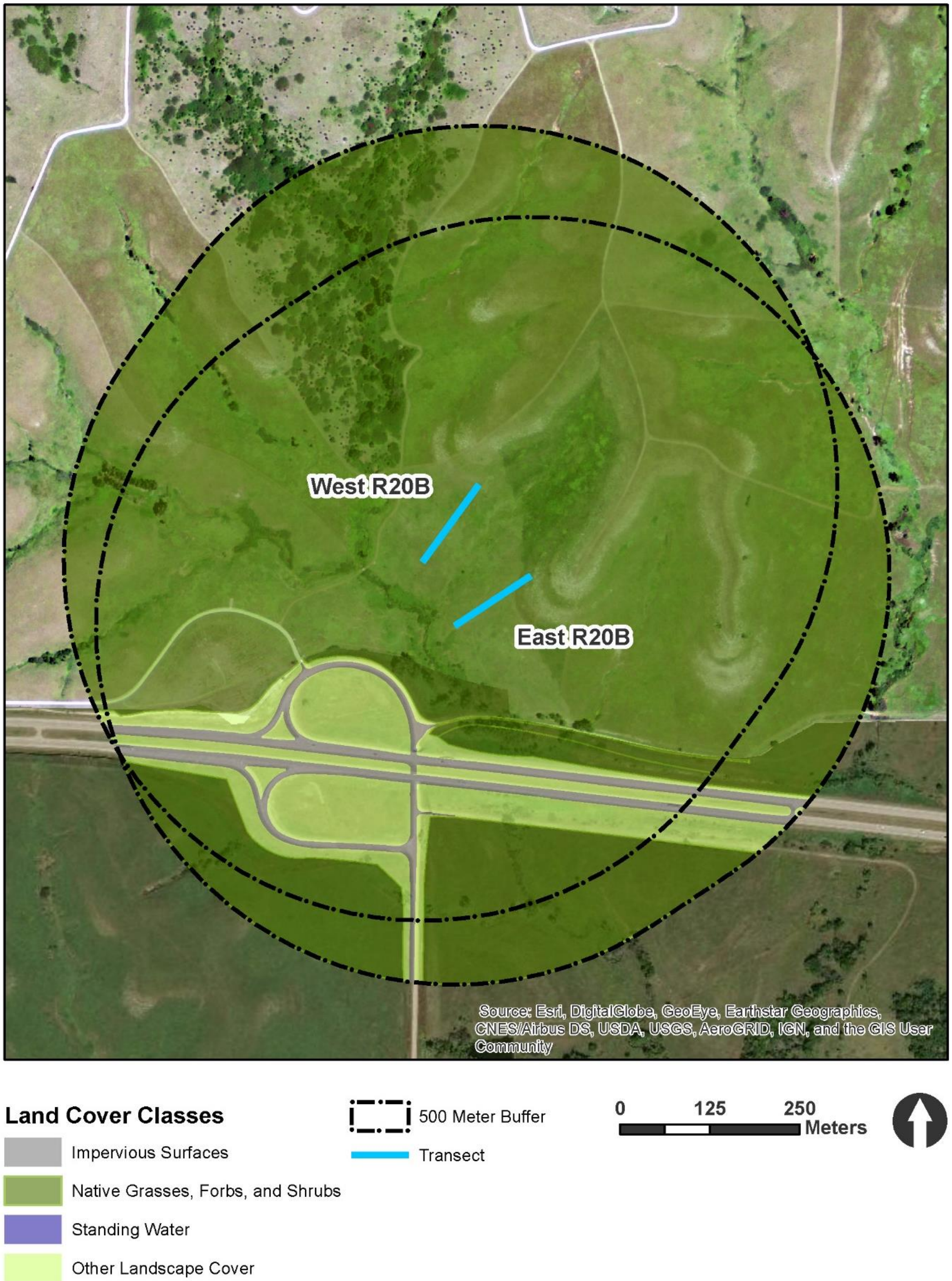

Figure 2.16. Land cover within 500 meters of the R20B Transects at Konza Prairie native prairie transects south of Manhattan, Kansas, digitized in 2018 using aerial imagery taken in 2012.

Chapter 3 - Butterfly Abundance, Richness, Diversity, and Behavior

3.1 Introduction

Pollinators are declining globally, but to what extent is uncertain (Potts et al., 2010, 2016; Vanbergen et al., 2013). Habitat loss is believed to be the most impactful driver on some pollinators, such as bees, with pesticide use, climate change, and other drivers all contributing to these declines (Potts et al., 2010). The more specialized pollinators tend to be those that habitat change affects the most (Vanbergen et al., 2013). Specialists are those species that require a specific environment and food and are less able to adapt to changing habitat conditions, while generalists can tolerate various environments and food sources (Lawrence, 2005). Specialist butterfly abundance declines are greater than generalists; of those specialists, tallgrass prairie butterfly specialists are declining faster than many others in the Midwest (S. Swengel, Schlicht, Olsen, & Swengel, 2011).

Examples of some tallgrass prairie butterfly specialists that are declining include the Regal Fritillary (*Speyeria idalia*), Poweshiek Skipperling (*Oarisma poweshiek*), Arogos Skipper (*Atrytone arogos*), Dakota Skipper (*Hesperia dacotae*), and Ottoe Skipper (*Hesperia ottoe*; Swengel et al., 2011). Reasons for these tallgrass prairie butterfly specialist declines are loss of habitat, overgrazing, invasive plants (Vogel, Debinski, Koford, & Miller, 2007), woody encroachment, and frequent prescribed burning of their habitat (Swengel, 1998; Swengel et al., 2011).

Urban areas have the potential to act as refuges for insect pollinator populations that rural areas may not because of large agricultural monocultures or intensive livestock operations and pesticide use in rural areas (Hall et al., 2016). Green roofs are one component of some urban centers that may aid pollinators, yet the value that green roofs provide to wildlife and whether they can be quality habitat is uncertain (Macivor & Ksiazek, 2015; Williams et al., 2014). Green roofs can support larger populations of organisms than conventional roofs (Williams et al., 2014). However, while some studies claim that green roofs can provide stepping stones for wildlife migrating through an urban area, support rare wildlife or species of conservation significance, and, comparable to ground-level landscapes, support similar abundances and diversity of wildlife, there is insufficient evidence to support or refute these claims and more studies are needed (Williams et al., 2014).

Butterflies are indicators of habitat quality (Kocher & Williams, 2000), so it is logical that studying the butterfly community could be an effective method when attempting to determine the habitat quality of a green roof. There is considerable research studying butterflies on green roofs in other parts of the world (Lee & Lin, 2015; Snep, Wallisdevries, & Opdam, 2011; Wei Wang et al., 2017), as well as studies in the tallgrass prairie of butterflies on native and reconstructed vegetation (e.g. Öckinger, Dannestam, & Smith, 2009; Ogden, 2017; Shepherd & Debinski, 2005; Swengel et al., 2011; Vogel et al., 2007). However, research of butterfly communities of green roofs planted with native vegetation in the tallgrass prairie is limited. Significant discussion in this literature has been devoted to how butterflies are affected by development, vegetation cover and diversity, number of floral blooms, prairie management, and patch and landscape characteristics.

With the limited research on green roof butterfly communities in the tallgrass prairie, it is important to assess whether a relatively small, isolated green roof planted with native vegetation in an urban setting can be used as butterfly habitat. The objectives of this chapter are to compare the butterfly abundance, species richness and composition, diversity, and behavior at the green roofs to native prairie and determine which of the vegetation variables from Chapter 2 are influencing each. Two separate studies were completed for the butterfly sampling: 1) a geospatial study, and 2) a modified Pollard walk (Pollard, 1977). The non-spatial Pollard walk study examines species composition, abundance, diversity, richness, and behavior. The geospatial study examines butterfly distribution and the plant-butterfly network. This chapter examines the non-spatial study. Chapter 4 discusses the geospatial study.

3.2 Methods

3.2.1 Field Surveys

I surveyed butterflies along the same transects where plant composition sampling occurred. I documented occurrence and relative abundance of butterflies using a Pollard walk sampling approach every three weeks from early May to late September in 2017 and every two weeks from early May to late September in 2018 (Pollard, 1977). Butterfly sampling generally occurred within a couple days of vegetation sampling. This was a nondestructive study and no butterflies were collected or intentionally harmed. Surveys occurred only when the following conditions were met: between 0800– 1630 (preferably in the morning), cloud conditions were part to full sun (50% or less as used by Clark, Reed, & Chew, 2007), air temperature was >15° C, and wind speeds were <24 kph.

These environmental factors were measured with a Kestrel 2000 Pocket Weather Meter and recorded prior to beginning the butterfly survey. In the event that wind conditions changed substantially during the study, it was again measured and I recorded the highest wind speed. When climatic conditions changed after the butterfly survey had been initiated, (e.g., wind gusts surpassed 24 kph or cloud cover surpassed 50%), I paused the survey until conditions were within protocol.

I walked each transect at a rate of approximately 10 m/minute (Davis, Hendrix, Debinski, Chiara, & Hemsley, 2008) stopping as needed to net, photograph, and identify butterflies present within five meters of the transect, five meters ahead, and within five meters of ground level. The behavior of each sighted butterfly was recorded, whether that be flying through the transect, nectaring, basking, mating, or ovipositing (Myers et al., 2012). Butterflies were identified to the lowest taxonomic level possible in the field, but photos aided in butterfly identification once returned from the field (Swengel, 2012). Because of similarities in appearance among some butterflies and difficulty in identifying on wing (i.e. grass skippers, Azures, and Sulphurs) they were combined into family or subfamily (Beck, 2016; Ogden, 2017).

3.2.2 Statistical Analysis

Butterfly data were organized by day of year to examine seasonal progression. Data were also categorized as early season (sessions 2, 3 ,4, 5, 7, 8, 9, 10, 11, and 12) and late season (sessions 6, 13, 14, 15, and 16). Dependent variables of butterfly abundance, richness, and specialist and generalist butterfly abundance data were not normally distributed, so data were log transformed. They were all skewed to the left due to the frequency of no (0) butterflies found. For statistical comparisons, I used 1) a one-way analysis of variance (ANOVA) to test differences among sites by early and late season; 2) for each response variable I fit a generalized linear model with site, season, and a two-way interaction as fixed effects to test for differences among sites over time; and 3) a stepwise multiple regression analysis was used to determine which combination of vegetation variables best predicted butterfly response variables across all sites. The specialist butterfly abundance data were still not normally distributed even after the log transformation, so a nonparametric test was used to analyze these data, the Kruskal-Wallis test instead of the ANOVA and generalized linear model.

The one-way ANOVA and Kruskal-Wallis tests were computed in R 3.4.3. Graphs with standard error bars were produced in Microsoft Excel Office 365 and Adobe Illustrator CS6. The generalized linear model was computed in SAS 9.4 with a Gaussian distribution using GLIMMIX and LSMEANS procedures to test the null hypothesis that there were no differences in mean butterfly abundance, diversity, and richness among sites and between early and late season.

Due to premature removal of transects, the urban prairie does not have as many sessions as the other sites. The unbalanced nature of the design caused issues within SAS, and estimates for the late season at the urban prairie were not established for butterfly richness and butterfly specialist abundance. To deal with this issue, I refit a generalized linear model for the late season data collected at the native prairie and Memorial Stadium. The model included the fixed effect of site and random effect of session.

I conducted a forward stepwise multiple regression analysis using the stepAIC function in the R 3.4.3 MASS package. This evaluated the significance of each vegetation variable at predicting the butterfly response variables for early and late season abundance, species richness, diversity, specialist butterfly abundance, and generalist butterfly abundance. Independent variables used were blossom index, visual obstruction, litter depth, total plant cover, plant evenness, plant richness, plant Shannon diversity index, larval host plant cover, woody cover, forb cover, graminoid cover, and forbs blooming. Specialist butterflies were defined as those that rely on native prairie plants for larval food or adult nectar; generalists were defined as those that use a variety of common native and non-native plants (Vogel, Koford, & Debinski, 2010).

Prior to the multivariate regression analysis, a Pearson Correlation matrix (see Appendix D: Pearson Correlation Matrix for All Variables) was created in R 3.4.3 to determine whether independent variables were correlated. No variables with correlation coefficients greater than 0.8 were included in the same model to reduce chances of collinearity. Plant Shannon diversity index and plant species richness were correlated (r = 0.93); I removed plant species richness from the analysis. Total plant cover and graminoid cover were correlated (r = 0.83); I removed total plant cover from the analysis. Litter depth and woody cover were correlated (r = 0.90); I removed litter depth from the analysis. Total plant cover and larval host plant cover were correlated (0.76), but both were kept in the analysis because a correlation coefficient of 0.8 was used as the threshold above which correlated variables were removed.

3.3 Results

3.3.1 General Results Across Time

During the Pollard walk study, 1,479 butterflies from at least 29 species were recorded (Table 3.1). Four species of sulphur (dainty sulphur, clouded sulphur, orange sulphur, and cloudless sulphur) were aggregated into sulphurs; grass skippers were not identified to the species level. Abundance was greatest towards the end of the summer for both years (Figure 3.1). There were several taxa seen nearly every session, such as eastern-tailed blues, sulphurs, grass skippers, monarchs, variegated fritillaries, and pearl crescents. Five species were only seen once over the entire study including the coral hairstreak, the eastern tiger swallowtail, the giant swallowtail, the great spangled fritillary, and the southern cloudywing. There were large populations of painted ladies in 2017. However, painted ladies were relatively rare in 2018. Nevertheless, because they were so abundant in 2017, this was the most abundant species overall at greater than 20% of the butterflies seen. Nearly half of the species observed compose less than 1% of all butterflies seen.

All the butterfly variables that were tracked increased throughout the season and peaked at the end of the season (Figure 3.1). The greatest rate of change was for generalist species abundance and least rate of change was for specialist species abundance.

3.3.2 Butterfly Abundance:

The one-way ANOVA showed butterfly abundance differed among sites for both early and late season (Figure 3.2). The greatest mean butterfly abundance for early season occurred at the Memorial Stadium site, while the lowest occurred at the urban prairie site, though there was no difference between the native prairie and urban prairie sites when the data were log-transformed ($F(2,67) = 1.30$, $P = 0.28$; Figure 3.3). The late season mean butterfly abundance at Memorial Stadium was nearly seven times the mean butterfly abundance at the native prairie when data were log-transformed ($F(1,28) = 37.34$, $P < 0.0001$; Figure 3.3). The late season mean abundance at the native prairie was comparable to that of the early season. However, the late season Memorial Stadium mean abundance was greater than six times the mean abundance of the early season, and much more variable.

The general linear model showed a significant interaction between season and site ($F(1,83.85) = 20.86$, $P < 0.0001$; Figure 3.4). Significant simple effects occurred at the Memorial Stadium between early and late season ($t(46.2) = -5.84$, $P < 0.001$), but not at the native prairie. Significant simple effects occurred between the native prairie and Memorial Stadium during the late season ($t(83.61) = -7.1$, $P < 0.001$), but there was no difference between any site during the early season.

A significant regression equation was found for early season butterfly abundance ($F(2,64) = 9.63$, $P < 0.001$), with an r^2 of 0.231 (Table 3.2). It was found that forb cover (β = 0.37, P <0.01) and forbs blooming (β = 0.231, P = 0.046) significantly predicted butterfly abundance. A significant regression equation was found for late season butterfly abundance ($F(2,27) = 23.26$, $P < 0.001$), with an r^2 of 0.633. Woody plant coverage ($\beta = -0.57$, $P < 0.01$) predicted butterfly abundance with a negative relationship, while forb coverage ($\beta = 0.29$, $P = 0.094$) was not a significant predictor of butterfly abundance.

3.3.2.1 Generalist and Specialist Abundance

No tallgrass prairie specialist species were found at Memorial Stadium (Figure 3.5), while both native prairie and urban prairie sites had specialist species. Overall, generalists were much more abundant than specialists. Generalist abundance in the early season was comparable at the native prairie and urban prairie, while Memorial Stadium had approximately twice as many generalists as the other sites (Figure 3.5; $F(2,67) = 4.38$, $P = 0.02$). For late season, Memorial Stadium had approximately seven times the generalist butterflies than the native prairie, though Memorial Stadium generalist abundance was much more variable ($F(1,28) = 20.46$, $P < 0.001$).

The general linear model showed a significant interaction effect for butterfly generalist abundance between site and season ($F(1,83.79) = 20.34$, $P < 0.0001$; Figure 3.6). Significant simple effects occurred at the Memorial Stadium between early and late season ($t(44.96) = -5.84$, $P < 0.001$), but not at the native prairie ($t(22.38) = -1.65$, $P = 0.21$). Significant simple effects occurred between the native prairie and Memorial Stadium during the late season ($t(83.56) = -7.47$, $P < 0.001$), but there was no difference between any site during the early season: native prairie and Memorial Stadium ($t(84.17) = -2.21$, $P = 0.11$); native prairie and urban prairie ($t(87.5) = -0.35$, $P = 0.99$); and Memorial Stadium and urban prairie ($t(87.6) = -2.26$, $P = 0.10$).

A significant regression equation was found for early season butterfly generalist abundance ($F(2,64) = 10.96$, $P < 0.0001$), with an r^2 of 0.26 (Table 3.2). It was found that forb coverage (β = 0.351, $P < 0.01$) and forbs blooming (β = 0.284, $P = 0.01$) were significant predictors for butterfly generalist abundance. A significant regression equation was found for late season butterfly generalist abundance ($F(1,28) = 27.33$, $P < 0.0001$), with an r^2 of 0.67. It was found that woody plant coverage (β = -0.58, $P < 0.001$) significantly predicted butterfly generalist abundance. Forb coverage (β = 0.30, $P = 0.07$) was not a significant predictor for butterfly generalist abundance.

The Kruskal-Wallis Test showed significant differences between sites for early season butterfly specialist abundances ($\chi^2 = 7.02$, $P = 0.03$, df = 2) and late season butterfly specialist abundances ($\chi^2 = 5.15$, $P = 0.02$, df = 1; Figure 3.5). A significant regression equation was found for early season butterfly specialist abundance ($F(3,63) = 6.73$, $P < 0.001$), with an r^2 of 0.24 (Table 3.2). It was found that visual obstruction (β = 0.33, $P = 0.01$), plant evenness (β = -0.38, $P < 0.01$), and graminoid coverage (β = 0.28, $P = 0.05$) significantly predicted butterfly specialist abundance. A significant regression equation was found for late season butterfly specialist abundance ($F(2,27) = 4.66$, $P = 0.02$), with an r^2 of 0.26. It was found that visual obstruction (β = 0.40, $P = 0.03$) significantly predicted butterfly specialist abundance, while plant evenness (β = -0.29, $P = 0.09$) was not a significant predictor.

3.3.3 Butterfly Richness and Species Composition

The one-way ANOVA showed butterfly richness did not differ among sites for the early season (Figure 3.7; $F(2,67) = 0.11$, $P = 0.90$), or for late season (Figure 3.7; $F(1,28) = 3.54$, $P = 0.07$). There was more variability in the late season richness. The general linear model found no significant main effect for early season butterfly richness among sites (Figure 3.8; $F(2,60.32) = 0.11$, $P = 0.90$) or late season butterfly richness among sites ($F(1,24) = 3.82$, $P = 0.06$).

A significant regression equation was found for early season butterfly species richness ($F(5,61) = 5.10$, $P < 0.001$), with an r^2 of 0.30 (Table 3.2). It was found that forb cover ($\beta = 0.47$, $P < 0.001$) significantly predicted butterfly richness, as did plant evenness ($\beta = -0.37$, $P = 0.018$), woody plant coverage ($\beta = 0.27$, $P < 0.05$), and forbs blooming ($\beta = 0.39$, $P = 0.003$). A significant regression equation was found for late season butterfly species richness ($F(2,27) = 5.95$, $P < 0.01$), with an r^2 of 0.31. It was found that forb cover ($\beta = 0.61$, $P < 0.01$) significantly predicted butterfly richness, while forbs blooming ($\beta = -0.29$, $P = 0.11$) was not a significant predictor.

The native prairie site had the most overall butterfly richness with 26 taxa found at the site (Table 3.3). In contrast, Memorial Stadium and the urban prairie each had only 18 taxa. The regal fritillary, a species of conservation concern, was found at both the native prairie and urban prairie sites but not Memorial Stadium. The giant swallowtail was only found at the urban prairie. The viceroy was only found at the native prairie. The gorgone checkerspot was only found at Memorial Stadium. Monarchs, among other generalists, were found at all sites. Photos of several butterflies found at my sites is pictured in Figure 3.9 and Figure 3.10.

3.3.4 Butterfly Diversity

The ANOVA showed mean butterfly diversity was not different in the early season ($F(2,67) = 0.11$, $P = 0.89$), or late season ($F(1,28) = 0.13$, $P = 0.72$; Figure 3.11). The general linear model found no significant main effect for butterfly diversity among sites (Figure 3.12; $F(2,85.37) = 0.27$, $P = 0.76$) or seasons ($F(1,16.01) = 1.07$, $P = 0.32$), and no interaction effect ($F(1,83.12) = 0.01$, $P = 0 .94$).

A significant regression equation was found for early season butterfly diversity ($F(3,63) = 5.55$, $P < 0.01$), with an r^2 of 0.21. It was found that larval host coverage ($\beta = 0.43$, $P <$

0.001), forbs blooming ($\beta = 0.38$, $P < 0.01$), and plant evenness ($\beta = -0.29$, $P = 0.03$) significantly predicted butterfly diversity (Table 3.2). A significant regression equation was found for late season butterfly diversity ($F(1,28) = 6.01$, $P = 0.02$), with an r^2 of 0.18. It was found that blossom index ($\beta = 0.42$, $P = 0.02$) significantly predicted butterfly diversity.

3.3.5 Butterfly Behavior

The proportion of butterflies flying was comparable at the native prairie and urban prairie sites, with flying being 60% of the total behavior observed at the native prairie and 58% at the urban prairie (Figure 3.13). Conversely, only 19% of the butterflies observed at Memorial Stadium were flying. The greatest proportion of nectaring behavior was observed at Memorial Stadium (61%), while very little nectaring behavior was observed at the urban prairie site (8%), and 25% of butterflies observed at the native prairie were nectaring. However, the greatest proportions of basking and perching behavior were observed at the urban prairie transects (34%). The least amount of basking behavior, proportionately, was observed at the native prairie site (14%), with 20% of butterflies observed at Memorial Stadium were basking.

3.4 Discussion

I compared the butterfly communities of two green roofs at Memorial Stadium, to native and urban prairie. The goal of this study was to understand whether these green roofs provide urban butterfly habitat and which on-site vegetation factors affect the butterfly community, so the roofs can be managed to improve the quality of that habitat. The indicators I used to evaluate the butterfly community were abundance (including for generalist and specialist butterflies), richness, diversity, and behavior. I found that Memorial Stadium did not support the same butterfly community that native prairie did, but the community it supported was noteworthy. Its butterfly community was more abundant than native prairie, composed entirely of generalists, consisted of the same mean species richness and diversity as the native prairie sites, and largely served as a source of food for foraging butterflies. Vegetation factors that tended to best predict butterfly abundance, richness, and diversity of all my sites were forb coverage and forbs blooming, while plant evenness was the most common negative predictor. There are many other variables that influence butterfly use of a green roof not covered by this study. While Memorial Stadium does not replace the need for native tallgrass prairie for specialist butterflies, this study indicates that it is possible to support butterflies in an urban setting within the tallgrass prairie landscape on a native plant green roof.

3.4.1 Butterfly Abundance

Memorial Stadium exhibited significantly greater abundance than the other sites for the late season, though the butterflies present there were all generalists. This study found that butterfly abundance increased with greater forb coverage and the number of species of forbs blooming and decreased with increasing coverage of woody vegetation.

Some studies have found a correlation between butterfly abundance and forb coverage. Hardy & Dennis (1999) found that butterfly species abundance declined with increasing urban cover as a result of reduced numbers of host plants and nectaring plants, with nectaring plants being more important. Similarly, a study comparing butterfly responses to various prairie restoration practices (i.e., burning and grazing) found a positive relationship between butterfly abundance and forb coverage (Vogel et al., 2007). Myers et al. (2012) compared butterfly communities of four different vegetation types (a switchgrass mix, a warm-season grass mix, a biomass mix, and a prairie mix) in Iowa. Their results show a significant relationship between the number of butterflies and forb blossoms (Myers et al., 2012).

During 2018, there was an intensive drought at Manhattan, Kansas, through mid-August. Because Memorial Stadium was irrigated, it kept producing floral resources in the early season while the native prairie site was not irrigated and did not produce as many floral resources as Memorial Stadium in the early season. This could have made Memorial Stadium attractive for butterflies. By late season, when the other study areas received precipitation, the native prairie had the same blossom index as the Memorial Stadium. However, during the drought, the deep litter layer at the native prairie site may have increased productivity over nearby surrounding sites at the research station that were recently burned or grazed and did not have the deep litter layer (Knapp & Seastedt, 1986). This could have resulted in more nectaring plants at my native prairie sites than the other nearby burned or grazed prairie around my study sites, thereby attracting butterflies and possibly influencing results.

Results for overall butterfly abundance were essentially identical to those for the generalist species because they made up most of the species observed. There were no habitat specialist butterfly species found at Memorial Stadium, while they were observed at other sites. My models indicated that in terms of specialist species abundance, specialist butterflies responded positively to increased visual obstruction and graminoid coverage, while responding negatively to plant evenness. In addition, woody plant cover was negatively associated with overall butterfly abundance during the late season. However, these factors could be just artefacts of the native prairie site. Even if Memorial Stadium had greater visual obstruction and graminoid coverage and less plant evenness and woody coverage, the green roof may still not be specialist habitat. Other studies indicate that habitat fragmentation and habitat size are important factors driving the specialist butterfly communities and overall abundance (Baguette & Stevens, 2013), so it could be that on-site vegetation factors are less important than the location and size of the green roof.

3.4.2 Butterfly Richness

Memorial Stadium mean butterfly richness did not statistically differ from the other sites; however, when considering overall butterfly richness, the native prairie had the greatest number of species. I found that forb and woody plant coverage, as well as number of species of forbs blooming, could best predict the number of butterfly species found at each site, while plant evenness was negatively associated with butterfly richness. Forb cover could best predict the number of late season butterfly species.

Studies of butterfly richness have found mixed results. In the tallgrass prairie of Manitoba, Canada, a recent study of butterflies along urban rights-of-way showed that available vegetation characteristics such as forb cover and vegetation height were greater predictors of butterfly abundance and richness than the density of urban development (Leston & Koper, 2017). Conversely, Clark et al. (2007), in Massachusetts, suggested that green space and number of forbs in bloom had a positive relationship with butterfly richness, similar to my results.

It seems intuitive that my blossom index, or number of blossoms, would be positively correlated with butterfly richness. For example, an Iowa study comparing remnant prairie with reconstructed prairie found that the number of blossoms and percent cover of litter were the greatest vegetation predictors of butterfly species richness. (Shepherd & Debinski, 2005). However, I did not find a significant relationship between number of blossoms and butterfly species richness. Researchers analyzing Kansas prairie restoration and native prairie sites give a possible explanation as to why number of blossoms was not a significant predictor. These authors attributed this lack of significance to the fact that some existing vegetation was not important nectar or host plants for butterflies (Debinski & Babbit, 1997). Similarly, density of regal fritillary (*Speyeria idalia*) butterflies has been linked to density of their preferred nectar sources (Moranz, Fuhlendorf, & Engle, 2014). It is likely that forbs blooming at some of my sites were not desirable nectar sources for some species of butterflies. If I had counted blossoms of only those forb species typically pollinated by butterflies, blossom index may have been more significant in my models. These results suggest that for improving butterfly richness at the Memorial Stadium, all floral resources are not equal and that preferred nectar sources should be planted, such as *Asclepias tuberosa*, *A. verticillata*, *Liatris aspera*, and *Vernonia baldwinii*.

3.4.3 Butterfly Diversity

Mean butterfly diversity at each site did not significantly differ, while overall diversity was greatest at the native prairie site. I found larval host coverage to be the greatest predictor of butterfly diversity for early season, with the number of forb species blooming also predicting butterfly diversity, and plant evenness a significant negative predictor. Blossom index was the only significant predictor of late season butterfly diversity.

Increasing diversity of plants is generally associated with greater diversity of animals because there is less competition among species to obtain their food (Tallamy, 2007). Memorial Stadium and native prairie sites had similar plant Shannon diversity, while the urban prairie had much greater diversity. Therefore, it is expected that urban prairie would have much greater butterfly diversity than the other two sites. This did not happen, and the shortened sampling period at the urban prairie may be the reason I did not measure greater butterfly diversity there. Different species of butterflies have different flight periods (Sekar, 2012), so the butterflies active during the late season were not included in the butterfly species diversity. Overall butterfly richness at the native prairie could have been greatest because the native prairie also had the greatest overall plant diversity. It also could be the result of increased coverage of invasive species at Memorial Stadium, which has been found to decrease pollinator diversity (Moron et al., 2009). Plants at the native prairie site tended to grow in larger patches, suggesting that the scale of the sampling plot relative to overall study area might be a factor contributing to this anomaly.

Other studies have indicated the importance of larval host plants for occurrence of butterflies using a site. Specialist butterflies have been shown to use habitat where their host is located making it unlikely for them to disperse to locations without their habitat (Sekar, 2012). The regal fritillary occurrence is correlated with its host plant, violets (Debinski & Kelly, 1998). The Fender's blue exists only near its larval host plants, lupine (Schultz & Dlugosch, 1999). One study, however, in boreal grasslands of Sweden found that sward height (what I am terming "visual obstruction"), flower abundance, and plant species composition were the greatest predictors of butterfly diversity (Bergman et al., 2008). This partially agrees with my findings: number of forbs blooming and blossom index were similar indicators to flower abundance. Interestingly, my study found visual obstruction was the greatest predictor of butterfly specialist abundance. Therefore, you would expect visual obstruction to be a predictor of butterfly diversity, as well. However, this did not hold true in my study.

Many other studies measuring butterfly diversity found landscape scale factors to be important. For example, a California study at 10 sites tracked butterfly species diversity over a period of 35 years. Their results suggest that reductions in diversity at lower elevations is attributed to habitat disturbance and fragmentation, as well as climate change (Forister et al., 2010). This suggests that if landscape-scale factors (such as surrounding vegetation, fragmentation, and roads) were included in analyses, models of diversity could be improved.

3.4.4 Butterfly Behavior

Most butterflies were using Memorial Stadium to forage. Conversely, the majority of butterflies at other sites were flying through. These behaviors could be attributed to limitation and distribution of floral resources at the other sites. It could also be indicative of other factors not included in my study.

I hypothesize that these behaviors at the Memorial Stadium indicate that it is a destination for butterflies, possibly because of the higher density of native nectar in that area of town. Whereas at my other study sites, butterflies are surrounded by floral resources that are less concentrated. Therefore, there is not the density of butterflies at the native prairie sites because the floral rewards they seek are more evenly distributed across the landscape. When considering energy expended, foraging for nectar is costly as butterflies are required to move between flowers and patches of flowers. Where they can increase nectar intake and limit locomotion, they will reduce energy costs (Willmer, 2011). Other nearby urban gardens such as The Meadow and International Student Center Rain-Garden could also be attracting butterflies into the K-State campus area. In addition, because landscapes around native prairie sites are managed differently (i.e., nearby areas are grazed and burned) there could be better or additional floral resources nearby, reducing the dependence of the butterflies on the particular area where the transects were located at the native prairie sites, meaning that this study could have underestimated butterflies at the native and urban prairie.

There are many factors not included in my study that could affect behavior of butterflies at each of my sites. Learning and dispersal ability may explain the patterns of butterfly behavior at each site. Some butterflies, such as Heliconius, have the ability to learn to navigate and remember routes to roosts and feeding sites using landmarks (Mallet, Longino, Murawski,

Murawski, & Simpson De Gamboa, 1987). Memorial Stadium has only been installed recently, and over time, more butterflies may be able to find and use the green roofs. The dispersal ability of butterflies is highly variable and dependent on factors such as wingspan, flight period, and habitat specificity (Sekar, 2012). Additional study examining the learning and dispersal ability of species-specific behaviors of butterflies using Memorial Stadium could better inform these behavior patterns.

In conclusion, many studies examining butterflies in urban areas found additional factors influencing butterfly habitat. Habitat area and context (Krauss & Steffan-Dewenter, Ingolf Tscharntke, 2003), fragmentation (Benvenuti, 2014; Summerville & Crist, 2001), urbanization (Bergerot, Fontaine, Renard, Cadi, & Julliard, 2010; Hardy & Dennis, 1999) and habitat availability (Angold et al., 2006) all appear to be important. Although these factors are out of scope for my study, they merit further investigation if better butterfly habitat is to be made available in urban environments on green roofs or by way of other green infrastructure.

In a world actively searching for ways to reduce biodiversity losses, green roofs can help support urban biodiversity, but only partially. These roofs do not replace the biodiversity or grassland specialists supported by native prairie, hence the need to preserve the remnants of the tallgrass prairie. Results from my study indicate that management and design of the green roof to increase butterfly abundance should focus on maintaining forb health to promote floral resources. It could also involve removing woody vegetation, increasing aboveground biomass and grass coverage, adding specialist larval host plants, and promoting some dominant plants. In order to do this, it is essential that the irrigation system be maintained so the vegetation can grow unstressed in the shallow substrates. Overseeding of some grasses and forbs could help fill in the bare ground, provide competition for the invasive plants growing on the roof, and add more seasonal floral resources. In combination with other types of urban green infrastructure, green roofs can certainly help provide habitat for butterflies and other important pollinators.

3.5 Tables

Table 3.1. Butterflies identified by session at native prairie, Memorial Stadium, and urban prairie during 2017 and 2018.

Common Name	**Scientific Name**	**Number Counted Each Session**															**Total**	**Proportion of Total**
	Session	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
Painted Lady[g]	*Vanessa cardui*	0	0	95	30	172	0	0	6	0	0	0	0	1	9	3	**316**	0.21
Grass Skipper spp. [g,s]	Family Hesperiidae, Subfamily: Hesperiinae	2	1	9	12	3	3	3	7	0	2	6	4	13	121	59	**245**	0.17
Eastern Tailed Blue[g]	*Everes comyntas*	24	7	3	7	11	25	6	13	10	11	7	54	31	6	4	**219**	0.15
Sulphur spp. [g]	*Colias* spp. and *Nathalis iole*	12	10	12	8	11	1	3	7	4	20	10	9	21	49	31	**208**	0.14
Silver Spotted Skipper [g]	*Epargyreus clarus*	0	0	1	0	0	2	2	0	0	0	2	0	0	103	25	**135**	0.09
Monarch[g]	*Danaus plexippus*	1	3	3	6	2	1	0	1	3	0	2	5	7	5	14	**53**	0.04
Variegated Fritillary[g]	*Euptoieta claudia*	2	4	3	4	0	1	0	6	4	3	7	0	4	4	6	**48**	0.03
Pearl Crescent[g]	*Phyciodes tharos*	4	2	1	0	2	0	0	11	11	1	2	0	2	2	1	**39**	0.03
Wild Indigo Duskywing[g]	*Erynnis baptisiae*	4	2	3	3	1	0	0	2	3	3	0	1	2	5	8	**37**	0.03
Gray Hairstreak[g]	*Strymon melinus*	1	0	0	0	0	0	0	4	2	2	0	0	4	20	2	**35**	0.02

Common Name	Scientific Name	Number Counted Each Session															Total	Proportion of Total
Common Wood Nymph[s]	*Cercyonis pegala*	0	8	1	2	1	0	0	0	0	7	2	3	8	0	1	**33**	0.02
Azure spp. [g]	*Celastrina ladon* and *Celastrina neglecta*	0	1	5	4	9	1	0	0	0	0	0	0	1	0	0	**21**	0.01
Regal Fritillary[s]	*Speyeria idalia*	5	1	0	2	0	0	0	1	5	2	3	0	2	0	0	**21**	0.01
Buckeye[g]	*Junonia coenia*	0	0	0	0	2	0	0	0	0	0	0	0	1	1	11	**15**	0.01
Reakirt's Blue[g]	*Hemiargus isola*	0	0	0	0	0	11	0	0	1	0	0	0	0	0	0	**12**	0.01
Common Checkered Skipper[g]	*Pyrgus communis*	0	0	0	0	0	1	0	0	2	0	0	0	1	2	1	**7**	<0.01
American Lady[g]	*Vanessa virginiensis*	0	1	0	0	0	0	0	3	1	0	0	0	0	1	0	**6**	<0.01
Black Swallowtail[g]	*Papilio polyxenes*	0	0	0	0	0	0	0	0	0	2	1	0	0	0	1	**4**	<0.01
Gray Copper[s]	*Lycaena dione*	0	0	0	0	0	0	0	1	2	0	1	0	0	0	0	**4**	<0.01
Red Admiral[g]	*Vanessa atalanta*	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	**4**	<0.01
Silvery Checkerspot[g]	*Chlosyne nycteis*	0	0	0	0	0	0	0	0	0	0	0	1	0	2	1	**4**	<0.01
Cabbage	*Pieris rapae*	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	**3**	<0.01

Common Name	Scientific Name	Number Counted Each Session															Total	Proportion of Total
White[g]																		
Gorgone Checkerspot[g]	*Chlosyne gorgone*	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	**3**	<0.01
Viceroy[s]	*Limenitis archippus* and *Basilarchia archippus*	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	**2**	<0.01
Coral Hairstreak[s]	*Satyrium titus*	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**	<0.01
Eastern Tiger Swallowtail[g]	*Papilio glaucus*	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**	<0.01
Giant Swallowtail[g]	*Papilio cresphonte*	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**	<0.01
Great Spangled Fritillary[s]	*Speyeria cybele*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**	<0.01
Southern Cloudywing[g]	*Thorybes bathyllus*	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**	<0.01

g = Generalist Species s = Grassland specialist species as defined by Vogel, Koford, & Debinski, 2010.

Table 3.2. Stepwise multiple regression results for native prairie, urban prairie, and Memorial Stadium (May through September 2017 and 2018)

Dependent Variable	Season	Independent Variables[1]	Standardized Coefficient (β)	Model R^2
Butterfly Abundance	Early	Forb Coverage	0.366**	0.231***
		Forbs Blooming	0.231*	
	Late	Woody Plant Coverage	-0.567**	0.633***
		Forb Coverage	0.286	
Generalist Abundance	Early	Forb Coverage	0.351**	0.255***
		Forbs Blooming	0.284**	
	Late	Woody Plant Coverage	-0.582***	0.669***
		Forb Coverage	0.296	
Specialist Abundance	Early	Visual Obstruction	0.328**	0.243***
		Plant Evenness	-0.376**	
		Graminoid Coverage	0.276*	
	Late	Visual Obstruction	0.395*	0.257*
		Plant Evenness	-0.291	
Butterfly Richness	Early	Forb Coverage	0.473***	0.295***
		Plant Evenness	-0.369**	
		Woody Plant Coverage	0.271*	
		Forbs Blooming	0.389**	
	Late	Forb Coverage	0.607**	0.306**
		Forbs Blooming	-0.290	
Butterfly Diversity	Early	Larval Host Coverage	0.430***	0.209**
		Forbs Blooming	0.384**	
		Plant Evenness	-0.287*	
	Late	Blossom Index	0.420*	0.177*

[1] Independent variables tested in models are: forbs blooming, forb coverage, woody plant coverage, larval host coverage, plant evenness, visual obstruction, and blossom index.
* $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

Table 3.3. Butterfly species composition found at site transects (May through September 2017 and 2018).

Common Name	Scientific Name	Memorial Stadium	Native Prairie	Urban Prairie
American Lady[g]	*Vanessa virginiensis*	✓	✓	✓
Azure sp[g]	*Celastrina ladon*	✓	✓	✓
Black Swallowtail[g]	*Papilio polyxenes*		✓	
Buckeye[g]	*Junonia coenia*	✓	✓	
Cabbage White[g]	*Pieris rapae*	✓	✓	
Checkered Skipper[g]	*Pyrgus communis*	✓	✓	✓
Common Wood Nymph[s]	*Cercyonis pegala*		✓	✓
Coral Hairstreak[s]	*Satyrium titus*		✓	
Eastern Tailed-Blue[g]	*Everes comyntas*	✓	✓	✓
Eastern Tiger Swallowtail[s]	*Papilio glaucus*			✓
Giant Swallowtail[s]	*Papilio cresphonte*			✓
Gorgone Checkerspot[g]	*Chlosyne gorgone*	✓		
Grass Skipper sp[g]	*Family: Hesperiidae, Subfamily: Hesperiinae*	✓	✓	✓
Gray Copper[s]	*Lycaena dione*		✓	
Gray Hairstreak[g]	*Strymon melinus*	✓	✓	✓
Great Spangled Fritillary[s]	*Speyeria cybele*		✓	
Monarch[g]	*Danaus plexippus*	✓	✓	✓
Painted Lady[g]	*Vanessa cardui*	✓	✓	✓
Pearl Crescent[g]	*Phyciodes tharos*	✓	✓	✓
Reakirt's Blue[g]	*Hemiargus isola*	✓	✓	✓
Red Admiral[g]	*Vanessa atalanta*	✓	✓	
Regal Fritillary[s]	*Speyeria idalia*		✓	✓
Silver Spotted Skipper[g]	*Epargyreus clarus*	✓	✓	✓
Silvery Checkerspot[g]	*Chlosyne nycteis*		✓	
Southern Cloudywing[g]	*Thorybes bathyllus*		✓	
Sulphur sp[g]	*Family: Pieridae, Subfamily: Coliadinae*	✓	✓	✓
Variegated Fritillary[g]	*Euptoieta claudia*	✓	✓	✓
Viceroy[s]	*Limenitis archippus and Basilarchia archippus*		✓	
Wild Indigo Duskywing[g]	*Erynnis baptisiae*	✓	✓	✓
	Total Taxa	18	26	18

NOTES:
g = generalist species and s = grassland specialist species as defined by Vogel, Koford, & Debinski, 2010.

3.6 Figures

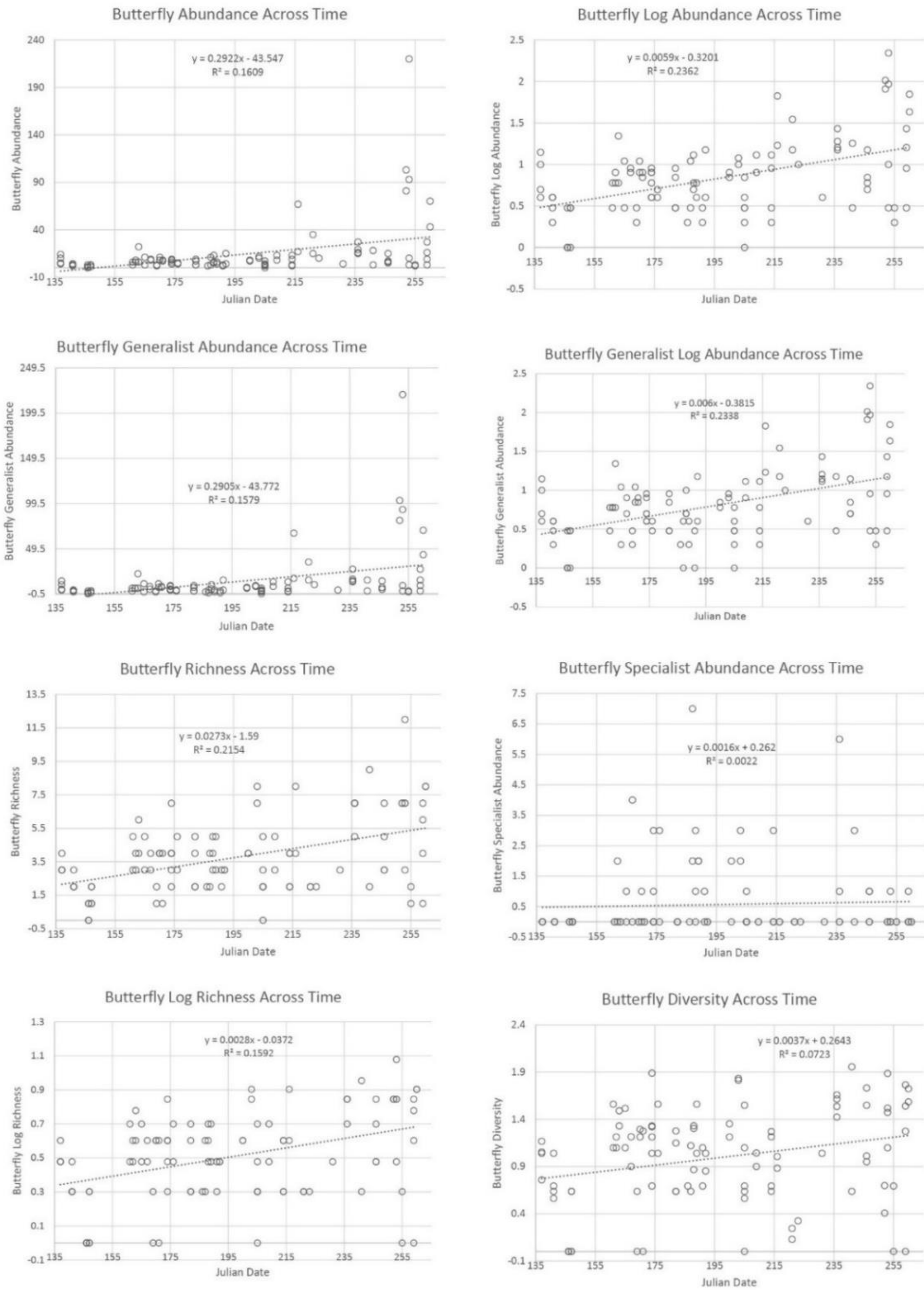

Figure 3.1. Butterfly abundance, richness, diversity, generalist abundance, and specialist abundance from May to September 2017 and 2018 at the urban prairie, native prairie, and Memorial Stadium transects.

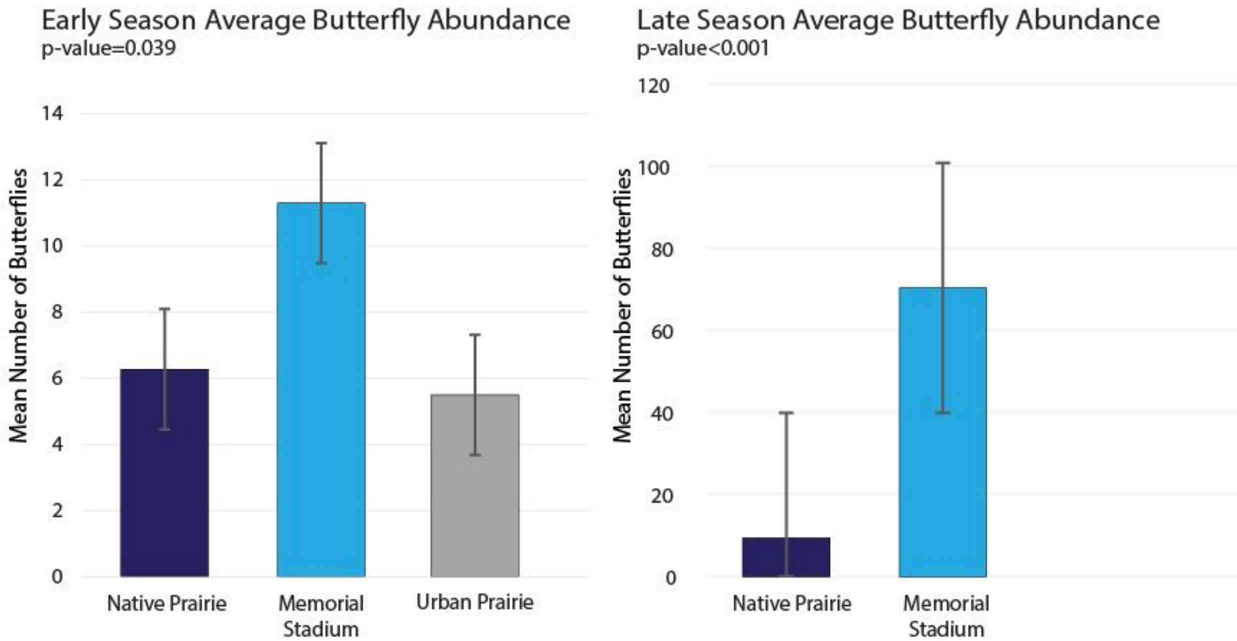

Figure 3.2. Early and late season mean butterfly abundance for 2017 and 2018 with error bars and ANOVA P-values at native prairie, Memorial Stadium, and urban prairie.

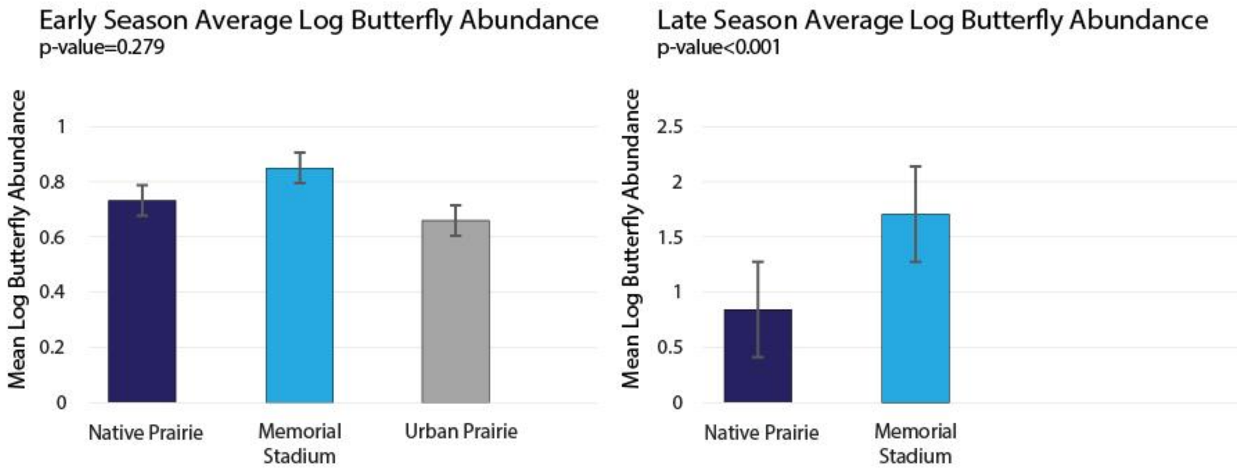

Figure 3.3. Early and late season log-transformed mean butterfly abundance for 2017 and 2018 with ANOVA P-values and error bars.

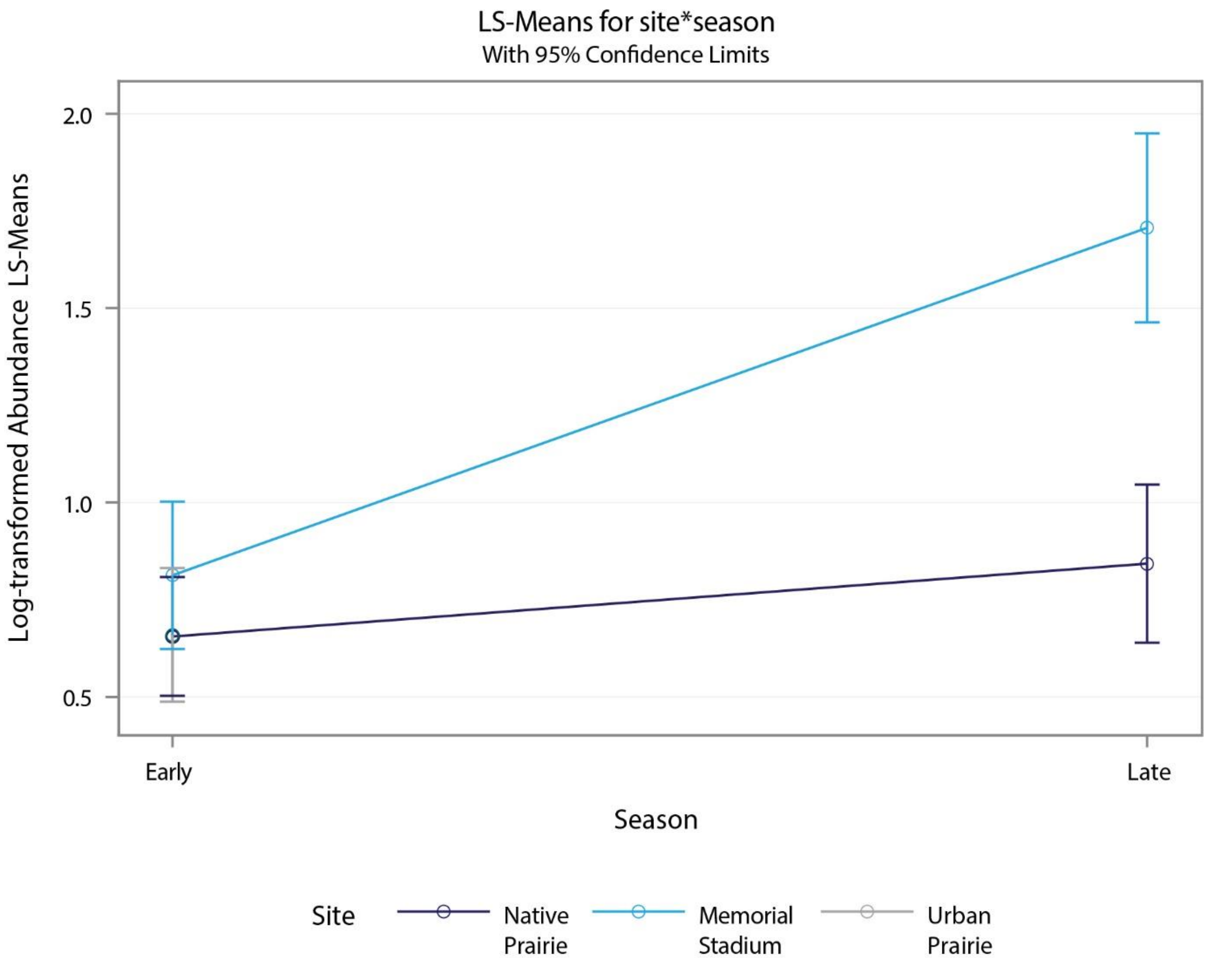

Figure 3.4. LS-Means for log-transformed butterfly abundance with 95% confidence intervals from general linear model 2017 and 2018 at native prairie, urban prairie, and Memorial Stadium.

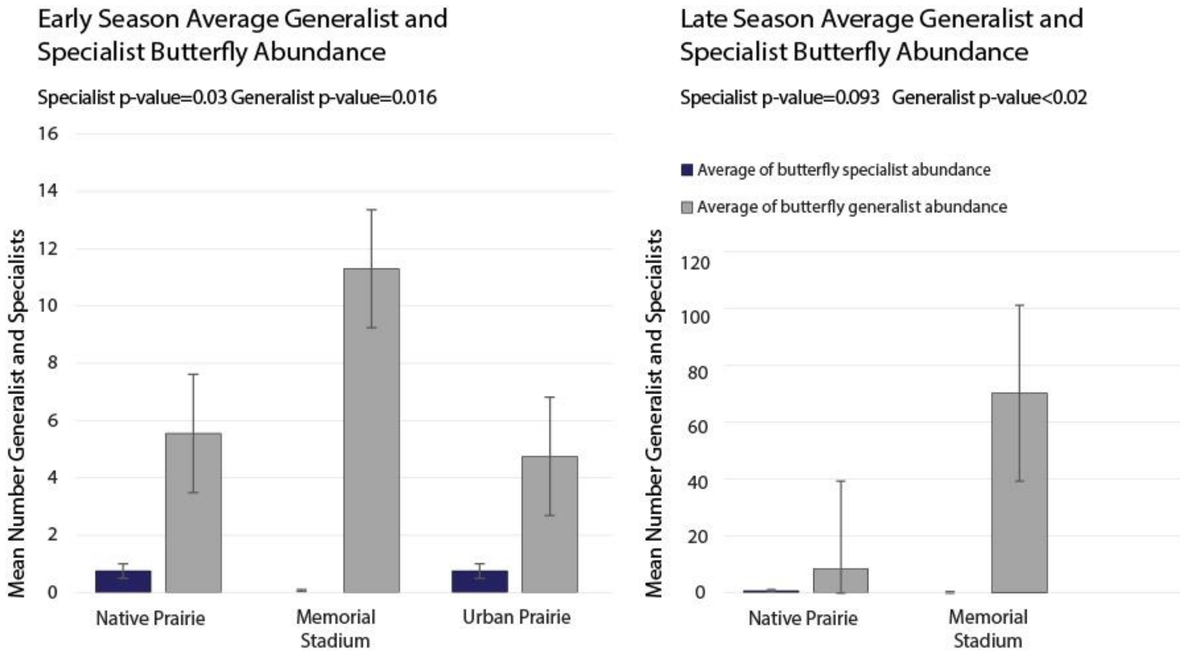

Figure 3.5. Early and late season mean generalist and specialist butterfly abundance with generalist ANOVA P-values and error bars and specialist Kruskall-Wallis P-values; 2017 and 2018 at the native prairie, Memorial Stadium, and urban prairie sites.

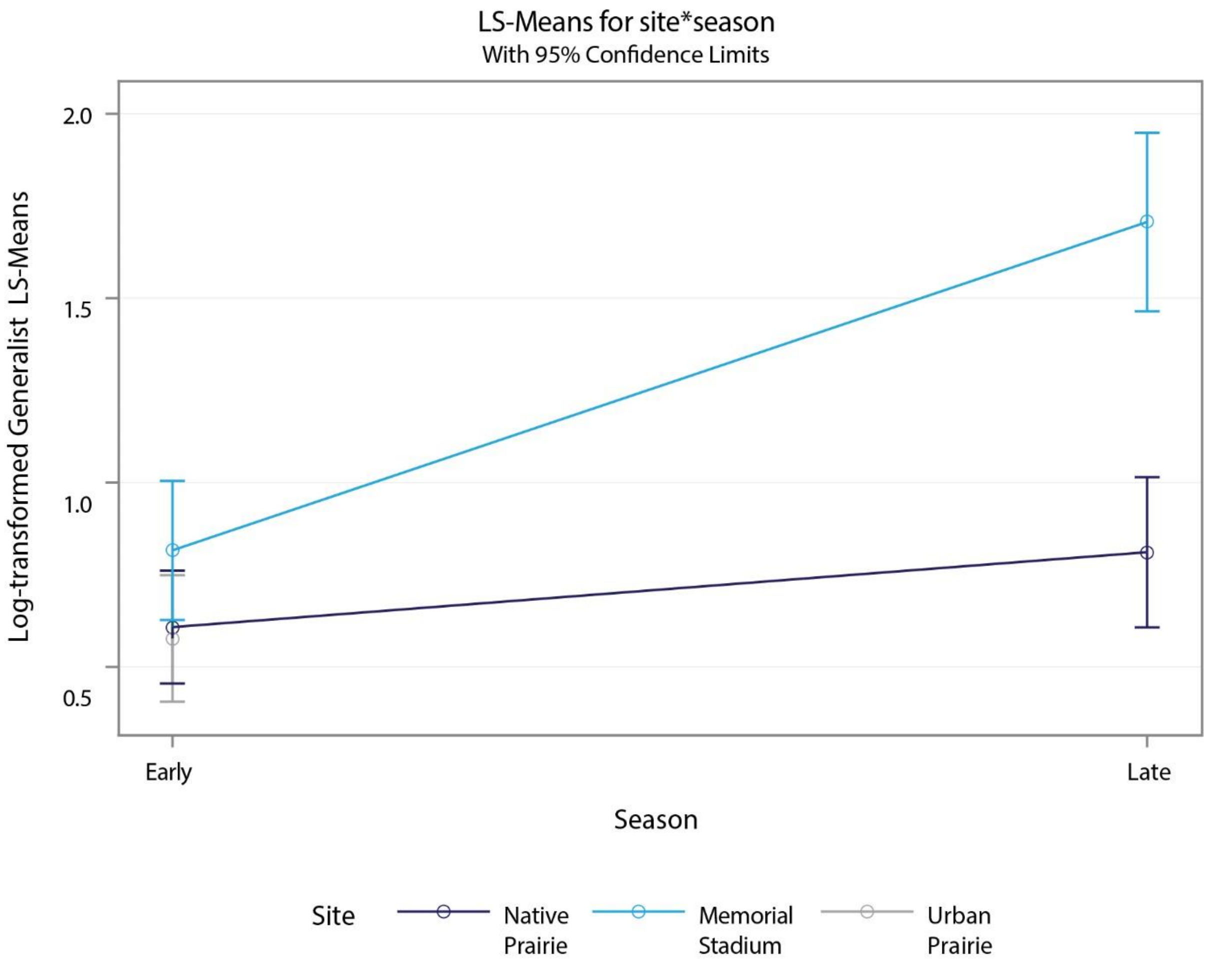

Figure 3.6. LS-means for log-transformed generalist butterfly abundance with 95% confidence intervals from general linear model 2017 and 2018 at native prairie, Memorial Stadium, and urban prairie.

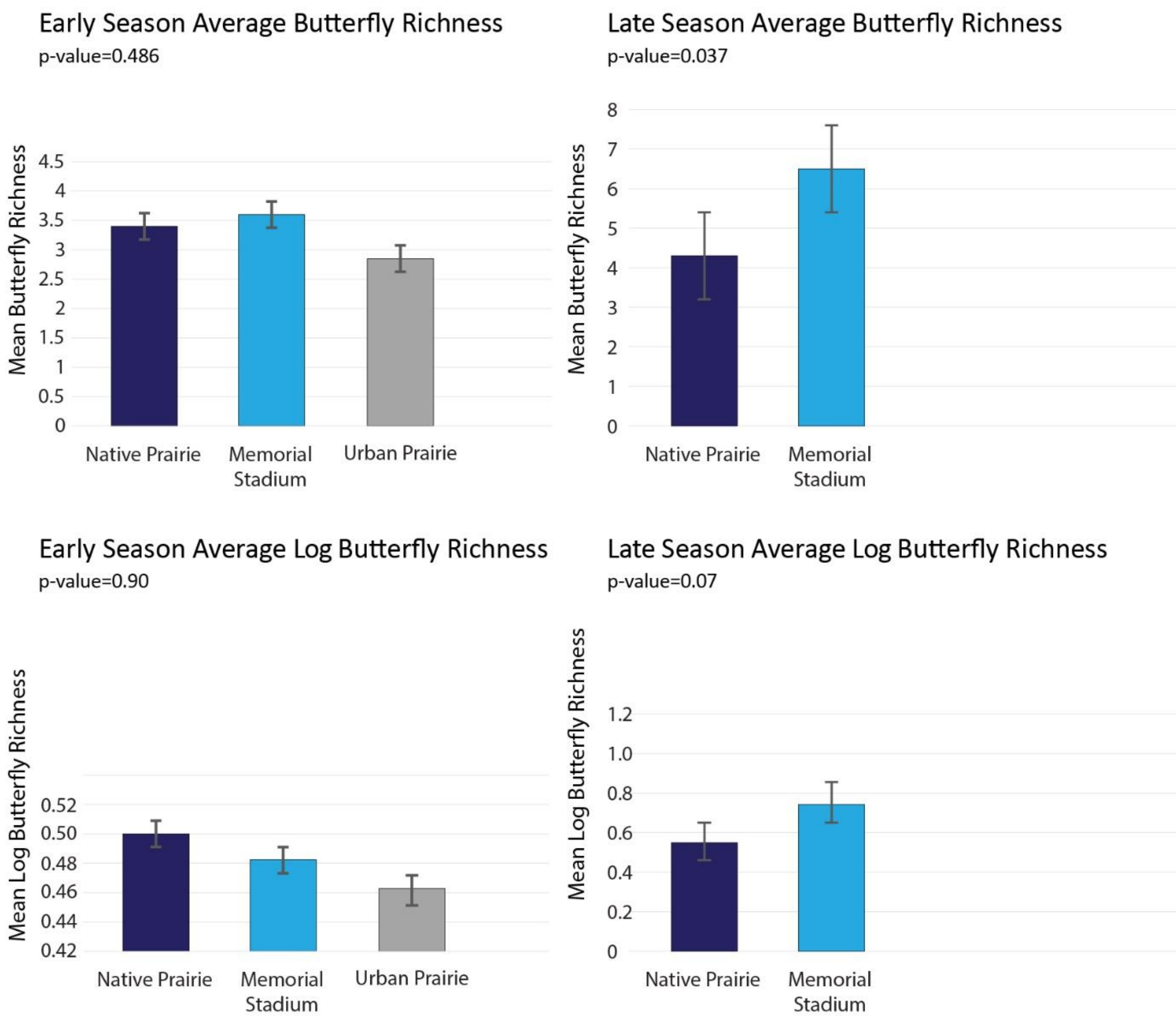

Figure 3.7. Early and late season mean butterfly richness and mean log butterfly richness with ANOVA P-values and error bars; 2017 and 2018 at native prairie, Memorial Stadium, and urban prairie.

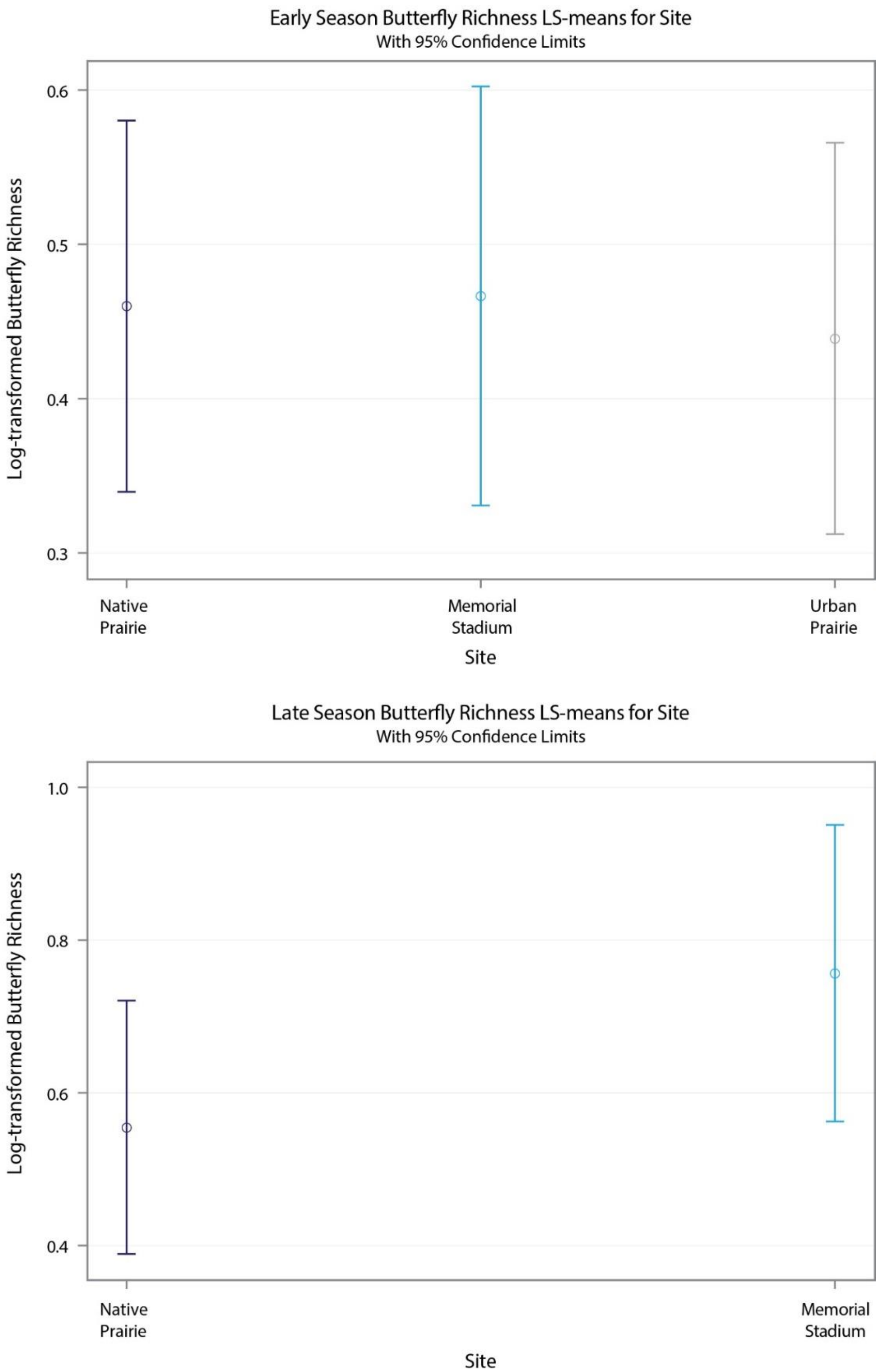

Figure 3.8. LS-means for log-transformed butterfly richness with 95% confidence intervals from general linear model 2017 and 2018 at native prairie, Memorial Stadium, and urban prairie.

Figure 3.9. Butterfly species composition photos from all sites.

Figure 3.10. Butterfly species composition photos from all sites.

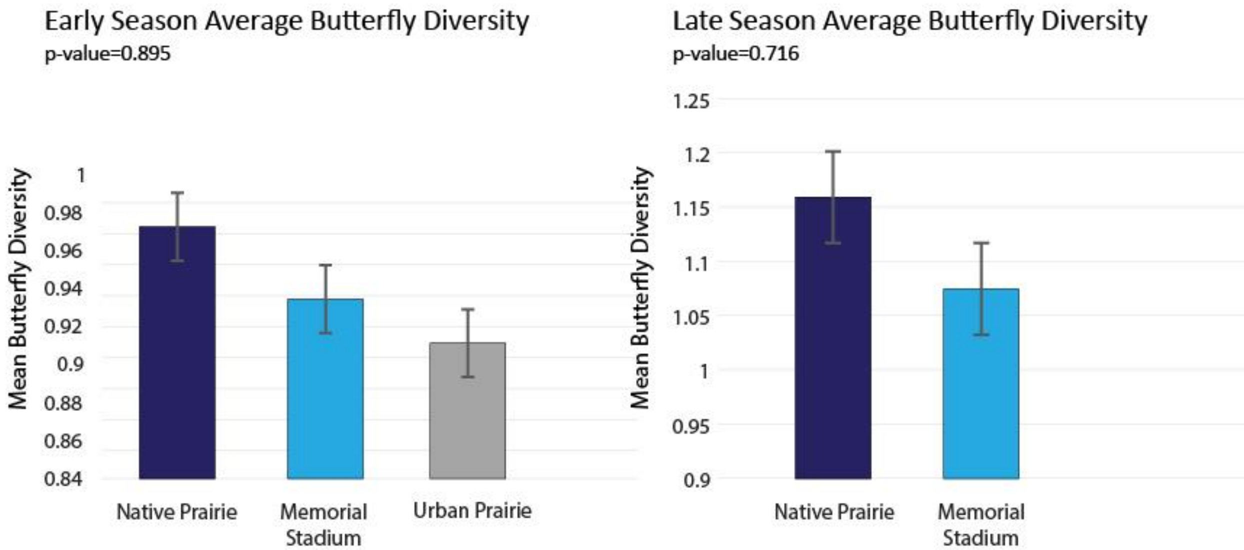

Figure 3.11. Early and late season mean butterfly diversity with ANOVA P-values and error bars; 2017 and 2018 at native prairie, Memorial Stadium, and urban prairie.

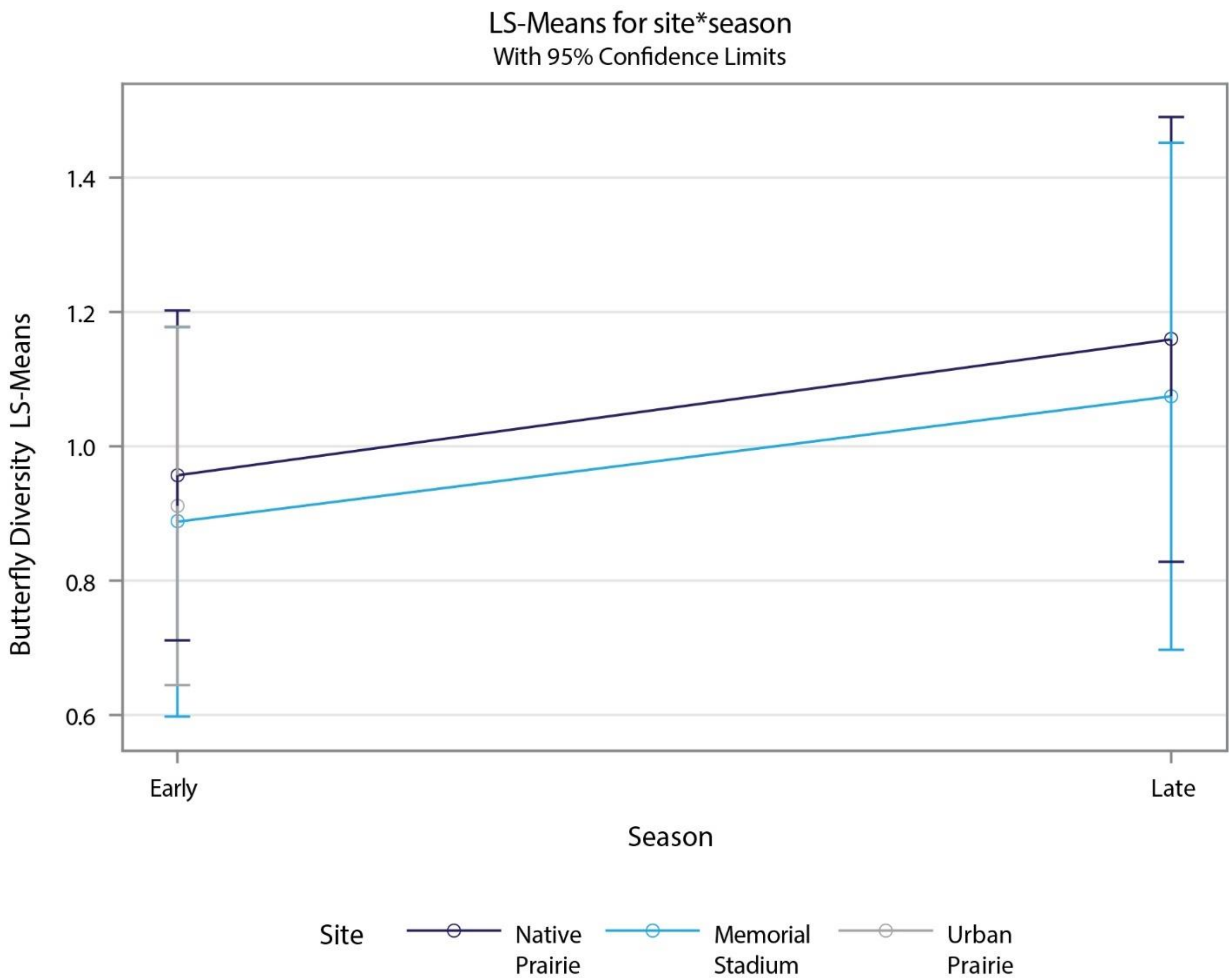

Figure 3.12. LS-means for butterfly diversity with 95% confidence intervals from general linear model; 2017 and 2018 at native prairie, Memorial Stadium, and urban prairie.

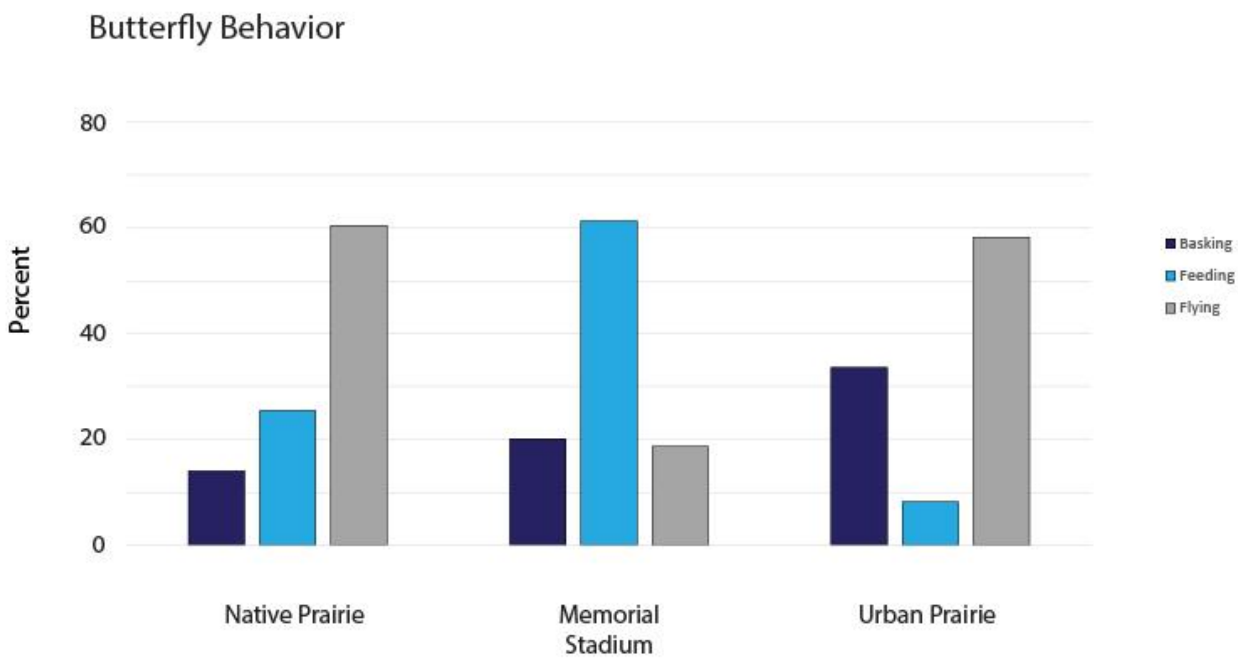

Figure 3.13. Butterfly behavior percentages for native prairie, Memorial Stadium, and urban prairie for 2017 and 2018.

Chapter 4 – Butterfly Spatial Distribution and Plant-Butterfly Interactions and Networks

4.1 Introduction

Greater than 300,000 plant species and 200,000 invertebrates participate in plant-pollinator interactions around the world (Burkle & Alarcón, 2011). Given that most plants can only reproduce sexually through pollination, this relationship is important to maintain plant genetic diversity and evolutionary change (Kearns, Inouye, & Waser, 1998). Even though bees are credited with being the primary pollinators, Lepidopterans, with elongated tongues and pollen-collecting scales and hair on their body (the name meaning “scaled wings”), are also essential pollinators (Willmer, 2011). For example, one study found that *Dianthus carthusianorum* is specialized for lepidoptera pollinators to the extent that the plant could be at risk if two vulnerable butterfly populations declined (Bloch, Werdenberg, & Erhardt, 2006).

Pollination is an example of a mutualism: an interaction in which both partners benefit (Willmer, 2011). Butterflies rely on plants to complete their life history processes, and similarly plants rely on pollination services from butterflies and other organisms. Many mutualisms, including pollination, can only take place if both participants can locate each other in space during the critical time for pollination to occur (Rafferty, CaraDonna, & Bronstein, 2015). In this chapter, I examine which butterflies were able to find which plants and their locations along the native prairie, urban prairie, and Memorial Stadium transects.

For this chapter, I conducted one observational study and am using the data obtained from it in two separate ways: 1) creation of a butterfly-plant visitor network for each transect and 2) conducting GIS spatial analyses including a hotspot analysis and a ordinary least squares analysis. Each of these analyses provide an alternative way to investigate my research questions:

how the butterfly community of Memorial Stadium compares to native and urban prairie and how on-site vegetation composition influences butterfly species richness, distribution, behavior, and abundance. Specifically, each butterfly-plant visitor network uses indices to evaluate how on-site vegetation composition influences species richness and abundance, as well as behavior, across sites. The GIS analyses seek to understand how on-site vegetation composition influences butterfly distribution along each transect.

Plant-pollinator bipartite networks are a way to document all of the interactions between plants and their visitors in a community (Willmer, 2011). In ecology, bipartite networks allow one to analyze the interaction of two trophic levels. (C. F. Dormann, Fründ, Blüthgen, & Gruber, 2009). In my study, this was the interaction between butterflies and plants. Topology describes the structure of these networks. Because I did not track all pollinators, I created plant-butterfly networks that document only butterfly visitation to plants. While traditional plant-pollinator networks track pollination only, I included all butterfly interactions with plants including mating, ovipositing, and resting or basking, in addition to nectaring. I did this because I was interested in all butterfly-plant interactions at my sites.

My main interest in understanding the plant-butterfly network was to see if there were plant species receiving preferential use by particular species of butterflies. If there were preferred plants, these plants could be added to green roofs to attract species of butterflies absent from the roofs. However, other interests in plant-butterfly networks were the numerous indices that can be used to describe plant-pollinator network topology and help understand how interactions and community processes compare across my sites.

One of the primary concerns of basic and applied ecology is linking ecological processes to spatial patterns (Vinatier, Tixier, Duyck, & Lescourret, 2011). I was interested in the spatial distribution of butterflies to see if areas of my sites received higher butterfly use than other areas, and then see which vegetation variables predicted spatial distribution. With my tabular vegetation data, I averaged my data across the entire transect. However, with the spatial data, one can see the spatial heterogeneity that is or is not present at each site. Understanding which areas of a green roof are under-utilized by butterflies and what factors are contributing can help target maintenance improvements.

4.2 Methods

4.2.1 Field Surveys

I walked the length of the 5-meter-wide transect locating butterflies. When a butterfly was observed on a plant, it was tracked for one minute. Then, on a pin flag was written the species of butterfly, species of plant(s) on which it was located, and behavior of the butterfly (i.e., nectaring, basking, mating, or ovipositing). One or more flags were placed where the butterfly interacted with the plant(s). After one minute, I moved on to find the next butterfly and repeat the process. When the study was complete, I retraced my steps with the Archer GPS unit and captured points at each of the flags, entering the information that was written on each flag into a custom data dictionary with domains stored on the GPS unit using ArcPad. The GPS unit was set at a maximum of 2.3-m position of dilution of precision (PDOP). All GIS data are reported in this chapter by transect, as opposed to by site due to the spatial nature of the data.

4.2.2 GIS Analyses

All data were analyzed in ESRI ArcMap 10.4.1 with the geographic coordinate system GCS_North_American_1983 and the projected coordinate system NAD_1983_UTM_Zone_14N.

4.2.2.1 Kernal Density and Hotspot Analysis

Butterfly data were clipped to transect boundaries, then the “kernal density” tool was used with a 0.1-m spatial resolution and the planar method. Kernal density estimates the concentration of points (butterfly-plant interactions) in a specified area. Then, using the output from this tool, the kernel density raster, the “optimized hotspot analysis” tool was used to analyze aggregations of butterfly points. In other words, I tested the null hypothesis that butterflies were randomly distributed across each transect. The incident data aggregation method was “count_incidents_within_fishnet_polygons.”

4.2.2.2 GIS Plant Interpolations

Values for each vegetation variable tracked at the plot level were interpolated in ArcMap. These variables were visual obstruction, litter, blossom index, plant Shannon diversity index, plant evenness, plant richness, total plant cover, larval host plant cover, woody cover, forb cover, and graminoid cover. Prior to interpolating, the four measurements for litter depth and visual obstruction were each averaged for each plot. Then, all sessions for each variable were averaged by plot and interpolated using the inverse distance weighted (IDW) tool at a spatial resolution of 0.25 m and a search radius of six points to estimate unsampled locations. These interpolations gave values to unsampled locations and became the independent variables of the spatial multiple regression analysis.

4.2.2.3 Spatial Multiple Regression

Using the “create fishnet” tool in ArcMap, I created a 0.25-m by 0.25-m grid over each transect and clipped it to the transect boundary. This grid was used to determine mean values with the “zonal statistics as table” tool with each of the GIS plant interpolation rasters. I combined all butterfly points for all sessions into one feature class. Then, I ran the “Kernal density" tool on the butterfly points with a 2-m search radius, following which, I used the grid and zonal statistics to create mean butterfly densities for each polygon in the grid. I joined all these mean values outputted from the zonal statisics into one table. I log-transformed or square-root-transformed the data in order to linearize the data with the butterfly density data. To determine if recorder location biased the location of sighted butterflies (i.e., more butterflies were sighted closer to the transect centerline), a Euclidean distance off of the centerline was calculated and added as an independent variable. All data were then clipped to a 2-m buffer off the transect centerline. Finally, I ran "Ordinary Least Squares" using all the vegetation variables as explanatory variables and the butterfly point density as the dependent variable for each transect. I performed six checks for each regression model, modifying the model until all variables included in the model had variance inflation factors (VIF) less than 7.5 and P values less than 0.05.

4.2.3 Network Analysis

All plant-butterfly interactions were tallied for each plant species. Then, using the "bipartite" and "vegan" libraries in R version 3.4.3, plant-butterfly webs were created and indices were calculated. The NODF (nested metric based on overlap and decreasing fill) was used for the nestedness metric.

4.3 Results

4.3.1 GIS Analyses

4.3.1.1 Kernal Density and Hotspot Analysis

To evaluate the distribution of butterflies at each site, kernal density and hotspot analyses were performed. As shown in Figure 4.1, Figure 4.2, Figure 4.3, Figure 4.4, Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8, butterfly density varied from 0 to 0.65. The Memorial Stadium transects had the highest densities. The Memorial Stadium east transect had the highest density over the largest area of any transect (Figure 4.1). Areas along the east edge of the roof (where the roof was highest) had the lowest densities on the roofs. The hotspot analysis results indicated that even though there were many areas of high density, the butterfly distribution was random.

The Memorial Stadium west transect had mostly areas of low density with some moderate density at the south end of the transect (Figure 4.2). This area is one of two areas statistically different from random. 15% of the transect were hotspot areas (Table 4.1). 6% of the transect has $P = 0.0003$. At the north end of the transect, there is a cold spot over 2% of the transect with $P = 0.0107$ and $z = -2.56$. This is the only cold spot at any transect.

The native prairie sites (R20A east and west, as well as R20B east and west) generally had low butterfly densities. The kernel density for R20A east had slightly higher density at the south end and in the center of the transect. The only area with a hotspot was at the south for 7% of the transect, and 2% had $P = 0.0001$, 4% of the transect had $P = .0018$, and 1% of the transect has $P = 0.0046$. R20A west's kernel density was almost all low except one slightly higher near the south end. There were two small areas totaling 3%with hotspots: one at the south end and one in the upper third. 2% of the transect had $P = 0.0003$ and 1% had $P = 0.0016$.

The kernel density for R20B east was almost entirely low with some slightly higher densities south of center and at the north end. In these locations there were two hotspots occupying 6% of the transect with P = 0.0019. The kernel density for R20B west was mostly low with four slightly higher density areas. There were two small areas with hotspots, one at the north end and one south of center. These areas occupied 7% of the transect area with 2% with $P = 0.0001$; 2% with $P = 0.0008$; and 3% with $P = 0.0043$.

The urban prairie sites (Warner east and Warner west) had low densities, with the east transect having slightly higher density. Neither of the transects had hotspots or cold spots.

4.3.1.2 Ordinary Least Squares

Due to high spatial autocorrelation of data, my models were biased. Therefore, all spatial statistics will not be reported here. Instead, I have reported relative importance of independent variables and whether that variable has a positive or negative relationship with the dependent variable, butterfly density. Beta values and R^2 values are listed in Table 4.2.

I found the most important predictor variables at Memorial Stadium east and west transects to be Euclidean distance (β = 0.82) and total plant coverage (β = 0.33), respectively. Larval host coverage was a negative predictor variable at both east (β = -0.08) and west (β = -0.27) Memorial Stadium transects.

At the native prairie R20a east transect the most important predictor variables included blossom index (β = 0.30) and woody cover (β = 0.15). Negative predictor variables included total cover (β = 0.26) and evenness (β = 0.20). The most important predictor variable for the R20A west transect was total plant coverage (β = 0.40), while visual obstruction (β = -0.31) was the most important negative predictor. Blossom index was also an important predictor for butterfly density at the native prairie R20b west transect (β = 0.41), as well as evenness (β = 0.40). The most important negative predictors at the R20b west transect were woody plant coverage (β = -0.29) and forb coverage (β = -0.21). The most important predictor variables for butterfly density at the native prairie R20b east transect were larval host coverage (β = 0.37) and graminoid cover (β = 0.20), while the most significant negative predictor variable was visual obstruction (β = -0.19).

At the urban prairie east transect, evenness (β = 0.25) and visual obstruction (β = 0.24) were the best variables for predicting butterfly distribution. The most significant negative predictors were larval host plant coverage (β = -0.23) and graminoid cover (β = -0.21).

4.3.2 Network Analysis

The plant-butterfly ecological network bipartite graphs are shown in Figure 4.9, Figure 4.11, Figure 4.13, Figure 4.15, and Figure 4.17. These figures show all the plants (bottom) that had butterflies (top) interacting with them. Lines connect butterflies and plants that had an interaction. The height of the black bars is proportional to the number of butterflies or plants in each taxon. The width of the grey bars connecting the butterflies and plants are proportional to the number of interactions between them (C. F. Dormann, Fruend, & Gruber, 2018).

Another way to visualize the bipartite network is the incidence matrix seen in Figure 4.10, Figure 4.12, Figure 4.14, and Figure 4.16. This matrix indicates whether butterflies interacted with plants (Delmas et al., 2019). The shading denotes how many interactions occurred, with darker representing greater interaction numbers.

Three indices were selected to evaluate the topology of the ecological networks at each of my study sites: plant and butterfly species, links per species, and nestedness. Each of these metrics are described below and listed in Table 4.3.

4.3.2.1 Butterfly and Plant Species

These indices describe the number of species that were found to be interacting in the ecological network during sampling (C. F. Dormann et al., 2009). As shown in Table 4.3 the native prairie sites had the greatest number of butterfly species interacting with plants (22) while Memorial Stadium had the greatest number of plant species (45) being interacted with by butterflies. The urban prairie had the least butterfly (12) and plant species (18) interacting with each other. At Memorial Stadium, the most common butterflies were grass skipper species, painted ladies, and eastern-tailed blues (Figure 4.9 and Figure 4.10). These were the same dominant butterflies at the native prairie, though evenness was greater at the native prairie (Figure 4.13 and Figure 4.14). At the urban prairie, the dominant butterflies were sulphur species, grass skipper species, eastern-tailed blues, and pearl crescents (Figure 4.17 and Figure 4.18). The most used plants at Memorial Stadium were the *Liatris* species. The remainder of the plants used were mostly forbs with a few graminoids. The most used plants at the native prairie were *Cirsium altissimum*, *Vernonia baldwinii*, *Andropogon gerardii*, and *Solidago altissima*. The most used plant at the urban prairie was a grass, *Sorgastrum nutans*, and the most used forb was *Linum sulcatum*.

4.3.2.2 Links Per Species

This index discusses the average number of links per species (C. F. Dormann et al., 2009). A link is defined as a single or multiple interactions between a plant species and a butterfly taxon (C. F. Dormann et al., 2009). As shown in Table 4.3, Memorial Stadium had the greatest links per species (2.71), followed by native prairie (1.98), while the urban prairie had the least (1.40).

4.3.2.3 Nestedness

Nestedness occurs in a network when there are a core group of generalists interacting with each other, and a group of specialists that only interact with the generalists (Bascompte, Jordano, Melian, & Olesen, 2003; Dalsgaard *et al*., 2013; Hegland, Nielsen, Lá Zaro, Bjerknes, & Totland, 2009). This creates asymmetric specialization where specialized plants typically interact with generalist pollinators and vice versa (Stang, Klinkhamer, & Van der Meijden, 2007). Perfect nestedness happens when species' interactions are perfect subsets of generalist species interactions. It is measured on a scale between 0 and 100, with 0 being perfectly nested. Of the ecological networks at the study sites, Memorial Stadium was the least nested (57.41) and the other two sites had similar nestedness (native prairie had 34.11 and urban prairie had 35.13; Table 4.3).

4.4 Discussion

4.4.1 GIS Analyses

The hotpot analysis was performed to identify locations most used by butterflies among sites. Overall, Memorial Stadium west transect had the greatest variability, largest hotspot, and the only cold spot. Two of the native prairie transects (R20A east and R20B west) also had hotspot density locations above 99%. I cannot explain why the Memorial Stadium west transect had such high densities at the south end, though it is likely floral resources. However, I believe the reason there is a coldspot at the north end was a result of senescing vegetation due to faulty irrigation. The native prairie densities I attribute to the density of floral resources from *Asclepias verticillata*, *Vernonia baldwinii*, and *Cirsium altissimum* where butterflies congregated.

The kernel density and hotspot analyses answer the question of "where," but perhaps the more important question is "why." In other words, we needed to determine what is causing the hotspots and why butterflies are congregating in those locations. I attempted to answer these questions using the Ordinary Least Squares tool in ArcMap. However, all models seem to have exhibited spatial autocorrelation which appears to be common when mapping species distribution data (Dormann et al., 2007). Further study could examine additional statistical tests to remove spatial autocorrelation from the data.

The methods used for spatial distribution are not standard, and I was curious whether recorder bias impacted the distribution I documented. So, I used the Euclidean distance tool to account for this potential recorder bias that more butterflies would be seen at the transect centerline as opposed to the edge. Data were clipped to 2 meters on either side of the centerline to reduce the potential for this recorder bias. However, Euclidean distance still appeared as a significant variable in some of my models, suggesting that the field methods used are not robust. For example, at the Memorial Stadium east transect Euclidean distance was the greatest predictor variable, possibly explained by the slope of the roof and height of vegetation which made it difficult to see butterflies at greater distances from the center of the transect. This could mean that butterfly abundances were underestimated along the edge of the transect.

4.4.2 Network Analysis

While Memorial Stadium had the greatest number of plant species interactions with butterflies, as well as greatest links per species, nestedness was lowest at this site. The native prairie site, however, had the greatest number of butterfly species interactions, in addition to the greatest nestedness among sites. The results from the network analysis seem to reinforce the results from Chapters 2 and 3, as well as give further understanding for practices to improve butterfly richness and abundance at Memorial Stadium. This section compares three bipartite network indices across sites and mechanisms contributing the network topology.

4.4.2.1 Butterfly and Plant Species

This index is comparable to overall species richness, but opposed to traditional richness, which includes all species in a community, this index only includes species that were involved in an interaction. The native prairie site had the greatest overall plant richness in our vegetation studies (108 species) and Memorial Stadium had the least, so it seems intuitive that these results would be similar in this network metric. However, this was not the case as Memorial Stadium had the greatest number of plant species being interacted with by butterflies. This could be explained by the behavior of the butterflies I found at each site: native prairie butterflies interacted less with the vegetation and flew through sites, whereas at Memorial Stadium, butterflies foraged more often. Native prairie had the greatest number of butterfly species consistent with the Pollard walk results, and butterfly species composition was similar, except one additional butterfly species, the American snout (*Libytheana carinenta*), was found at the native prairie site.

The ratio of pollinators to plants in other studies has been found to be 3:1 so that plant extinctions are much more significant in a community because of the redundancy of pollinators (Memmott, Waser, & Price, 2004). I did not see this ratio in my data probably because I did not use the entire pollinator community, just butterflies. Either adding other pollinators to the study or supplementing my data with other pollinator literature would likely change these ratios.

4.4.2.2 Links Per Species

This is the average number of links (any number of interactions) between each butterfly and plant species. Memorial Stadium had the greatest links per species which could be a result of the high abundance of butterflies similar to findings from a previous study (Olesen, Stefanescu, & Traveset, 2011). One long-term study of a plant-butterfly network showed that generalist species, both butterflies and plants, with higher links per species were more persistent over time, whereas specialist species with less than two links were less persistent (Olesen et al., 2011). Because greater forb coverage and number of species of forbs blooming was an indictor of greater butterfly abundance at Memorial Stadium (see Chapter 3), then forb coverage and number of species of forbs blooming could increase the links per species and thereby temporal persistence of the butterfly community.

4.4.2.3 Nestedness

Mutualistic networks, such as plant-pollinator networks, are highly nested (Bascompte et al., 2003). Studies show that nestedness increases the resiliency of a plant-pollinator network. Because of the nested structure, there is redundancy in the core generalist species, which may make the network less vulnerable to extinction and improve its resiliency (Schweiger et al., 2010). Thus, because of assymetric specialization of these networks, communities with generalist plants may be able to support more specialist pollinators. Therefore, Memorial Stadium specialist butterfly richness may be improved by adding generalist plant species.

Among sites, Memorial Stadium had the greatest number of plant species interactions, but also the least nestedness which may seem contradictory. However, given the results from the plant composition sampling, far more plant species were observed at the native prairie site (108), which may explain why the native prairie exhibited the greatest nestedness among sites. This characteristic may allow specialist butterflies to persist because of assymetrical specialization and the specialist butterfly's ability to interact with less-fluctuating, generalist plants (Bascompte et al., 2003). Further study could be used to determine which generalist plant species present at the native prairie site could be used at Memorial Stadium to increase nestedness and richness.

In conclusion, adding generalist plants should increase nestedness at Memorial Stadium. By studying the network matrix at the urban and native prairie, one can pinpoint which species should be added to Memorial Stadium to encourage specialist butterflies. Some species of plants to consider are *Vernonia baldwinnii*, *Linum sulcatum*, and *Asclepias* species. From looking at the hotspot analyses, one can see the importance of diligently maintaining the irrigation system since the malfunctioning irrigation system resulted in the roof being underutilized by butterflies at the coldspot on the north of the west Memorial Stadium. Taking each of these actions can help improve the butterfly community at Memorial Stadium.

4.5 Tables

Table 4.1. Hotspot analysis results by transect for native prairie, urban prairie, and Memorial Stadium from data collected in 2017 and 2018.

Site	Hotspot								
	99% Confidence			95% Confidence			90% Confidence		
	%	Average Z-score	Average P-value	%	Average Z-score	Average P-value	%	Average Z-score	Average P-value
Memorial Stadium East	0	NA	NA	0	NA	NA	0	NA	NA
Memorial Stadium West	6	3.6315	0.0003	5	3.1271	0.0020	2	2.6467	0.0082
R20A East	2	3.8612	0.0001	4	3.1616	0.0018	1	2.8362	0.0046
R20A West	0	NA	NA	2	3.7047	0.0003	1	3.1638	0.0016
R20B East	0	NA	NA	6	3.1589	0.0019	0	NA	NA
R20B West	2	4.0673	0.0001	2	3.3699	0.0008	3	2.8749	0.0043
Warner East	0	NA	NA	0	NA	NA	0	NA	NA
Warner West	0	NA	NA	0	NA	NA	0	NA	NA

NOTE: NA = Not applicable

Table 4.2. Spatial ordinary least squares results for the response variable butterfly density from sampling conducted during 2017 and 2018.

Site	Transect	Independent Variables[1]	Standardized Coefficient (β)	Adjusted Model R^2
Memorial Stadium	East	Blossom Index	0.02***	0.66
		Graminoid Cover	-0.05***	
		Larval Host Coverage	-0.08***	
		Visual Obstruction	0.06***	
		Euclidean Distance	0.82***	
	West	Evenness	0.25***	0.11
		Larval Host Coverage	-0.27***	
		Litter	-0.03*	
		Richness	-0.05***	
		Total Plant Coverage	0.33***	
		Visual Obstruction	0.10***	
		Woody Cover	0.04***	
Native Prairie	R20A East	Euclidean Distance	0.02*	0.12
		Blossom Index	0.30***	
		Evenness	-0.20***	
		Forb Coverage	0.08***	
		Larval Host Coverage	-0.08***	
		Litter Depth	-0.19***	
		Richness	-0.04**	
		Total Cover	-0.26***	
		Woody Cover	0.15***	
	R20A West	Euclidean Distance	-0.10***	0.06
		Blossom Index	0.11***	
		Evenness	-0.06***	
		Forb Coverage	-0.07***	
		Graminoid Cover	0.09***	
		Richness	-0.20***	
		Total Plant Coverage	0.40***	
		Visual Obstruction	-0.31***	
	R20B East	Blossom Index	0.05***	.10
		Evenness	-0.09***	

Table 4.2. Spatial ordinary least squares results for the response variable butterfly density from sampling conducted during 2017 and 2018.

		Visual Obstruction	-0.19***	
		Larval Host Coverage	0.37***	
		Litter Depth	-0.04*	
		Richness	-0.08***	
		Total Cover	0.03***	
		Woody Cover	0.08***	
		Euclidean Distance	-0.09***	
		Graminoid Cover	0.20***	
	R20B West	Blossom Index	0.41***	0.23
		Evenness	0.40***	
		Forb Coverage	-0.21***	
		Larval Host Coverage	-0.20***	
		Litter Depth	0.27***	
		Richness	-0.06**	
		Total Cover	0.09***	
		Woody Cover	-0.29***	
Urban Prairie	East	Euclidean Distance	-0.05***	0.16
		Blossom Index	0.19***	
		Evenness	0.25***	
		Forb Coverage	-0.05***	
		Graminoid Cover	-0.21***	
		Richness	-0.12***	
		Visual Obstruction	0.24***	
		Larval Host Coverage	-0.23***	
		Litter Depth	0.06***	
	West	Euclidean Distance	-0.02*	0.13
		Evenness	0.03*	
		Forb Coverage	0.43***	
		Larval Host Coverage	-0.15***	
		Litter Depth	-0.33***	
		Richness	-0.43***	
		Visual Obstruction	0.21***	

[1] Independent variables tested in models are: graminoid coverage, forb coverage, woody plant coverage, larval host coverage, plant evenness, total plant coverage, Shannon diversity index, plant richness, visual obstruction, litter depth, blossom index, and Euclidean distance from transect centerline.

* $P < 0.05$ ** $P < 0.01$ *** $P < 0.001$

Table 4.3. Butterfly species, plant species, links per species, and nestedness network analysis indices from data sampled in 2017 and 2018 at the Memorial Stadium, native prairie, and urban prairie sites.

Site	Butterfly Species	Plant Species	Links Per Species	Nestedness
Memorial Stadium	17	45	2.71	57.41
Native Prairie	22	42	1.98	34.11
Urban Prairie	12	18	1.40	35.13

4.6 Figures

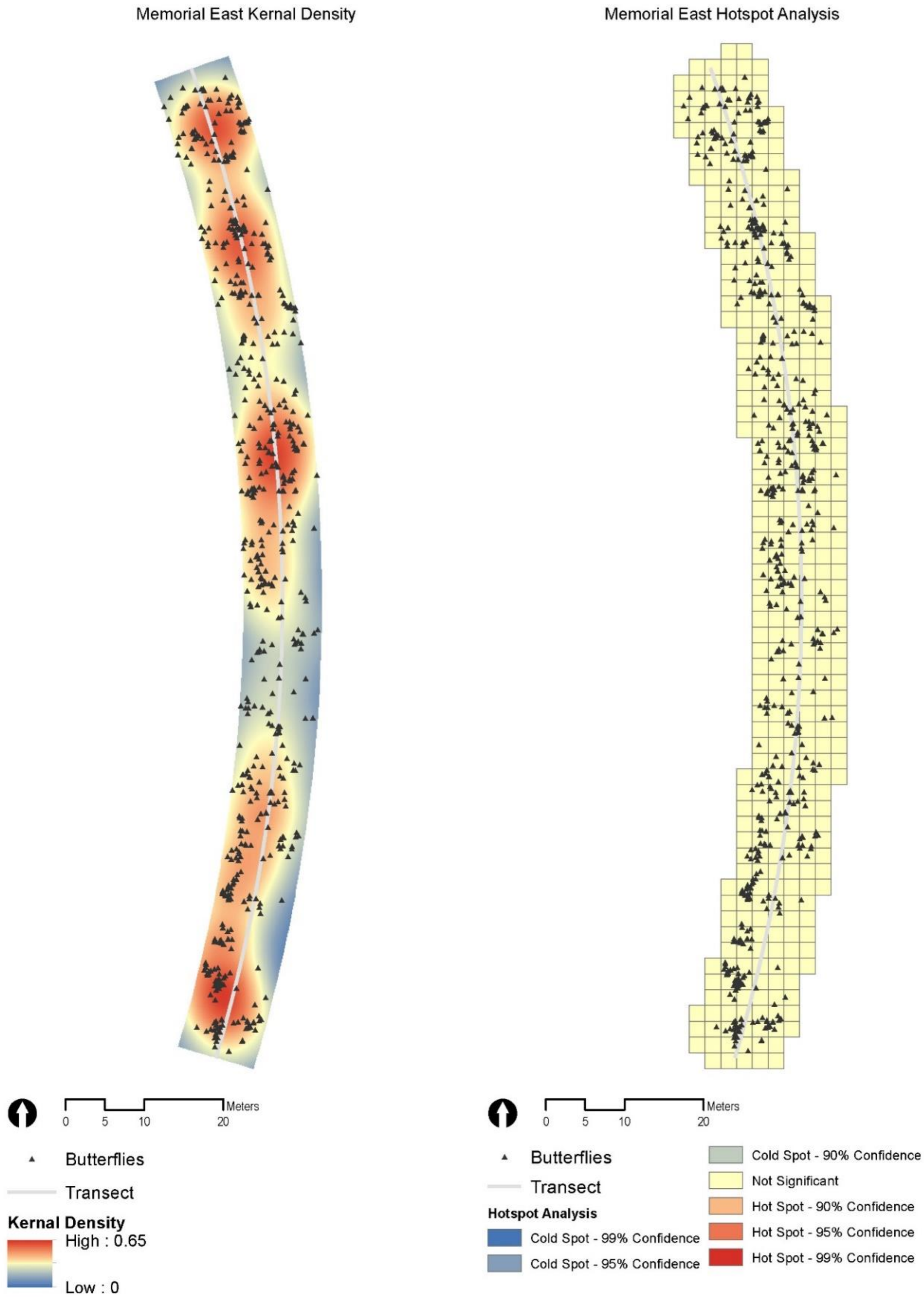

Figure 4.1. Memorial Stadium east transect kernal density and hotspot analysis with butterfly-plant interaction locations from 2017 and 2018.

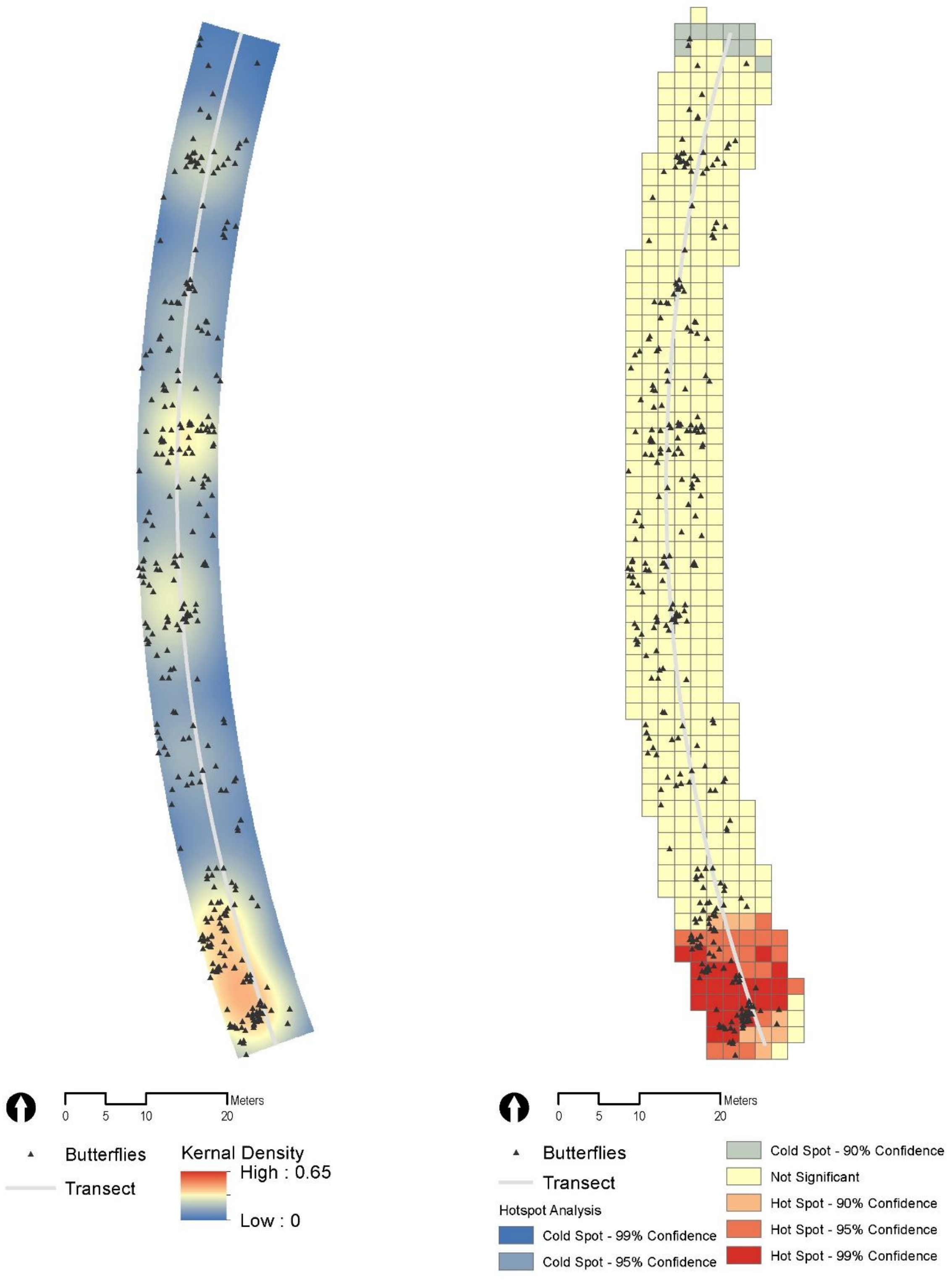

Figure 4.2. Memorial Stadium west transect kernal density and hotspot analysis with butterfly-plant interaction locations from 2017 and 2018.

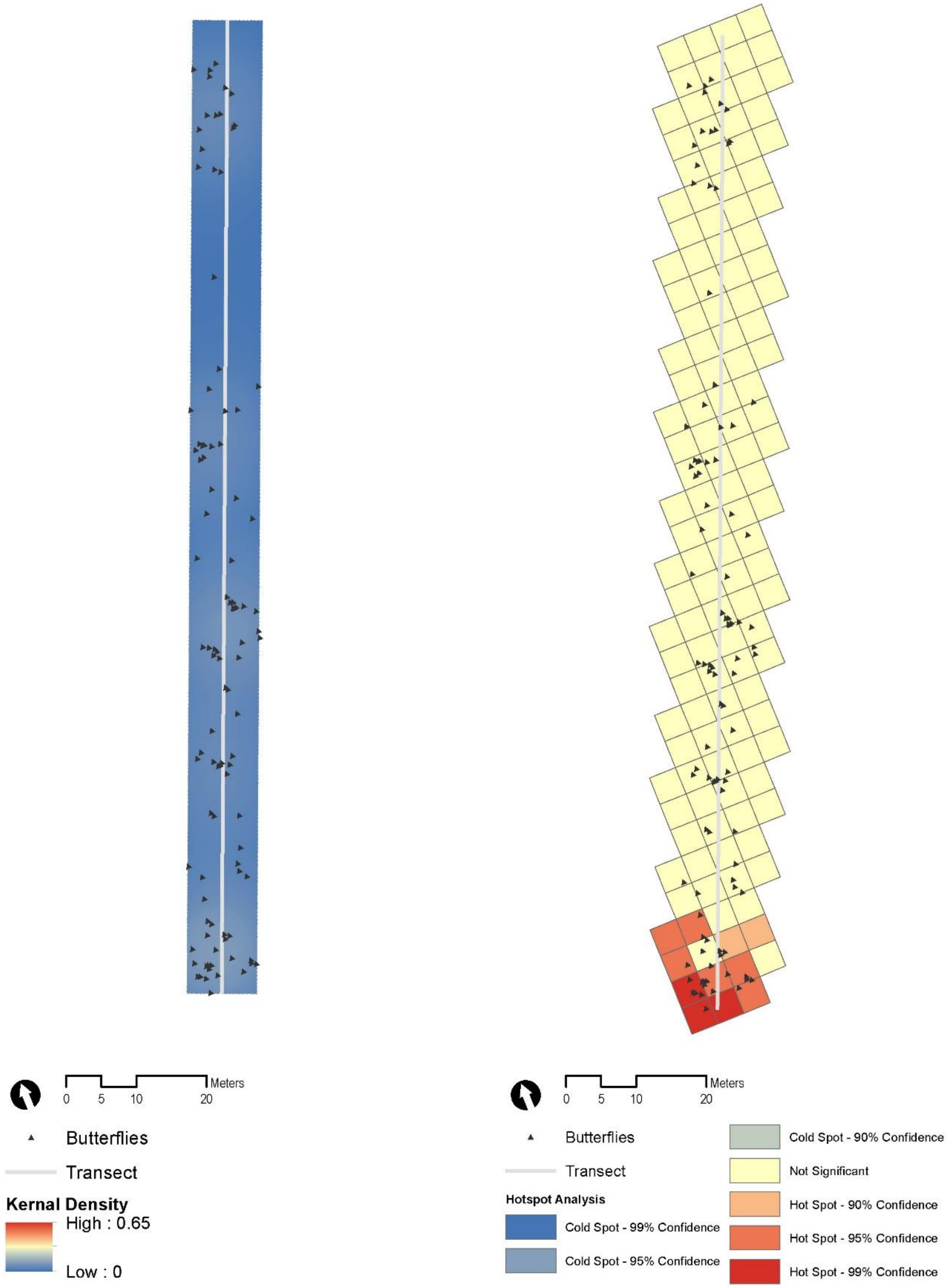

Figure 4.3. Native prairie R20A east transect kernal density and hotspot analysis with butterfly-plant interaction locations from 2017 and 2018.

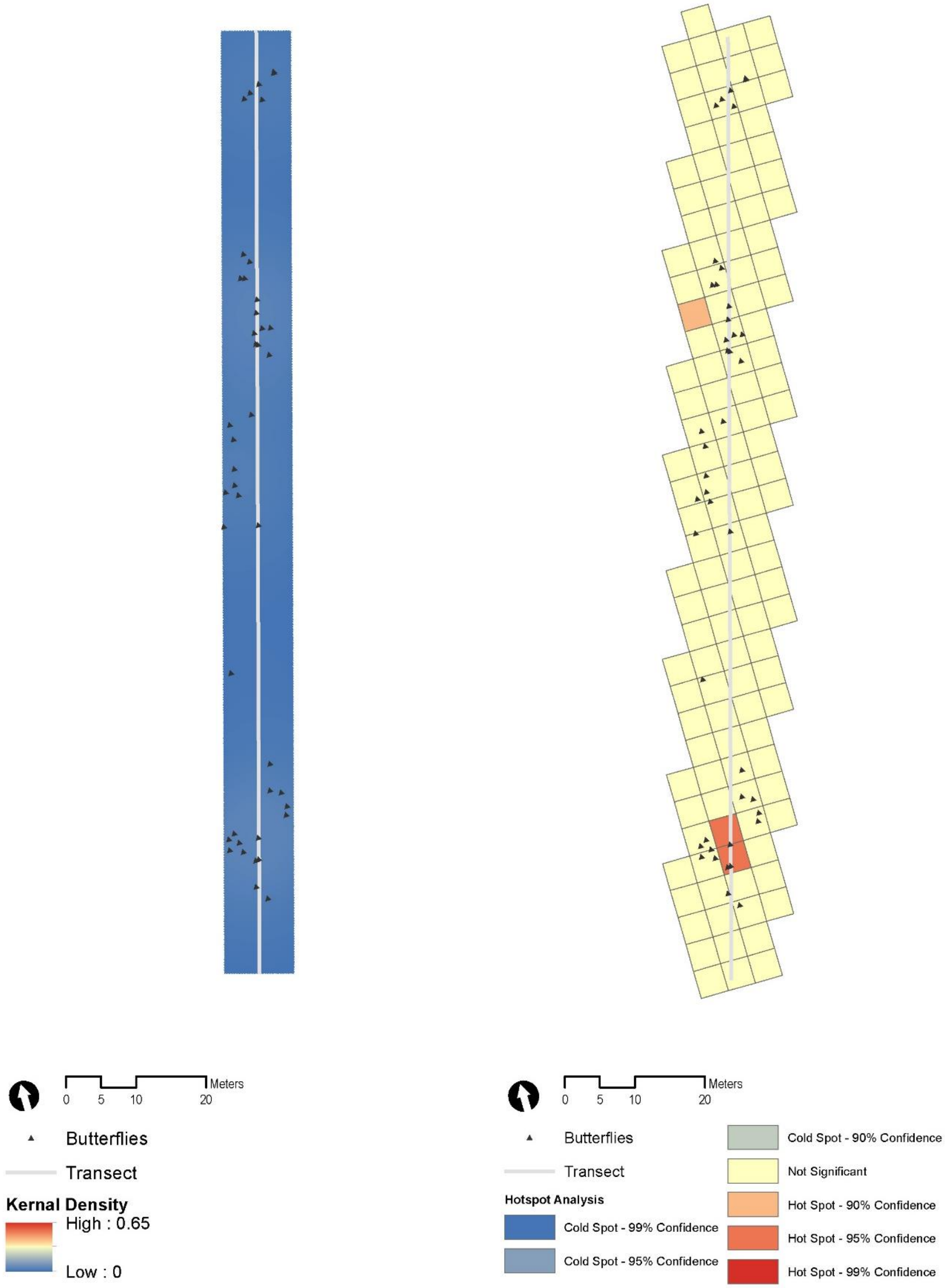

Figure 4.4. Native prairie R20A west transect kernal density and hotspot analysis with butterfly-plant interaction locations from 2017 and 2018.

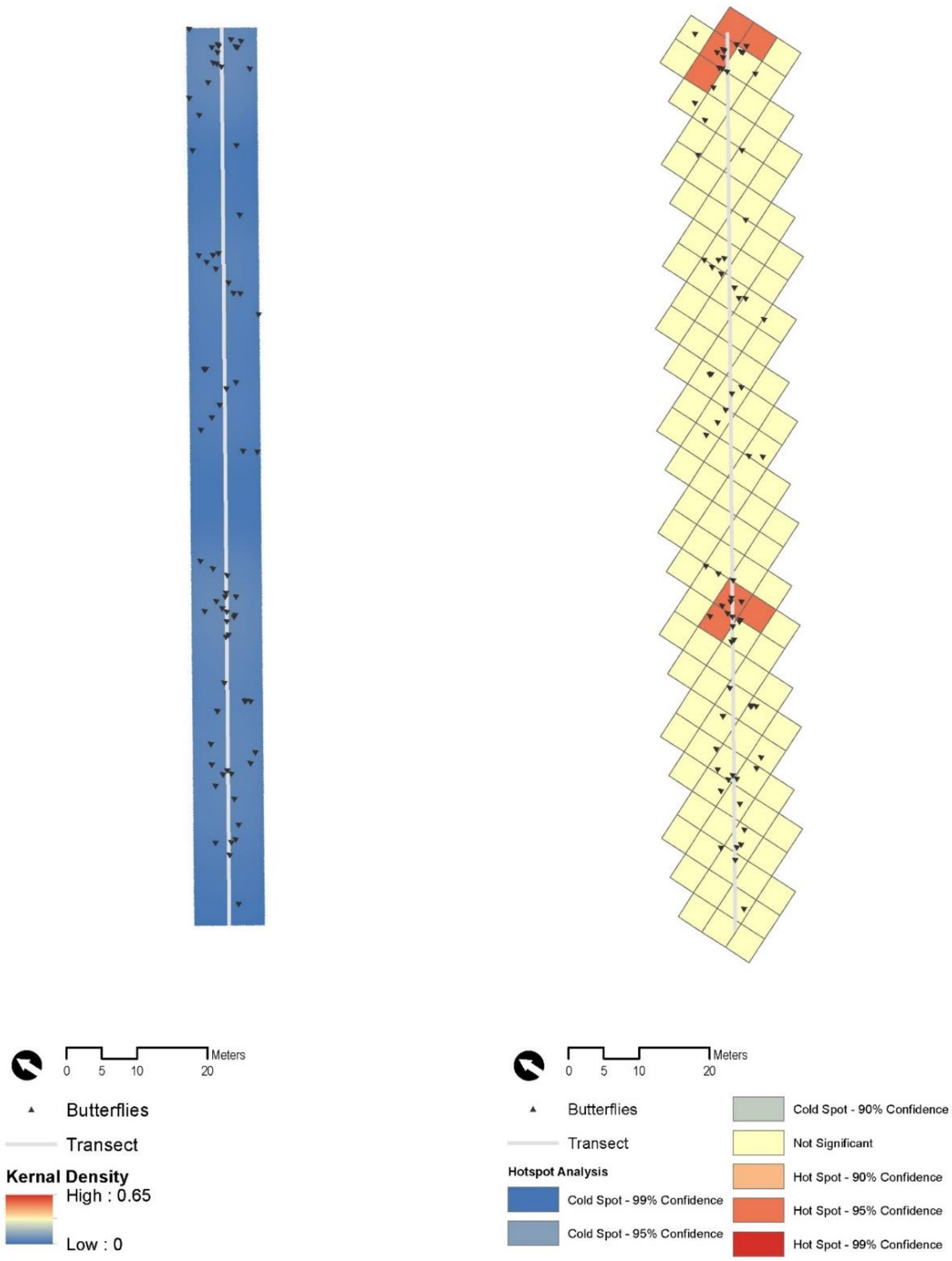

Figure 4.5. Native prairie R20B east transect kernal density and hotspot analysis with butterfly-plant interaction locations from 2017 and 2018.

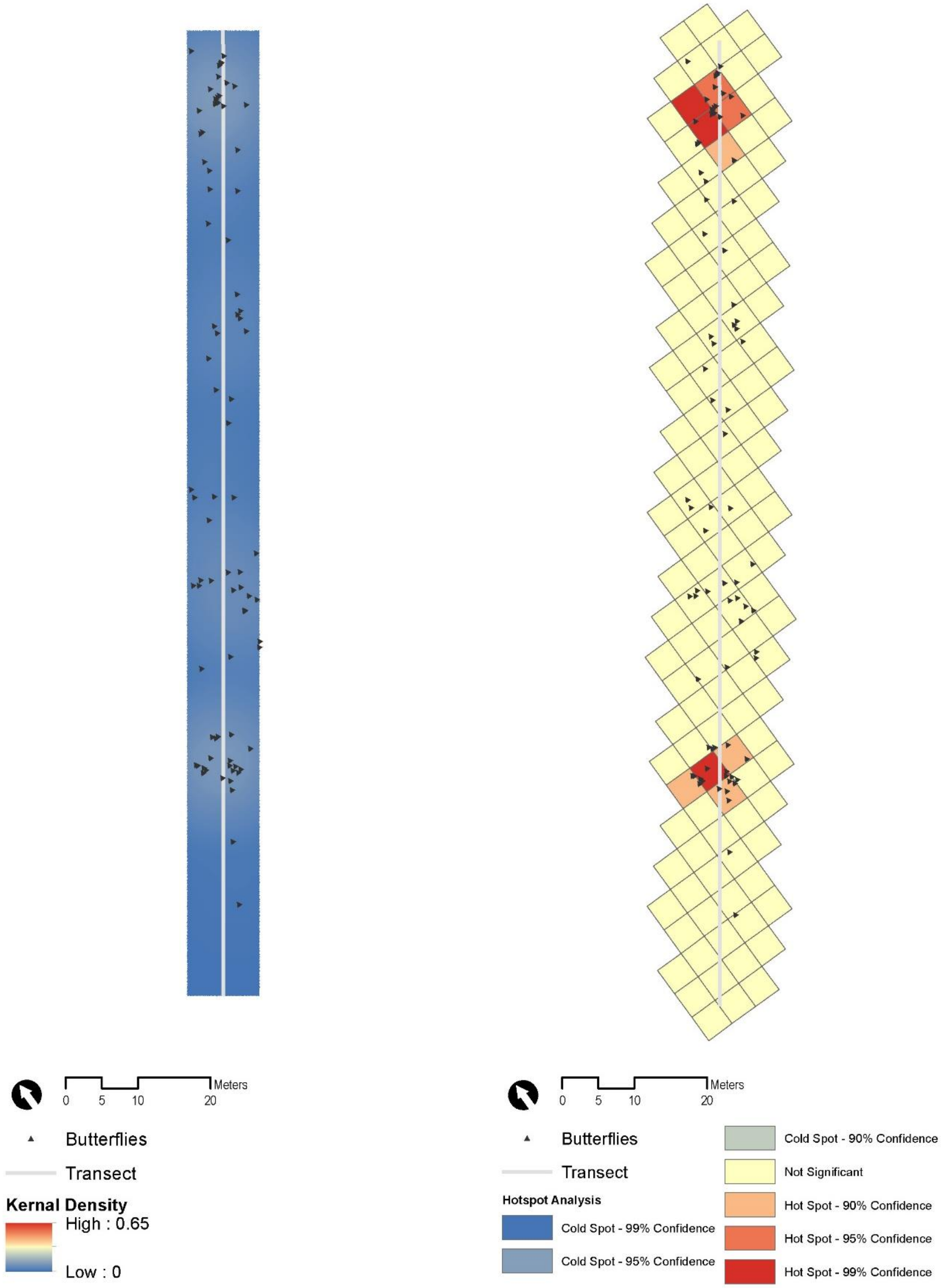

Figure 4.6. Native prairie R20B west transect kernal density and hotspot analysis with butterfly-plant interaction locations from 2017 and 2018.

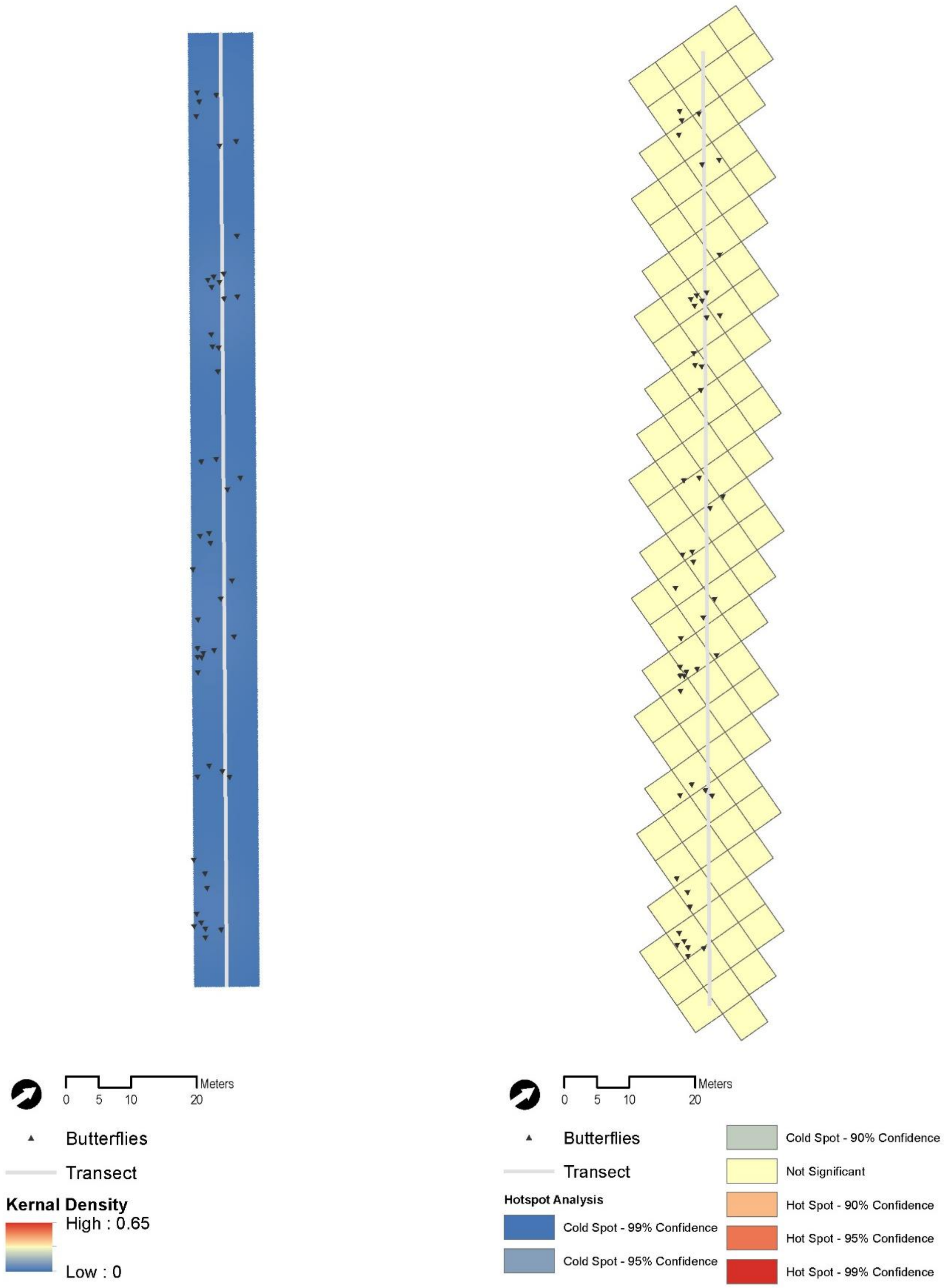

Figure 4.7. Urban prairie east transect kernal density and hotspot analysis with butterfly-plant interaction locations from 2017 and 2018.

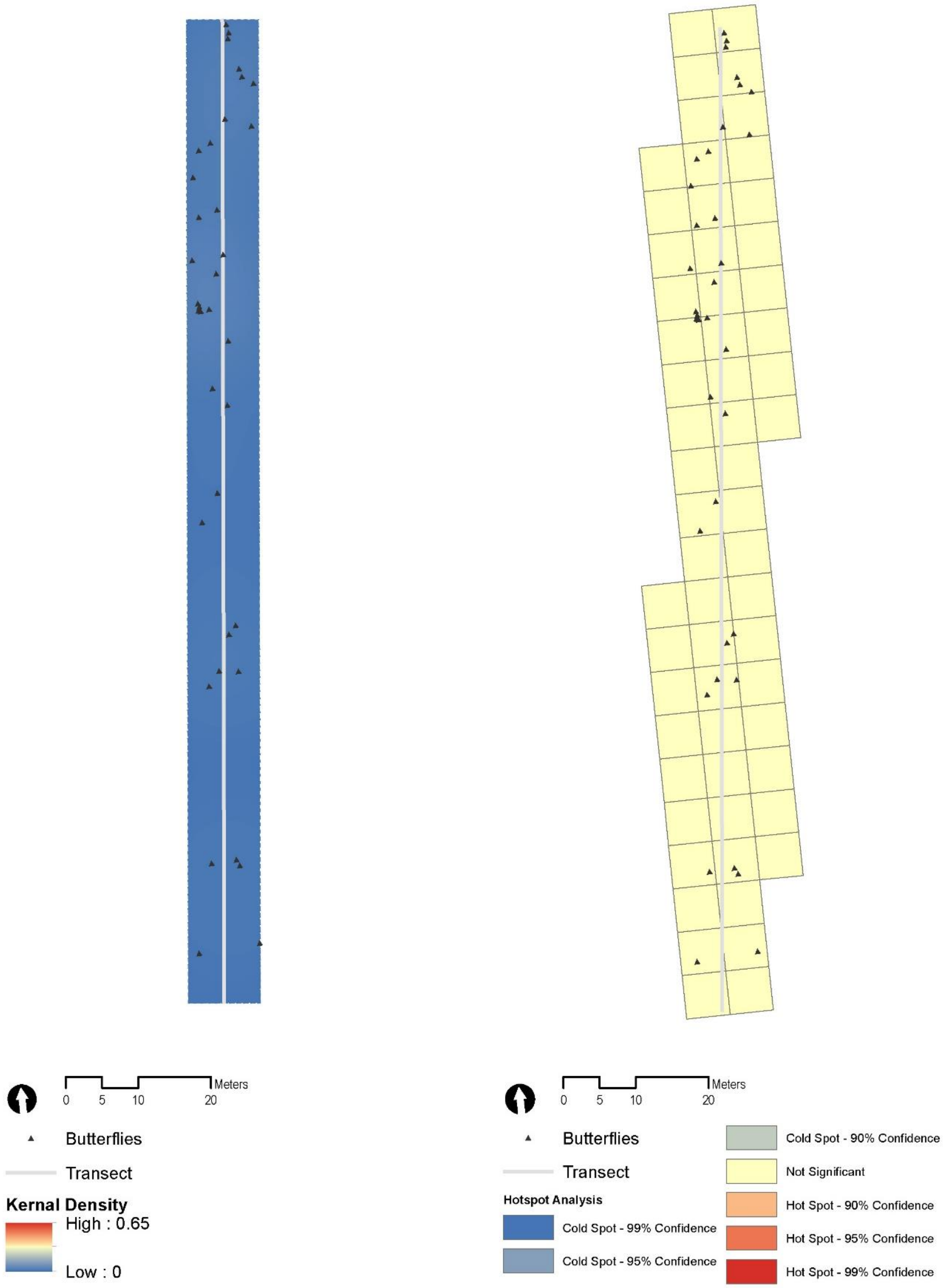

Figure 4.8. Urban prairie west transect kernal density and hotspot analysis with butterfly-plant interaction locations from 2017 and 2018.

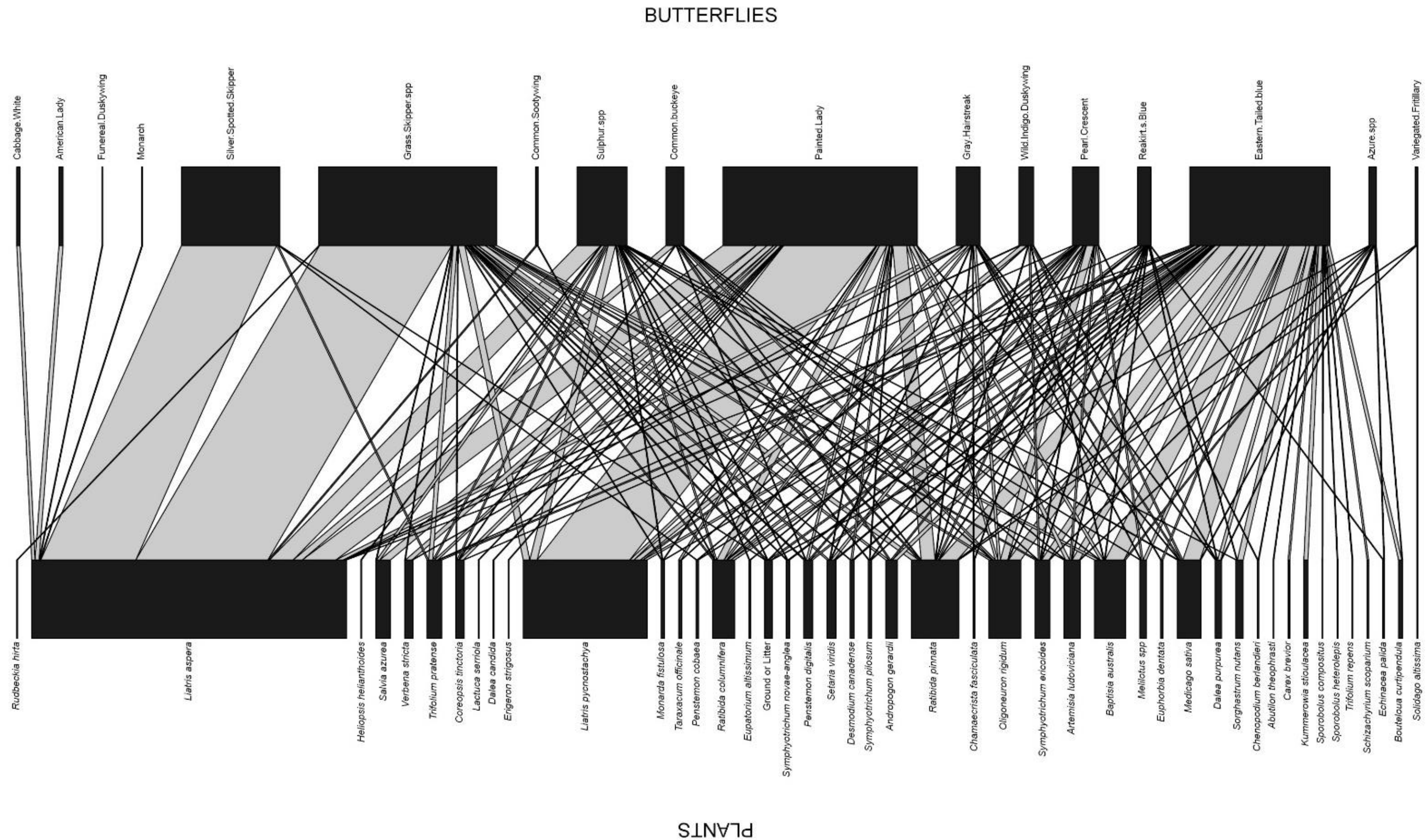

Figure 4.9. Memorial Stadium plant-butterfly bipartite network showing nectaring, ovipositing, mating, and basking interactions between plants and butterflies during 2017 and 2018. Thicker lines indicate a greater proportion of interactions.

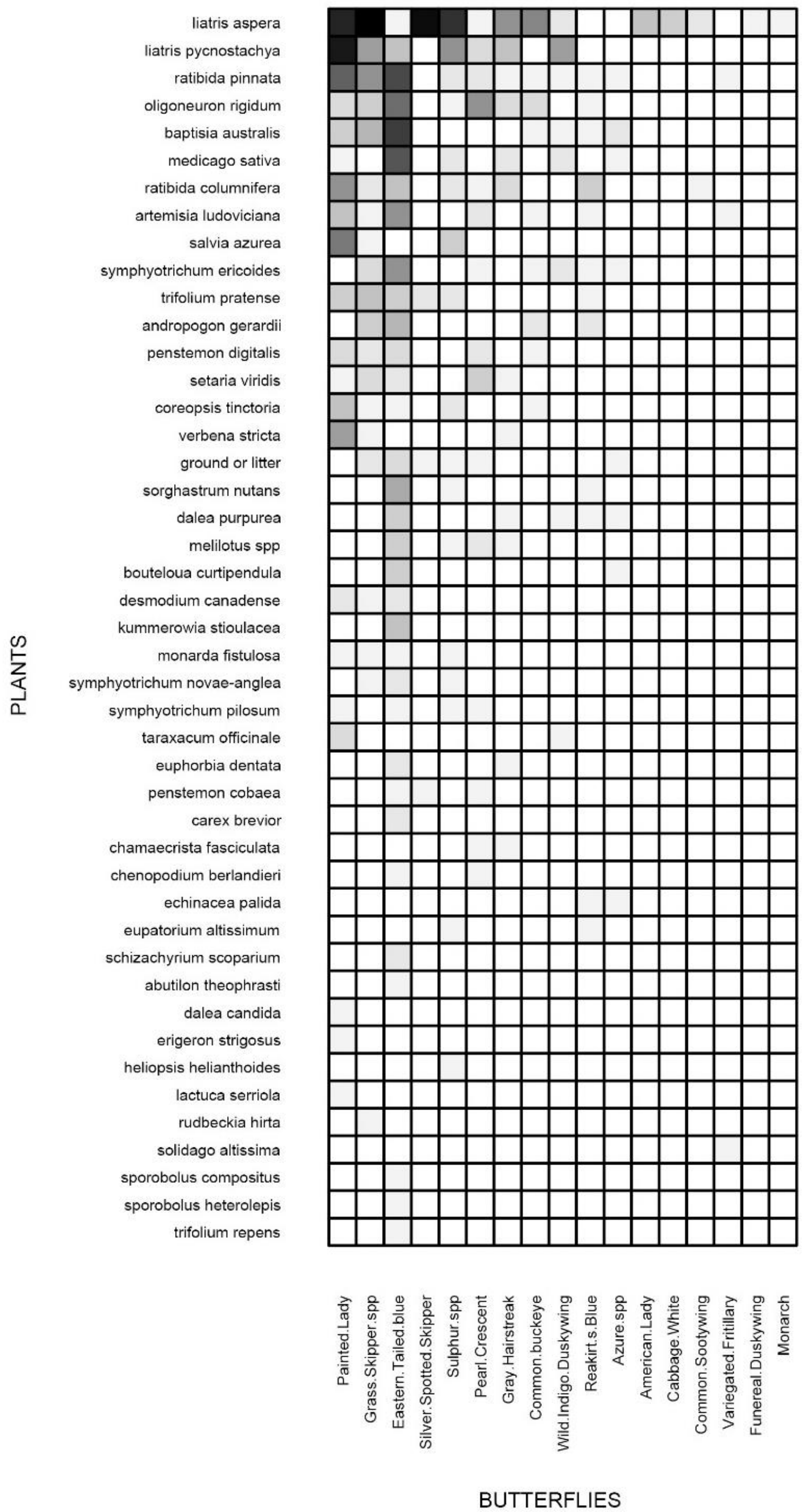

Figure 4.10. Memorial Stadium incidence matrix depicting plant-butterfly interactions using field data from 2017 and 2018. Darker shading indicates greater number of interactions.

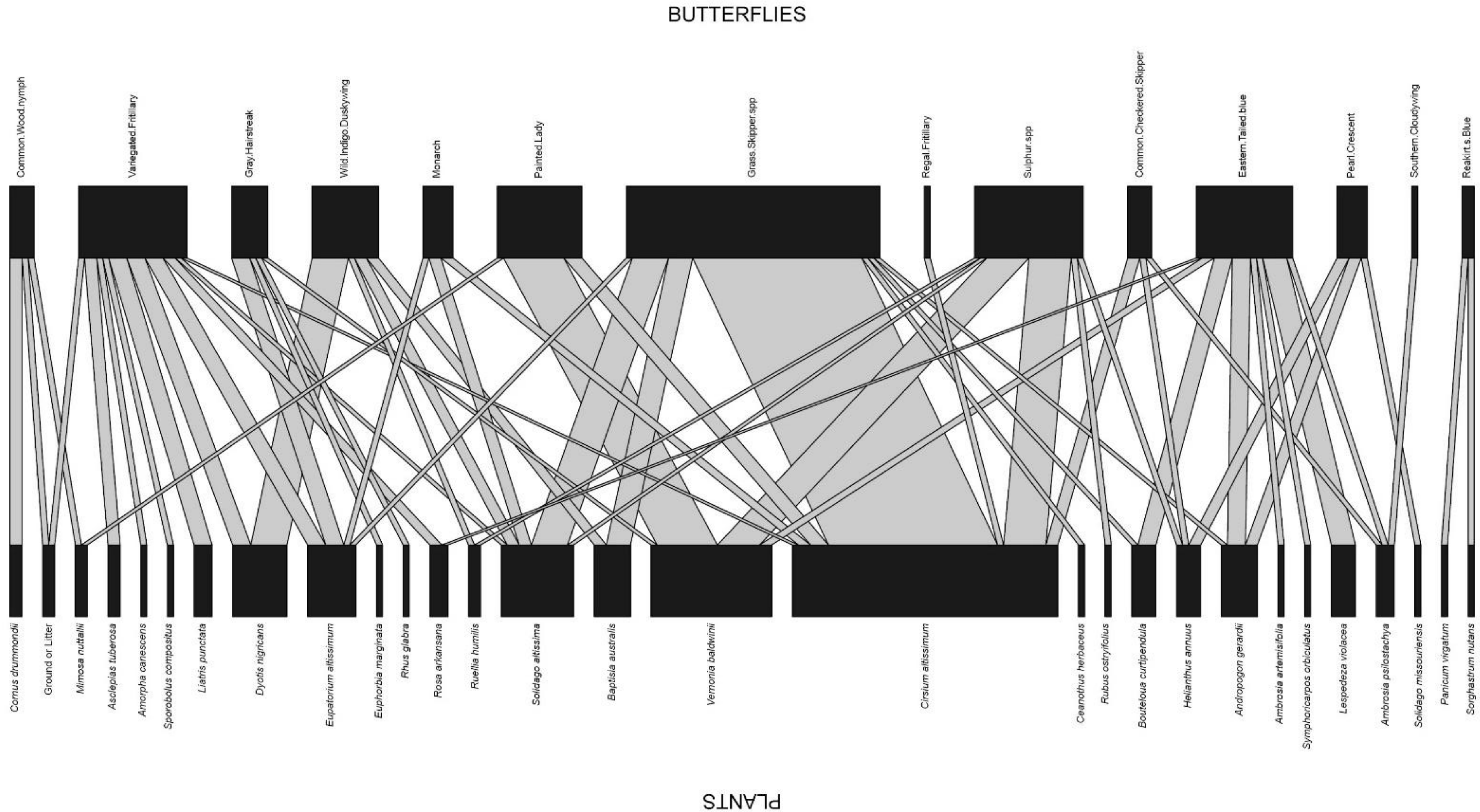

Figure 4.11. Native prairie R20A plant-butterfly bipartite network showing nectaring, ovipositing, mating, and basking interactions between plants and butterflies during 2017 and 2018. Thicker lines indicate a greater proportion of interactions.

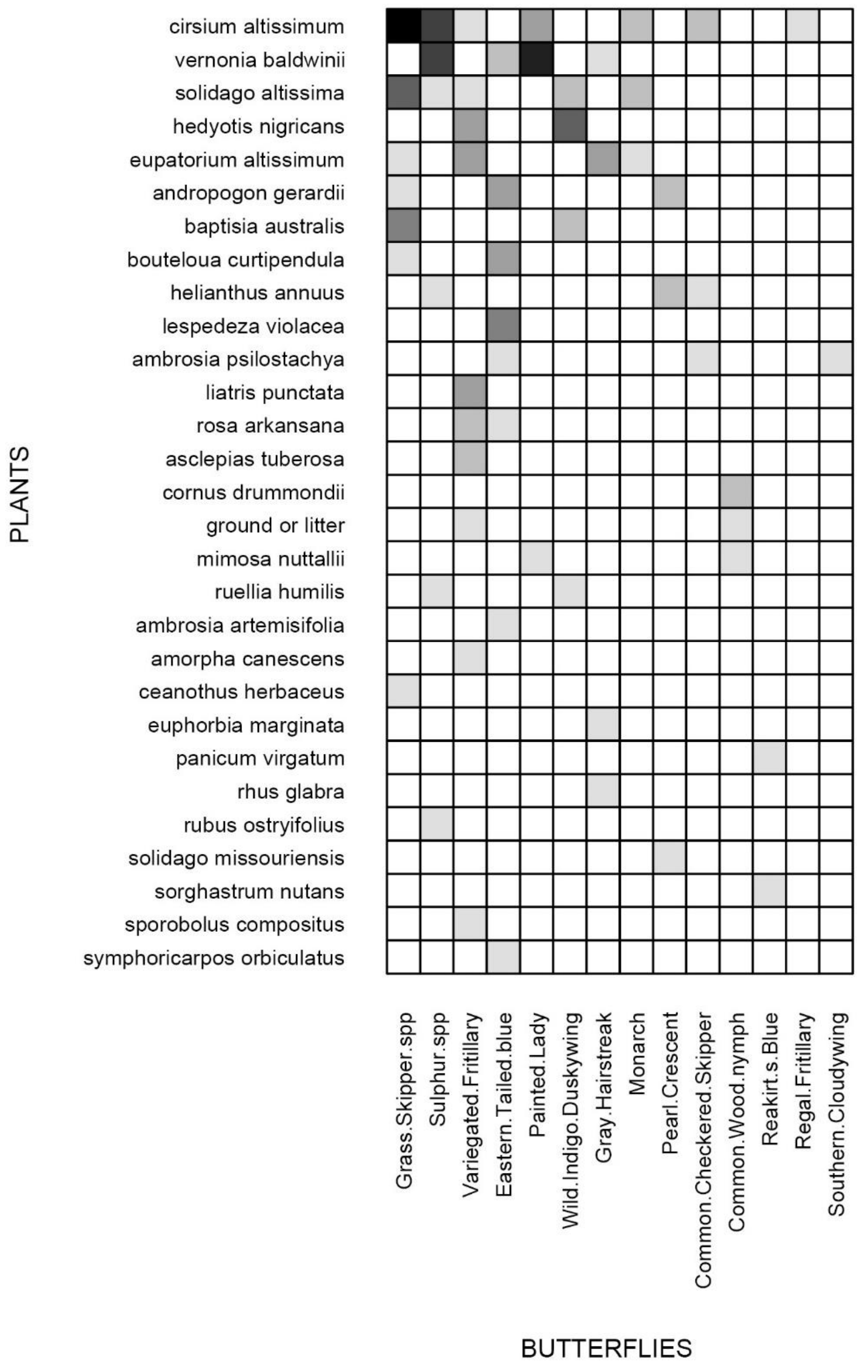

Figure 4.12. Native prairie R20A incidence matrix depicting plant-butterfly interactions using field data from 2017 and 2018. Darker shading indicates a greater number of interactions.

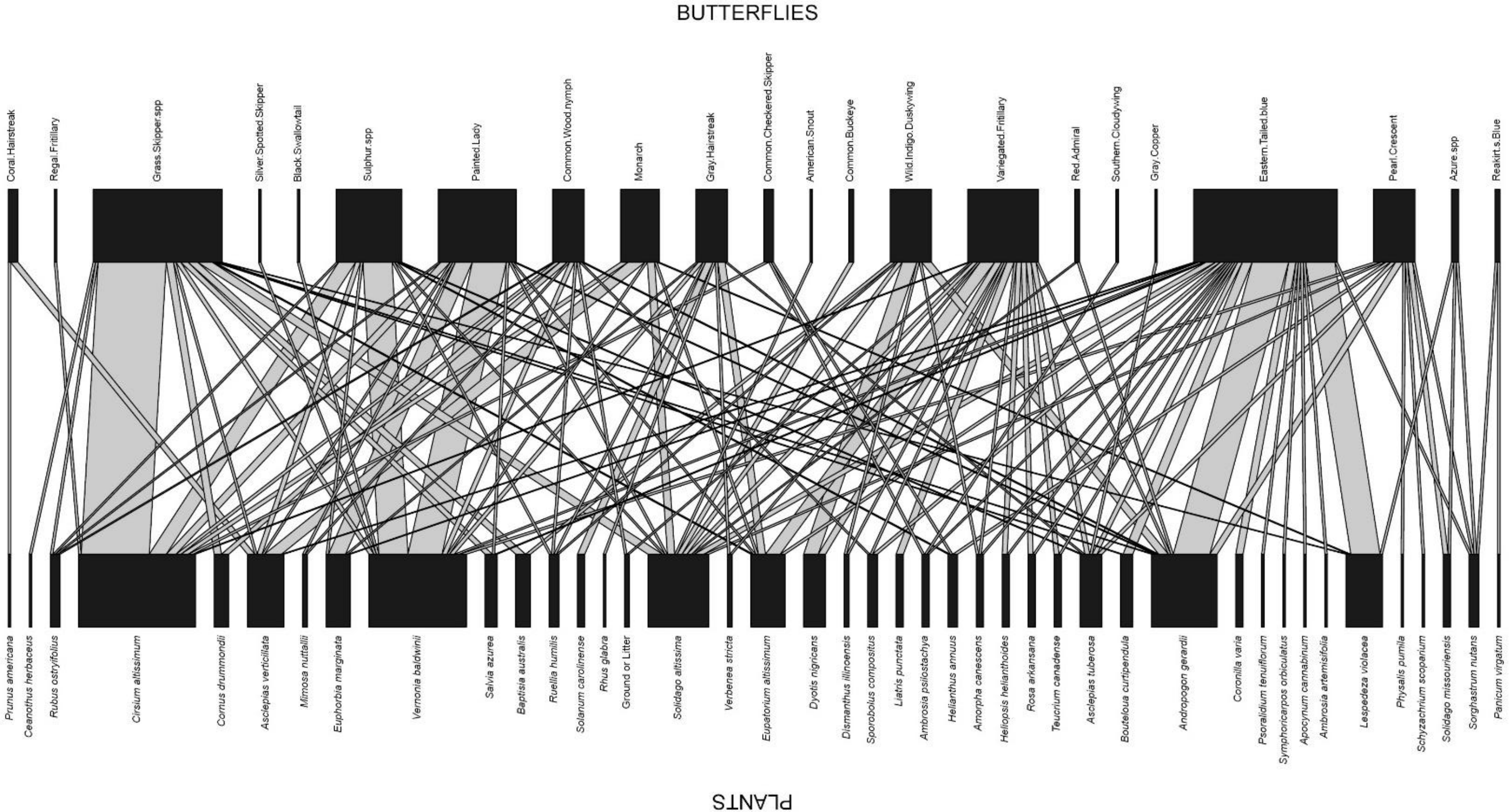

Figure 4.13. Native prairie R20A and R20B plant-butterfly bipartite network showing nectaring, ovipositing, mating, and basking interactions between plants and butterflies during 2017 and 2018. Thicker lines indicate a greater proportion of interactions.

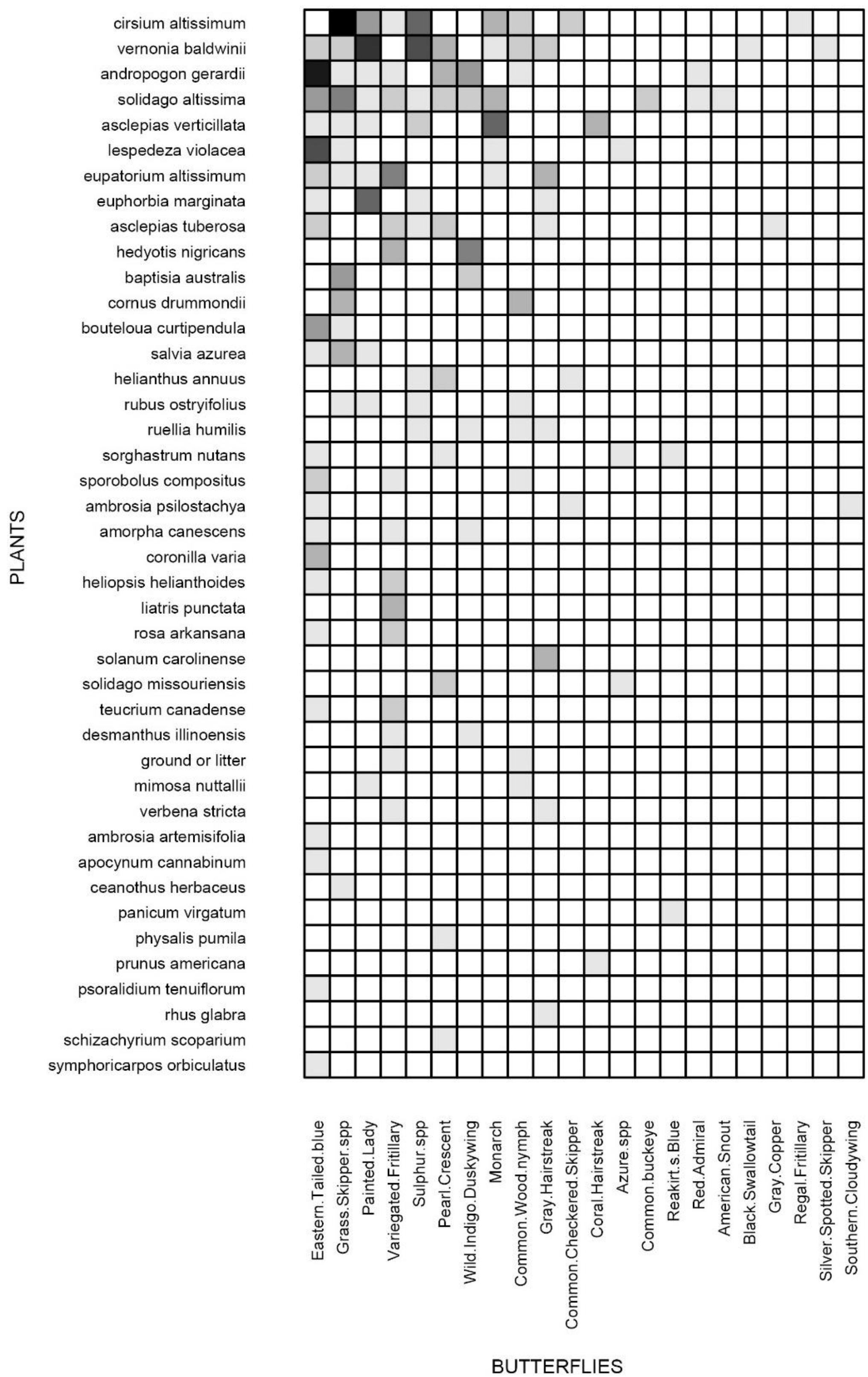

Figure 4.14. R20A and R20B incidence matrix depicting plant-butterfly interactions using field data from 2017 and 2018. Darker shading indicates a greater number of interactions.

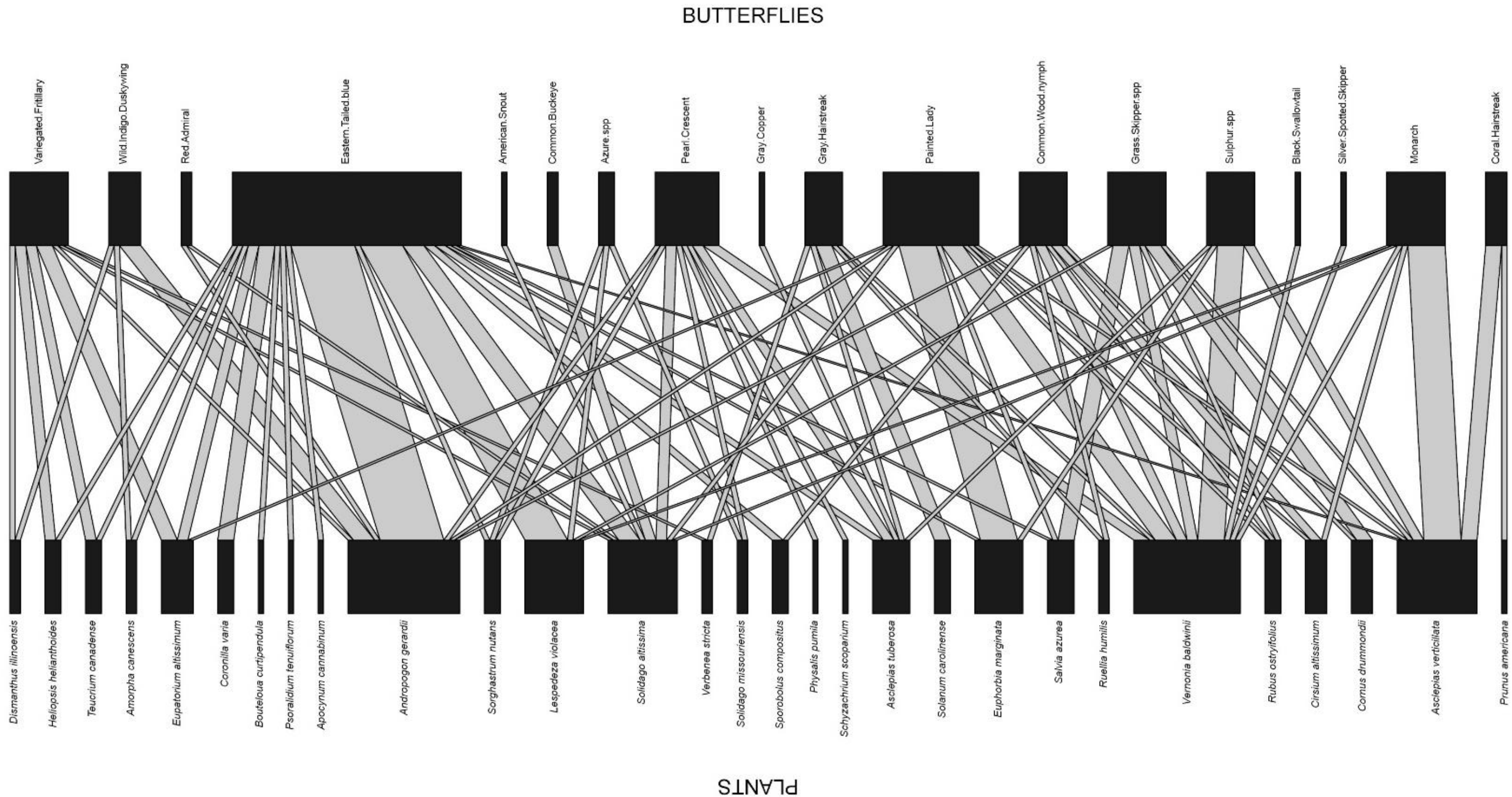

Figure 4.15. Native prairie R20B plant-butterfly bipartite network showing nectaring, ovipositing, mating, and basking interactions between plants and butterflies during 2017 and 2018. Thicker lines indicate a greater proportion of interactions.

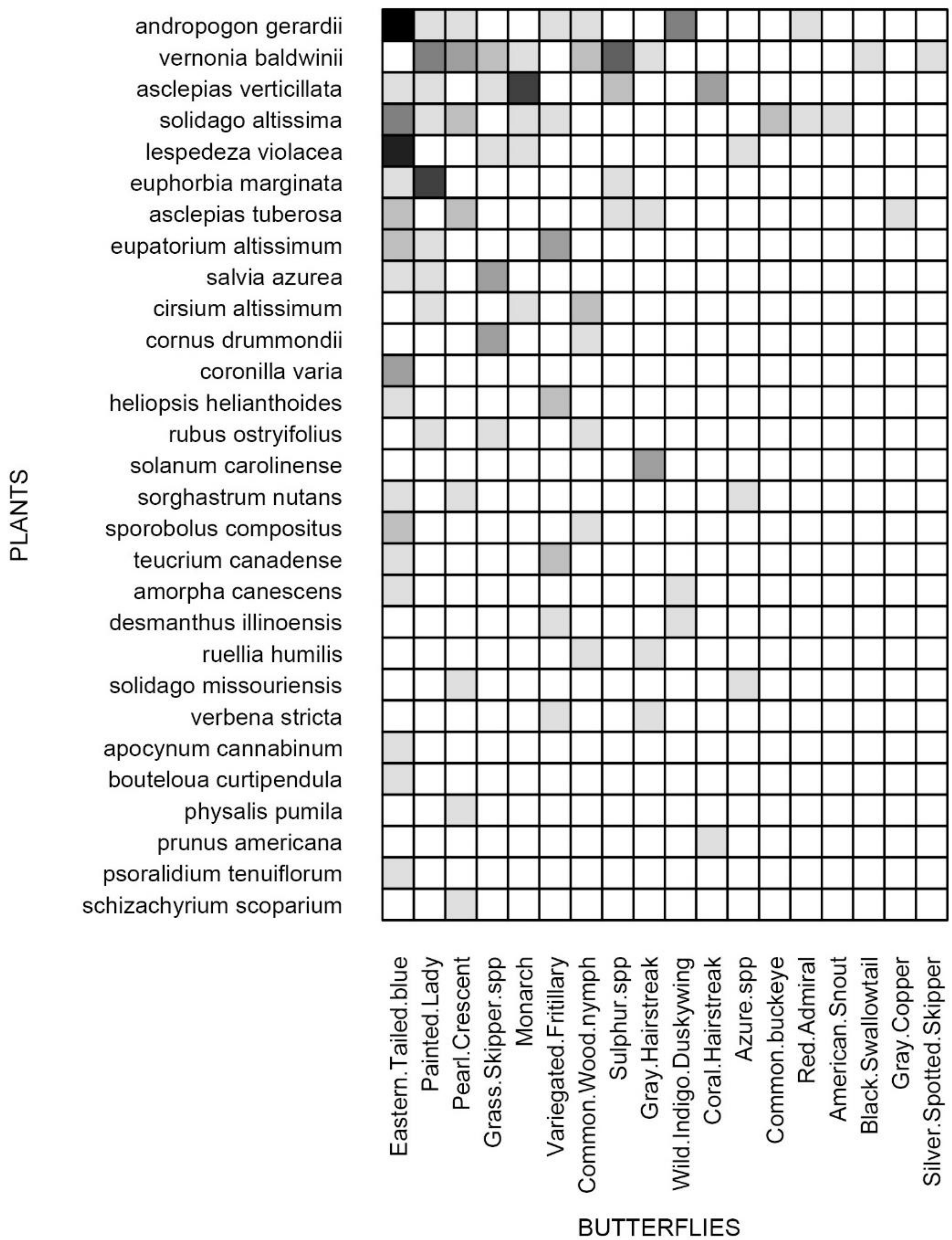

Figure 4.16. R20B incidence matrix depicting plant-butterfly interactions using field data from 2017 and 2018. Darker shading indicates a greater number of interactions.

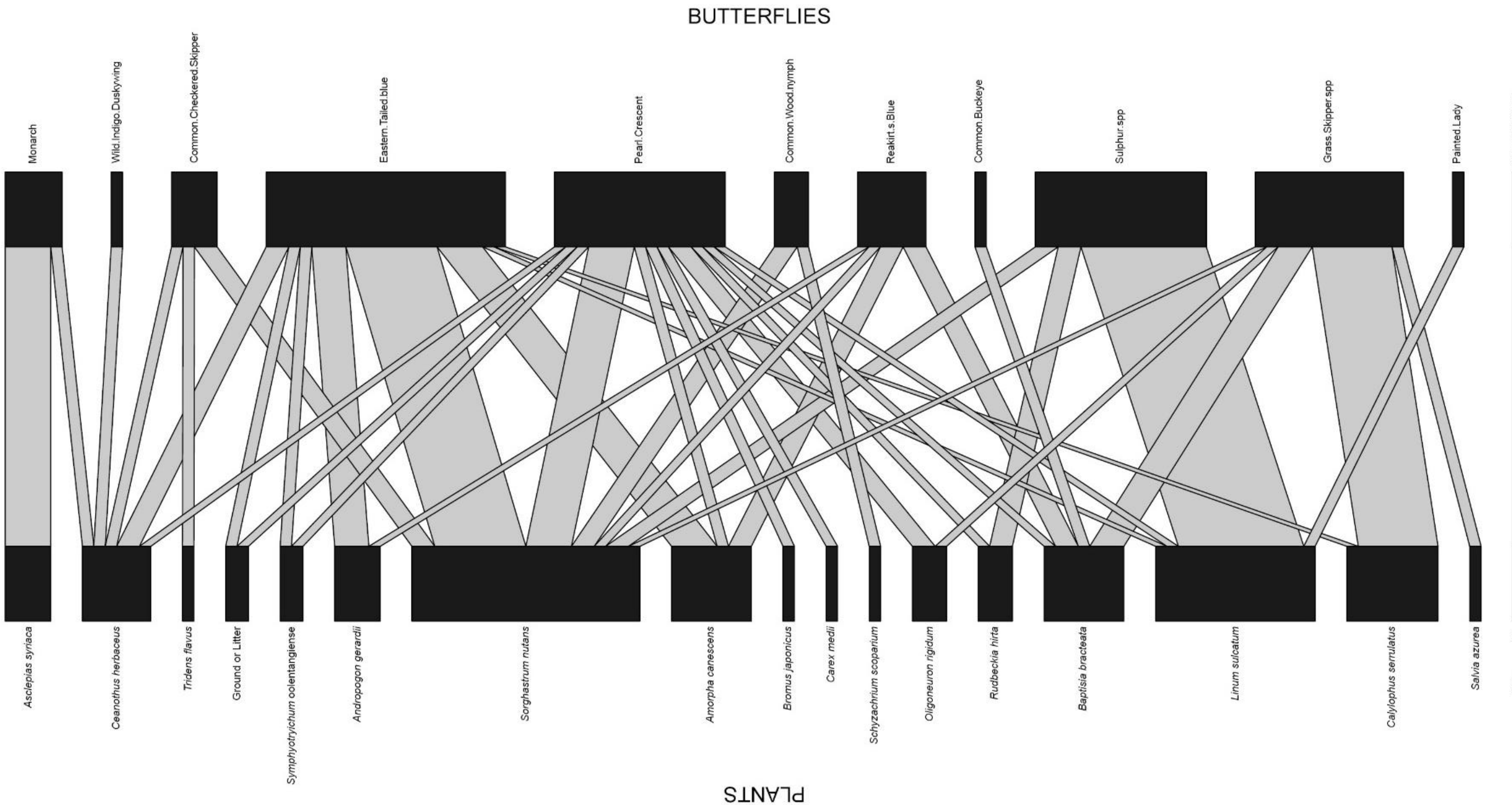

Figure 4.17. Urban prairie plant-butterfly bipartite network showing nectaring, ovipositing, mating, and basking interactions between plants and butterflies during 2017 and 2018. Thicker lines indicate a greater proportion of interactions.

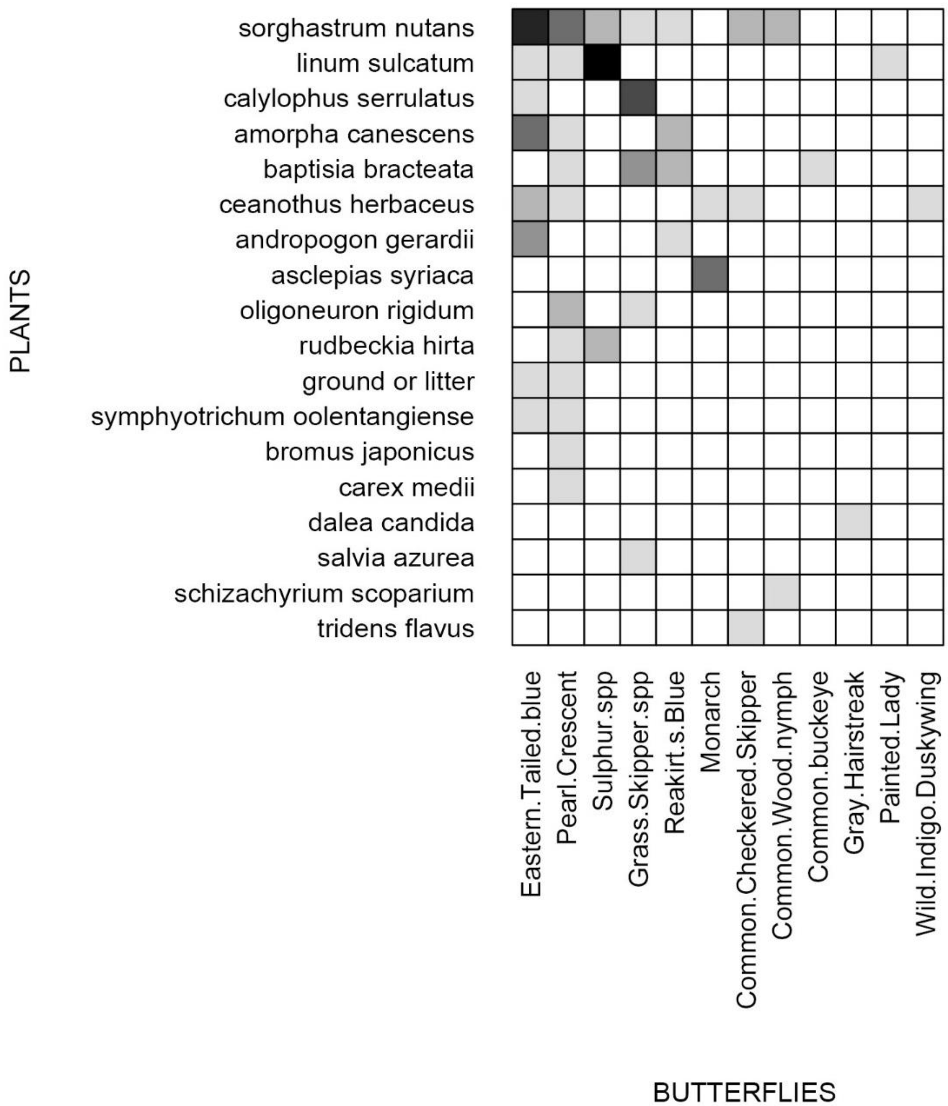

Figure 4.18. Urban prairie incidence matrix depicting plant-butterfly interactions using field data from 2017 and 2018. Darker shading indicates a greater number of interactions.

Chapter 5 - Green Roof Planning, Design, Construction, and Management Implications

5.1 Introduction

Green roof research has largely concentrated on design and engineering constraints up until relatively recently when the ecological potential of green roofs began being studied (Blank et al., 2013). Through these studies, green roofs have been found to provide a variety of benefits including reducing stormwater quanitity and improving stormwater quality, enhancing thermal insulation of buildings beneath them, reducing urban pollutants, and improving sound proofing of structures (Benvenuti, 2014; Sutton, 2015). Still, little research has focused on the potential value of green roofs to provide habitat, and there are many questions related to how green roofs can improve urban biodiversity that still need to be answered (Blank et al., 2013).

The objectives of this project were to: 1) determine to what extent a green roof is used by butterflies in comparison to native and urban prairie, and 2) understand how on-site vegetation composition influences the butterfly communities using a site. I found Memorial Stadium provided habitat for a much higher abundance of late season butterflies than either native or urban prairie. The mean number of species of butterflies using Memorial Stadium was comparable to native and urban prairie, but the specialist butterflies present at the prairie sites were absent from Memorial Stadium. Forbs, floral resources, and aboveground biomass were important for butterfly communities, while plant evenness negatively impacted the butterfly community.

Using study results, my final goal is to develop practical guidelines landscape architects and urban designers can use to improve green roof and other green infrastructure butterfly habitat in the tallgrass prairie. In this chapter, I discuss potential green roof design, construction, and maintenance implications for butterfly habitat structured around outcomes from my study. I conclude this thesis by presenting some additional research questions that would be helpful to know to improve green roof design for urban pollinators.

5.2 Design and Construction Guidelines

Considering the study findings from the previous chapters, there are several tactics that can be employed during the planning, design, construction, and maintenance phases of a green roof project to increase butterfly diversity, abundance, and richness. Green roofs generally have several standard components that make up the system such as waterproofing, root barrier, a drainage layer, substrate (soil), plant material, and some have an irrigation system (Sutton, 2015). Some of these components can be designed to improve butterfly habitat. While my study did not focus on analyzing these components for optimization of pollinator biodiversity, I have outlined below several outcomes of my study that suggest ways pollinator biodiversity can be improved on green roofs and how green roof design and construction can be modified to promote a rich and abundant butterfly community.

5.2.1 Outcome 1: Green roofs do not replace native prairie

Memorial Stadium is not currently providing habitat for specialist butterfly species, those species that are not able to readily adapt to changing environmental conditions. Over time this may change, but right now it shows the importance of keeping native prairie intact. Therefore, the most important finding from my study is to not expect humans to engineer urban infrastructure that is able to provide the same ecosystem services as native prairie. Preserve native prairie; it provides butterfly habitat this green roof cannot replace. Landscape architects, developers, property owners, and planners need to avoid developing native lands. When a client demands it, advocate to preserve as much of that native land as possible. Educate clients about the social, economic, and environmental importance of native prairie so they can clearly see the justification; people tend to make better decisions when they understand the consequences of their actions.

5.2.2 Outcome 2: Forbs were consistently important for butterflies

I found that more species of forbs in bloom increased the total number of early season butterflies, the number of species of early season butterflies, and early season butterfly diversity. I also found the coverage of forbs to be associated with an increase in the number of early season butterflies and the number of species of early and late season butterflies. The majority of butterflies using Memorial Stadium were nectaring.

These findings suggest adding species of forbs that bloom in the early season (May through July) should increase the number of butterflies and species of butterflies using the green roofs. Some attractive species that bloom early season and were used by butterflies in my study include butterfly milkweed (*Asclepias tuberosa*), whorled milkweed (*Asclepias verticillata*) serrate-leaf evening primrose (*Oenothera serrulata*), snow-on-the-mountain (*Euphorbia marginata*), narrow-leaf bluets (*Hedyotis nigricans*), and grooved flax (*Linum sulcatum*), as shown in Figure 5.1. Adding more forb coverage should also increase the number of early season butterflies as well as early and late season butterfly diversity. There is a large amount of bare ground on Memorial Stadium, so adding more forbs will also help fill in this space and provide competition for invasives and other undesirable plant species. Figure 5.2 shows possible native plant species to include on a green roof to increase late season blooming forbs.

Design and construction actions that should be considered to promote more abundant and richer butterfly communities are those that promote the growth and flowering of forbs, including retention of water and substrate characteristics. Deeper substrates have been found to improve flowering of herbaceous perennials and reduce winter kill (Sutton, 2015). Green roof substrates with organic matter (though not exceeding 15%) or minimal fertilizer have been shown to maintain non-succulent native midwestern perennial plant health (Rowe, Monterusso, & Rugh, 2006). In the variable climate of the tallgrass prairie where there may be long periods of little to no precipitation, plants may become water stressed and delay flowering. Retention of water on green roofs to minimize drought impacts can be improved with deeper substrates (Mentens, Raes, & Hermy, 2006). This is especially important to consider on a sloped roof like the Memorial Stadium because they have lower water retention (Sutton, 2015). However, structural integrity of the building must be considered when selecting substrate depths. Denser vegetation canopies can reduce evaporation from the soil and also intercept more water (Sutton, 2015). Therefore, green roofs trying to promote floral resources and forb coverage for butterflies should use deeper substrates, be constructed with less slope, and promote denser vegetation canopies.

While my study did not look at ground-level urban garden benefits to butterflies, the importance of forbs on the green roofs and at the native prairie sites implies that forbs will likewise be important in urban parks and gardens. Retrofitting a structure with a green roof is expensive, especially one with deeper substrates like Memorial Stadium. Creating planting beds on the ground could likely be just as effective at providing floral resources for butterflies as a green roof, but at much less cost. There are many opportunities to replace existing turf or non-native landscape cover with forbs that are beneficial for native pollinators.

5.2.3 Outcome 3: Butterflies preferred some plants

I found that greater coverage of larval host plants increased butterfly diversity and that there were some species of plants used across all sites more prevalently than others. Appendix C: Larval Host Plants is a list of larval hostplants of butterflies found at all of the study sites.

Adding specialist host plants to the roof might be beneficial in attracting those specialist species and a more diverse butterfly community. For example, the Regal Fritillary (*Speyeria idalia*) larvae use violets (*Viola spp*.) for food and this could be planted on green roofs to increase butterfly species diversity. This plant has been successfully used on other green roofs, including extensive green roofs in Minnesota by Kestrel Design Group (Sutton, 2015).

Of the plants growing on Memorial Stadium currently, those that were most used by butterflies were *Liatris aspera*, *Liatris pycnostachya*, *Ratibida pinnata*, *Ratibida columnifera*, *Baptisia australis*, *Oligoneuron rigidim,* and alfalfa (*Medicago sativa*). Those most used at the native prairie were *Cirsium altissimum, Vernonia baldwinii, Andropogon gerardii*, *Solidago altissima*, *Asclepias verticillata*, *Lespedeza violacea,* and *Eupatorium altissimum*. The most used plants at the urban prairie were *Sorghastrum nutans*, *Linum sulcatum, Oenothera serrulata*, *Amorpha canescens, Baptisia bracteata*, *Ceonothus herbaceus*, and *Andropogon geradii*. Many of these plants were dominant at my sites and therefore may not be preferentially chosen by butterflies, but instead were merely present when a butterfly needed a basking or resting location.

While it is uncertain whether all of the plants most used by butterflies at the urban and native prairies will perform well on Memorial Stadium, some of the plants are already growing on Memorial Stadium. Attractive plants desired by butterflies in this study that are worth attempting on a green roof (and I have not found currently growing on Memorial Stadium) are *Vernonia baldwinii, Asclepias verticillata*, *Linum sulcatum*, *Oenothera serrulata*, *Baptisia bracteata*, and *Lespedeza violacea*. Even though *Cirsium altissimum* was the most used plant at the native prairie, it is a thistle and generally thought of as a nuisance and unsightly, so it may be against safety and attractiveness goals of a public green roof project. However, this generalist plant species could potentially attract specialist butterfly species, increase nestedness, and thereby improve site butterfly richness. The woody plants, *Amorpha canescens* and *Ceonothus herbaceus*, while attractive for butterflies, may have more aggressive roots that could damage the waterproofing membrane of a green roof, unless designing for an intensive green roof system or using a heavy-duty root barrier.

When selecting plants, it is important to consider the flowering phenology. Target species to provide asynchronous flowering so there are consistent floral resources for butterflies. *Liatris* species were a butterfly favorite at each of my sites, though they were rare at the native and urban prairies so it does not appear in my data that they were actually preferred. Therefore, select additional *Liatris* species that flower earlier in the season, such as *Liatris punctata*. *Asclepias* species were also butterfly favorites at the native and urban prairie sites. Adding some species to Memorial Stadium would add nectar sources for many butterflies, as well as the monarch butterfly's larval host. Some species to consider in addition to the *A. verticillata* are *A. tuberosa*, *A. viridis*, and *A. viridiflora* as these species prefer dry, rocky soils (Haddock, 2019) similar to green roof substrate. *A. verticillata*, installed by seed only, have been shown to thrive on the extensive Target Center Green roof in Minnesota (Sutton, 2015). These species would provide floral resources for late spring and summer, larval resources for migrating monarchs, and increase the coverage of generalist plant species to encourage both generalist and specialist butterfly interactions. It is important to source plants and seed locally to avoid plant maladaptation (Bower, Clair, & Erickson, 2014).

5.2.4 Outcome 4: Reduce plant evenness, but increase plant biomass

I found that plant evenness reduced specialist butterfly abundance, butterfly richness, and butterfly diversity. I also found that a higher visual obstruction increased butterfly specialist abundance. This means that a plant community consisting of some dominant plants and some rare plants can support a greater number of species of butterflies as opposed to a plant community having even coverage of all plants. Additionally, having aboveground biomass should increase the specialist butterflies using a green roof. For example, even though dominant native grasses such as Indiangrass (*Sorghastrum nutans*) and Big Bluestem (*Andropogon gerardii*) do not provide nectar sources, they still provide biomass and places for butterflies to rest or bask on a green roof. Therefore, it is important to include them on green roofs. These findings suggest that when creating green roof planting plans, designers should focus on having a variety of plants with varying species coverage and include forbs and grasses to increase the aboveground biomass.

5.3 Maintenance Guidelines

I found that butterflies are coming to the Memorial Stadium green roofs largely to nectar on native perennial vegetation. Generally, with increased floral display there is increased visitation to plants and more flowers probed by pollinators (Willmer, 2011). Therefore, more blossoms at the stadium should result in more use by butterflies and other pollinators. To provide more nectar to butterflies, the plant material needs to be managed in a manner that encourages blossoms while butterflies are active. This has several implications for management, and seven implications are noted below.

1) Ensure nutrients are available in the substrate to allow forbs to reproduce. Green roof nutrients generally leach out of the substrate (Sutton, 2015), which may limit floral displays. Because of the shallow substrates and slope of the roof, this may make the Memorial Stadium especially prone to nutrient deficiencies. This may require annual spring soil testing to determine if fertilization is needed (Sutton, 2015). However, one study found that more fertile substrates

resulted in less resiliency during drought (Bates et al., 2013), so if no irrigation system is in place on a green roof in an arid climate, it may be better to use less nutrients.

2) Cut back vegetation before or after butterflies are active. Mowing has increased bee and butterfly abundance in some studies (Buchmann & Wojcik, 2012), but all too often prairie is cut back during late summer along roadsides or in parks. Unfortunately, cutting back during this time period removes blossoms for an abundance of butterflies; my study found that butterfly abundance increases from spring until late summer, therefore late season mowing removes the floral resources needed when the greatest abundance of butterflies are active.

3) When vegetation is cut back, keep the trimmings on the roof to allow a litter layer to develop. This may help the plants by indirectly insulating their roots and holding in moisture to prevent damage during temperature extremes and periods of drought. It may also allow butterflies whose larvae overwinter in the litter to use the roof for rearing their young.

4) Maintain the irrigation system so water is evenly distributed on the roof giving plants the best chance for survival. Water-stressed plants may delay flowering (Willmer, 2011), which will reduce the number of blossoms available for butterflies. Because of the steep slopes and low water holding capacity of the substrate at the Memorial Stadium, it could be helpful to use a “soak and cycle” irrigation schedule here and at other roofs that use overhead irrigation (https://www.johnson.k-state.edu/lawn-garden/agent-articles/miscellaneous/soak-and-cycle-lawn-irrigation.html). This may help reduce the amount of runoff from the irrigation system and allow more water to be retained in the substrate, thereby reducing irrigation water necessary to keep plant material alive. Plant productivity goals, however, must be balanced with water conservation practices so as to not detract from K-State’s commitment to sustainability.

5) Monitor the plant community for asynchronous blooming. If there are times on the green roof during the growing season when there are no perennials blooming, there likely are no floral resources for foraging butterflies during that time. Consider consulting native plant nurseries, local botanists, or explore nearby native prairie to find nectar-providing plants blooming at that time and then add these species to the green roof to provide consistent, season-long nectar for butterflies.

6) Overseed periodically with additional species of forbs and grasses to fill in the bare ground so that native perennial vegetation can, over time, outcompete invasive species. While additional forbs will add more floral resources for pollinators, adding grasses will also increase the aboveground biomass, which I found to be a predictor of butterfly specialist species.

7) Remove woody vegetation consistently to not only protect the roofing membrane, but to improve the butterfly community. Woody plant roots are more aggressive than forbs or grasses and need to be removed before their roots can penetrate the waterproofing membrane. It is easiest to remove woody plants while they are young and can be pulled out by hand. When larger, they cannot be pulled out and need to be cut back and a stump or brush killing herbicide applied to the remaining stem. This study found woody vegetation to negatively impact butterfly abundance, but to improve butterfly richness. Given the possible negative impacts on the structure of a green roof, however, that would take precedence over butterfly richness. Of course for some green roofs, a heavy-duty root barrier may allow for woody plants

Because of the difficult growing conditions on green roofs, vegetation must be suited to the harsh environment. However, because of limited ages of green roofs, it is still unclear how to best manage green roof vegetation for sustainability over the long-term (Benvenuti, 2014). These seven practices will hopefully improve the floral resources for butterflies, attract more butterflies and other pollinators, and thereby improve pollination and seed set of the plants encouraging reproduction of the vegetation.

5.4 A side note: Warner Park

The peculiar plant and butterfly communities at Warner Park deserve special mention. Having a native remnant prairie like Warner Park in an urban context is a unique amenity for Manhattan, Kansas. This study found plants at Warner Park that have no herbarium record in Riley County, not even at Konza Prairie. I attribute the high diversity to the haying management that it receives at late summer. However, summer haying is negatively impacting the floral resources for butterflies; all the late season blossoms are being removed. During the first season when the site was hayed all around my transect, most of the floral resources remaining in the vicinity were at my transect. Similar to the isolated setting of the green roofs, an enormous abundance of butterflies congregated at my transects. I did not observe this phenomenon the second season due to my transects being accidentally removed and all the floral resources removed. This shows the importance of even a narrow swath of unmowed vegetation at Warner Park for butterflies and other pollinators. I found the majority of forbs blooming at Warner Park bloom at the end of the summer, therefore the haying is removing the majority of the floral resources the park is producing.

This study suggests that pollinators near Warner Park are nectar limited and that additional floral resources are needed as evidenced by the large numbers of butterflies that used the site when the surrounding vegetation was hayed, particularly in the late season when the most butterflies are active. I suggest that patches of plants are not hayed, but are left standing for the benefit of pollinators. The haying has reduced woody encroachment at this prairie and maintained its high diversity, so it is important to continue haying. However, if areas of vegetation at Warner Park are left intact and these areas are rotated annually, it would be beneficial for pollinators and still maintain the plant diversity. In addition, to supplement the few forbs blooming in the early season, it would be beneficial for butterflies if the site was overseeded or planted with some forbs that bloom earlier. This will benefit regal fritillary and other butterflies that need nectar earlier in the year. These early season forbs will not be impacted by the late summer haying that is removing the blossoms of the late blooming forbs.

5.5 Accomplishing this Research Project

For other people wanting to undertake a similar project, I have been asked to document some of the strategies I used, and what could have made my project even better. When beginning this research project, I did not correctly estimate the amount of work involved nor did I understand the reliance I would have on other people.

By far the most important thing I did for this research project was to develop and maintain relationships with people willing to help me and those managing my research sites. Jeff Taylor, the botanist at Konza Prairie, took me out to my research sites and taught me the plants back in March and April of 2017. Afterwards, he let me send him photos of seedlings and plants and helped me identify them. I could not have learned the diversity of plants without his assistance. For a project that deals with this much data, there was no way I could have used paper documentation. Being able to use an iPad with Jeff's custom application he created in Filemaker saved me an enormous amount of time.

As a poor grad student, forming relationships with other researchers and facility personnel helped save me a lot in research costs and improve the quality of my research. I was able to use materials (T-posts, post pounder, and short posts) from facilities manager, Joe Myers, and PhD student, Ellen Welti, for marking and installing my transects. Lee Skabelund provided a small sledge hammer, iPad, and Robel poles so I did not need to purchase these. John Briggs let me use a GPS unit that belongs to the Division of Biology so I could do the spatial aspect of my study. Amanda Kuhl gave me access to LTER personnel so I could have students available to help me. She also let me borrow her Kestrel weather meter when mine quit working and was awaiting a new one in the mail.

I learned the butterflies by using a book that both Ellen Welti and Sarah Ogden recommended, *Kaufman Field Guide to Butterflies of North America*. I looked up other studies from around Kansas to see the most common species in my area, and I studied those species in my book. Then, I took my camera and butterfly net outside to random places and started photographing and catching butterflies. I studied their flight patterns prior to catching because that proved to be an effective way to identify them on the fly. At first it was extremely difficult for me to catch the butterflies (even though I have played baseball and tennis for years and have decent hand eye coordination), so using my camera with a long zoom lens to photograph them became my most common method of identifying them. This ended up providing lots of imagery for presentations, as well.

There are a couple things I wish I would have done better. The first is that I wish I had written down and agreed upon how the green roofs were to be maintained for the duration of my study. Facilities, my professor, and I all needed to agree on this prior to initiating my study to ensure the most robust study possible. The second thing I wish I had done was maintain a more open dialog with the city personnel managing Warner Park. This would have prevented some unexpected events there such as the haying of my transects. I also would have liked to have better marked off my transects at each site so that less unintended changes would have taken place at each of them. Finally, I think I would have avoided taking any classes the first summer doing field work. I took two courses, one of which was my first statistics class, and combining that with doing field work for this study was too time intensive, I never had time for a break, I went 11 months straight without seeing any family, and it negatively impacted my health.

5.6 Conclusion

This is just a single multi-site study in one city, in a single ecoregion with high climatic variability. Other climates and locations could have different results. Because plants and butterflies are so dependent on the climate and context, studies should be completed in other geographic regions to better understand how urban butterfly communities may respond to native plant green roofs under different conditions.

Another factor to consider is how the findings of this study would change in five or ten years from now. Time will likely change the plant community as vulnerable plants die out, a litter layer develops, and other plants outcompete neighbors. Longer-lived butterflies may learn routes to the green roofs and change the diversity of butterflies using the roofs. Though not addressed in my study, the landscape surrounding the green roofs will undoubtedly change. Perhaps with more native vegetation surrounding Memorial Stadium, additional butterfly species will find it worth their time to forage in this area of campus. Conversely, with additional urban development, the butterfly community may diminish. It could be informative to analyze these two green roofs over time and see how the plant and butterfly communities respond to the many changes that will likely occur.

Another fruitful area of future research on these green roofs related to butterfly habitat could be to implement some of the suggestions from my study and see how the butterfly community responds. For example, I found that the coverage of larval host plants and number of forb species blooming were significant predictors of butterfly species diversity. It could be interesting to see if, after overseeding or planting additional forbs and hostplants onto the roof, would diversity increase, and new butterfly species use the roof? If we add generalist plant species to the roof, will nestedness increase? Could the addition of a large-scale native planting nearby make the green roof usable by specialist butterflies? These types of studies would help differentiate which of my findings are merely artefacts of each site and which variables are truly impacting butterfly communities. These manipulations may be able to help us better understand what the limiting factors are for specialist species.

In conclusion, the butterfly community of the Memorial Stadium is remarkable in comparison to nearby urban and rural prairie. Its butterfly abundance is greater than native prairie, the mean species richness is comparable to native prairie, but the prairie specialist species are absent from the roof. There are several on-site vegetation factors that appear to be influencing the butterfly communities at each site. Green roof design should focus on adding floral and larval resources, aboveground biomass, and by planting more native perennial forbs and some grasses and allowing some litter to accumulate. Implementing some of the design guidelines outlined in this chapter, analyzing the roofs over time, and spreading this study to native plant green roofs in other climates and geographic regions, as well as studying in conjunction with other urban green infrastructure in public parks and on private properties, will help us better understand how green roofs can contribute to urban pollinator habitat.

5.7 Figures

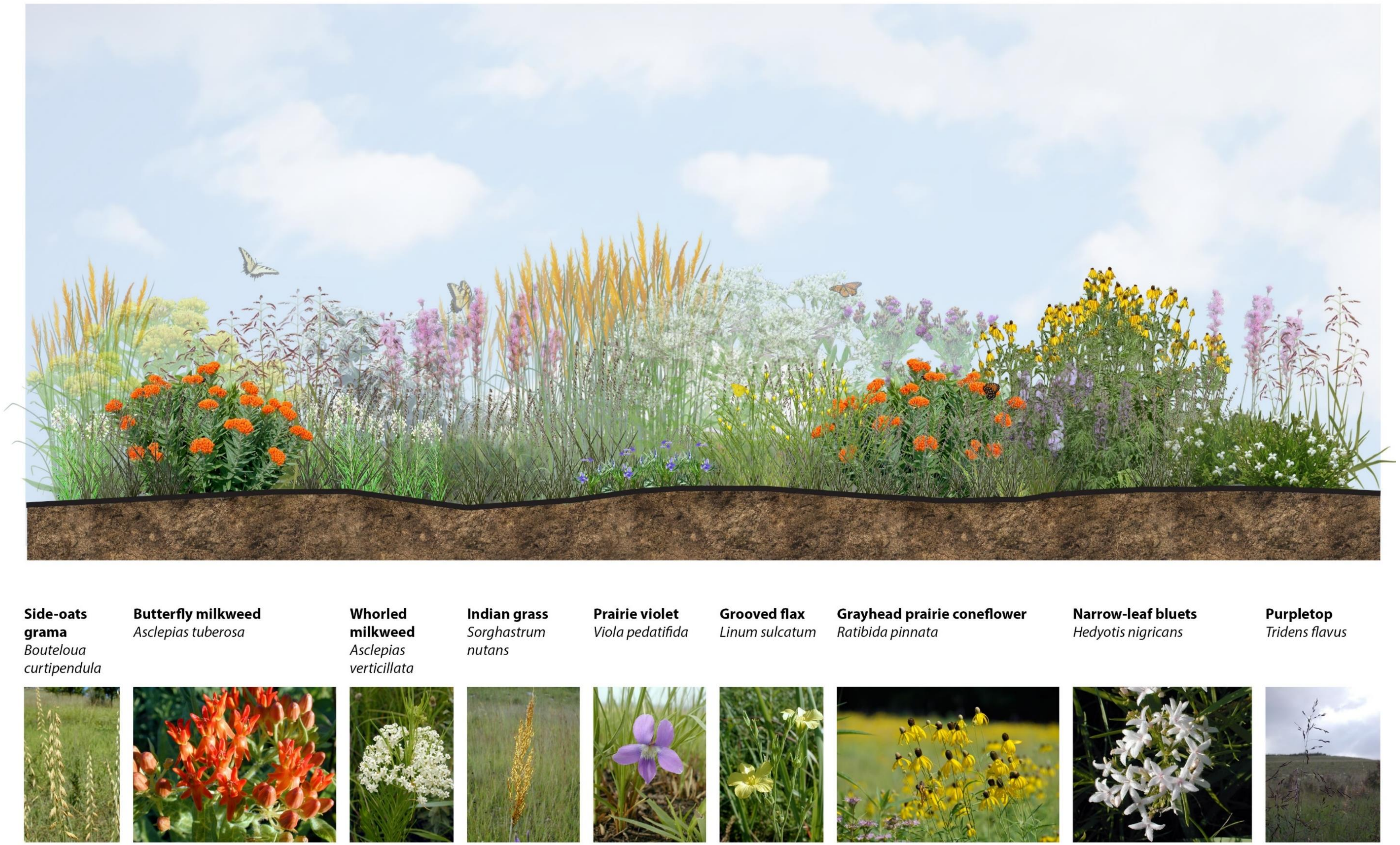

Figure 5.1. Section rendering showing potential native tallgrass prairie grasses and forbs during early season planted on a semi-intensive green roof.

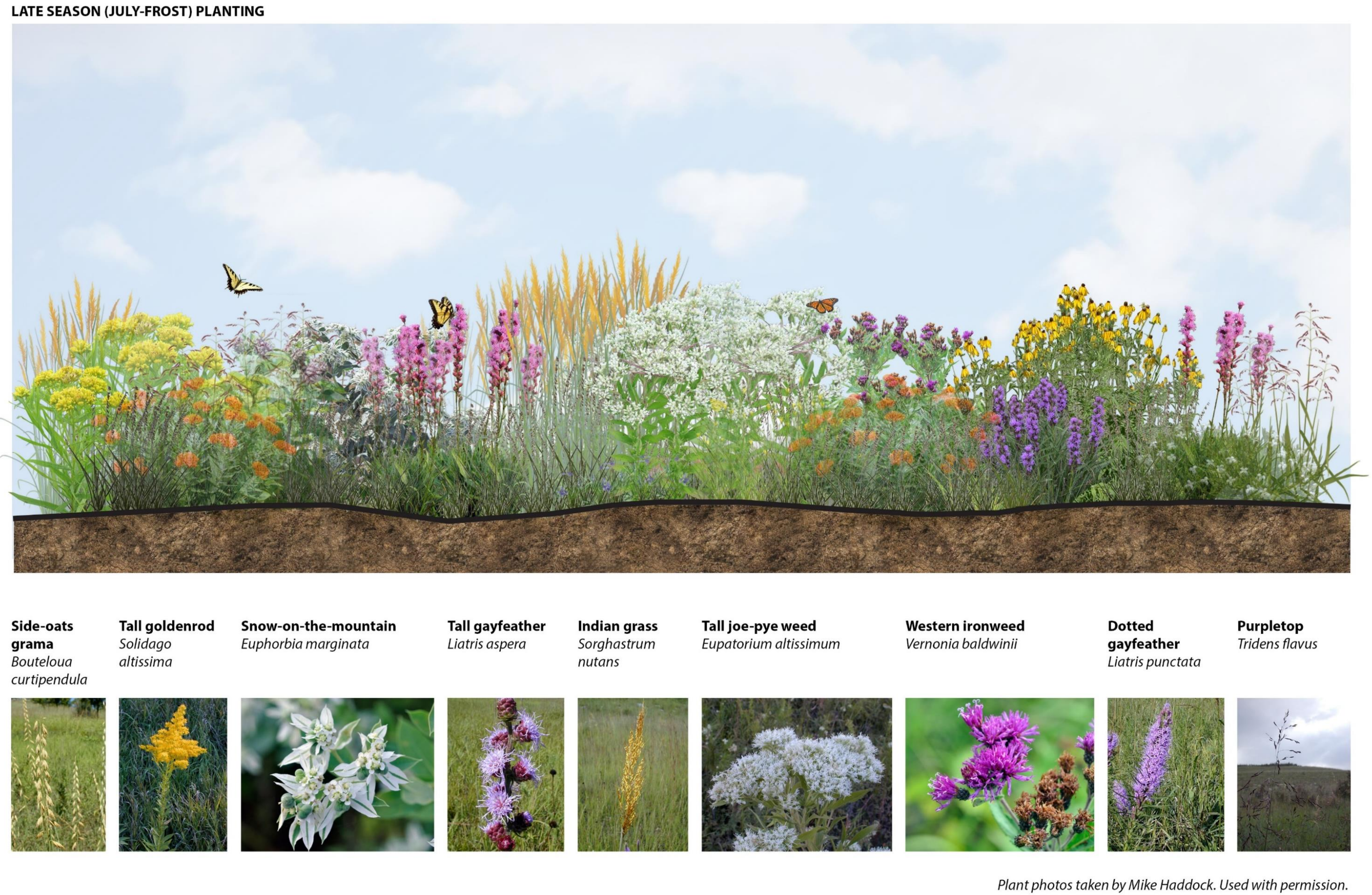

Figure 5.2. Section rendering showing potential native tallgrass prairie grasses and forbs during late season planted on a semi-intensive green roof.

5.8 Literature Cited

Alarcó, R., Waser, N. M., Ollerton, J., Alarco´n, R., & Waser, N. M. (2008). Year-to-year variation in the topology of a plant Á pollinator interaction network Online Early (OE): 1-OE. *Oikos*. https://doi.org/10.1111/j.2008.0030-1299.16987.x

Anderson, B., & Johnson, S. D. (2008). The geographical mosaic of coevolution in a plant-pollinator mutualism. *Evolution*, *62*(1), 220–225. https://doi.org/10.1111/j.1558-5646.2007.00275.x

Angold, P. G., Sadler, J. P., Hill, M. O., Pullin, A., Rushton, S., Austin, K., … Thompson, K. (2006). Biodiversity in urban habitat patches. *Science of the Total Environment*, *360*, 196–204. https://doi.org/10.1016/j.scitotenv.2005.08.035

Baer, S., Blair, J., Collins, S., & Knapp, A. (2004). Plant community responses to resource availability and heterogeneity during restoration. *Oecologia*, *139*, 617–629. https://doi.org/10.1007/s00442-004-1541-3

Baguette, M., & Stevens, V. (2013). Predicting minimum area requirements of butterflies using life-history traits. *Journal of Insect Conservation*, *17*(4), 645–652. Retrieved from http://s3.amazonaws.com/academia.edu.documents/43971967/Predicting_minimum_area_requirements_of_20160321-10426-s7bral.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1494887131&Signature=vLUJLKoaw3qkV3nknhhAfL%2BBVKg%3D&response-content-disposition=inline

Bartomeus, I., Park, M. G., Gibbs, J., Danforth, B. N., Lakso, A. N., & Winfree, R. (2013). Biodiversity ensures plant–pollinator phenological synchrony against climate change. *Ecology Letters*. https://doi.org/10.1111/ele.12170

Bascompte, J., Jordano, P., Melian, C. J., & Olesen, J. M. (2003). The nested assembly of plant-animal mutualistic networks. *Proceedings of the National Academy of Sciences*, *100*(16), 9383–9387. https://doi.org/10.1073/pnas.1633576100

Bates, A. J., Sadler, J. P., & Mackay, R. (2013). Vegetation development over four years on two green roofs in the UK. *Urban Forestry & Urban Greening*, *12*, 98–108. https://doi.org/10.1016/j.ufug.2012.12.003

Beck, C. (2016). *General Pollinator Monitoring Protocol*. Columbus, Ohio.

Benvenuti, S. (2014). Wildflower green roofs for urban landscaping, ecological sustainability and biodiversity. *Landscape and Urban Planning*, *124*, 151–161. Retrieved from https://www.researchgate.net/profile/Stefano_Benvenuti2/publication/260016259_Wildflower_green_roofs_for_urban_landscaping_ecological_sustainability_and_biodiversity/links/00b4953b3f631a7ab3000000.pdf

Bergerot, B., Fontaine, B., Renard, M., Cadi, A., & Julliard, R. (2010). Preferences for exotic flowers do not promote urban life in butterflies. *Landscape and Urban Planning*. https://doi.org/10.1016/j.landurbplan.2010.02.007

Bergman, K.-O., Ask, L., Askling, J., Ignell, H., Wahlman, H., Milberg, P., … Wahlman, · H. (2008). Importance of boreal grasslands in Sweden for butterXy diversity and eVects of local and landscape habitat factors. *Biodivers Conserv*, *17*, 139–153. https://doi.org/10.1007/s10531-007-9235-x

Bezemer, T. M., Harvey, J. A., & Cronin, J. T. (2014). Response of Native Insect Communities to Invasive Plants. *Annual Review of Entomology*, *59*, 119–141. https://doi.org/10.1146/annurev-ento-011613-162104

Blair, J., Nippert, J., & Briggs, J. (2014). Grassland Ecology. In R. K. Monson (Ed.), *Ecology and the Environment* (pp. 389–423). New York: Springer New York. https://doi.org/10.1007/978-1-4614-7501-9_14

Blank, L., Vasl, A., Levy, S., Grant, G., Kadas, G., Dafni, A., & Blaustein, L. (2013). Directions in green roof research: A bibliometric study. *Building and Environment*, *66*, 23–28. https://doi.org/10.1016/j.buildenv.2013.04.017

Bloch, D., Werdenberg, N., & Erhardt, A. (2006). Pollination crisis in the butterfly-pollinated wild carnation Dianthus carthusianorum ? *New Phytologist*, *169*, 699–706. https://doi.org/10.1111/j.1469-8137.2005.01653.x

Bower, A. D., Clair, J. B. St., & Erickson, V. (2014). Generalized provisional seed zones for native plants. *Ecological Applications*, *24*(5), 913–919. https://doi.org/10.1890/13-0285.1

Brock, J. P., Kaufman, K., Bowers, R., Bowers, N., & Hassler, L. (2003). *Kaufman field guide to butterflies of North America*. Houghton Mifflin. Retrieved from https://www.barnesandnoble.com/p/kaufman-field-guide-to-butterflies-of-north-america-kenn-kaufman/1102540834/2695219568021?st=PLA&sid=BNB_DRS_Marketplace+Shopping+greatbookprices_00000000&2sid=Google_&sourceId=PLGoP24179&k_clickid=3x24179

Brues, C. T. (1920). The Selection of Food-Plants by Insects, with Special Reference to Lepidopterous Larvae. *The American Naturalist*, *54*(633), 313–332. Retrieved from https://www.jstor.org/stable/pdf/2456552.pdf

Buchmann, S., & Wojcik, V. A. (2012). Pollinator conservation and management on electrical transmission and roadside rights-of-way: a review. *Journal of Pollination Ecology*, *7*(3), 16–26. Retrieved from https://www.researchgate.net/publication/285822202

Burghardt, K. T., Tallamy, D. W., & Shriver, G. W. (2009). Impact of native plants on bird and butterfly biodiversity in suburban landscapes. *Conservation Biology*, *23*(1), 219–224. https://doi.org/10.1111/j.1523-1739.2008.01076.x

Burkle, L. A., & Alarcón, R. (2011). The future of plant-pollinator diversity: understanding interaction networks across time, space, and global change. *American Journal of Botany*, *98*(3), 528–538. https://doi.org/10.3732/ajb.1000391

Clark, P. J., Reed, J. M., & Chew, F. S. (2007). Effects of urbanization on butterfly species richness, guild structure, and rarity. *Urban Ecosystems*, *10*, 321–337. https://doi.org/10.1007/s11252-007-0029-4

Collins, S. L., & Calabrese, L. B. (2011). Effects of fire, grazing and topographic variation on vegetation structure in tallgrass prairie. *Journal of Vegetation Science*, *23*(3), 563–575. https://doi.org/10.1111/j.1654-1103.2011.01369.x

Collins, S. L., Knapp, A., Briggs, J., Blair, J., & Steinauer, E. M. (1998). Modulation of Diversity by Grazing and Mowing in Native Tallgrass Prairie. *Science*, *280*, 745–747. Retrieved from www.sciencemag.org

Dalsgaard, B., Trøjelsgaard, K., Martín González, A. M., Nogués-Bravo, D., Ollerton, J., Petanidou, T., … Olesen, J. M. (2013). Historical climate-change influences modularity and nestedness of pollination networks. *Ecography*, *36*, 1–10. https://doi.org/10.1111/j.1600-0587.2013.00201.x

Daubenmire, R. F. (1959). Canopy coverage method of vegetation analysis. *Northwest Sci*, *33*, 39–64.

Davis, J. D., Debinski, D. M., & Danielson, B. J. (2007). Local and landscape effects on the butterfly community in fragmented Midwest USA prairie habitats. *Landscape Ecol*, *22*, 1341–1354. https://doi.org/10.1007/s10980-007-9111-9

Davis, J. D., Hendrix, S. D., Debinski, D. M., Chiara, A., & Hemsley, J. (2008). Butterfly, bee and forb community composition and cross-taxon incongruence in tallgrass prairie fragments. *Journal of Insect Conservation*, *12*, 69–79. https://doi.org/10.1007/s10841-006-9063-4

Debinski, D. M., & Babbit, A. M. (1997). Butterfly Species in Native Prairie and Restored Prairie. *The Prairie Naturalist*, *29*, 219–227. Retrieved from http://www.public.iastate.edu/~debinski/documents/PraiNat-D%26Babbit97.pdf

Debinski, D. M., & Kelly, L. (1998). Decline of Iowa Populations of the Regal Fritillary (Speyeria idalia) Drury. *Journal of the Iowa Academy of Science: JIAS*, *105*(1), 16–22. Retrieved from https://scholarworks.uni.edu/cgi/viewcontent.cgi?referer=https://scholar.google.com/&httpsredir=1&article=1298&context=jias

Delmas, E., Besson, M., Héì Ene Brice, M., Burkle, L. A., Dalla Riva, G. V, Fortin, M.-J., … Poisot, T. (2019). Analysing ecological networks of species interactions. *Biological Reviews*, *94*, 16–36. https://doi.org/10.1111/brv.12433

Didham, R. K., Ghazoul, J., Stork, N. E., & Davis, A. J. (1996). Insects in fragmented forests: a functional approach. *Trends in Ecology and Evolution*, *11*(6). https://doi.org/10.1016/0169-5347(96)20047-3

Dormann, C. F., Fruend, J., & Gruber, B. (2018). *Visualising Bipartite Networks and Calculating Some (Ecological) Indices Version 2.11*. Retrieved from https://github.com/biometry/bipartite

Dormann, C. F., Fründ, J., Blüthgen, N., & Gruber, B. (2009). Indices, Graphs and Null Models: Analyzing Bipartite Ecological Networks. *The Open Ecology Journal*, *2*, 7–24. Retrieved from http://www.goedoc.uni-goettingen.de/goescholar/bitstream/handle/1/5837/Dormann.pdf?sequence=1

Dormann, C., McPherson, J., Araújo, M., Bivand, R., Bolliger, J., Carl, G., … Wilson, R. (2007). Methods to account for spatial autocorrelation in the analysis of species distributional data: a review. *Ecography*, *30*(5), 609–628. https://doi.org/10.1111/j.2007.0906-7590.05171.x

Ehrlich, P. R., & Raven, P. H. (1964). Butterflies and Plants: A Study in Coevolution. *Evolution*, *18*(4), 586–608. https://doi.org/10.1111/j.1558-5646.1964.tb01674.x

Federal Register. (2014). Endangered and Threatened Wildlife and Plants; 90-Day Findings on Two Petitions. Retrieved from https://www.federalregister.gov/documents/2014/12/31/2014-30574/endangered-and-threatened-wildlife-and-plants-90-day-findings-on-two-petitions

Forister, M. L., McCall, A. C., Sanders, N. J., Fordyce, J. A., Thorne, J. H., O'Brien, J., … Shapiro, A. M. (2010). Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(5), 2088–2092. https://doi.org/10.1073/pnas.0909686107

Gilbert, L. E. (1980). Ecological Consequences of a Coevolved Mutualism Between Butterflies and Plants. In *Coevolution of animals and plants* (pp. 210–240). Austin: University of Texas Press. Retrieved from https://pdfs.semanticscholar.org/0076/6c54b3665b2903b6866f43fbb29546914b76.pdf

Graves, S. D., & Shapiro, A. M. (2003). Exotics as host plants of the California butterfly fauna. *Biological Conservation*, *110*, 413–433.

Guiney, M. S., & Oberhauser, K. S. (2008). Insects as flagship conservation species. *Terrestrial Arthropod Reviews*, *1*, 111–123. https://doi.org/10.1163/187498308X414733

Haddock, M. (2019). Kansas Wildflowers and Grasses.

Hall, D. M., Camilo, G. R., Tonietto, R. K., Ollerton, J., Ahrné, K., Arduser, M., … Threlfall, C. G. (2016). The city as a refuge for insect pollinators. *Conservation Biology*, *31*(1), 24–29. https://doi.org/10.1111/cobi.12840

Hardy, P. B., & Dennis, R. L. H. (1999). The impact of urban development on butterflies within a city region. *Biodiversity and Conservation*, *8*, 1261–1279.

Hartnett, D. C., Hickman, K. R., & Walter, L. E. (1996). Effects of Bison Grazing, Fire, and Topography on Floristic Diversity in Tallgrass Prairie. *Journal of Range Management*, *49*(5), 413–420. Retrieved from ftp://godzilla.wnmu.edu/Norris/Range Vegetation/2013/Lecture Midterm Scientific Papers/Hartnett al. 2009 Effect of Bison Fire Topography on Prairie.pdf

Hegland, S. J., Nielsen, A., Lá Zaro, A., Bjerknes, A.-L., & Totland, Ø. (2009). How does climate warming affect plant-pollinator interactions? *Ecology Letters*, *12*, 184–195. https://doi.org/10.1111/j.1461-0248.2008.01269.x

Kansas State University. (2019). Konza Prairie Biological Station. Retrieved August 2, 2019, from https://kpbs.konza.k-state.edu/

Kearns, C. A., Inouye, D. W., & Waser, N. M. (1998). Endangered Mutualisms: The Conservation of Plant-Pollinator Interactions. *Source: Annual Review of Ecology and Systematics Annu. Rev. Ecol. Syst*, *29*, 83–112. Retrieved from http://www.jstor.org/stable/221703

Knapp, A., Blair, J. M., Briggs, J. M., Collins, S. L., Hartnett, D. C., Johnson, L. C., & Towne, E. G. (1999). The Keystone Role of Bison in North American Tallgrass Prairie. *BioScience*, *49*(1), 39–50. https://doi.org/10.2307/1313492

Knapp, A., Briggs, J., Hartnett, D., & Collins, S. (1998). *Grassland dynamics : long-term ecological research in tallgrass prairie* (1st ed.). Oxford University Press.

Knapp, A., & Seastedt, T. R. (1986). Detritus Accumulation Limits Productivity of Tallgrass Prairie. *BioScience*, *36*(10), 662–668. Retrieved from https://www-jstor-org.er.lib.k-state.edu/stable/pdf/1310387.pdf?refreqid=excelsior%3Ae350e4b9fda2cad0e21c7f86d738c65d

Knapp, A., & Seastedt, T. R. (1998). Introduction: Grasslands, Konza Prairie, and Long-Term Ecological Research. In A. K. Knapp, J. M. Briggs, D. C. Hartnett, & S. L. Collins (Eds.), *Grassland Dynamics*. New York: Oxford University Press.

Knerl, A., & Bowers, M. D. (2013). Incorporation of an Introduced Weed into the Diet of a Native Butterfly: Consequences for Preference, Performance and Chemical Defense. *Article in Journal of Chemical Ecology*. https://doi.org/10.1007/s10886-013-0355-3

Kocher, S. D., & Williams, E. H. (2000). The diversity and abundance of North American butterflies vary with habitat disturbance and geography. *Journal of Biogeography*, *27*, 785–794.

Kowarik, I. (2011). Novel urban ecosystems , biodiversity , and conservation. *Environmental Pollution*, *159*, 1974–1983. https://doi.org/10.1016/j.envpol.2011.02.022

Krauss, J., & Steffan-Dewenter, Ingolf Tscharntke, T. (2003). How does landscape context contribute to effects of habitat fragmentation on diversity and population density of butterflies? *Journal of Biogeography*, *30*, 889–900. https://doi.org/10.1046/j.1365-2699.2003.00878.x

Ksiazek, K., Fant, J., & Skogen, K. (2012). An assessment of pollen limitation on Chicago green roofs. *Landscape and Urban Planning*, *107*(4), 401–408. https://doi.org/10.1016/j.landurbplan.2012.07.008

Lawrence, E. (2005). *Henderson's Dictionary of Biology*. (E. Lawrence, Ed.) (Thirteenth). Essex, England: Pearson Education Limited.

Lee, L.-H., & Lin, J.-C. (2015). Green Roof Performance Towards Good Habitat for Butterflies in the Compact City. *International Journal of Biology*, *7*(2), 103.

Leston, L., & Koper, N. (2017). Urban rights-of-way as extensive butterfly habitats: A case study from Winnipeg, Canada. *Landscape and Urban Planning*, *157*, 56–62. https://doi.org/10.1016/j.landurbplan.2016.05.026

Lotts, K., & Naberhaus, T. (2017). Butterflies and Moths of North America | collecting and sharing data about Lepidoptera. Retrieved June 12, 2017, from https://www.butterfliesandmoths.org/

Macivor, J. S., & Ksiazek, K. (2015). Chapter 14. Invertebrates on Green Roofs. In *Green Roof Ecosystems*.

Madre, F., Vergnes, A., Machon, N., & Clergeau, P. (2014). Green roofs as habitats for wild plant species in urban landscapes: First insights from a large-scale sampling. *Landscape and Urban Planning*, *122*, 100–107. https://doi.org/10.1016/j.landurbplan.2013.11.012

Mallet, J., Longino, J., Murawski, D., Murawski, A., & Simpson De Gamboa, A. (1987). Handling Effects in Heliconius: Where Do all the Butterflies Go? *Journal of Animal Ecology*, *56*, 377–386. Retrieved from http://abacus.gene.ucl.ac.uk/jim/pap/mallet87JAE.pdf

Matteson, K. C., & Langellotto, G. A. (2010). Determinates of inner city butterfly and bee species richness. *Urban Ecosystems*, *13*(3), 333–347. https://doi.org/10.1007/s11252-010-0122-y

Mccain, K. N. S., Baer, S. G., Blair, J. M., & Wilson, G. W. T. (2010). Dominant Grasses Suppress Local Diversity in Restored Tallgrass Prairie. *Restoration Ecology*, *18*(1), 40–49. https://doi.org/10.1111/j.1526-100X.2010.00669.x

Mckinney, A. M., & Goodell, K. (2011). Plant-pollinator interactions between an invasive and native plant vary between sites with different flowering phenology. *Plant Ecology*, *212*, 1025–1035. https://doi.org/10.1007/s11258-010-9882-y

Meffe, G. K., Allen-Wardell, G., Bernhardt, P., Bitner, R., Feinsinger, P., Jones, C. E., & Kevan, P. (1998). The Potential Consequences of Pollinator Declines on the Conservation of Biodiversity and Stability of Food Crop Yields. *Conservation Biology*, *12*(1), 8–17. Retrieved from https://pubag.nal.usda.gov/pubag/downloadPDF.xhtml?id=24807&content=PDF

Memmott, J., Waser, N. M., & Price, M. V. (2004). Tolerance of pollination networks to species extinctions. *Proceedings of the Royal Society*, *271*, 2605–2611. https://doi.org/10.1098/rspb.2004.2909

Mentens, J., Raes, D., & Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning*, *77*, 217–226. https://doi.org/10.1016/j.landurbplan.2005.02.010

Moranz, R. A., Fuhlendorf, S. D., & Engle, D. M. (2014). Making sense of a prairie butterfly paradox: The effects of grazing, time since fire, and sampling period on regal fritillary abundance. *Biological Conservation*, *173*, 32–41. https://doi.org/10.1016/j.biocon.2014.03.003

Moron, D., Lenda, M., Skórka, P., Szentgyörgyi, H., Settele, J., & Woyciechowski, M. (2009). Wild pollinator communities are negatively affected by invasion of alien goldenrods in grassland landscapes. *Biological Conservation*, *142*, 1322–1332. https://doi.org/10.1016/j.biocon.2008.12.036

Myers, M. C., Hoksch, B. J., & Mason, J. T. (2012). Butterfly response to floral resources during early establishment at a heterogeneous prairie biomass production site in Iowa, USA. *Insect Conserv*, *16*, 457–472. https://doi.org/10.1007/s10841-011-9433-4

National Oceanic and Atmospheric Administration. (2003). *Daubenmire Method*. Retrieved from https://casedocuments.darrp.noaa.gov/northwest/cbay/pdf/cb-mon1m.pdf

Nilsson, L. A. (1988). The evolution of flowers with deep corolla tubes. *Nature*, *334*, 147–149. Retrieved from http://php.auburn.edu/academic/classes/biol/7560/folkerts/nilssonflowers.pdf

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., … Rowe, B. (2007). Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *BioScience*, *57*(10), 823. https://doi.org/10.1641/B571005

Öckinger, E., Dannestam, Å., & Smith, H. G. (2009). The importance of fragmentation and habitat quality of urban grasslands for butterfly diversity. *Landscape and Urban Planning*, *93*(1), 31–37. https://doi.org/10.1016/j.landurbplan.2009.05.021

Ogden, S. B. (2017). *Responses of grassland birds and butterflies to control of sericea lespedeza with fire and grazing*. Kansas State University. Retrieved from http://krex.k-state.edu/dspace/bitstream/handle/2097/34618/SarahOgden2017.pdf?sequence=1

Olesen, J. M., Stefanescu, C., & Traveset, A. (2011). Strong, Long-Term Temporal Dynamics of an Ecological Network. *PLoS ONE*, *6*(11), 26455. https://doi.org/10.1371/journal.pone.0026455

Pimm, S. L., & Raven, P. (2000). Biodiversity. Extinction by numbers. *Nature*, *403*(6772), 843–845. https://doi.org/10.1038/35002708

Pleasants, J. M., & Oberhauser, K. S. (2013). Milkweed loss in agricultural fields because of herbicide use: effect on the monarch butterfly population. *Insect Conservation and Diversity*, (6), 135–144. https://doi.org/10.1111/j.1752-4598.2012.00196.x

Pollard, E. (1977). A method for assessing changes in the abundance of butterflies. *Biological Conservation*, *12*(2), 115–134. https://doi.org/10.1016/0006-3207(77)90065-9

Polley, W. H., Derner, J. D., & Wilsey, B. J. (2005). Patterns of Plant Species Diversity in Remnant and Restored Tallgrass Prairies. *Restoration Ecology*, *13*(3), 480–487. Retrieved from http://digitalcommons.unl.edu/usdaarsfacpub

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., & Kunin, W. E. (2010). Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, *25*(6). https://doi.org/10.1016/j.tree.2010.01.007

Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Aizen, M. A., Biesmeijer, J. C., Breeze, T. D., … Vanbergen, A. J. (2016). Safeguarding pollinators and their values to human well-being. *Nature Publishing Group*, *540*. https://doi.org/10.1038/nature20588

Rafferty, N. E., CaraDonna, P. J., & Bronstein, J. L. (2015). Phenological shifts and the fate of mutualisms. *Oikos*, *124*(1), 14–21. https://doi.org/10.1111/oik.01523

Robel, R. J., Briggs, J. N., Dayton, A. D., & Hulbert, L. C. (1970). Relationships between Visual Obstruction Measurements and Weight of Grassland Vegetation. *Journal of Range Management*, *23*(4), 295–297. Retrieved from http://www.jstor.org/stable/3896225

Rosenzweig, M. L. (2003). Reconciliation ecology and the future of species diversity. *Oryx*, *37*(2). https://doi.org/10.1017/S0030605303000371

Rowe, D. B., Monterusso, M. A., & Rugh, C. L. (2006). Assessment of Heat-expanded Slate and Fertility Requirements in Green Roof Substrates. *Hort Technology*, *16*(3). Retrieved from https://journals.ashs.org/horttech/view/journals/horttech/16/3/article-p471.pdf

Schultz, C. B., & Dlugosch, K. M. (1999). Nectar and hostplant scarcity limit populations of an endangered Oregon butterfly. *Oecologia*, *119*, 231–238.

Schweiger, O., Biesmeijer, J. C., Bommarco, R., Hickler, T., Hulme, P. E., Klotz, S., … Settele, J. (2010). Multiple stressors on biotic interactions: how climate change and alien species interact to affect pollination. *Biological Reviews*, *85*, 777–795. https://doi.org/10.1111/j.1469-185X.2010.00125.x

Sekar, S. (2012). A meta-analysis of the traits affecting dispersal ability in butterflies: can wingspan be used as a proxy? *Journal of Animal Ecology*, *81*(174–184). https://doi.org/10.1111/j.1365-2656.2011.01909.x

Shepherd, S., & Debinski, D. M. (2005). Evaluation of isolated and integrated prairie reconstructions as habitat for prairie butterflies. *Biological Conservation*, *126*, 51–61. https://doi.org/10.1016/j.biocon.2005.04.021

Skabelund, L. (2016). *Lee R. Skabelund Jarvis Proposal*.

Skabelund, L., Decker, A., Moore, T., Shrestha, P., & Bruce, J. (2017). Monitoring two large scale prairie-like green roofs in Manhattan, Kansas. In *15th Annual Cities Alive Green Roof and Wall Conference*. Seattle.

Smith, L. M., & Cherry, R. (2014). Effects of Management Techniques on Grassland Butterfly Species Composition and Community Structure. *The American Midland Naturalist*, *172*(2), 227–235. https://doi.org/10.1674/0003-0031-172.2.227

Snep, R. P. H., Wallisdevries, M. F., & Opdam, P. (2011). Conservation where people work : A role for business districts and industrial areas in enhancing endangered butterfly populations ? *Landscape and Urban Planning*, *103*, 94–101. https://doi.org/10.1016/j.landurbplan.2011.07.002

Spellerberg, I. F., & Fedor, P. J. (2003). A tribute to Claude Shannon (1916-2001) and a plea for more rigorous use of species richness, species diversity and the "Shannon-Wiener" Index. *Global Ecology & Biogeography*, *12*, 177–179. https://doi.org/10.1046/j.1466-822X.2003.00015.x

Stang, M., Klinkhamer, P., & Van der Meijden, E. (2007). Asymmetric specialization and extinction rick in plant-flower visitor webs: a matter of morphology or abundance. *Oecologia*, *151*(3), 442–453. Retrieved from www.bred.nl

Steffan-Dewenter, I., & Tscharntke, T. (2000). Butterfly community structure in fragmented habitats. *Ecology Letters*, *3*(5), 449–456. https://doi.org/10.1111/j.1461-0248.2000.00175.x

Summerville, K. S., & Crist, T. O. (2001). Effects of Experimental Habitat Fragmentation on Patch Use by Butterflies and Skippers (Lepidoptera). *Ecology*, *82*(5), 1360–1370. Retrieved from http://www.jstor.org/stable/2679995

Sutton, R. K. (2015). *Green Roof Ecosystems*. (R. K. Sutton, Ed.), *Green Roof Ecosystems* (1st ed., Vol. 223). Springer International Publishing. https://doi.org/10.1007/978-3-319-14983-7

Swengel, A. (1996). Effects of Fire and Hay Management on Abundance of Prairie Butterflies. *Biological Conservation*, *76*, 73–85. https://doi.org/10.1016/0006-3207(95)00085-2

Swengel, A. (1998). Effects of Management on Butterfly Abundance in Tallgrass Prairie and Pine Barrens. *Biological Conservation*, *83*(l), 77–89. https://doi.org/10.1016/S0006-3207(96)00129-2

Swengel, A. B. (1998). Comparisons of butterfly richness and abundance measures in prairie and barrens. *Biodiversity and Conservation*, *7*(1639–1659). Retrieved from https://www.researchgate.net/profile/Ann_Swengel/publication/282293227_Comparisons_of_butterfly_richness_and_abundance_measures_in_prairie_and_barrens/links/560acdb408ae4d86bb14a118/Comparisons-of-butterfly-richness-and-abundance-measures-in-prairie-and-b

Swengel, A. B. (2012). *Butterfly Conservation Management in Midwestern Open Habitats Part 6: Surveying and monitoring butterflies*. Retrieved from http://www.naba.org/chapters/nabawba/WBAPDFs/PART6ButterflyConservation.pdf

Swengel, S., Schlicht, D., Olsen, F., & Swengel, A. (2011). Declines of prairie butterflies in the midwestern USA. *Journal of Insect Conservation*, *15*(1–2), 327–339. https://doi.org/10.1007/s10841-010-9323-1

Tallamy, D. W. (2007). *Bringing Nature Home: How You Can Sustain Wildlife with Native Plants*. Portland, Oregon: Timber Press.

Taylor, J., Mayfield, M., & Breckon, G. (2018). The Vascular Flora of Konza Prairie: An Update. Pacific Grove, CA.: LTER All Scientists Meeting. NSF Long Term Ecological Research Network.

U.S. Fish and Wildlife Service. (2017). Save the monarch butterfly | U.S. Fish and Wildlife Service. Retrieved March 2, 2017, from https://www.fws.gov/savethemonarch/

U.S. Forest Service. (2000). Wings Across the Americas. Retrieved March 2, 2017, from https://www.fs.fed.us/global/wings/butterflies/welcome.htm

Urquhart, F. A. (1960). *The Monarch Butterfly*.

Van Der Merwe, D., Skabelund, L. R., Sharda, A., Blackmore, P., & Bremer, D. (2017). Towards characterizing green roof vegetation using color-infrared and thermal sensors. In *Cities Alive 15th Annual Green Roof & Wall Conference*. Seattle. Retrieved from http://www.k-state.edu/greenroofs/images/pdf_docs/CitiesAlive2017_VanDerMerwe_Skabelund_Paper_22Aug2017.pdf

Vanbergen, A. J., Garratt, M. P., Vanbergen, A. J., Baude, M., Biesmeijer, J. C., Britton, N. F., … Wright, G. A. (2013). Threats to an ecosystem service: Pressures on pollinators. *Frontiers in Ecology and the Environment*, *11*(5), 251–259. https://doi.org/10.1890/120126

Vinatier, F., Tixier, P., Duyck, P.-F. F., & Lescourret, F. F. (2011). Factors and mechanisms explaining spatial heterogeneity: a review of methods for insect populations. *Methods in Ecology and Evolution*, *2*, 11–22. https://doi.org/10.1111/j.2041-210X.2010.00059.x

Vogel, J. A., Debinski, D. M., Koford, R. R., & Miller, J. R. (2007). Butterfly Responses to Prairie Restoration Through Fire and Grazing. *Biological Conservation*, *140*(78). https://doi.org/10.1016/j.biocon.2007.07.027

Vogel, J. A., Koford, R. R., & Debinski, D. M. (2010). Direct and indirect responses of tallgrass prairie butterflies to prescribed burning. *Insect Conserv*, *14*, 663–677. https://doi.org/10.1007/s10841-010-9295-1

Wei Wang, J., Hock Poh, C., Ting Tan, C. Y., Naomi Lee, V., Jain, A., Webb, E. L., … Webb, E. L. (2017). Building biodiversity: drivers of bird and butterfly diversity on tropical urban roof gardens. *Ecosphere*, *8*(9). https://doi.org/10.1002/ecs2.1905

Williams, N. S. G., Lundholm, J., & Macivor, S. (2014). Do green roofs help urban biodiversity conservation? *Journal of Applied Ecology*, *51*, 1643–1649. https://doi.org/10.1111/1365-2664.12333

Willmer, P. (2011). *Pollination and Floral Ecology*. Princeton University Press. Retrieved from https://press.princeton.edu/titles/9485.html

Chapter 6 - Additional Materials

6.1 Appendix A: Plants at Each Study Site

Plants found within study plots

Family	Species	Native Prairie Sites	Memorial Stadium Green Roofs	Urban Prairie
Acanthaceae	*Ruellia humilis*	✓		✓
Acanthaceae	*Ruellia strepens*		✓	
Amaranthaceae	*Amaranthus retroflexus*		✓	
Anacardiaceae	*Rhus glabra*	✓		
Apocynaceae	*Apocynum cannabinum*	✓		✓
Asclepiadaceae	*Asclepias stenophylla*	✓		
Asclepiadaceae	*Asclepias sullivantii*	✓		✓
Asclepiadaceae	*Asclepias syriaca*	✓		
Asclepiadaceae	*Asclepias tuberosa*	✓		
Asclepiadaceae	*Asclepias verticillata*	✓		
Asclepiadaceae	*Asclepias viridis*	✓		✓
Asteraceae	*Achillea millefolium*		✓	✓
Asteraceae	*Ageratina altissima*	✓		
Asteraceae	*Ambrosia artemisiifolia*			✓
Asteraceae	*Ambrosia psilostachya*	✓		✓
Asteraceae	*Antennaria neglecta*			✓
Asteraceae	*Artemisia ludoviciana*	✓	✓	
Asteraceae	*Brickellia eupatorioides*	✓		
Asteraceae	*Cirsium altissimum*	✓		✓
Asteraceae	*Cirsium undulatum*			✓
Asteraceae	*Conyza canadensis*	✓	✓	✓
Asteraceae	*Coreopsis tinctoria*		✓	
Asteraceae	*Echinacea angustifolia*			✓
Asteraceae	*Echinacea pallida*		✓	
Asteraceae	*Erechtites hieraciifolia*	✓		✓
Asteraceae	*Erigeron annuus*		✓	✓
Asteraceae	*Erigeron strigosus*		✓	✓
Asteraceae	*Eupatorium altissimum*	✓		
Asteraceae	*Helianthus annuus*	✓	✓	
Asteraceae	*Helianthus pauciflorus*	✓		
Asteraceae	*Hieracium longipilum*			✓
Asteraceae	*Hymenopappus scabiosaeus*			✓
Asteraceae	*Krigia cespitosa*		✓	
Asteraceae	*Lactuca ludoviciana*		✓	
Asteraceae	*Lactuca serriola*		✓	
Asteraceae	*Liatris aspera*		✓	

Plants found within study plots

Family	Species	Native Prairie Sites	Memorial Stadium Green Roofs	Urban Prairie
Asteraceae	*Liatris punctata*	✓		
Asteraceae	*Liatris pycnostachya*		✓	
Asteraceae	*Solidago rigida*		✓	✓
Asteraceae	*Packera plattensis*			✓
Asteraceae	*Pseudognaphalium obtusifolium*	✓		
Asteraceae	*Ratibida columnifera*	✓	✓	✓
Asteraceae	*Ratibida pinnata*		✓	
Asteraceae	*Rudbeckia hirta*		✓	✓
Asteraceae	*Silphium laciniatum*	✓		
Asteraceae	*Solidago altissima*	✓	✓	
Asteraceae	*Solidago canadensis*	✓		
Asteraceae	*Solidago missouriensis*	✓		✓
Asteraceae	*Solidago nemoralis*			✓
Asteraceae	*Symphyotrichum drummondii*			✓
Asteraceae	*Symphyotrichum ericoides*	✓	✓	✓
Asteraceae	*Symphyotrichum lanceolatum*	✓		
Asteraceae	*Symphyotrichum novae-angliae*		✓	
Asteraceae	*Symphyotrichum oblongifolium*	✓		✓
Asteraceae	*Symphyotrichum oolentangiense*			✓
Asteraceae	*Symphyotrichum pilosum*		✓	
Asteraceae	*Taraxacum officinale*		✓	
Asteraceae	*Vernonia baldwinii*	✓		
Asteraceaec	*Ambrosia artemisiifolia*	✓		
Boraginaceae	*Lithospermum canescens*	✓		
Boraginaceae	*Lithospermum incisum*	✓		✓
Caprifoliaceae	*Lonicera maackii*		✓	
Caprifoliaceae	*Symphoricarpos orbiculatus*	✓		✓
Caryophyllaceae	*Arenaria serpyllifolia*			✓
Caryophyllaceae	*Dianthus armeria*			✓
Clusiaceae	*Hypericum perforatum*			✓
Commelinaceae	*Tradescantia occidentalis*		✓	
Commelinaceae	*Tradescantia ohiensis*		✓	
Convolvulaceae	*Convolvulus arvensis*		✓	
Cornaceae	*Cornus drummondii*	✓		
Cupressaceae	*Juniperus virginiana*		✓	
Cyperaceae	*Carex brevior*		✓	✓
Cyperaceae	*Carex gravida*		✓	
Cyperaceae	*Carex inops*		✓	✓
Cyperaceae	*Carex meadii*			✓
Cyperaceae	*Eleocharis compressa*	✓		
Euphorbiaceae	*Acalypha ostryifolia*	✓		

Plants found within study plots

Family	Species	Native Prairie Sites	Memorial Stadium Green Roofs	Urban Prairie
Euphorbiaceae	*Acalypha virginica*	✓		
Euphorbiaceae	*Euphorbia glyptosperma*		✓	
Euphorbiaceae	*Euphorbia maculata*		✓	
Euphorbiaceae	*Euphorbia nutans*	✓	✓	
Euphorbiaceae	*Euphorbia prostrata*		✓	
Euphorbiaceae	*Euphorbia serpens*		✓	
Euphorbiaceae	*Croton monanthogynus*	✓		
Euphorbiaceae	*Euphorbia corollata*	✓		
Euphorbiaceae	*Euphorbia davidii*		✓	
Euphorbiaceae	*Euphorbia dentata*	✓	✓	
Euphorbiaceae	*Euphorbia marginata*	✓		
Euphorbiaceae	*Euphorbia spathulata*	✓		
Euphorbiaceae	*Tragia betonicifolia*	✓		
Fabaceae	*Amorpha canescens*	✓		✓
Fabaceae	*Baptisia australis*	✓	✓	
Fabaceae	*Baptisia bracteata*	✓	✓	✓
Fabaceae	*Dalea candida*	✓		✓
Fabaceae	*Dalea multiflora*	✓		
Fabaceae	*Dalea purpurea*	✓	✓	✓
Fabaceae	*Desmanthus illinoensis*	✓		
Fabaceae	*Desmodium canadense*		✓	
Fabaceae	*Kummerowia stipulacea*		✓	
Fabaceae	*Lespedeza capitata*	✓		
Fabaceae	*Lespedeza violacea*	✓		
Fabaceae	*Medicago lupulina*		✓	
Fabaceae	*Medicago sativa*		✓	
Fabaceae	*Melilotus officinalis*		✓	✓
Fabaceae	*Mimosa nutallii*	✓		✓
Fabaceae	*Psoralea tenuiflora*	✓		✓
Fabaceae	*Securigera varia*	✓		
Fabaceae	*Trifolium pratense*		✓	
Fabaceae	*Trifolium repens*		✓	
Iridaceae	*Sisyrinchium campestre*	✓		✓
Lamiaceae	*Monarda fistulosa*		✓	
Lamiaceae	*Salvia azurea*		✓	✓
Lamiaceae	*Scutellaria parvula*	✓		
Lamiaceae	*Teucrium canadense*	✓		
Liliaceae	*Allium stellatum*		✓	
Linaceae	*Linum sulcatum*	✓		✓
Lythraceae	*Lythrum alatum*	✓		
Malvaceae	*Abutilon theophrasti*		✓	

Plants found within study plots

Family	Species	Native Prairie Sites	Memorial Stadium Green Roofs	Urban Prairie
Malvaceae	*Callirhoe involucrata*	✓		✓
Nyctaginaceae	*Mirabilis albida*	✓		
Onagraceae	*Oenothera serrulata*	✓		✓
Onagraceae	*Oenothera speciosa*	✓		
Onagraceae	*Oenothera villosa*		✓	
Oxalidaceae	*Oxalis dillenii*		✓	
Oxalidaceae	*Oxalis stricta*	✓		✓
Oxalidaceae	*Oxalis violacea*	✓		✓
Plantaginaceae	*Plantago virginica*			✓
Poaceae	*Agrostis hyemalis*	✓	✓	
Poaceae	*Andropogon gerardii*		✓	✓
Poaceae	*Bouteloua curtipendula*	✓	✓	✓
Poaceae	*Bouteloua gracilis*		✓	✓
Poaceae	*Bromus inermis*			✓
Poaceae	*Bromus japonicus*			✓
Poaceae	*Dichanthelium ovale*	✓		✓
Poaceae	*Dichanthelium linearifolium*			✓
Poaceae	*Dichanthelium oligosanthes*	✓	✓	✓
Poaceae	*Digitaria cognata*			✓
Poaceae	*Elymus canadensis*	✓		
Poaceae	*Eragrostis spectabilis*	✓		✓
Poaceae	*Koeleria macrantha*			✓
Poaceae	*Panicum virgatum*	✓	✓	✓
Poaceae	*Paspalum setaceum*			✓
Poaceae	*Poa compressa*			✓
Poaceae	*Poa pratensis*	✓	✓	✓
Poaceae	*Schedonorus arundinaceus*		✓	✓
Poaceae	*Schedonorus pratensis*			✓
Poaceae	*Schizachyrium scoparium*	✓	✓	✓
Poaceae	*Setaria pumila*		✓	
Poaceae	*Setaria viridis*	✓	✓	
Poaceae	*Sorghastrum nutans*	✓	✓	✓
Poaceae	*Sphenopholis obtusata*	✓		
Poaceae	*Sporobolus compositus*	✓	✓	✓
Poaceae	*Sporobolus heterolepis*	✓	✓	✓
Poaceae	*Tridens flavus*		✓	✓
Poaceae	*Vulpia octoflora*			✓
Polygalaceae	*Polygala verticillata*			✓
Ranunculaceae	*Anemone caroliniana*			✓
Rhamnaceae	*Ceanothus herbaceous*	✓		✓
Rosaceae	*Crataegus phaenopyrum*		✓	✓

Plants found within study plots

Family	Species	Native Prairie Sites	Memorial Stadium Green Roofs	Urban Prairie
Rosaceae	*Prunus americana*	✓	✓	
Rosaceae	*Pyrus calleryana*		✓	✓
Rosaceae	*Rosa arkansana*	✓		✓
Rosaceae	*Rubus pensylvanicus*	✓		
Rubiaceae	*Cruciata pedemontana*			✓
Rubiaceae	*Galium aparine*	✓		
Rubiaceae	*Hedyotis nigricans*	✓		
Salicaceae	*Populus deltoides*		✓	
Scrophulariaceae	*Penstemon cobaea*		✓	
Scrophulariaceae	*Penstemon digitalis*		✓	
Scrophulariaceae	*Penstemon tubiflorus*			✓
Solanaceae	*Physalis heterophylla*	✓		
Solanaceae	*Physalis longifolia*	✓		
Solanaceae	*Physalis pumila*	✓		✓
Solanaceae	*Physalis virginiana*	✓		✓
Solanaceae	*Solanum carolinense*	✓	✓	
Ulmaceae	*Celtis occidentalis*	✓		
Ulmaceae	*Ulmus americana*	✓		✓
Ulmaceae	*Ulmus pumila*		✓	✓
Ulmaceae	*Ulmus rubra*	✓		✓
Urticaceae	*Parietaria pensylvanica*	✓		
Violaceae	*Viola pedatifida*	✓		✓

6.2 Appendix B: Response and Predictor Variables

Variable Name	Description	Type	Reference	Chapter
Larval Host Cover	Combined canopy coverage of larval host plants listed in Appendix C: Larval Host Plants	Predictor	Not applicable	2, 3, 4
Blossom Index	This index was calculated using the following formula: $$x_{plot} = \sum \frac{b}{b_{max}}$$ Where *x*=blossom index, *b*=species blossom count, and b_{max}=yearly maximum species blossom count.	Predictor	Not applicable	2, 3, 4
Litter Depth	Depth of litter measured at each corner of the Daubenmire frame and averaged for each plot	Predictor	Not applicable	2, 3, 4
Total Plant Cover	Combined canopy cover of each species of plant	Predictor	(Daubenmire, 1959)	2, 3, 4
Plant Evenness	Relative cover of plant species	Predictor	https://www.sciencedirect.com/topics/earth-and-planetary-sciences/species-evenness	2, 3, 4
Plant Richness	Total number of plant species found in each Daubenmire plot	Predictor	https://www.sciencedirect.com/topics/earth-and-planetary-sciences/species-richness	2, 3, 4
Plant Shannon Diversity Index	$$\text{Shannon Index (H)} = -\sum_{i=1}^{s} p_i \ln p_i$$ Where p is the proportion (n/N) of coverage of one particular species found (n) divided by the total plot cover (N), ln is the natural log, Σ is the sum of the	Predictor	https://entnemdept.ifas.ufl.edu/hodges/protectus/lp_webfolder/9_12_grade/student_handout_1a.pdf	2, 3, 4

Variable Name	Description	Type	Reference	Chapter
	calculations, and s is the number of species.			
Woody Cover	Combined canopy cover of each species of woody plant	Predictor	Not applicable	2, 3, 4
Forb Cover	Combined canopy cover of each species of forb	Predictor	Not applicable	2, 3, 4
Graminoid Cover	Combined canopy cover of each species of graminoid	Predictor	Not applicable	2, 3, 4
Forbs Blooming	Total number of forb species blooming within the transect	Predictor	Not applicable	2, 3
Visual Obstruction	Aboveground biomass	Predictor	(Robel et al., 1970)	
Butterfly Generalist Abundance	Number of generalist butterflies found in transect using Pollard walk	Response	Not applicable	3
Butterfly Specialist Abundance	Number of specialist butterflies found in transect using Pollard walk	Response	Not applicable	3
Butterfly Diversity	Shannon Index (H) = $-\sum_{i=1}^{s} p_i \ln p_i$ Where p is the proportion (n/N) of individuals of one particular species found (n) divided by the total number of individuals found (N), ln is the natural log, Σ is the sum of the calculations, and s is the number of species.	Response	https://entnemdept.ifas.ufl.edu/hodges/protectus/lp_webfolder/9_12_grade/student_handout_1a.pdf	3
Butterfly Log Richness	Log-transformed butterfly richness	Response	Not applicable	3

Variable Name	Description	Type	Reference	Chapter
Butterfly Richness	Total number of butterfly species found in transect using Pollard walk	Response	https://www.sciencedirect.com/topics/earth-and-planetary-sciences/species-richness	3
Butterfly Log Abundance	Log-transformed butterfly abundance	Response	Not applicable	3
Butterfly Abundance	Total number of butterflies found in transect using Pollard walk	Response	Not applicable	3

6.3 Appendix C: Larval Host Plants

Larval Host Plants of Butterflies Found at Study Sites

American Lady (*Vanessa virginiensis*)		
Achillea millefolium	*Eupatorium altissimum*	*Silphium laciniatum*
Ageratina altissima	*Helianthus annuus*	*Solidago altissima*
Ambrosia artemisiifolia	*Helianthus pauciflorus*	*Solidago canadensis*
Ambrosia psilostachya	*Hieracium longipilum*	*Solidago missouriensis*
Antennaria neglecta	*Hymenopappus scabiosaeus*	*Solidago nemoralis*
Artemisia ludoviciana	*Krigia caespitosa*	*Solidago rigida*
Brickellia eupatorioides	*Lactuca ludoviciana*	*Symphyotrichum drummondii*
Cirsium altissimum	*Lactuca serriola*	*Symphyotrichum ericoides*
Cirsium undulatum	*Liatris aspera*	*Symphyotrichum lanceolatum*
Conyza canadensis	*Liatris punctata*	*Symphyotrichum novae-angliae*
Coreopsis tinctoria	*Liatris pycnostachya*	*Symphyotrichum oblongifolium*
Echinacea angustifolia	*Packera plattensis*	*Symphyotrichum oolentangiense*
Echinacea pallida	*Pseudognaphalium obtusifolium*	*Symphyotrichum pilosum*
Erechtites hieraciifolia	*Ratibida columnifera*	*Taraxacum officinale*
Erigeron annuus	*Ratibida pinnata*	*Vernonia baldwinii*
Erigeron strigosus	*Rudbeckia hirta*	
Arogos Skipper (*Atrytone arogos*)		
Andropogon gerardii	*Panicum virgatum*	*Schizachyrium scoparium*
Azure sp (*Celastrina ladon*)		
Ceonothus herbaceous	*Cornus drummondii*	
Black Swallowtail (*Papilio polyxenes*)		
Solidago altissima	*Solidago missouriensis*	*Solidago rigida*
Solidago canadensis	*Solidago nemoralis*	
Common Buckeye (*Junonia coenia*)		
Penstemon cobaea	*Penstemon tubiflorus*	*Ruellia humilis*
Penstemon digitalis	*Plantago virginica*	
Cabbage White (*Pieris rapae*)		
None present		
Clouded Sulphur		
Medicago lupulina	*Melilotus officinalis*	*Trifolium repens*
Medicago sativa	*Trifolium pratense*	
Cloudless Sulphur (*Phoebis sennae*)		
None present		
Common Checkered Skipper (*Skipper*)		
Abutilon theophrasti	*Callirhoe involucrata*	
Common Wood Nymph (*Cercyonis pegala*)		
Agrostis hyemalis	*Dichanthelium linearifolium*	*Schedonorus arundinaceus*
Andropogon gerardii	*Dichanthelium oligosanthes*	*Schedonorus pratensis*
Bouteloua curtipendula	*Digitaria cognata*	*Schizachyrium scoparium*
Bouteloua gracilis	*Eleocharis compressa*	*Setaria pumila*

Larval Host Plants of Butterflies Found at Study Sites

Bromus arvensis	*Elymus canadensis*	*Setaria viridis*
Bromus inermis	*Eragrostis spectabilis*	*Sorghastrum nutans*
Carex brevior	*Koeleria macrantha*	*Sphenopholis obtusata*
Carex gravida	*Panicum virgatum*	*Sporobolus compositus*
Carex inops	*Paspalum setaceum*	*Sporobolus heterolepis*
Carex meadii	*Poa compressa*	*Tridens flavus*
Cyperus x mesochorus	*Poa pratensis*	*Vulpia octoflora*
Dichanthelium ovale		
Coral Hairstreak (*Satyrium titus and titus*)		
Prunus americana		
Dainty Sulphur (*Nathalis iole*)		
Galium aparine		
Delaware Skipper (*Anatrytone logan/Atrytone)*		
Andropogon gerardii	*Panicum virgatum*	
Eastern Tailed Blue (*Everes comyntas*)		
Desmodium canadense	*Lespedeza capitata*	*Melilotus officinalis*
Desmodium canescens	*Lespedeza violacea*	*Trifolium pratense*
Kummerowia stipulacea	*Medicago lupulina*	*Trifolium repens*
Eastern Tiger Swallowtail (*Papilio glaucus*)		
Prunus americana	*Ulmus pumila*	*Ulmus rubra*
Ulmus americana		
Fiery Skipper (*Hylephila phyleus*)		
Agrostis hyemalis	*Elymus canadensis*	*Schizachyrium scoparium*
Andropogon gerardii	*Eragrostis spectabilis*	*Setaria pumila*
Bouteloua curtipendula	*Koeleria macrantha*	*Setaria viridis*
Bouteloua gracilis	*Panicum virgatum*	*Sorghastrum nutans*
Bromus arvensis	*Paspalum setaceum*	*Sphenopholis obtusata*
Bromus inermis	*Poa compressa*	*Sporobolus compositus*
Dichanthelium ovale	*Poa pratensis*	*Sporobolus heterolepis*
Dichanthelium linearifolium	*Schedonorus arundinaceus*	*Tridens flavus*
Dichanthelium oligosanthes	*Schedonorus pratensis*	*Vulpia octoflora*
Digitaria cognata		
Giant Swallowtail (*Papilio cresphonte*)		
None present		
Gorgone Checkerspot (*Chlosyne gorgone*)		
Helianthus annuus	*Helianthus pauciflorus*	
Gray Hairstreak (*Strymon melinus*)		
Amorpha canescens	*Asclepias verticillata*	*Hypericum perforatum*
Asclepias stenophylla	*Asclepias viridis*	*Lespedeza capitata*
Asclepias sullivantii	*Croton capitatus*	*Medicago sativa*
Asclepias syriaca	*Croton monanthogynus*	*Melilotus officinalis*
Asclepias tuberosa	*Desmodium canadense*	*Trifolium repens*

Larval Host Plants of Butterflies Found at Study Sites

Great Spangled Fritillary (*Speyeria Cybele*)		
Viola pedatifida		
Gray Copper (*Lycaena dione*)		
None present		
Hackberry Emperor (*Asterocampa celtis*)		
Celtis occidentalis		
Monarch (*Danaus plexippus*)		
Asclepias stenophylla	*Euphorbia corollata*	*Euphorbia marginata*
Asclepias sullivantii	*Euphorbia davidii*	*Euphorbia prostrata*
Asclepias syriaca	*Euphorbia dentata*	*Euphorbia serpens*
Asclepias tuberosa	*Euphorbia glyptosperma*	*Euphorbia spathulata*
Asclepias verticillata	*Euphorbia maculata*	*Euphorbiae nutans*
Asclepias viridis		
Orange Sulphur (*Colias eurytheme*)		
Baptisia australis	*Medicago lupulina*	*Securigera varia*
Baptisia bracteata	*Medicago sativa*	*Trifolium pratense*
Lespedeza capitata	*Melilotus officinalis*	*Trifolium repens*
Lespedeza violacea	*Psoralea tenuiflora*	
Ottoe Skipper (*Hesperia ottoe*)		
Andropogon gerardii	*Bromus arvensis*	*Digitaria cognata*
Bouteloua curtipendula	*Bromus inermis*	*Schizachyrium scoparium*
Bouteloua gracilis		
Painted Lady (*Vanessa cardui*)		
Achillea millefolium	*Helianthus pauciflorus*	*Silphium laciniatum*
Ageratina altissima	*Hieracium longipilum*	*Solidago altissima*
Ambrosia artemisiifolia	*Hymenopappus scabiosaeus*	*Solidago canadensis*
Ambrosia psilostachya	*Krigia cespitosa*	*Solidago missouriensis*
Antennaria neglecta	*Lactuca ludoviciana*	*Solidago nemoralis*
Artemisia ludoviciana	*Lactuca serriola*	*Solidago rigida*
Brickellia eupatorioides	*Liatris aspera*	*Symphyotrichum drummondii*
Cirsium altissimum	*Liatris punctata*	*Symphyotrichum ericoides*
Cirsium undulatum	*Liatris pycnostachya*	*Symphyotrichum lanceolatum*
Conyza canadensis	*Medicago sativa*	*Symphyotrichum novae-angliae*
Coreopsis tinctoria	*Packera plattensis*	*Symphyotrichum oblongifolium*
Echinacea angustifolia	*Parietaria pensylvanica*	*Symphyotrichum oolentangiense*
Echinacea pallida	*Pseudognaphalium obtusifolium*	*Symphyotrichum pilosum*
Erechtites hieraciifolia	*Ratibida columnifera*	*Taraxacum officinale*
Erigeron annuus	*Ratibida pinnata*	*Trifolium pratense*
Erigeron strigosus	*Rudbeckia hirta*	*Trifolium repens*
Eupatorium altissimum	*Salvia azurea*	*Vernonia baldwinii*
Helianthus annuus		
Pearl Crescent (*Phyciodes tharos*)		
Achillea millefolium	*Eupatorium altissimum*	*Rudbeckia hirta*

Larval Host Plants of Butterflies Found at Study Sites

Ageratina altissima	*Helianthus annuus*	*Silphium laciniatum*
Ambrosia artemisiifolia	*Helianthus pauciflorus*	*Solidago altissima*
Ambrosia psilostachya	*Hieracium longipilum*	*Solidago canadensis*
Antennaria neglecta	*Hymenopappus scabiosaeus*	*Solidago missouriensis*
Artemisia ludoviciana	*Krigia cespitosa*	*Solidago nemoralis*
Brickellia eupatorioides	*Lactuca ludoviciana*	*Solidago rigida*
Cirsium altissimum	*Lactuca serriola*	*Symphyotrichum drummondii*
Cirsium undulatum	*Liatris aspera*	*Symphyotrichum ericoides*
Conyza canadensis	*Liatris punctata*	*Symphyotrichum lanceolatum*
Coreopsis tinctoria	*Liatris pycnostachya*	*Symphyotrichum novae-angliae*
Echinacea angustifolia	*Packera plattensis*	*Symphyotrichum oblongifolium*
Echinacea pallida	*Plantago virginica*	*Symphyotrichum oolentangiense*
Erechtites hieraciifolia	*Pseudognaphalium obtusifolium*	*Symphyotrichum pilosum*
Erigeron annuus	*Ratibida columnifera*	*Taraxacum officinale*
Erigeron strigosus	*Ratibida pinnata*	*Vernonia baldwinii*
Reakirt's Blue (*Hemiargus isola*)		
Dalea candida	*Medicago sativa*	*Mimosa quadrivalvis*
Dalea purpurea	*Melilotus officinalis*	*Trifolium repens*
Desmanthus illinoensis		
Red Admiral (*Vanessa atalanta*)		
Parietaria pensylvanica		
Regal Fritillary (*Speyeria idalia*)		
Viola pedatifida		
Sachem (*Atalopedes campestris*)		
Poa pratensis		
Silver Spotted Skipper (*Chlosyne nycteis*)		
Helianthus annuus	*Helianthus pauciflorus*	*Rudbeckia hirta*
Southern Cloudywing (*Thorybes bathyllus*)		
Desmodium canadense	*Lespedeza capitata*	*Trifolium pratense*
Variegated Fritillary (*Euptoieta claudia*)		
Linum sulcatum	*Plantago virginica*	*Viola pedatifida*
Viceroy (*Limenitis archippus and Basilarchia archippus*)		
Prunus americana		
Wild Indigo Duskywing (*Erynnis baptisiae*)		
Baptisia australis	*Baptisia bracteata*	*Securigera varia*
Zabulon Skipper (*Poanes zabulon*)		
Elymus canadensis	*Poa pratensis*	*Tridens flavus*
Eragrostis spectabilis		

NOTES:

Larval host plants for grass skipper species and sulphur species other than those listed have not been included because of the large number of species and because no other species were identified.

Larval host plants were compiled from the Natural History Museum Database at Tring:

Larval Host Plants of Butterflies Found at Study Sites

http://www.nhm.ac.uk/our-science/data/hostplants/search/list.dsml? I included all entries for USA, Neartic, Cosmopolitan, and New World.
Azures, Silvery Checkerspot, Gorgone Checkerspot, and Gray Copper were not in the Natural History Museum at Tring database, so I used a compilation of data from butterfliesandmoths.org, Kaufman Field Guide to Butterflies of North America, and North American Butterfly Association.org.

6.4 Appendix D: Pearson Correlation Matrix for All Variables

	Butterfly Abundance	Butterfly Log Abundance	Butterfly Richness	Butterfly Log Richness	Butterfly Diversity	Butterfly Specialist Abundance	Butterfly Generalist Abundance	Forbs Blooming	Temperature	Wind Speed	Clouds	Graminoid Cover	Forb Cover	Woody Cover	Larval Host Plant Cover	Plant Shannon Diversity Index	Plant Richness	Plant Evenness	Total Plant Cover	Litter Depth	Visual Obstruction	Blossom Index
Butterfly Abundance	1.000	0.760	0.649	0.502	0.190	0.057	0.999	0.218	0.093	0.092	0.127	0.135	0.479	0.348	0.043	0.077	0.148	0.181	0.109	0.421	0.125	0.081
Butterfly Log Abundance		1.000	0.836	0.804	0.522	0.132	0.751	0.308	0.051	0.017	0.156	0.087	0.574	0.312	0.164	0.106	0.177	0.184	0.213	0.448	0.055	0.144
Butterfly Richness			1.000	0.951	0.807	0.272	0.635	0.215	0.019	0.167	0.085	0.023	0.486	0.110	0.245	0.163	0.210	0.058	0.250	0.242	0.038	0.258
Butterfly Log Richness				1.000	0.899	0.299	0.488	0.206	0.023	0.107	0.027	0.041	0.428	0.063	0.262	0.112	0.150	0.063	0.276	0.208	0.068	0.223
Butterfly Diversity					1.000	0.346	0.175	0.125	0.085	0.199	0.001	0.064	0.196	0.109	0.269	0.136	0.115	0.096	0.190	0.009	0.086	0.282
Butterfly Abundance						1.000	0.099	0.171	0.155	0.175	0.010	0.213	0.065	0.304	0.254	0.065	0.017	0.195	0.188	0.174	0.341	0.083
Butterfly Generalist Abundance							1.000	0.224	0.099	0.085	0.128	0.144	0.480	0.360	0.032	0.075	0.148	0.189	0.101	0.427	0.139	0.078
Forbs Blooming								1.000	0.014	0.020	0.348	0.186	0.336	0.321	0.128	0.069	0.015	0.288	0.004	0.405	0.105	0.370
Temperature									1.000	0.035	0.043	0.098	0.046	0.077	0.117	0.015	0.004	0.036	0.059	0.084	0.077	0.038
Wind Speed										1.000	0.083	0.136	0.041	0.358	0.266	0.105	0.081	0.179	0.141	0.289	0.206	0.320
Clouds											1.000	0.231	0.196	0.213	0.082	0.123	0.095	0.051	0.097	0.250	0.036	0.295
Graminoid Cover												1.000	0.061	0.545	0.653	0.587	0.517	0.399	0.834	0.408	0.464	0.043
Forb Cover													1.000	0.384	0.304	0.016	0.198	0.458	0.483	0.533	0.095	0.163
Woody Cover														1.000	0.467	0.073	0.085	0.116	0.326	0.896	0.483	0.048
Host Cover															1.000	0.075	0.043	0.168	0.760	0.258	0.407	0.006
Plant Shannon Diversity Index																1.000	0.933	0.600	0.497	0.075	0.163	0.033
Plant Richness																	1.000	0.315	0.331	0.041	0.098	0.016
Plant Evenness																		1.000	0.549	0.220	0.255	0.005
Total Plant Cover																			1.000	0.140	0.521	0.073
Litter Depth																				1.000	0.435	0.035
Visual Obstruction																					1.000	0.102
Blossom Index																						1.000

Cells shaded red indicate a high correlation (>0.80) between variables.

6.5 Appendix E: Plant GIS Interpolation Maps

Figure 6.1. Memorial Stadium east blossom index and plant richness inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

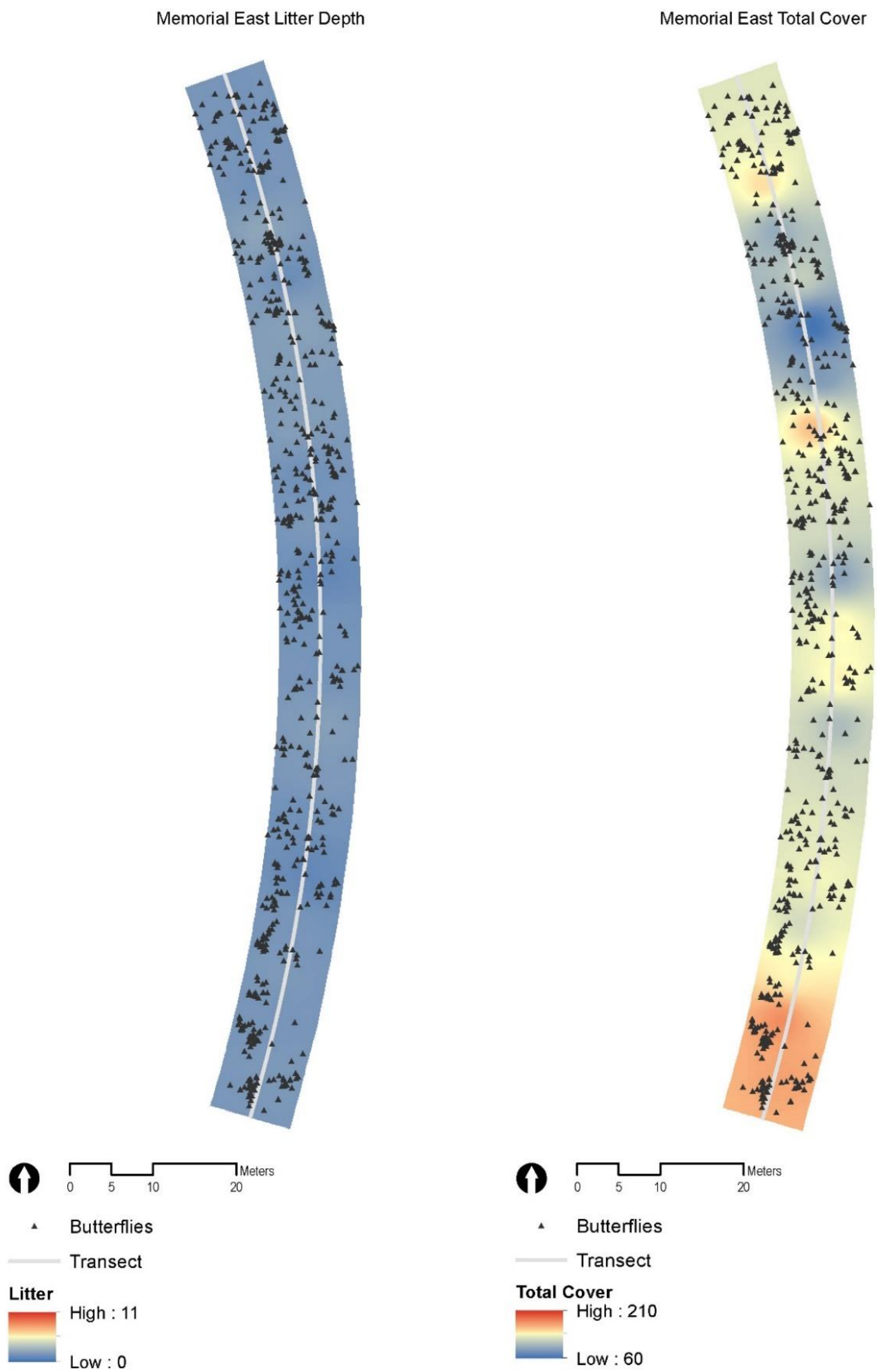

Figure 6.2. Memorial Stadium east litter depth and total plant cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

Figure 6.3. Memorial Stadium east plant evenness and shannon diversity inverse distance weighted interpolations with butterfly interaction locations 2017 and 2018

Figure 6.4. Memorial Stadium east host plant cover and woody cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

Figure 6.5. Memorial Stadium east forb cover and visual obstruction inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

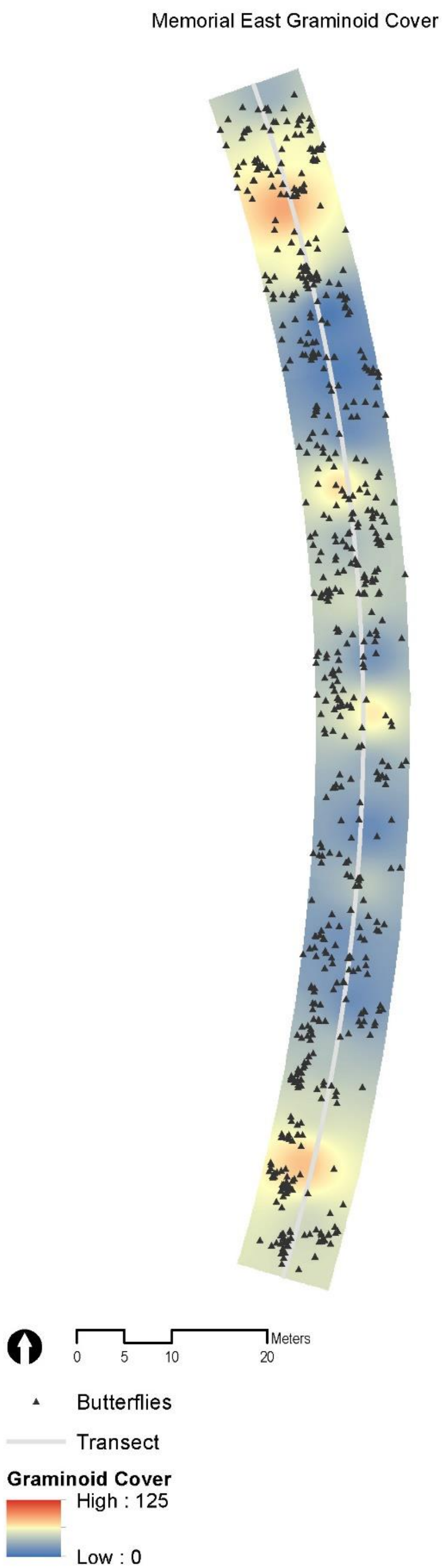

Figure 6.6. Memorial Stadium east graminoid cover inverse distance weighted interpolation with butterfly interaction locations from data collected in 2017 and 2018

Figure 6.7. Memorial Stadium west blossom index and plant richness inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

Figure 6.8. Memorial Stadium west litter depth and total plant cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

Figure 6.9. Memorial Stadium west plant evenness and shannon diversity inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

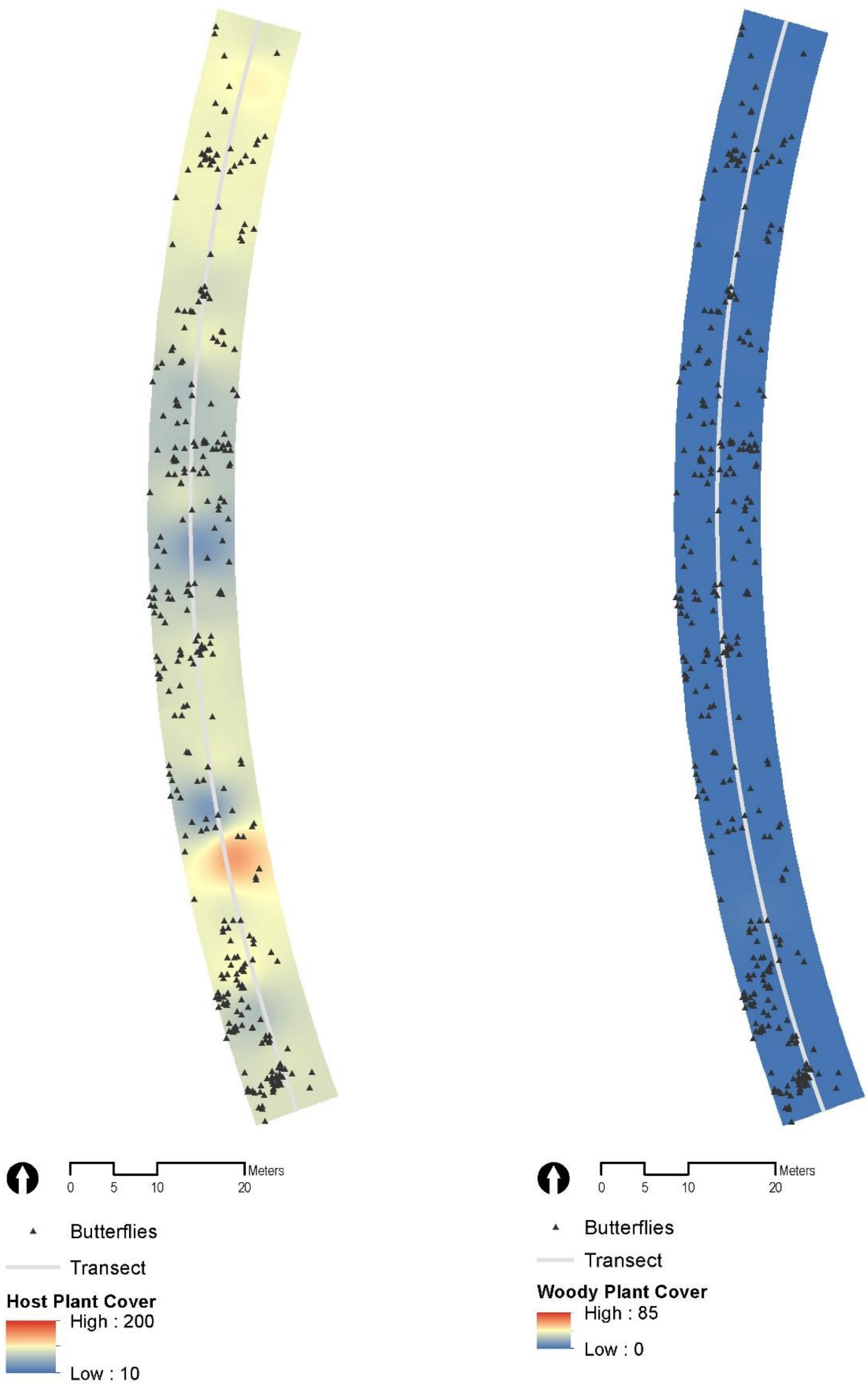

Figure 6.10. Memorial Stadium west host plant cover and woody cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

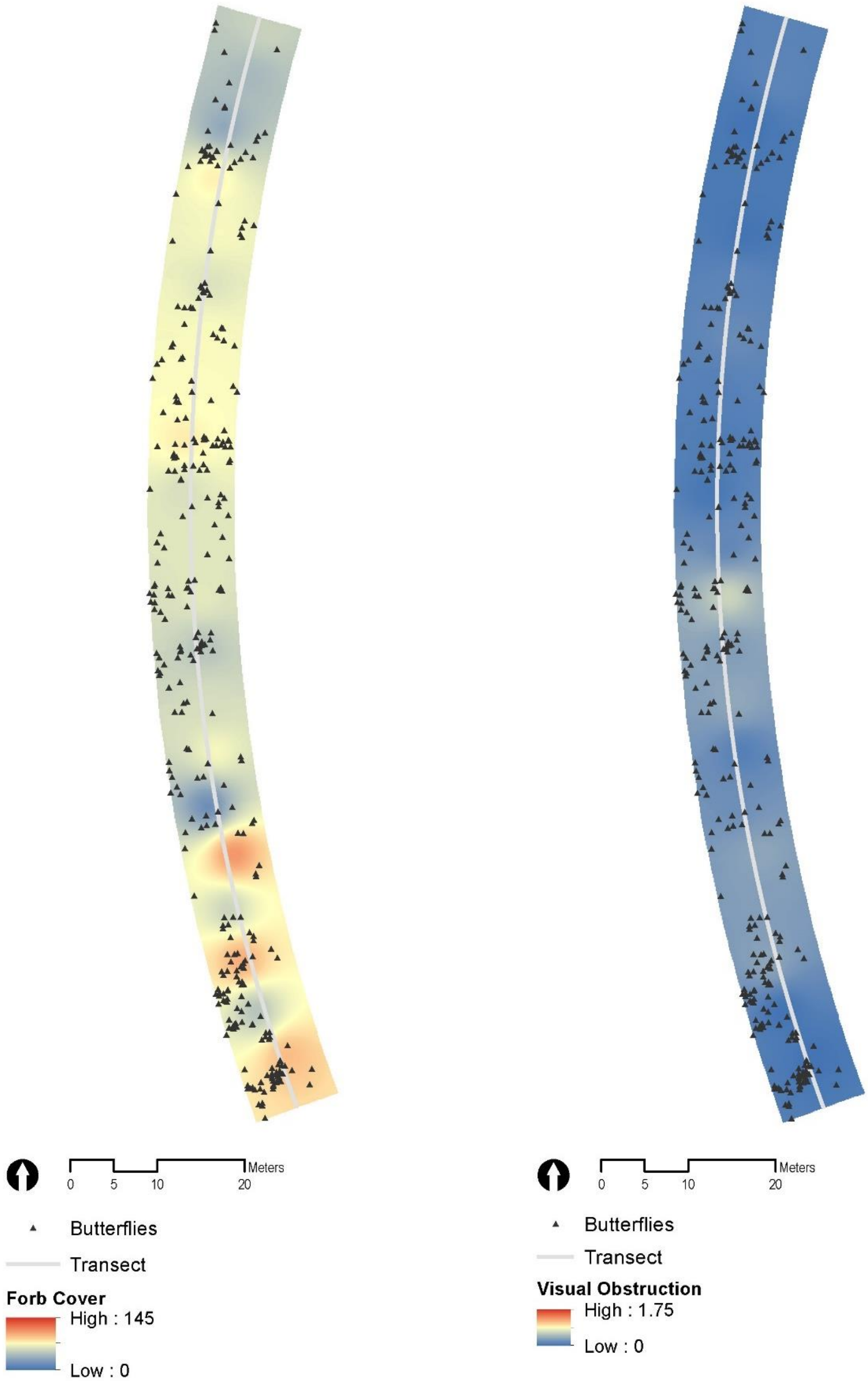

Figure 6.11. Memorial Stadium west forb cover and visual obstruction inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

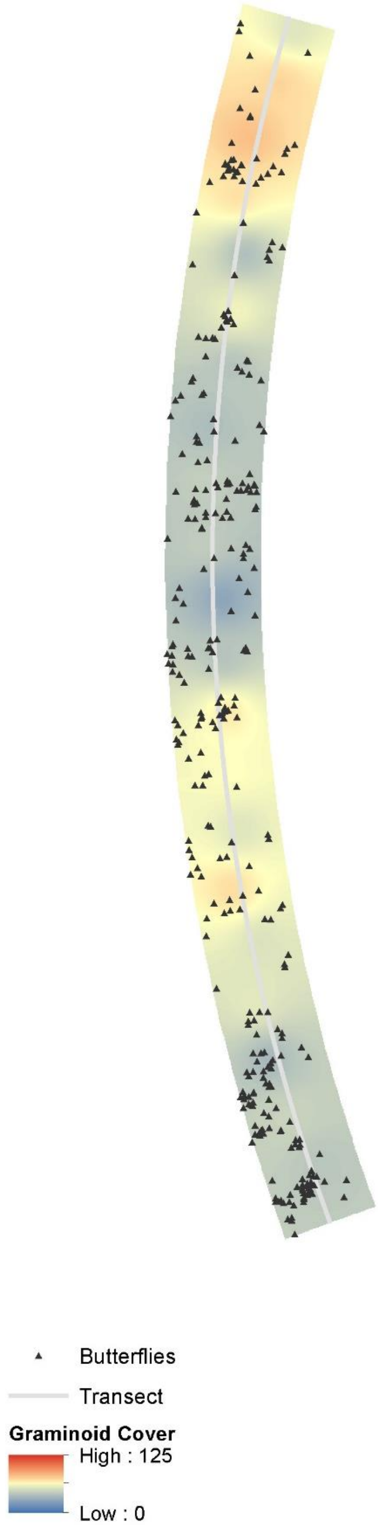

Figure 6.12. Memorial Stadium west graminoid cover inverse distance weighted interpolation with butterfly interaction locations from data collected in 2017 and 2018

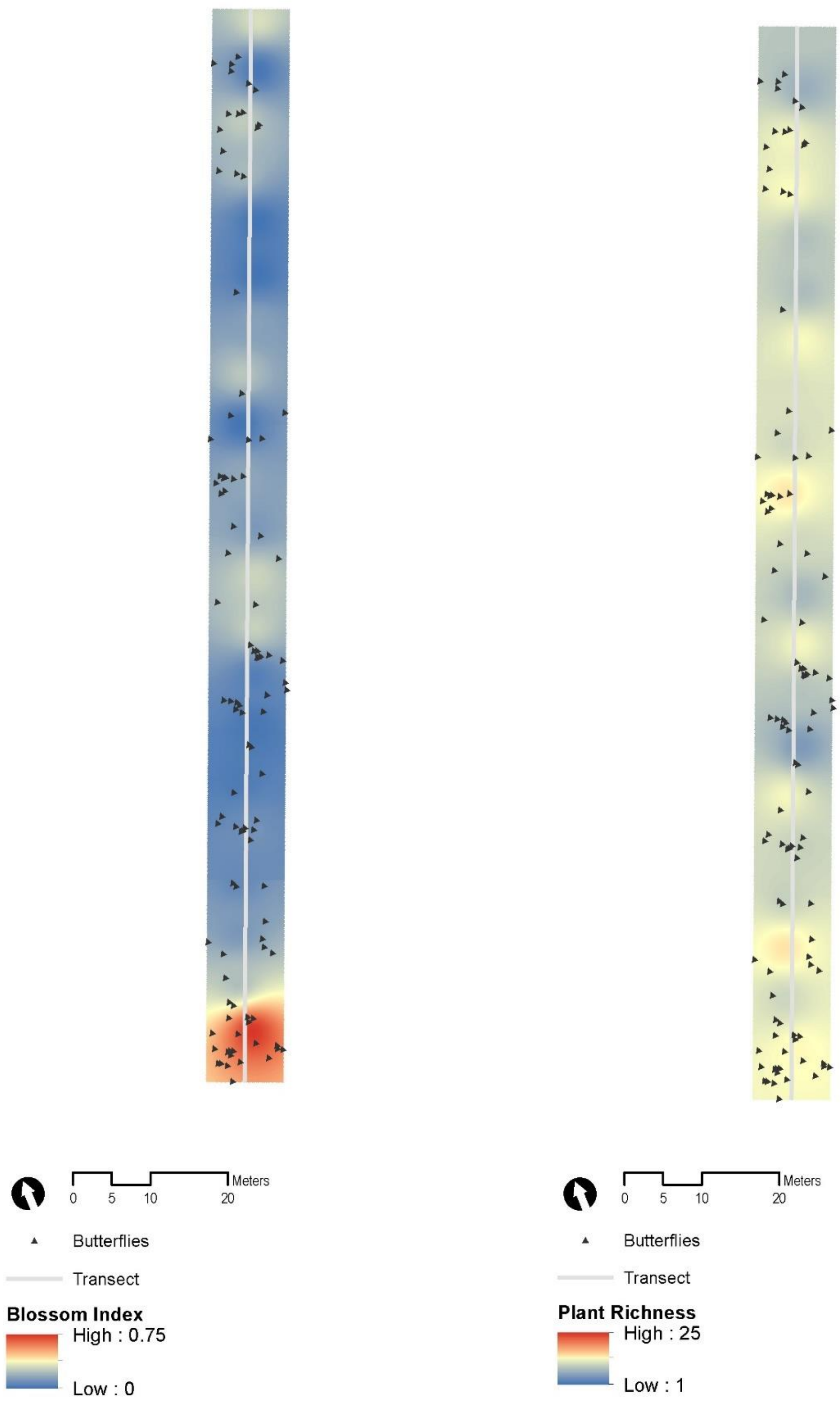

Figure 6.13. R20A east blossom index and plant richness inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

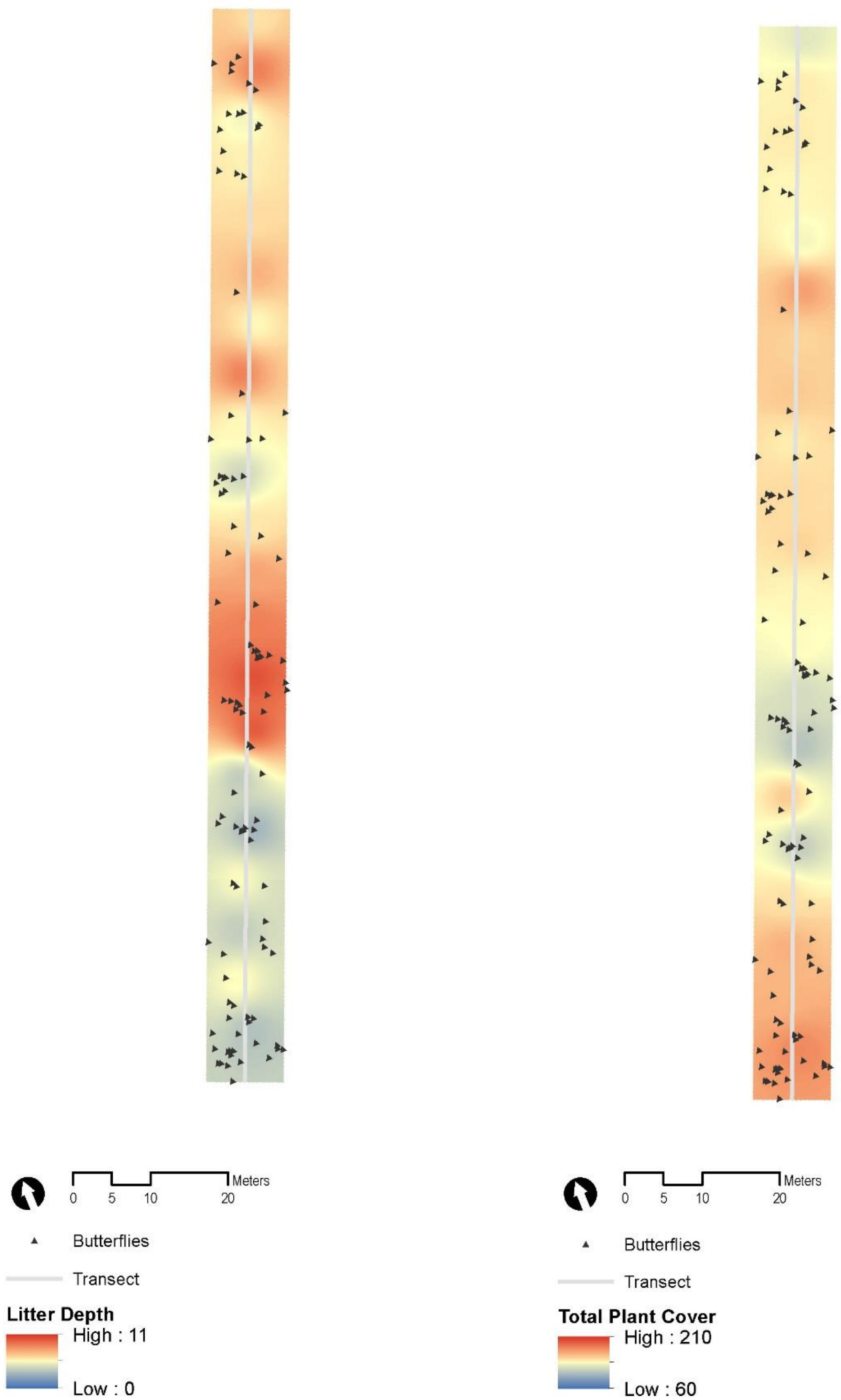

Figure 6.14. R20A east litter depth and total plant cover invwerse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

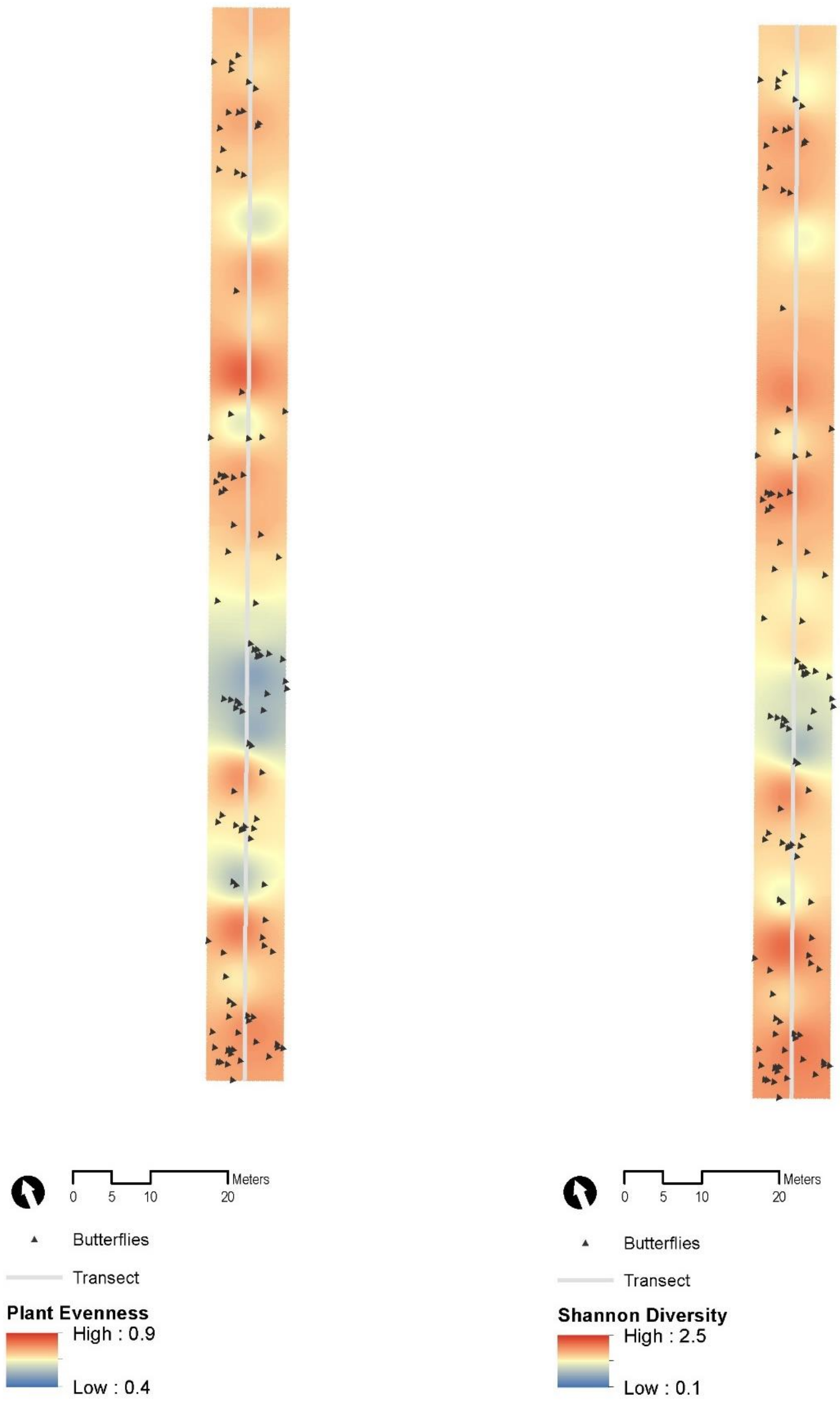

Figure 6.15. R20A east plant evenness and Shannon diversity inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

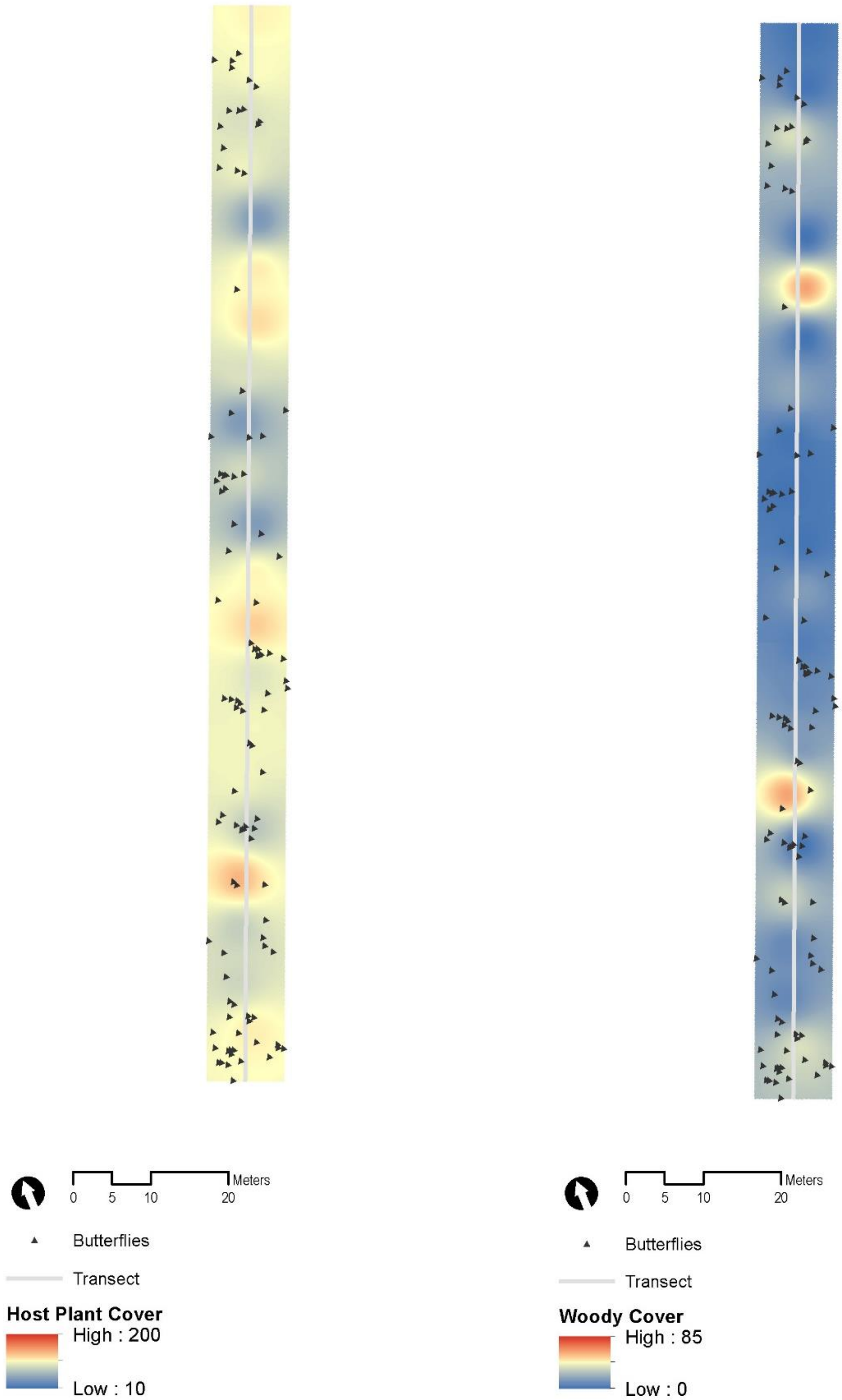

Figure 6.16. R20A east host plant cover and woody cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

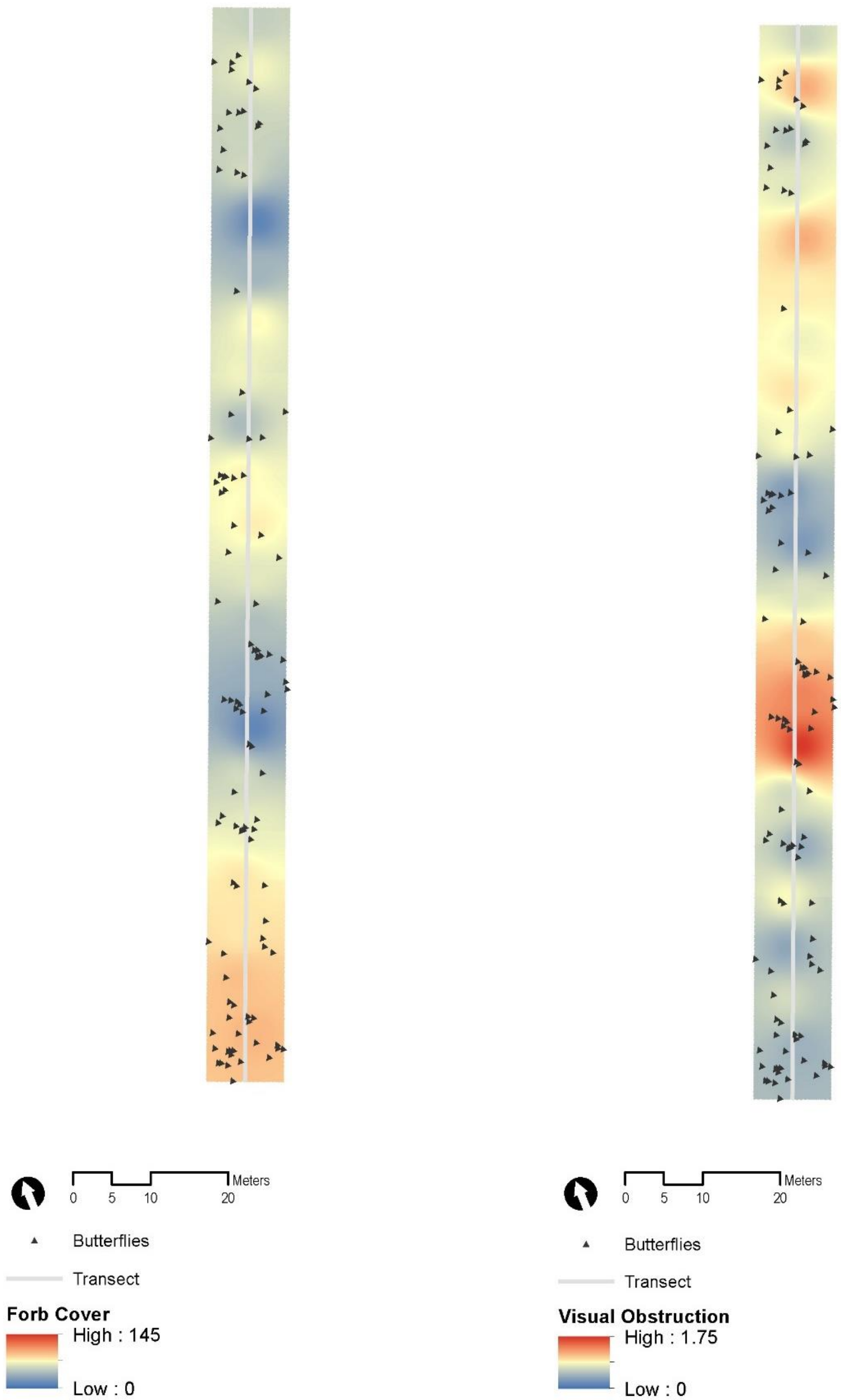

Figure 6.17. R20A east forb cover and visual obstruction inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

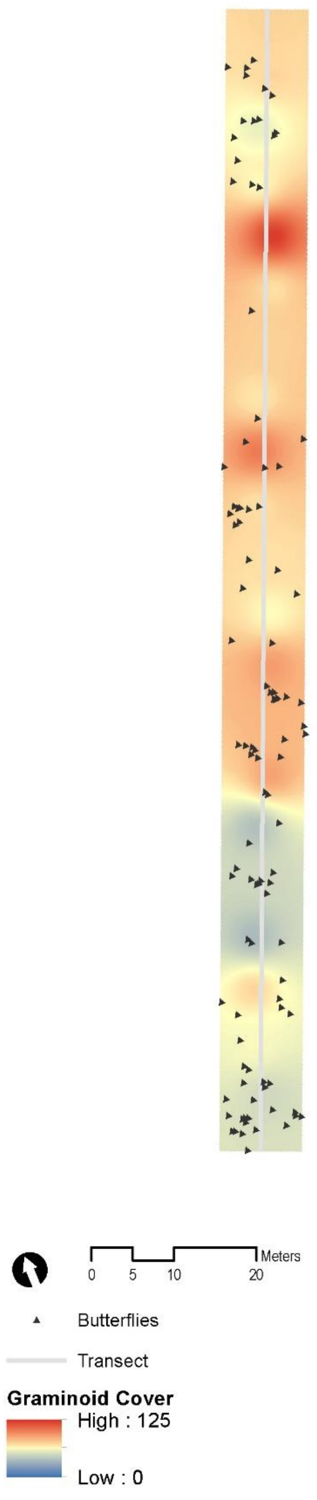

Figure 6.18. R20A east graminoid cover inverse distance weighted interpolation with butterfly interaction locations from data collected in 2017 and 2018

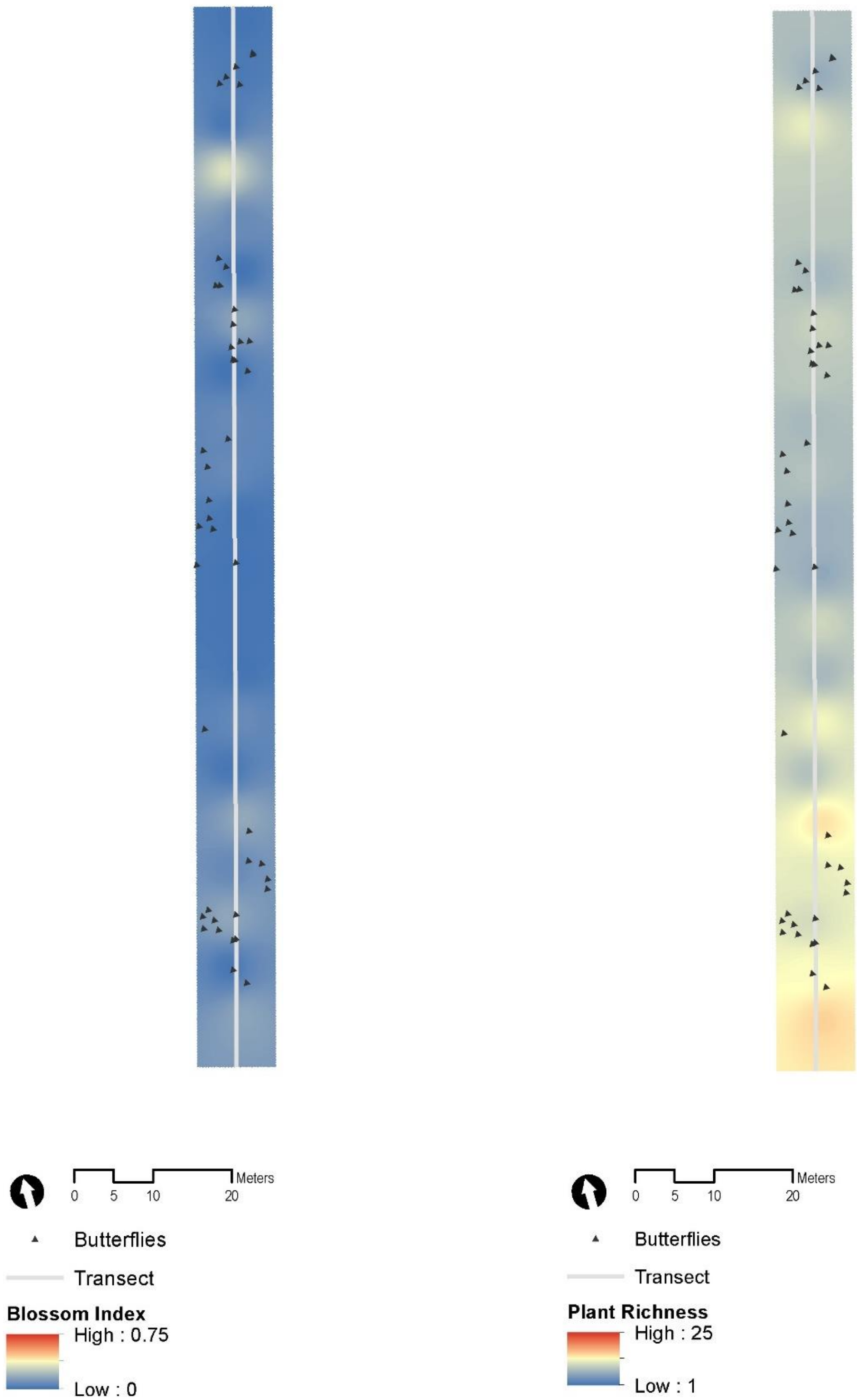

Figure 6.19. R20A west blossom index and plant richness inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

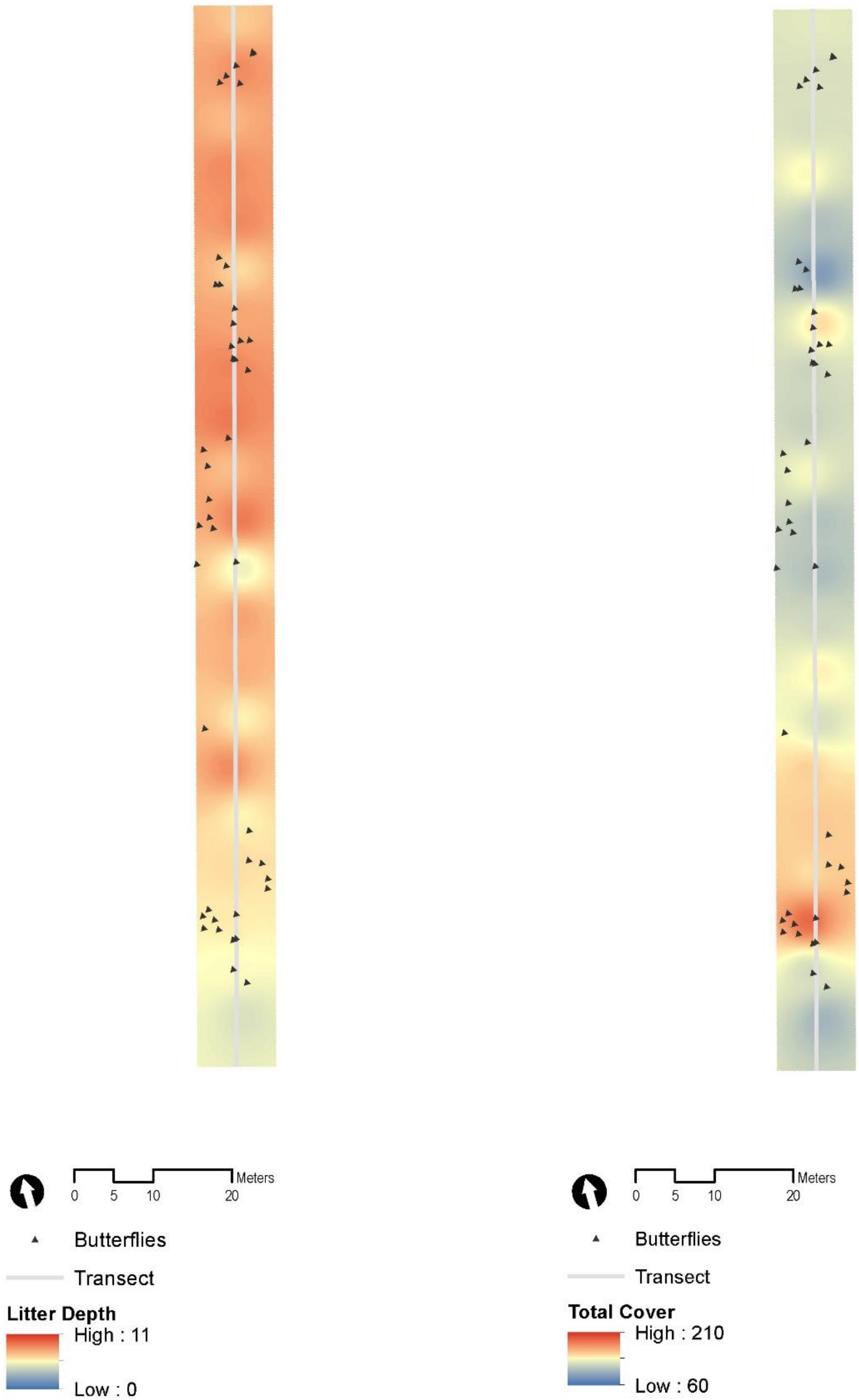

Figure 6.20. R20A west litter depth and total plant cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

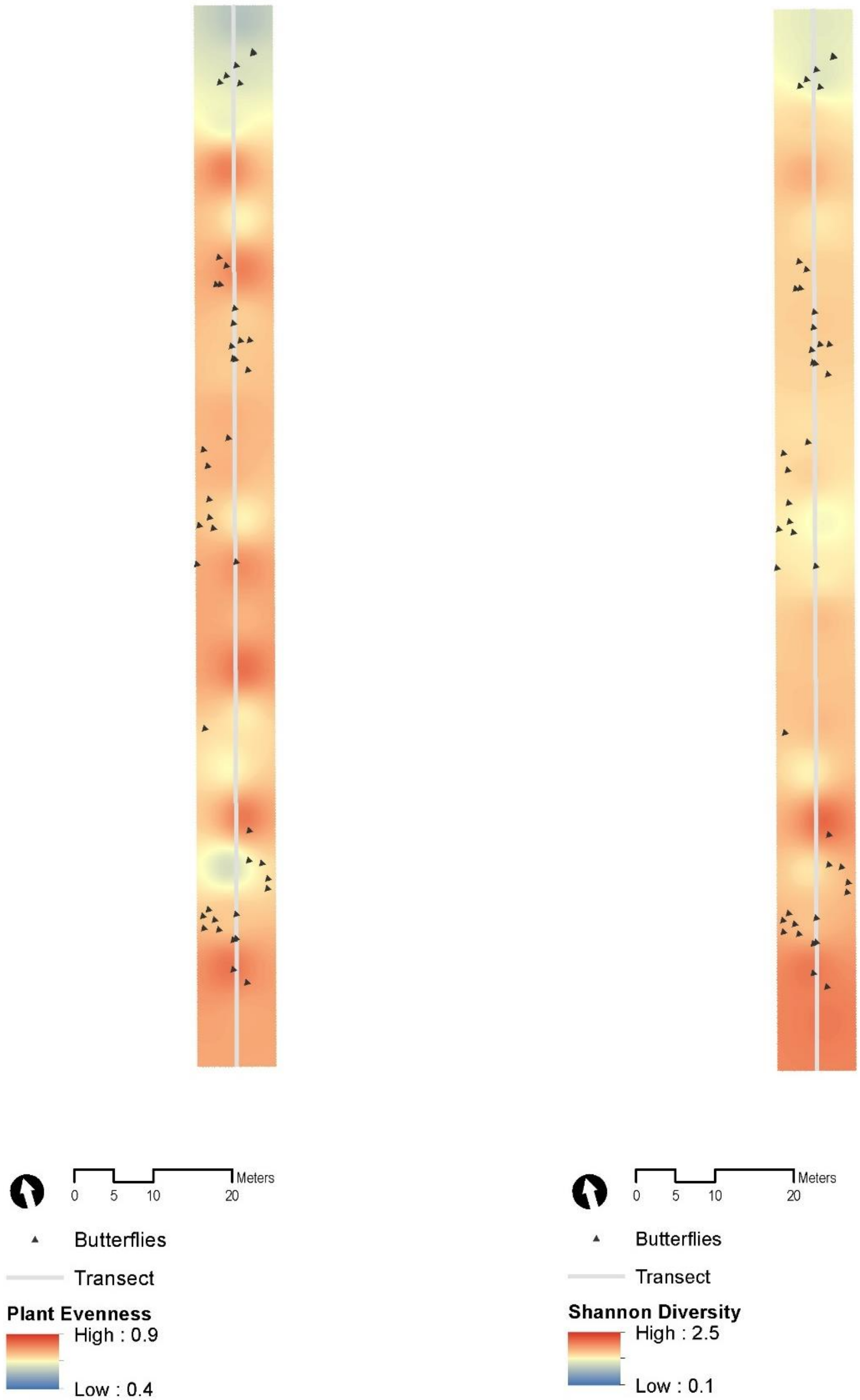

Figure 6.21. R20A west plant evenness and shannon diversity inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

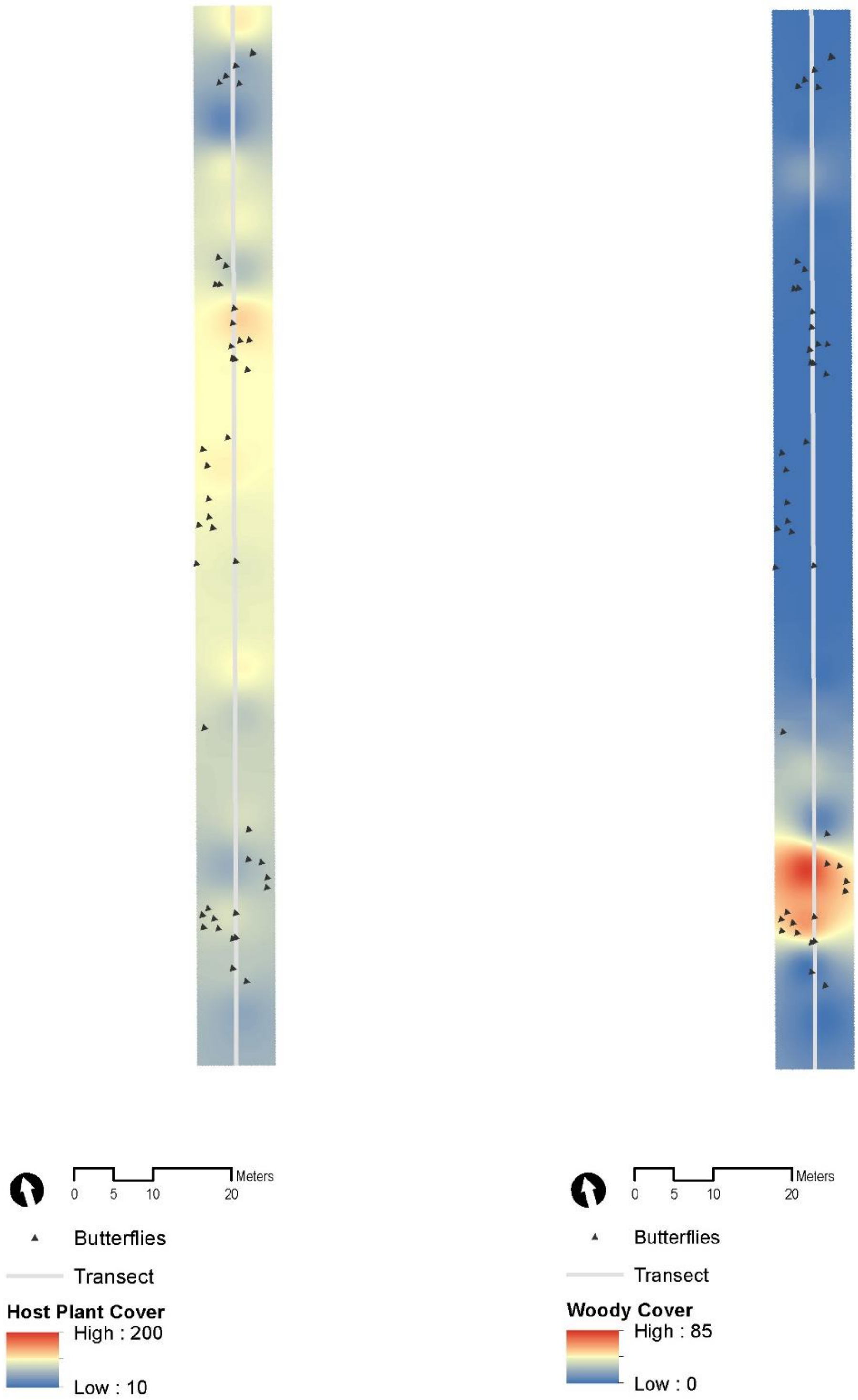

Figure 6.22. R20A west host plant cover and woody cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

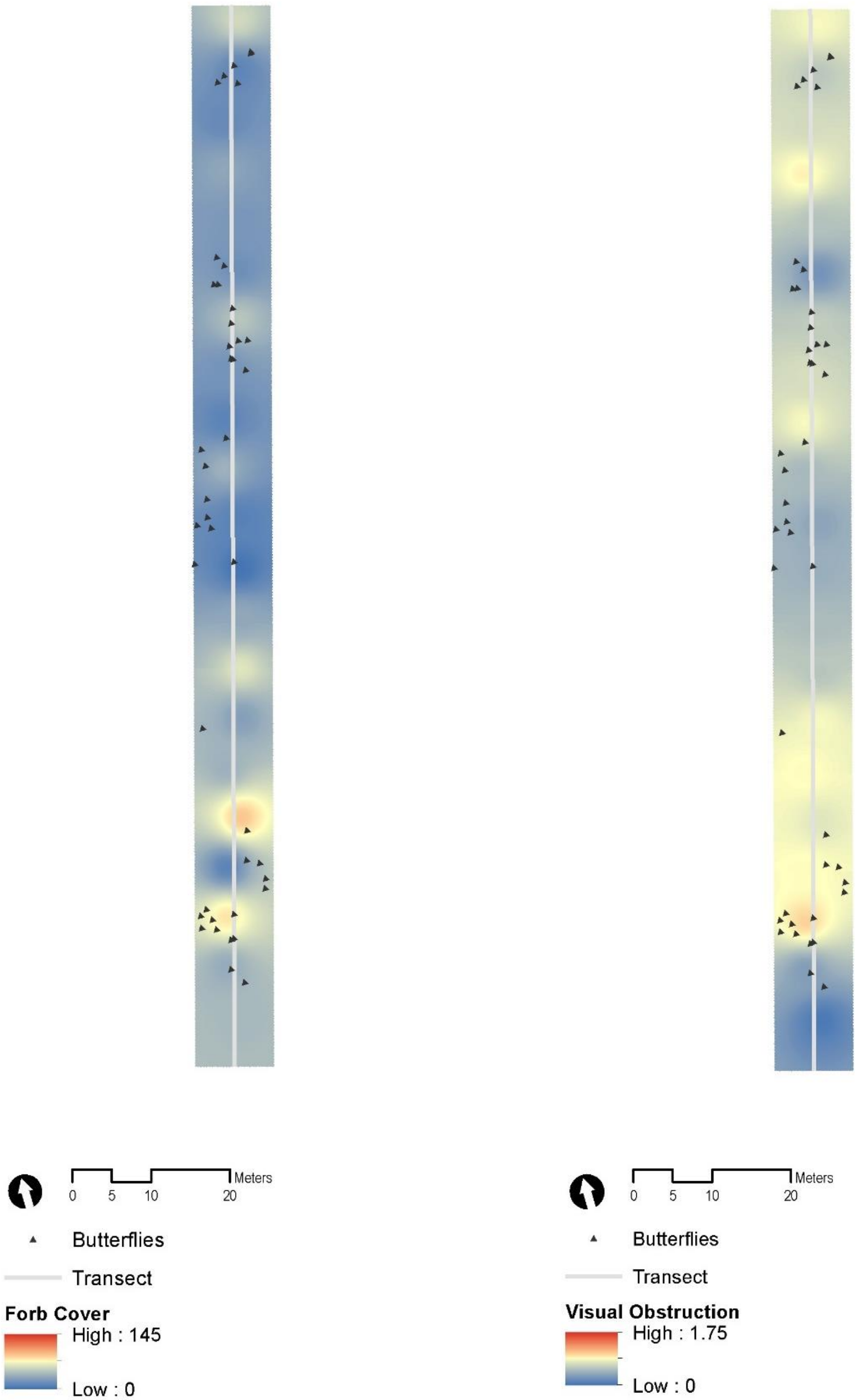

Figure 6.23. R20A west forb cover and visual obstruction inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

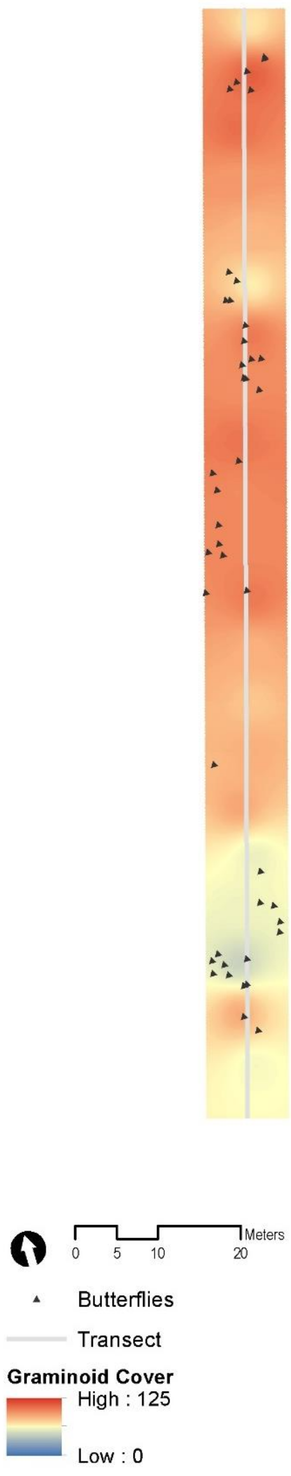

Figure 6.24. R20A west graminoid cover inverse distance weighted interpolation with butterfly interaction locations from data collected in 2017 and 2018

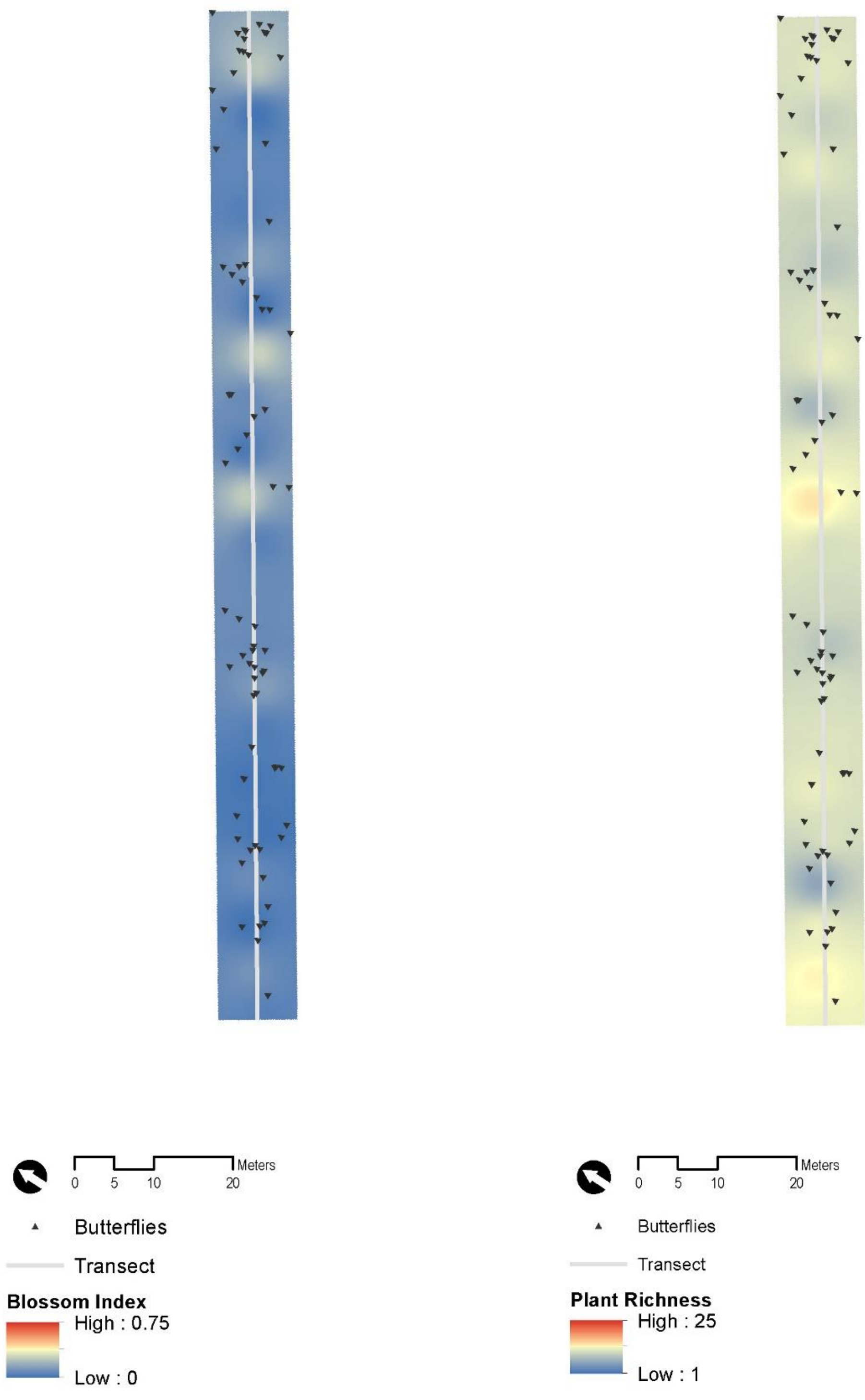

Figure 6.25. R20B east blossom index and plant richness inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

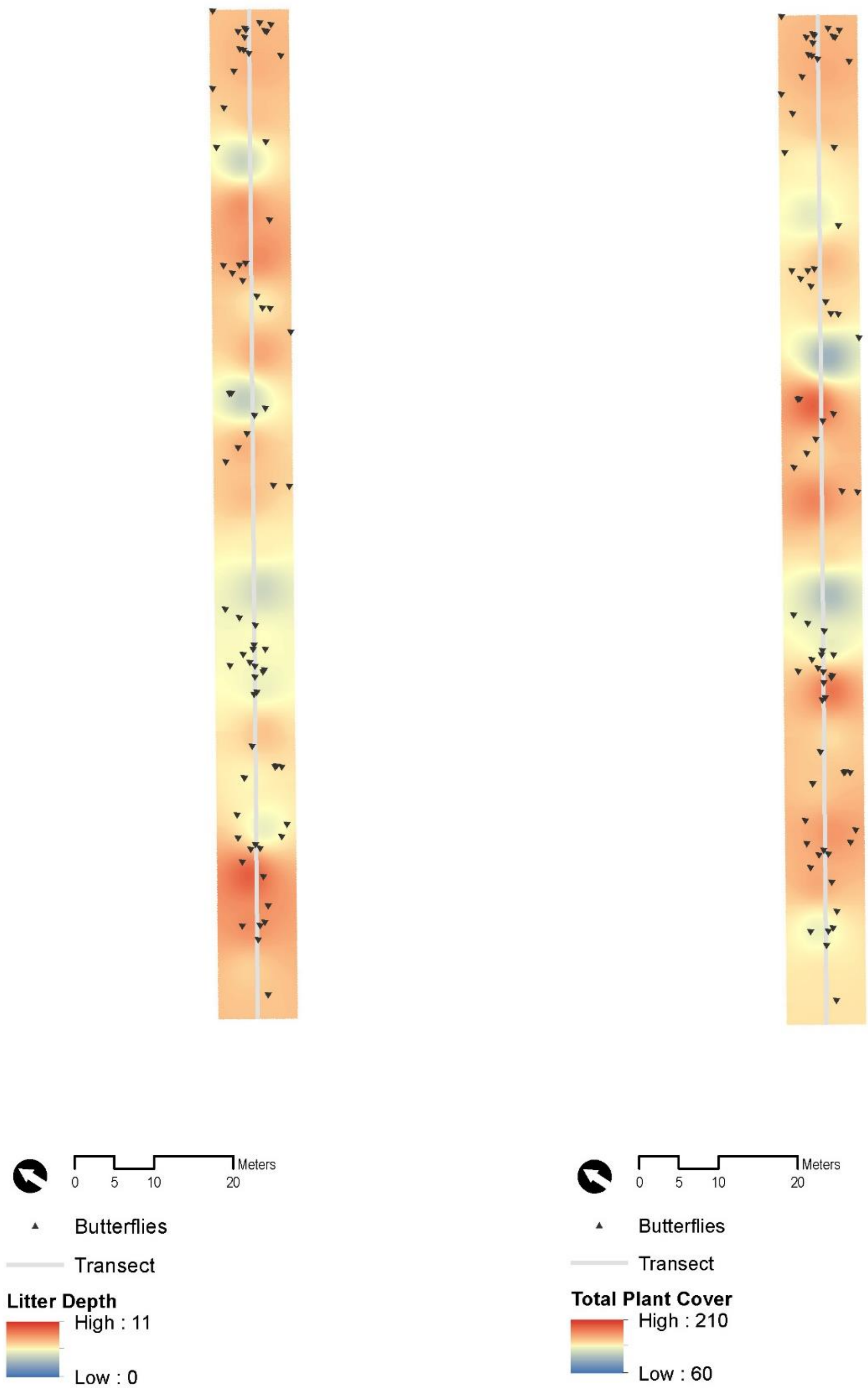

Figure 6.26. R20B east litter depth and total plant cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

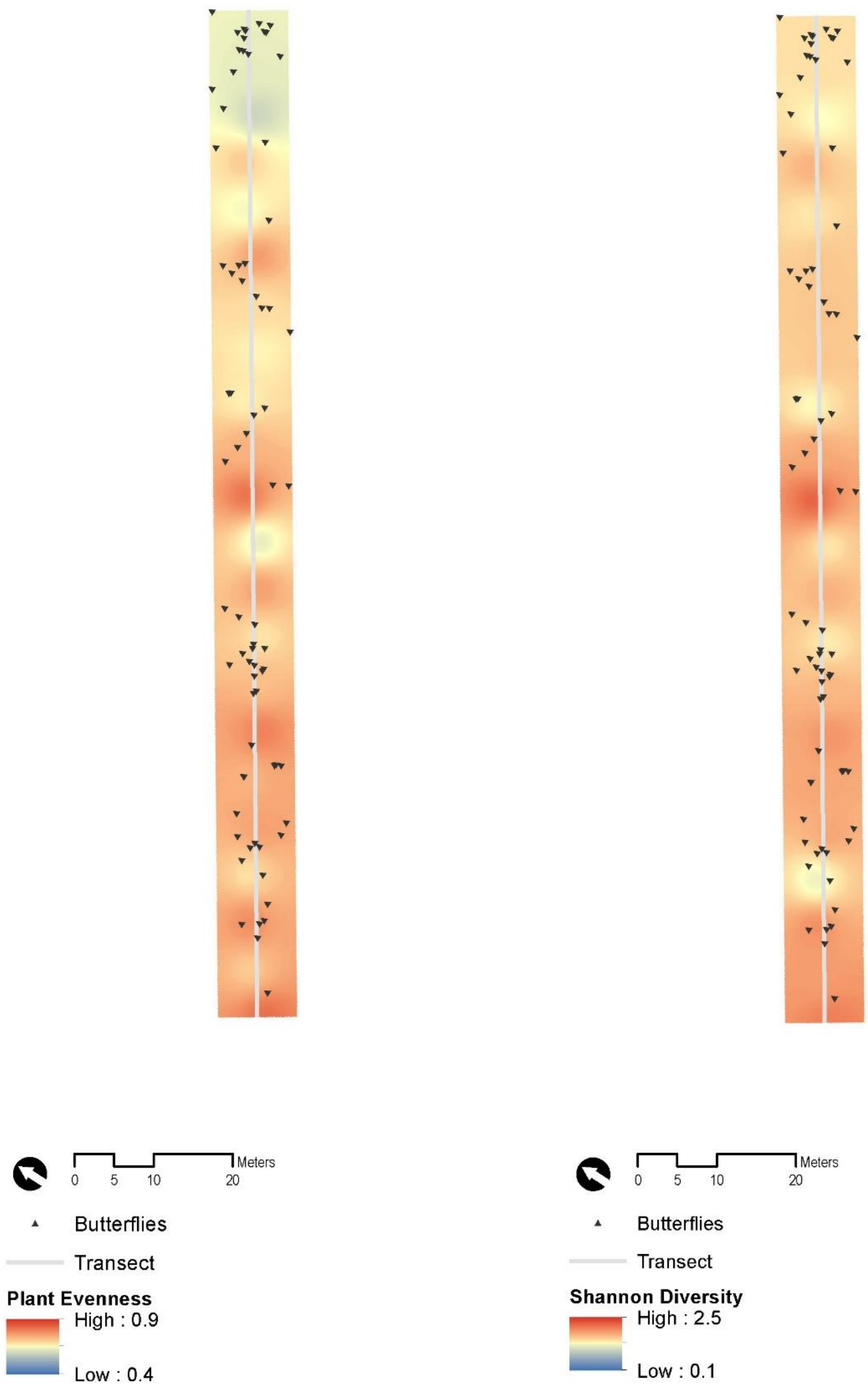

Figure 6.27. R20B east plant evenness and shannon diversity inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

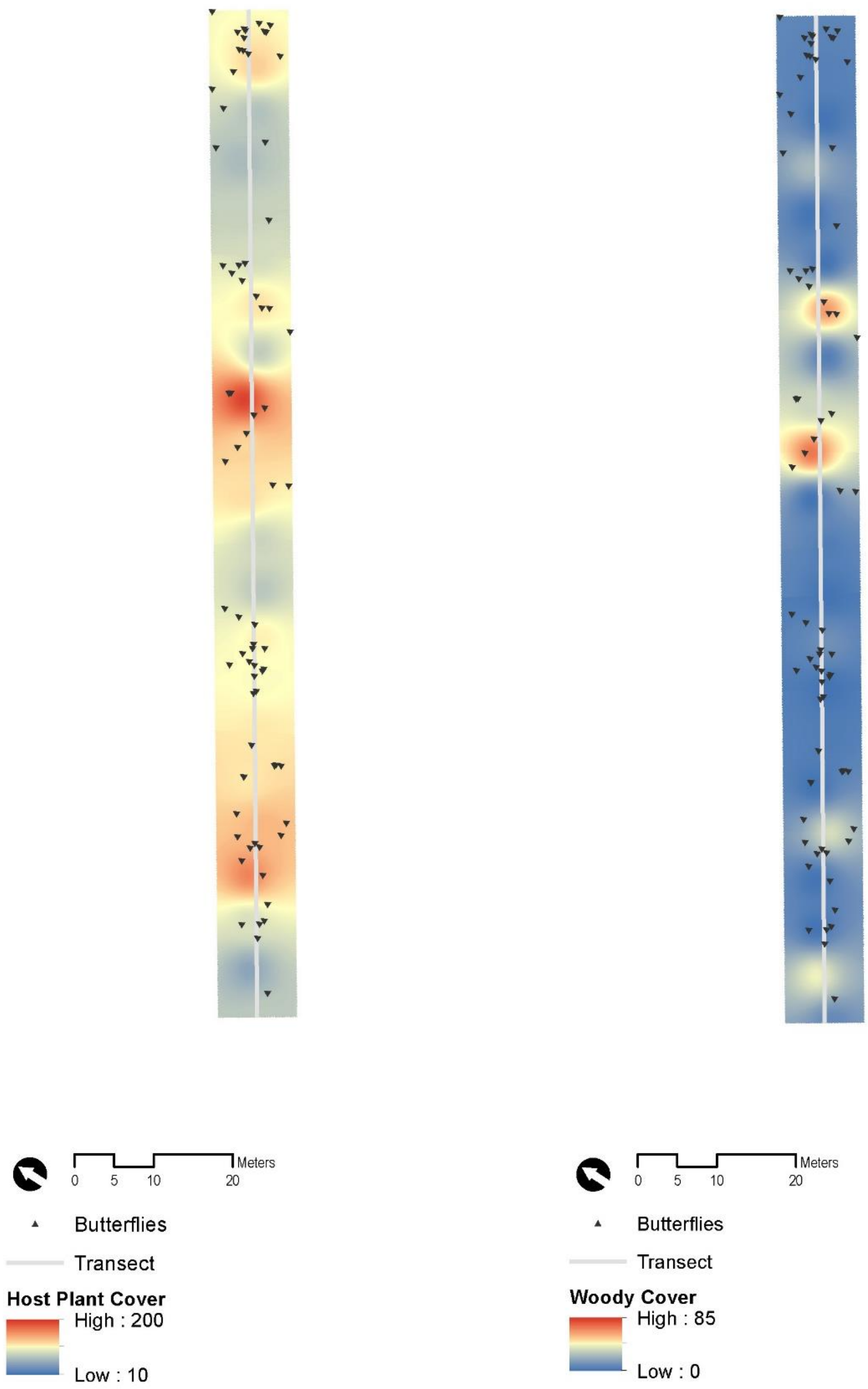

Figure 6.28. R20B east host plant cover and woody cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

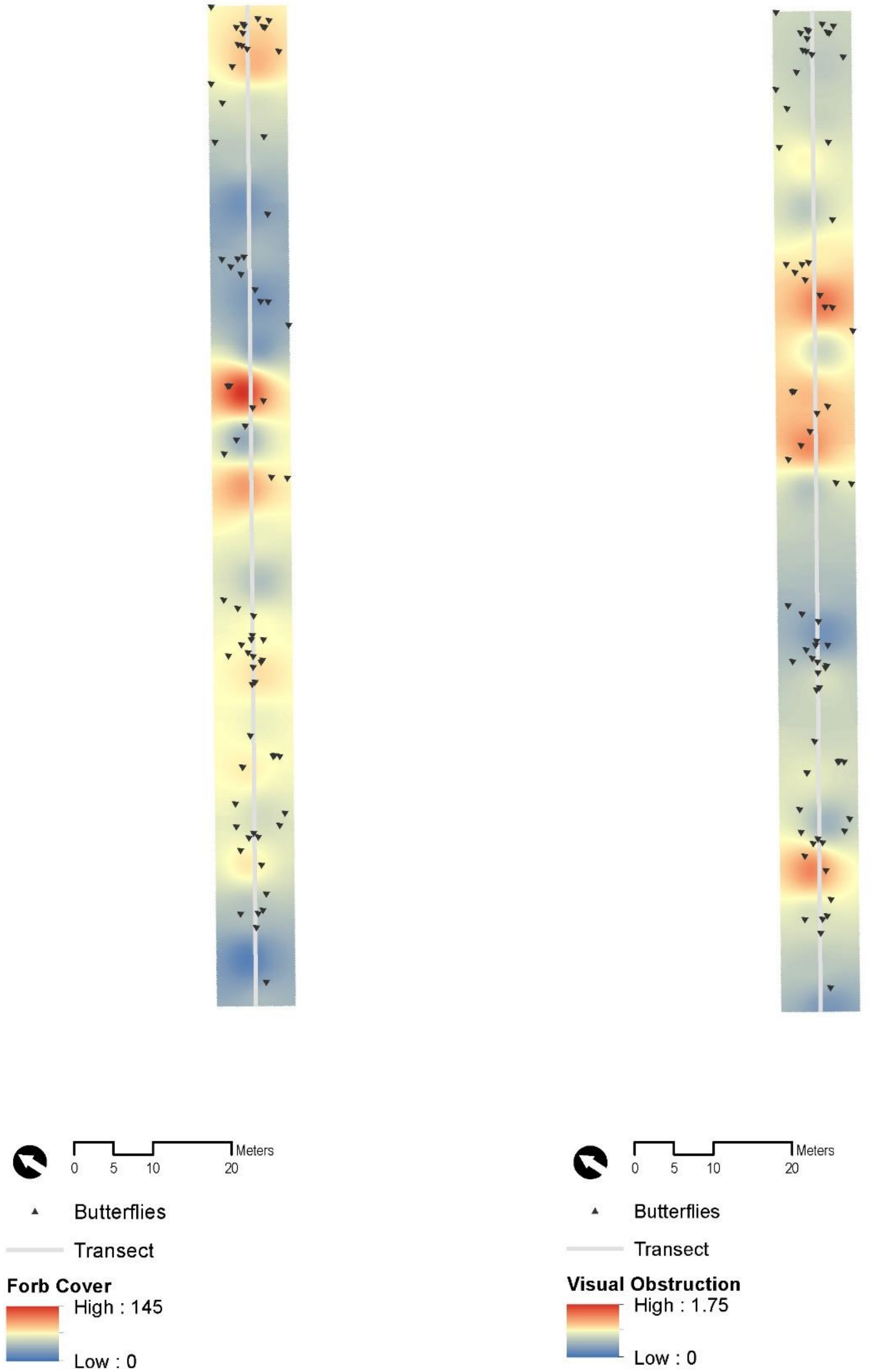

Figure 6.29. R20B east forb cover and visual obstruction inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

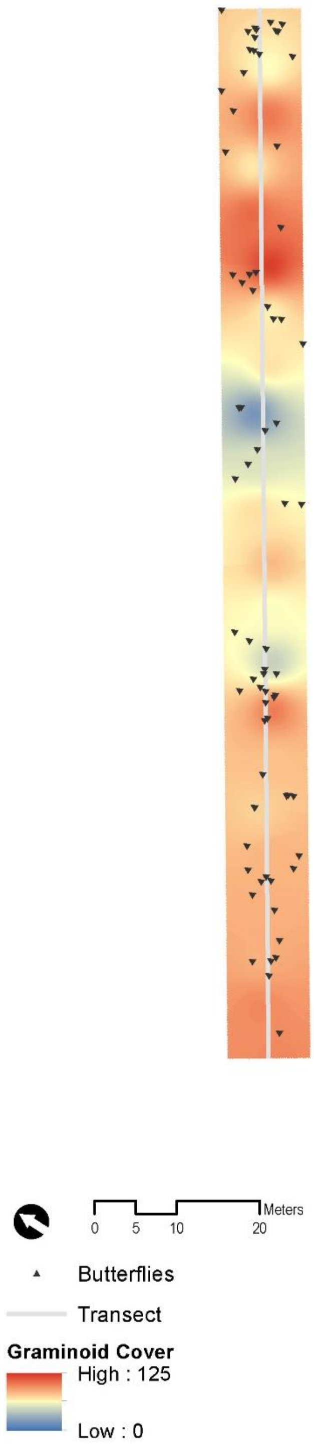

Figure 6.30. R20B east graminoid cover inverse distance weighted interpolation with butterfly interaction locations from data collected in 2017 and 2018

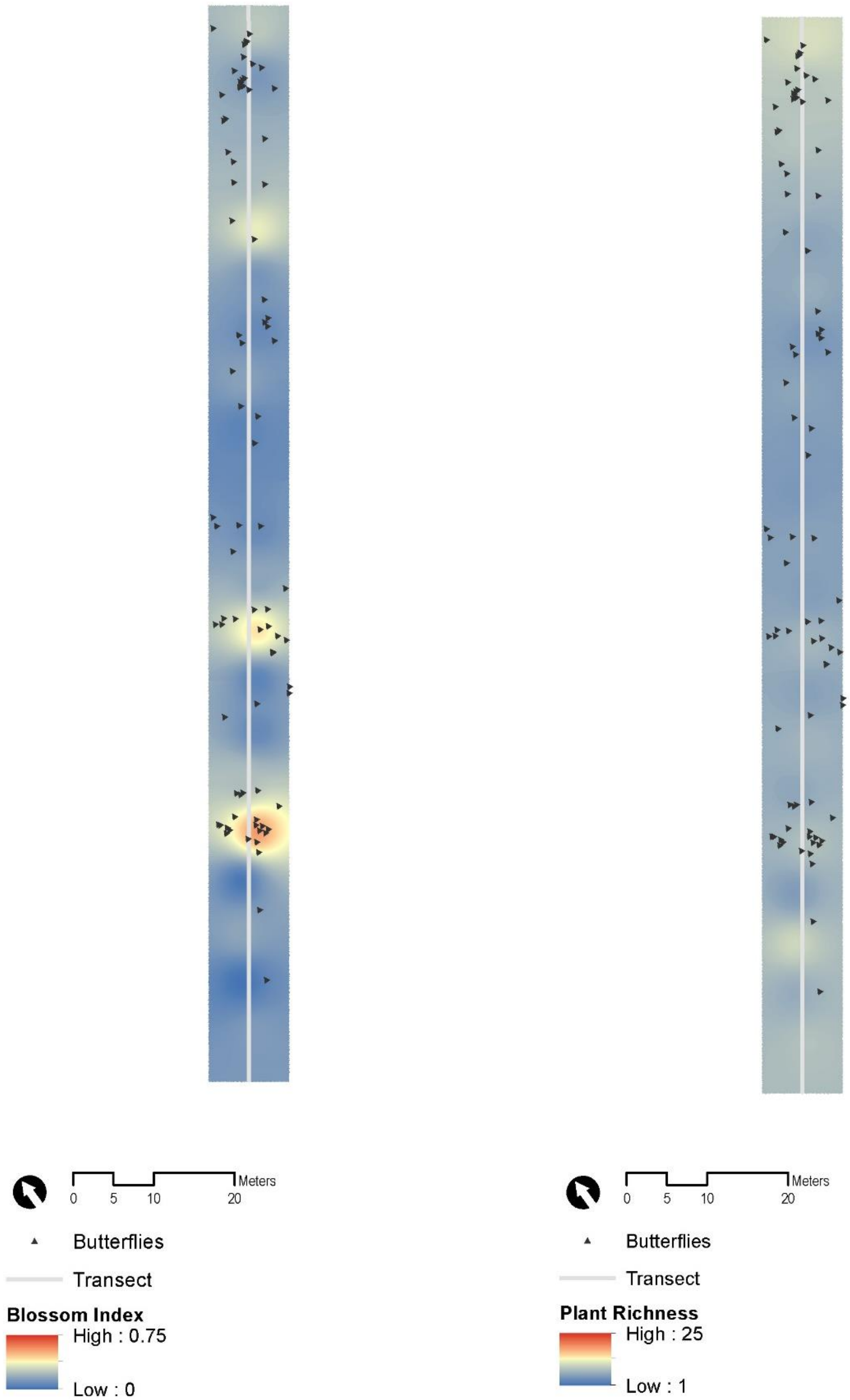

Figure 6.31. R20B west blossom index and plant richness inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

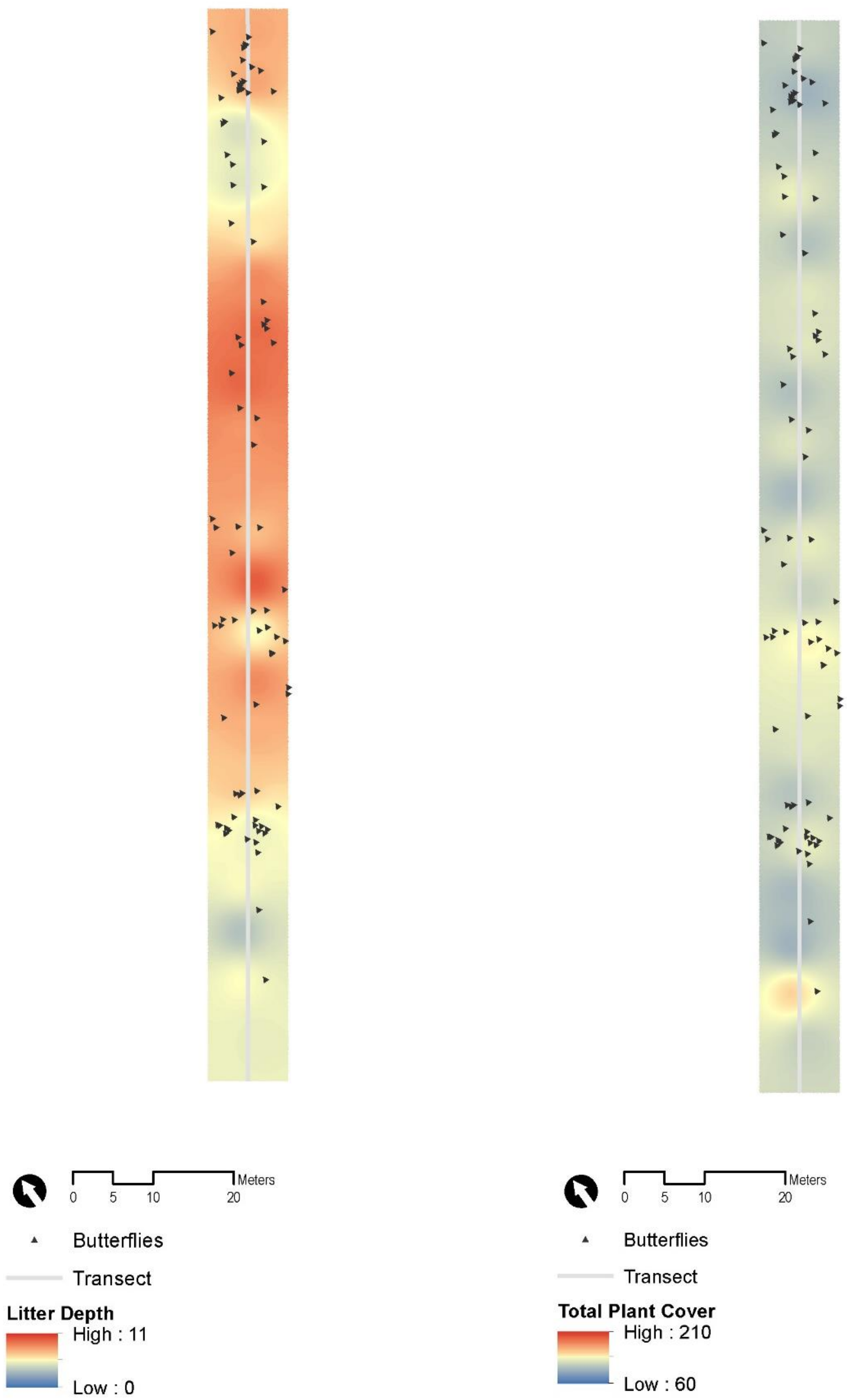

Figure 6.32. R20B west litter depth and total plant cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

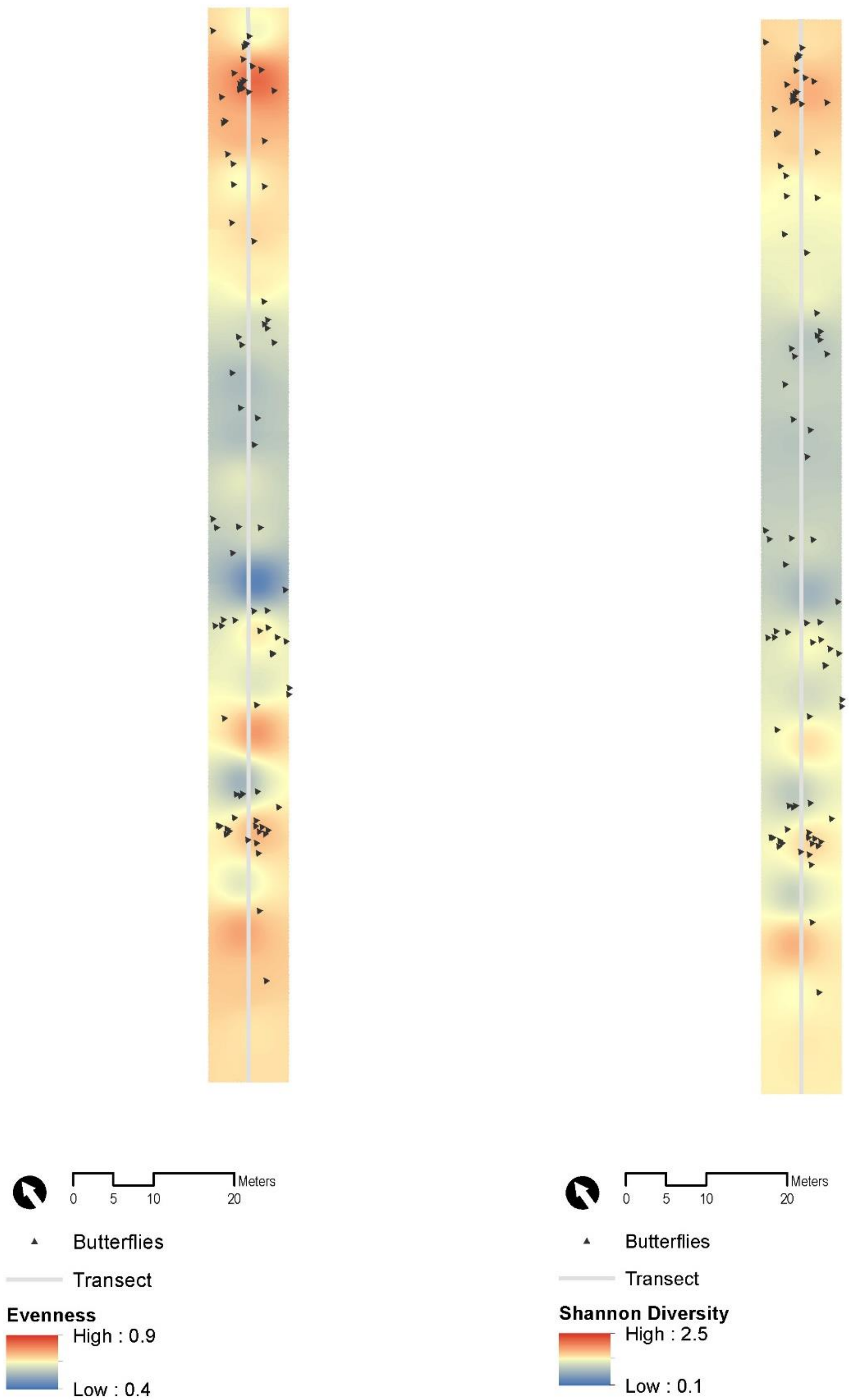

Figure 6.33. R20B west plant evenness and shannon diversity inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

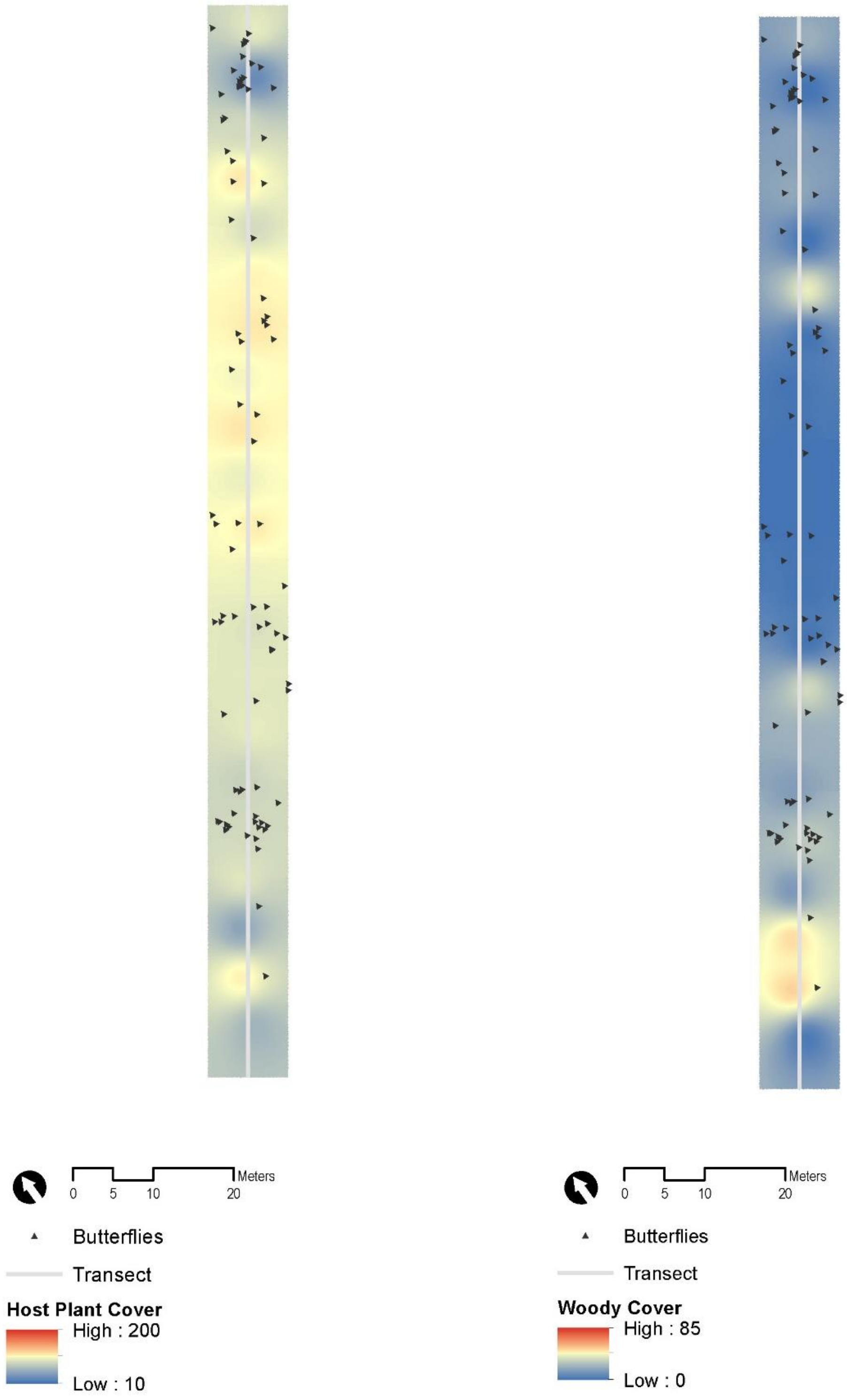

Figure 6.34. R20B west host plant cover and woody cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

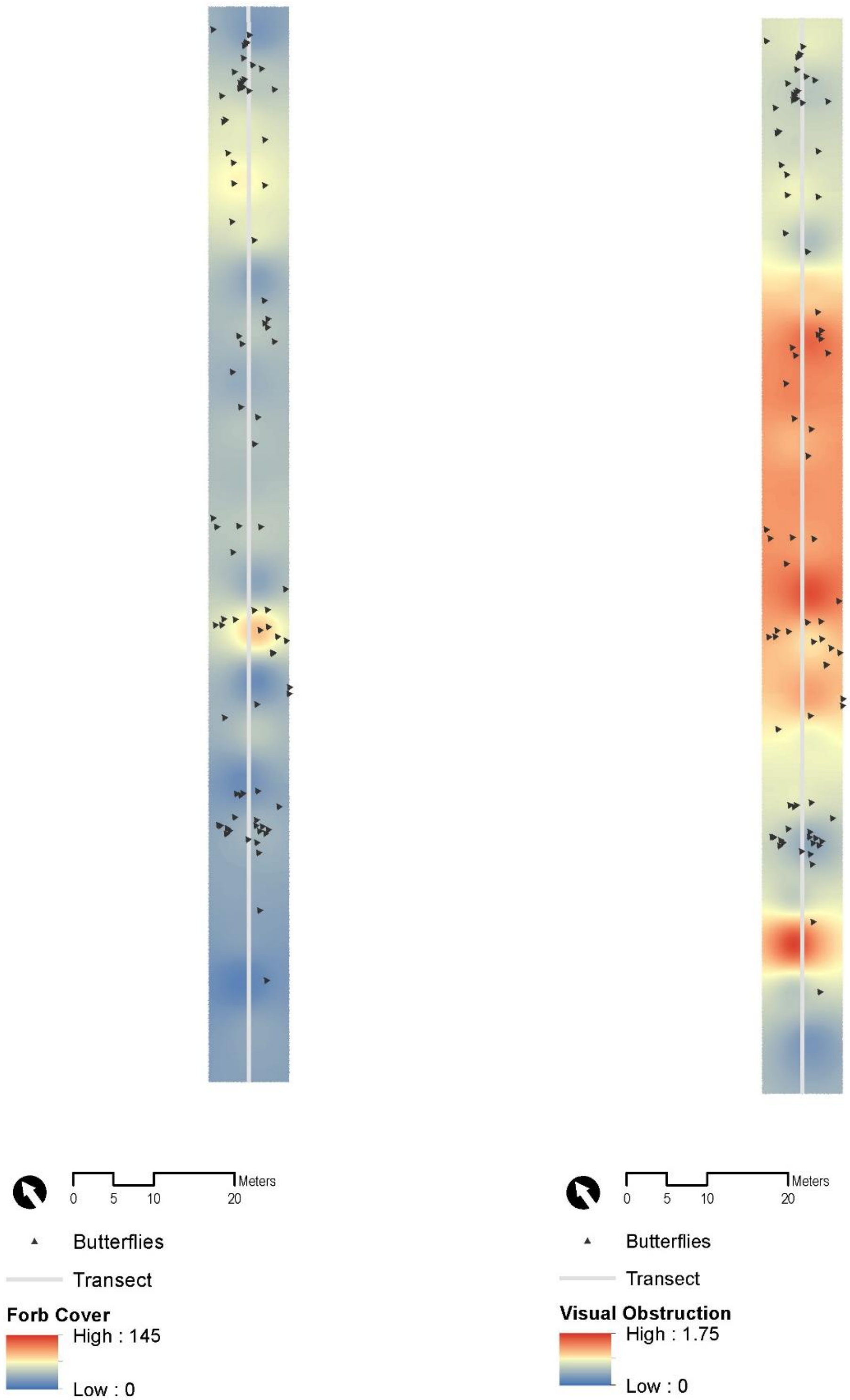

Figure 6.35. R20B west forb cover and visual obstruction inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

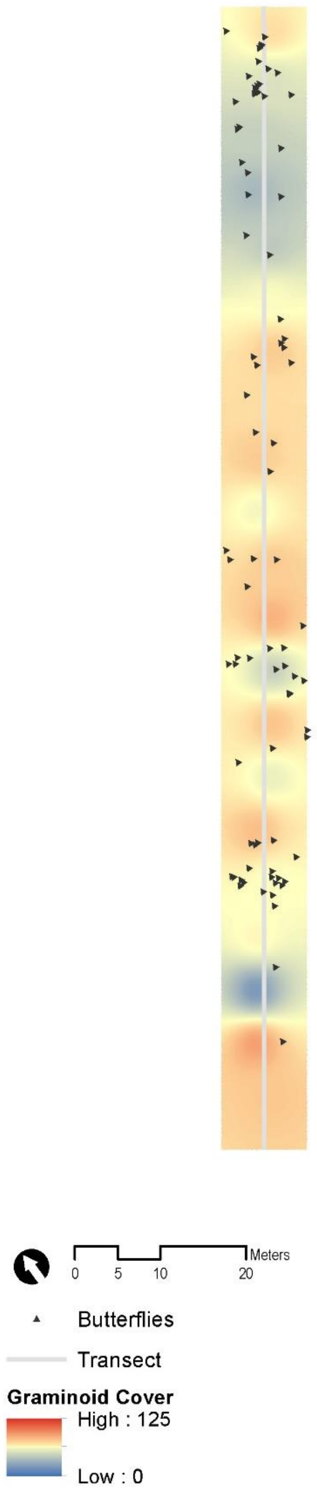

Figure 6.36. R20B west graminoid cover inverse distance weighted interpolation with butterfly interaction locations from data collected in 2017 and 2018

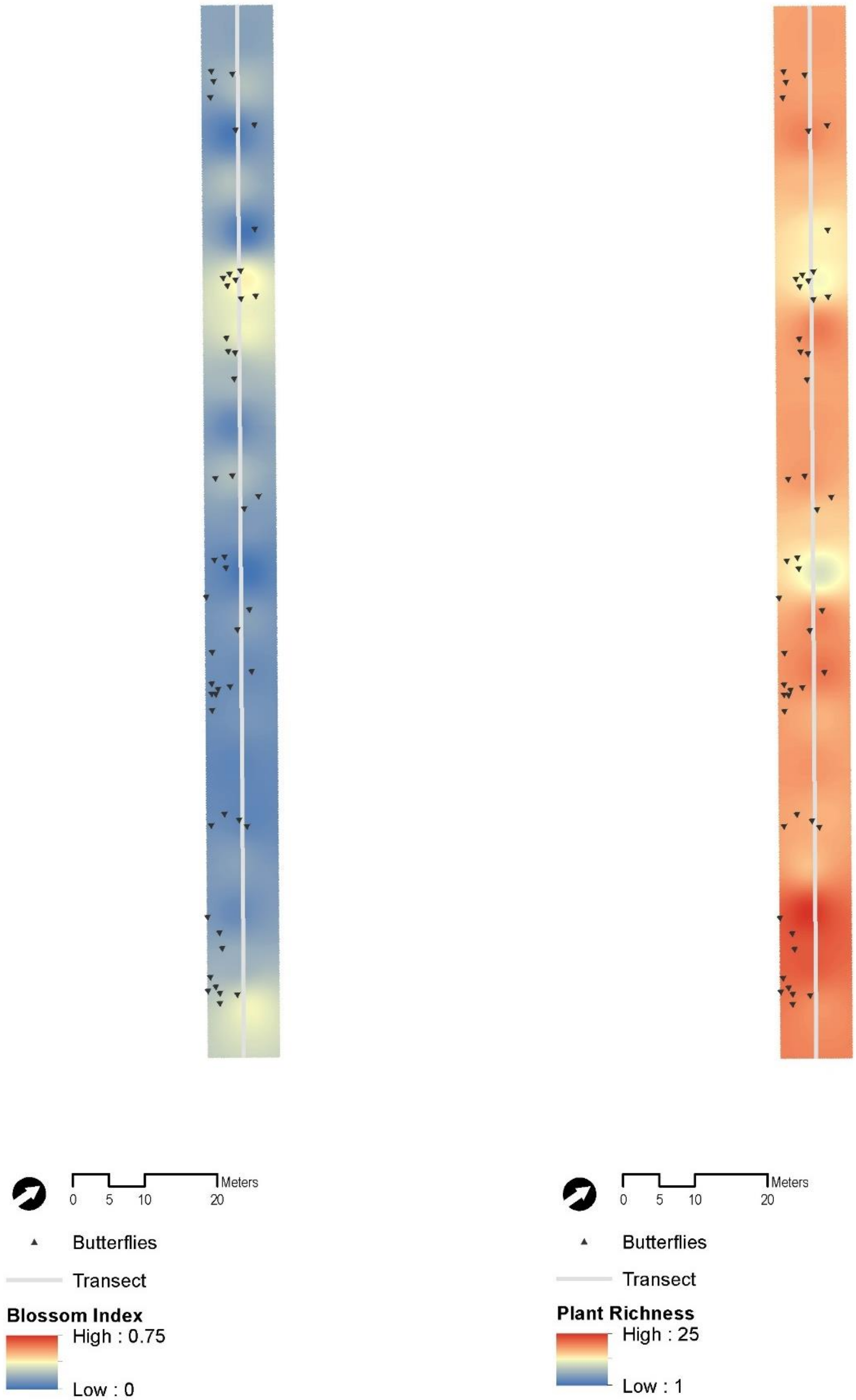

Figure 6.37. Warner east blossom index and plant richness inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

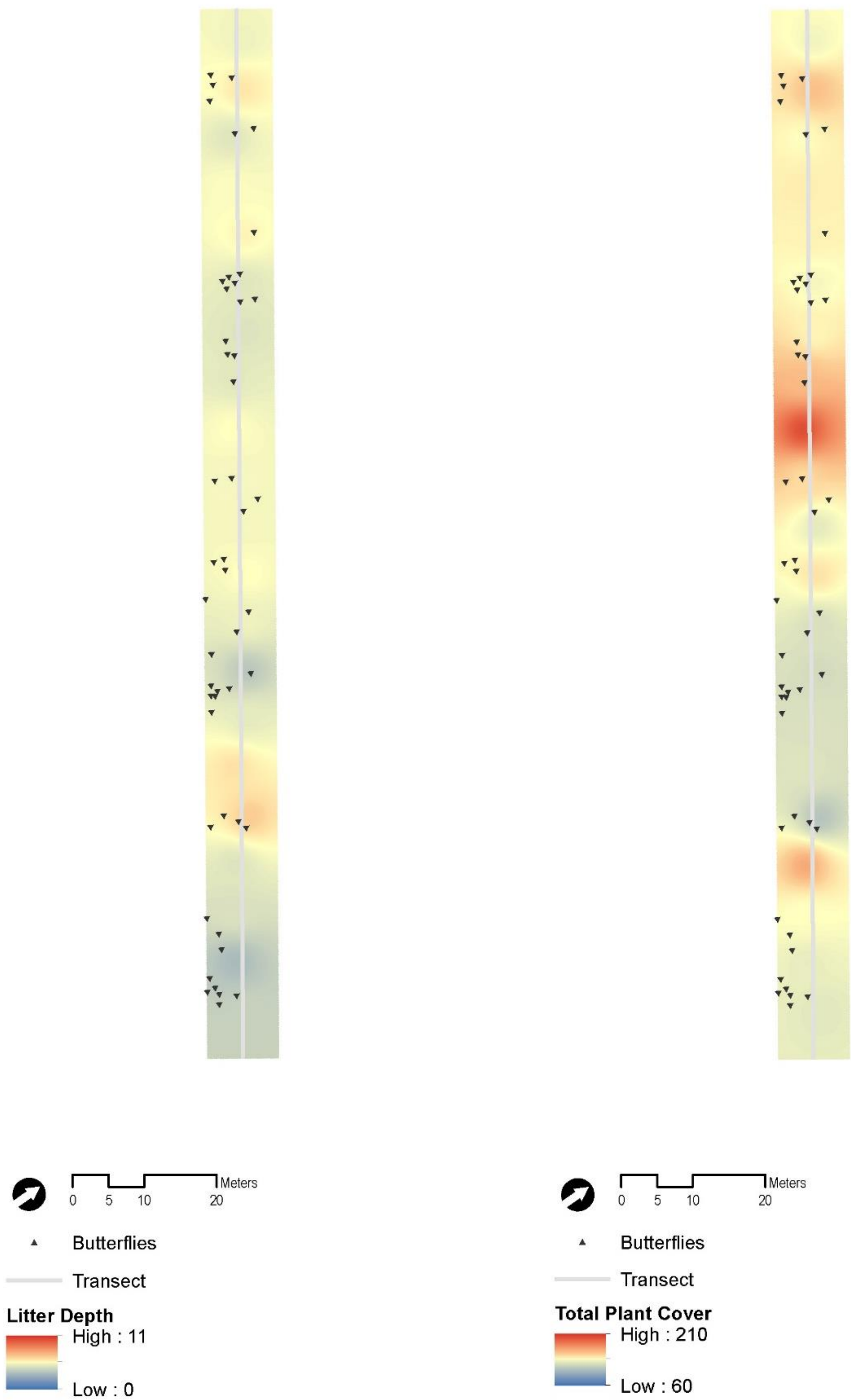

Figure 6.38. Warner east litter depth and total plant cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

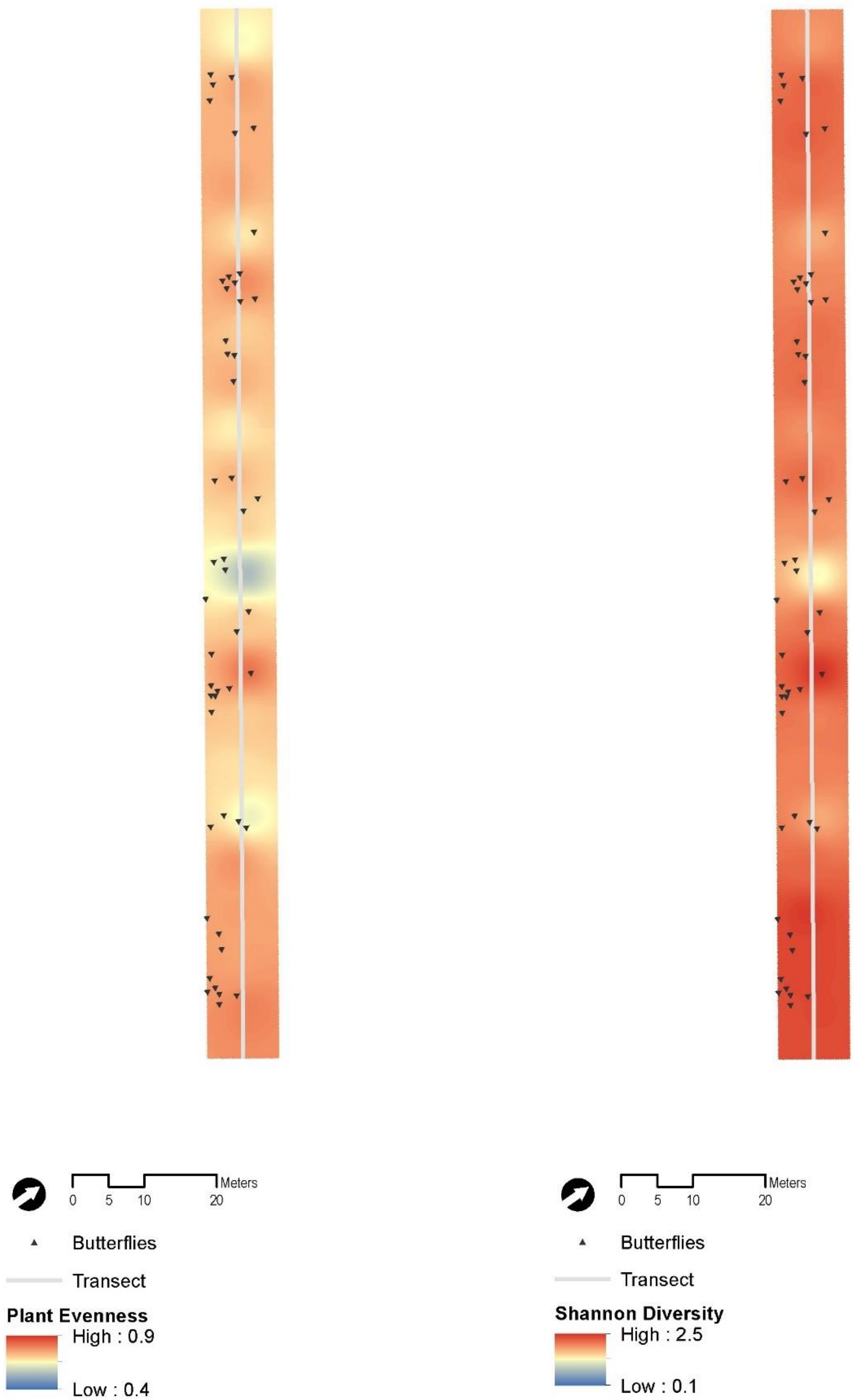

Figure 6.39. Warner east plant evenness and shannon diversity inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

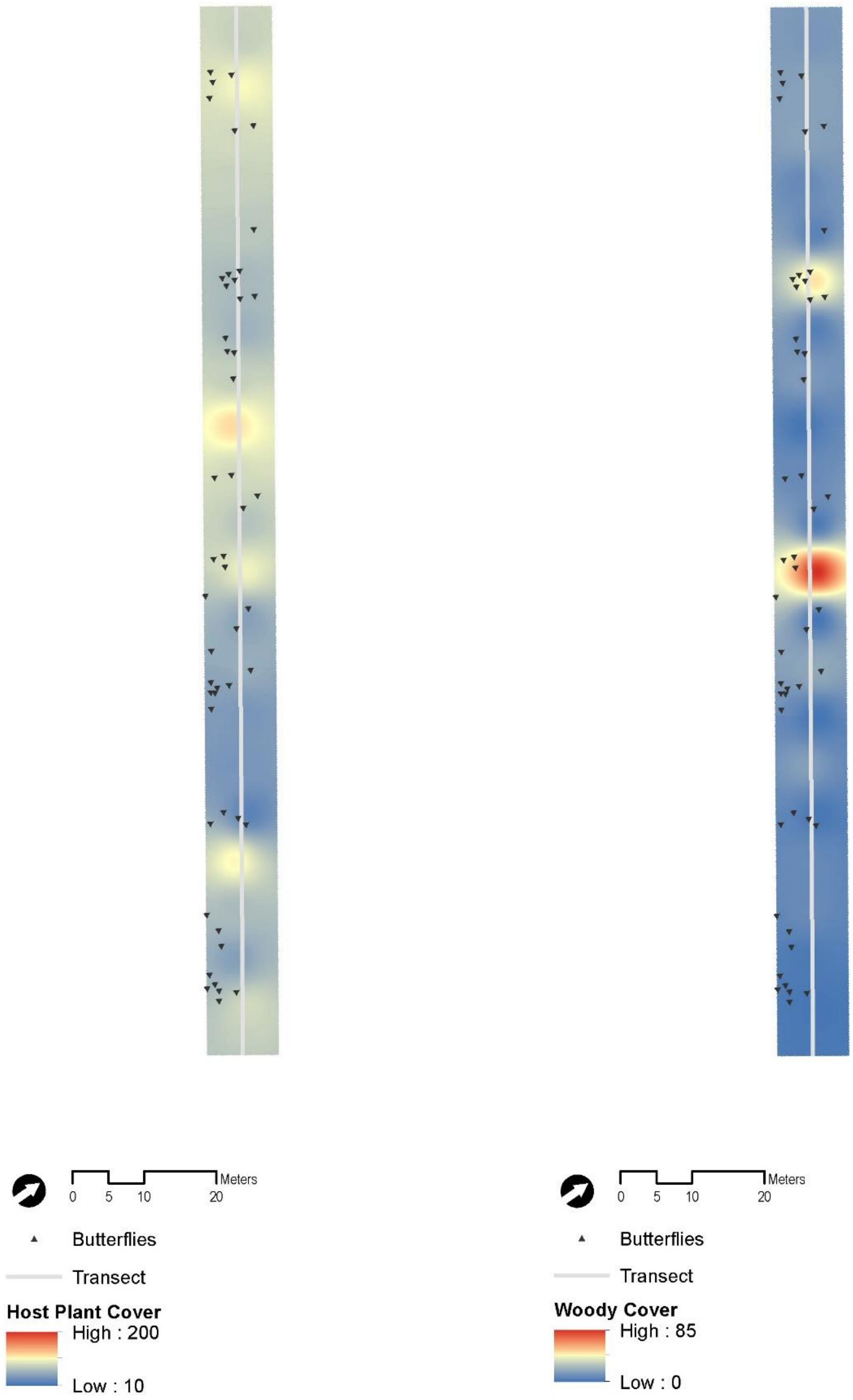

Figure 6.40. Warner east host plant cover and woody cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

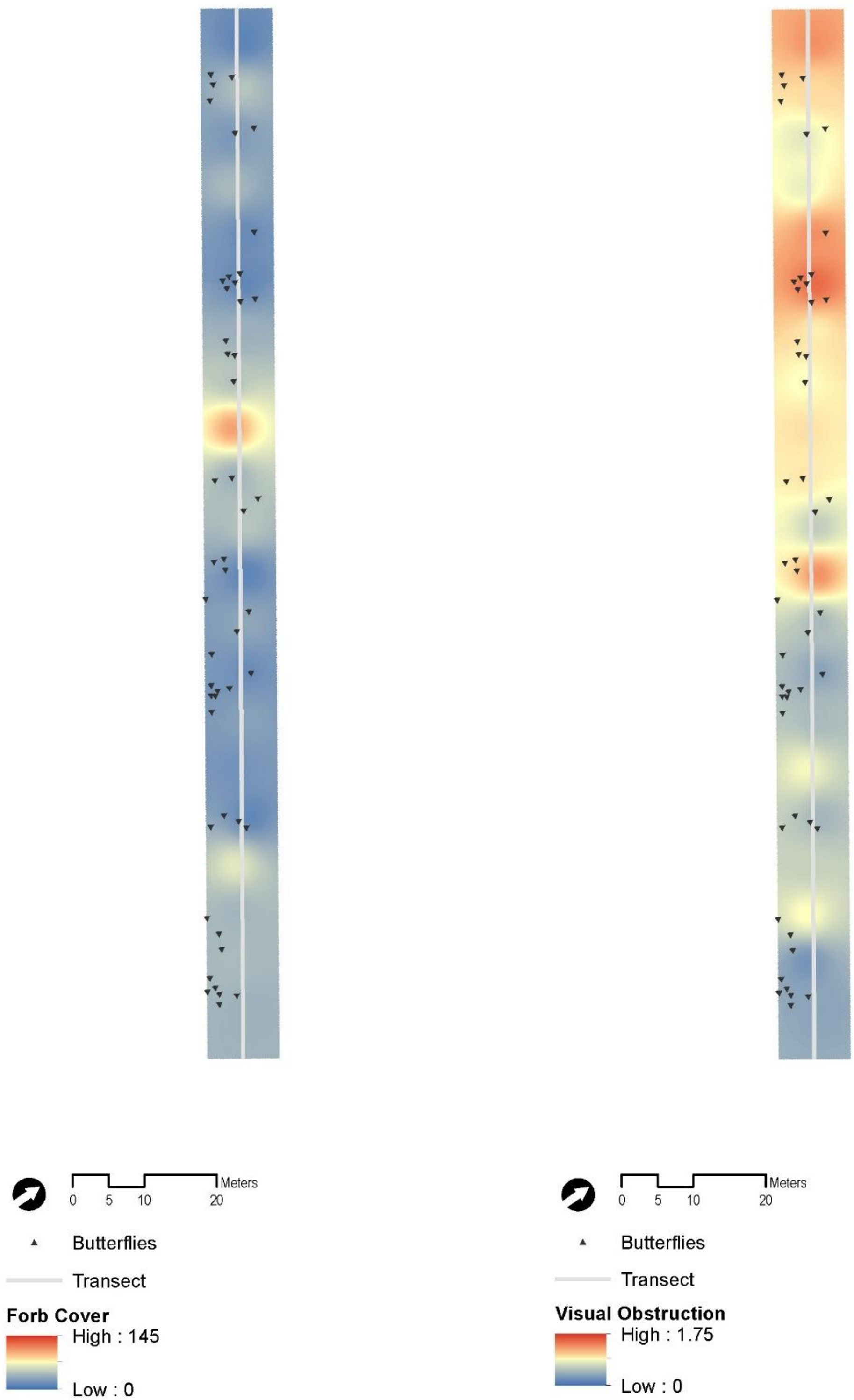

Figure 6.41. Warner east forb cover and visual obstruction inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

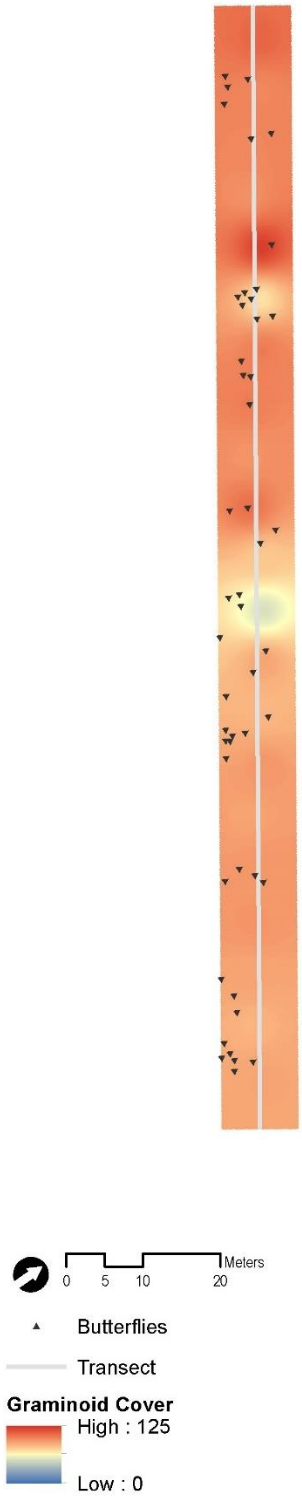

Figure 6.42. Warner east graminoid cover inverse distance weighted interpolation with butterfly interaction locations from data collected in 2017 and 2018

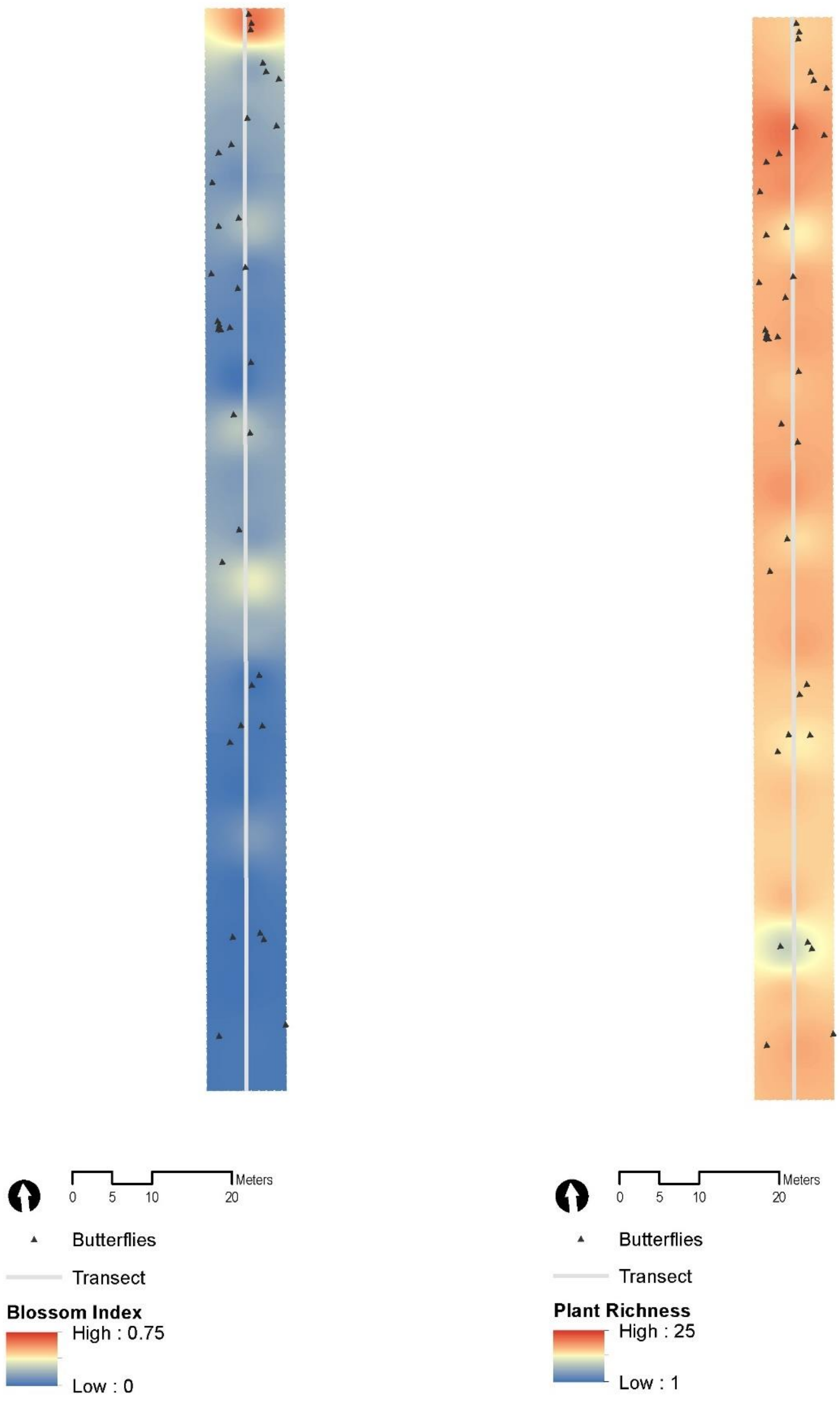

Figure 6.43. Warner west blossom index and plant richness inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

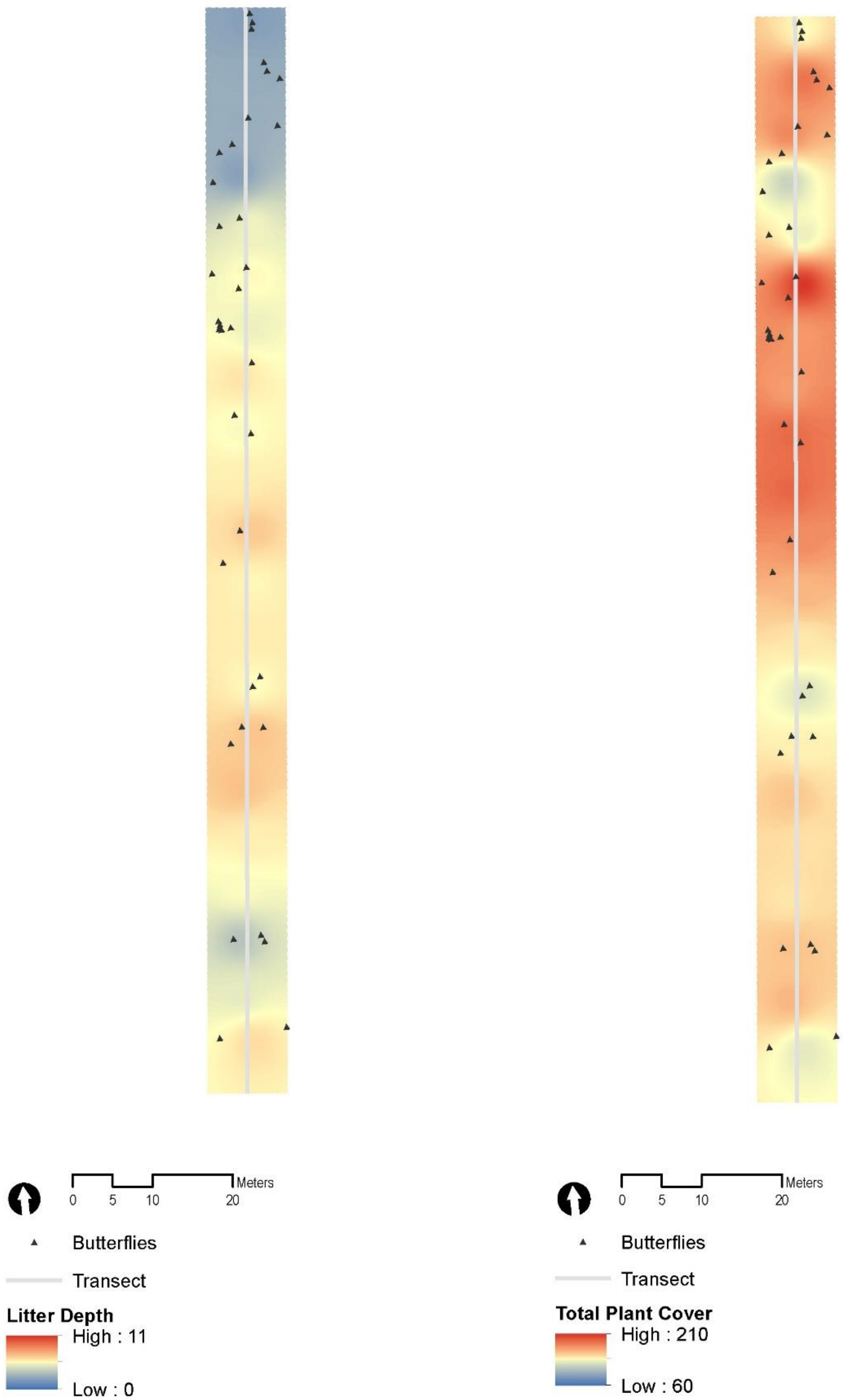

Figure 6.44. Warner west litter depth and total plant cover inverse distance weighted interpolations with butterfly interaction locations

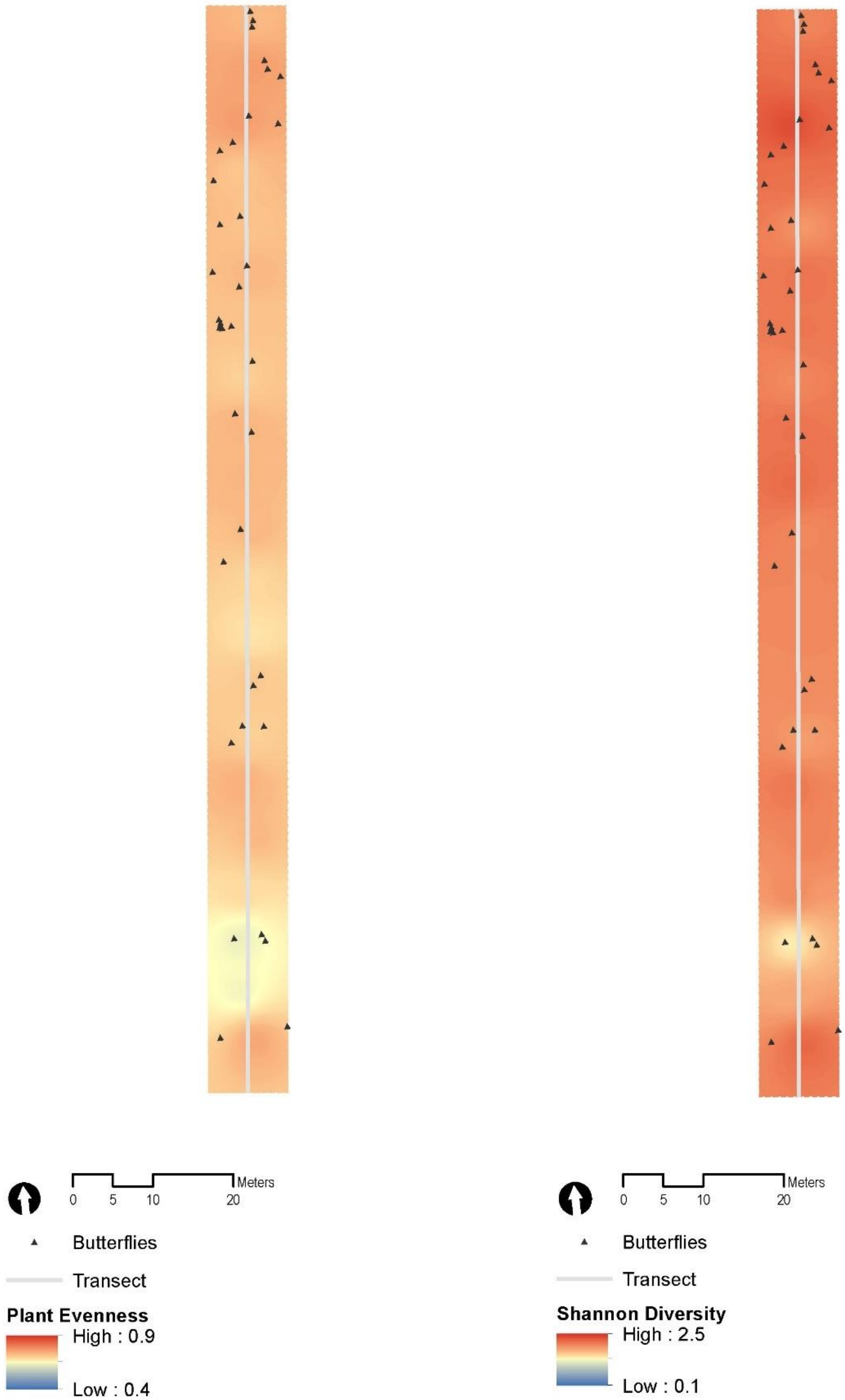

Figure 6.45. Warner west plant evenness and shannon diversity inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

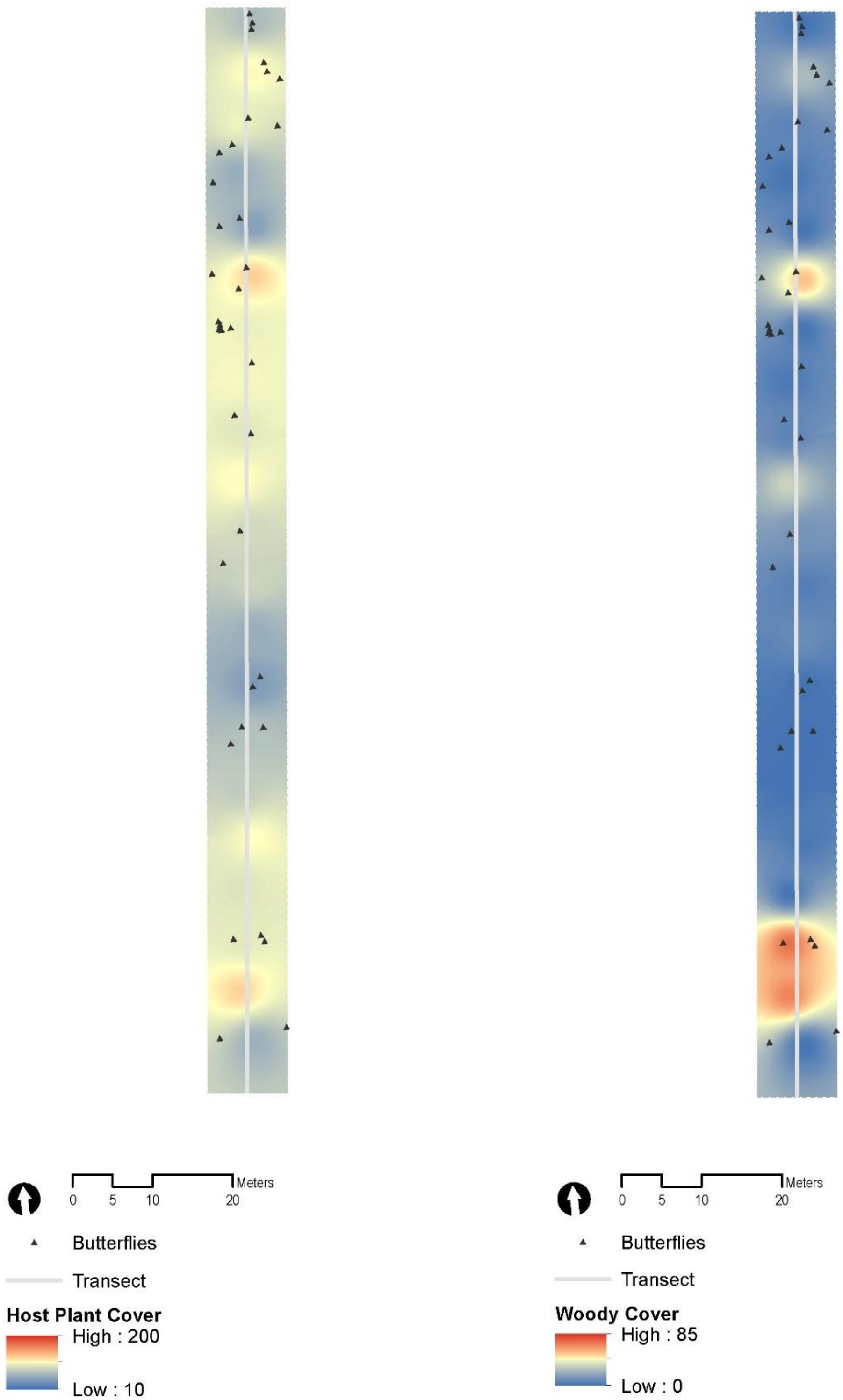

Figure 6.46. Warner west host plant cover and woody cover inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

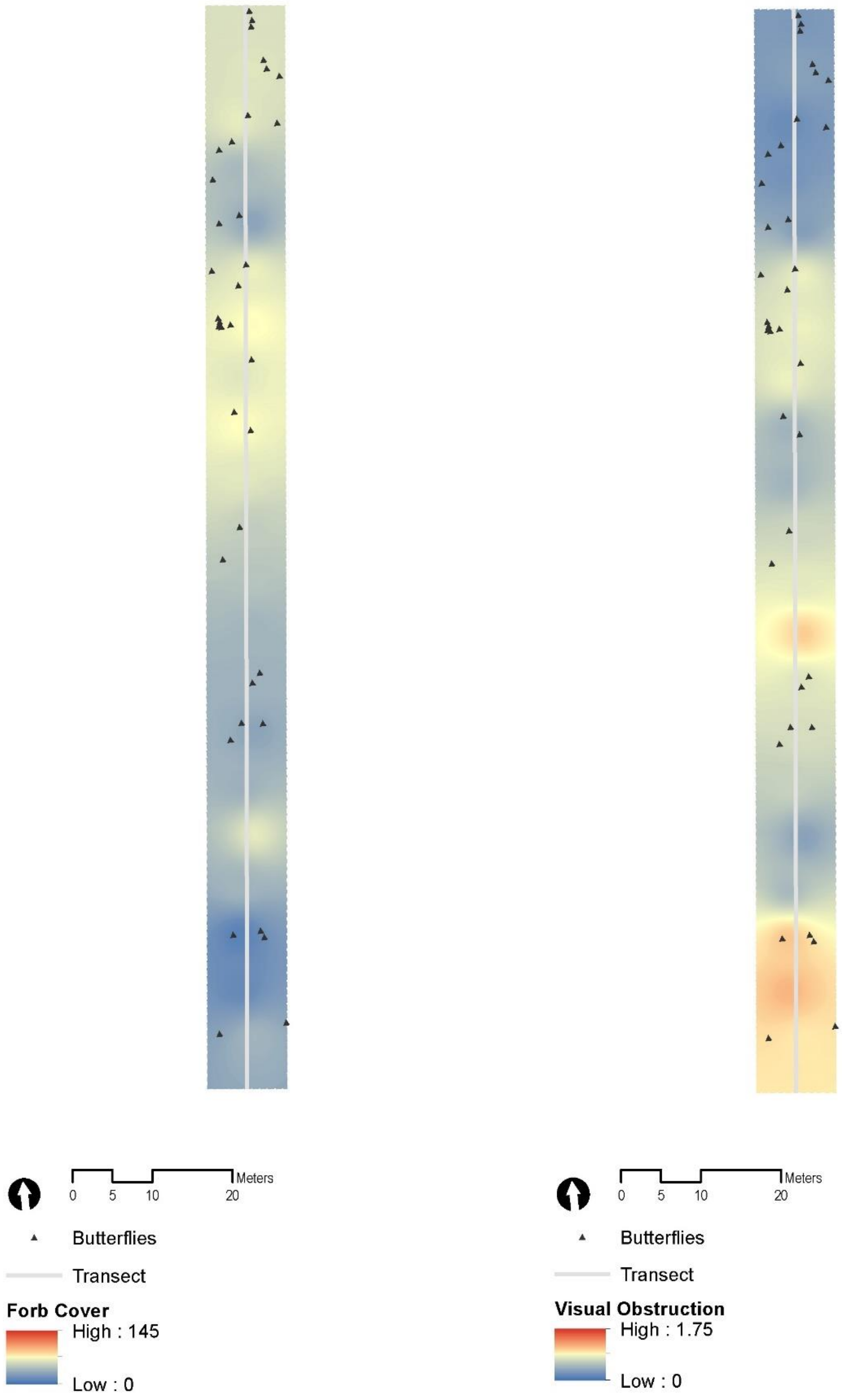

Figure 6.47. Warner west forb cover and visual obstruction inverse distance weighted interpolations with butterfly interaction locations from data collected in 2017 and 2018

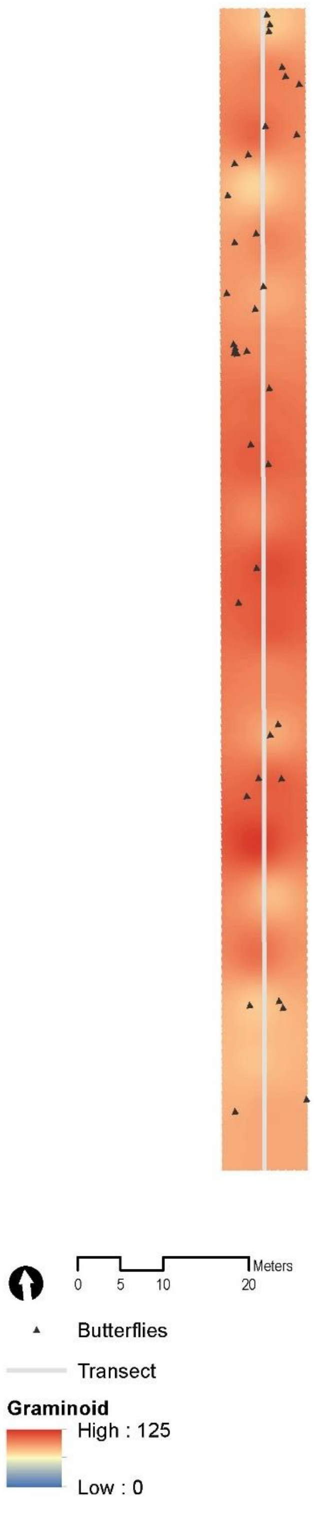

Figure 6.48. Warner west graminoid cover inverse distance weighted interpolation with butterfly interaction location from data collected in 2017 and 2018