EVALUATING THE CONTEXT DEPENDENCIES OF FLORAL PROVISIONING FOR BENEFICIAL ARTHROPODS

by

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(Under the Direction of Jason M. Schmidt)

ABSTRACT

Beneficial arthropods provide essential services to agricultural crops, however their population has come under threat globally because of intensive agricultural practices and habitat reduction. Designing diverse agricultural landscapes has the potential to improve crop pollination and pest regulation. In our study, we assessed the effects of three commercial wildflower mixes, landscape context and irrigation on beneficial arthropod populations and flower production over two growing seasons, 2016 and 2017. Flower mixes were sown in 19 plots in Tifton, Georgia, in four landscape treatments: irrigated vs. non-irrigated, combined with adjacent to agricultural fields vs. woodland. The arthropod communities were sampled visually and with a suction sampler. Floral resources were quantified manually and also from aerial images of the flower plots captured with an Unmanned Aerial Vehicle (UAV). A positive relationship between the density of floral resources and pollinator visits was observed during both years. Our results indicate that incorporating native floral resources would highly benefit the pollinator communities in the agricultural ecosystems.

INDEX WORDS: Beneficial arthropods, native wildflower plantings, ecosystem services, habitat management, ecological intensification.

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DEDICATION

I would like to dedicate this work to my dearest family and friends, whose support and motivation have helped me to pursue my passion.

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INTRODUCTION AND LITERATURE REVIEW

Current land use patterns driven by intensive agriculture supporting high-yielding crop varieties combined with increased chemical and mechanical inputs, has led to negative environmental impacts (Firbank et al., 2008). The intensive exploitation of productive land and natural resources for high yields has raised concerns over the sustainability of these practices to meet future human needs (Robertson, 2015; Steffen et al., 2015). Numerous studies have documented the loss of biodiversity (José-María et al., 2011; Kleijn et al., 2009) including arthropods (Hendrickx et al., 2007) in agricultural landscapes. In addition to species richness, trait and functional diversity is also declining (Gagic et al., 2015; Gámez-Virués et al., 2015) and can result in a loss of ecosystem services. Ecosystem services in agricultural landscapes, which include pollination, gene diversity among crops, pest control, habitat for natural predators, beneficial microbes, nutrient cycling, soil fertility and watershed control, have deteriorated in several regions of the world. Applied agro-ecological research has started to recognize several approaches and initiatives to revive the ecosystem functions in agricultural landscapes.

Present agricultural landscapes by design have reduced vegetative diversity over vast areas resulting in simplified crop landscape across different spatial scales (Benton et al., 2003). The implications of such cropping systems and landscape intensification on beneficial insects are now well-known. For instance, homogeneous crop landscapes tend to have fewer arthropods than more complex landscapes containing mixtures of cropland, forests and grasslands (Tscharntke et al., 2008). As the amount of non-crop habitat contributing to landscape complexity increases, the abundance and diversity of beneficial arthropods increases (Blaauw & Isaacs, 2014).

Furthermore, populations of pollinators and natural enemies that move into cropland rises with the proximity to complex habitats near the agricultural fields (Shackelford et al., 2013).

The global population is estimated to increase by 50% by the year 2050 thereby doubling the demand for food supply (Tilman et al., 2002). Apart from food production, the demand for crops utilized as industrial raw materials is also predicted to increase (Norris, 2008). Current remnant habitat fragments in agricultural landscapes are not likely to provide sufficient resources for beneficial communities, which in turn may lead towards loss in naturally provided ecosystem services (Kruess & Tscharntke, 1994). The detrimental effects on fragile ecosystems and biodiversity are, thus, set to increase in the future years. This brings about the need for sustainable agriculture and addressing the role of agroecosystems in biodiversity conservation.

Arthropod mediated ecosystem services

Ecosystem services can be any of the natural processes which are controlled by ecosystems to sustain human life (Daily, 1997; Fiedler et al., 2008) including provisioning of clean air and water, regulation of climate (Fiedler et al., 2008), and carbon sequestration and storage (Kremen et al., 2004). According to Millennium Ecosystem Assessment (2003) arthropods are potentially involved in the four broad types of services defined as : (i) provisioning services, that correspond to material or energy outputs from the ecosystems; (ii) supporting services, that allow the maintenance of other ecosystem services; (iii) regulating services, that regulate the magnitude and directionality of ecosystem processes; and (iv) cultural services, that do not provide material benefits but have an educational, spiritual or aesthetic value. Of the multiple services they provide, regulating services such as pollination and biological control aids in the increased production of agricultural goods (Losey & Vaughan, 2006). The maintenance of natural or semi natural habitat in agricultural ecosystems tend not only maximizes these provisioning services but also serves the purpose of providing supporting services such as conserving the biodiversity of native flora and arthropods (Noriega et al., 2017).

Among pollinators, bees are essential for pollinating the majority of crops all over the globe (Kremen et al., 2002). Both managed and wild bee pollinator populations affect the pollination services in a landscape (Potts et al., 2010), which are valued to be around $180 billion annually (Gallai et al., 2009). Current estimates indicate that bees pollinate about 77% of the agricultural crops worldwide (Delaplane et al., 2000; Klein et al., 2007). A widely used and mass produced bee is the European honey bee, *Apis mellifera* (Garibaldi et al., 2013; Potts et al., 2010; Winfree et al., 2007). European honey bees have been introduced in most agricultural areas by growers as they are easy to manage, but this species has been facing a number of challenges which include loss of floral resources and an increased threat from pathogens and pesticides (Goulson et al., 2008; Neumann & Carreck, 2010). In the United States alone there has been a decline of 58% in the population of honeybees (Winfree et al., 2009), as a result there has been increased concern about the vulnerability of agricultural pollination systems. The importance of wild bees for crop pollination has generally been overlooked but bees can participate in increased pollination in cropland if the crops are located near natural habitat (Klein et al., 2012; Winfree et al., 2007). At least 20 % of pollination services in the US is estimated to be from wild pollinators (Koh et al., 2016). With the risks associated with relying on one bee species for pollination globally, research on promoting species rich wild-bee communities and other pollinating insets is needed to secure this important ecosystem service over space and time (Nelson et al., 2009; Rader et al., 2016; Winfree & Kremen, 2009). Aside from agricultural crops, around 80% of wild plant species are dependent on insect pollination; thereby, the decline of European honey bee as well as native wild bee species likely has negative effects on wild plant populations (Potts et al., 2010).

Constanza et al. (1997) valued the biological control provided by insect natural enemies in agricultural ecosystems to be nearly $400 billion, annually. Agricultural systems can sustain a diverse group of predators and parasitoids (Rand et al., 2006), but both the lack of habitat and intensive use of pesticide make agricultural areas resource poor for natural enemies (Geiger et al., 2010). The abundance and diversity of natural enemies are generally greater in more complex agricultural landscapes with natural or semi-natural habitat (Gurr et al., 2017) than in simple homogenized landscapes (Bianchi et al., 2006; Chaplin-Kramer et al., 2011). A majority of the generalist predators are known to extensively utilize non crop habitat in search of alternative prey (Symondson, 2002). Hence, scarcity of viable alternative habitats can cause the reduction of pest control services and increase the likelihood of surges in pest populations (Chaplin-Kramer et al., 2011).

Habitat management to enhance insect mediated ecosystem services

Habitat management is a practice that involves the manipulation or restoration of land resources to conserve wildlife to mitigate the effects of habitat loss. It has been used for decades as a successful tool in different ecosystems for wildlife conservation. In agriculture, habitat management was introduced with the aim of overcoming the dilution of ecosystem services (Landis et al., 2000). Habitat management in agriculture has been extensively shown to enhance various ecosystem services such as nutrient management, water holding capacity, weed control, disease control, carbon sequestration, pest control and pollination (Kremen & Miles, 2012; Landis et al., 2000). Habitat management promotes biodiversity in agricultural landscapes at different spatial scales through practices located within field, across the whole farm and at the landscape level. At the local scale or within crop scale habitat management can be implemented by having genetic diversity within crop or varietal diversity within a single crop. For example, through composting and manuring, soils harbor diverse microbial and invertebrate communities which in turn promote nutrient cycling (Mäder et al., 2002; Reganold et al., 2010). At the landscape scale, habitat management can include multiple intercropped species or integration of non-crop plantings or semi-natural communities of plants, around field perimeters and across multiple fields. By enhancing floral diversity on farms through insectary strips, hedgerows, or retention of semi-natural areas, farmers may enhance or attract natural enemies and wild pollinators to their crops and thereby increase pest control or reduce the need for honey bee rentals for crop pollination (Kremen & Miles, 2012; Letourneau et al., 2011; Morandin & Winston, 2005).

Habitat management practices that incorporate species richness and landscape-scale diversification (Geiger et al., 2010), may contribute to development of beneficial arthropod communities with the potential to provide more effective services (Crowder et al., 2010; Letourneau & Bothwell, 2008). Analysis across multiple crop types strongly show that wild pollinator communities decrease significantly in abundance and richness in agricultural landscapes with extreme habitat loss or increased distance to natural habitat (Garibaldi et al., 2011; Ricketts et al., 2008; Winfree et al., 2009). Managed honey bees have also suffered in recent years from various diseases, pesticides, and other environmental stresses, and are in decline in many countries around the globe (Neumann & Carreck, 2010); therefore the contributions of wild pollinators to crop pollination (comprised of many other bee species as well as other insects) have taken on new significance (Eilers et al., 2011; Klein et al., 2007; Potts et al., 2010). For crops, pollination service delivery depends largely on flower visitor density and typically on particular locally abundant pollinator species, which are demographically the least vulnerable to habitat loss or degradation (Garibaldi et al., 2016; Kleijn et al., 2015; Winfree et al., 2015).

Farm management practices significantly affect the availability and quality of foraging and nesting resources for pollinators (Requier et al., 2015). The effects of sustainable farming practices and other agri-environment schemes have been generally positive on pollinator populations (Batáry et al., 2015; Scheper et al., 2013). For instance, a 60 % increase in pollinator richness and 130 % increase in abundance has been attributed to the enhancement of the diversity and abundance of floral resources in organic wheat fields that provide nectar and pollen for pollinator species across three widely separated regions of Germany (Holzschuh et al., 2007; Holzschuh et al., 2008). Shackelford et al. (2013) found that pollinators consistently benefit from natural habitats at both local and landscape levels. Increased landscape heterogeneity, within as little as 250 m of managed agricultural lands has been found to strongly buffer against negative effects of intensive management practices (Perović et al., 2018). Hence landscape heterogeneity and farming practices can positively influence pollinator popultions (Andersson et al., 2013). Several studies have substantiated that as complexity increases in the landscape structure, the abundance and diversity of natural enemy population increases. (Bianchi et al., 2006; Chaplin-Kramer et al., 2011; Letourneau et al., 2011; Rusch et al., 2016; Shackelford et al., 2013; Veres et al., 2013). Letourneau et al. (2011) carried out a meta-analysis in a local spatial context perspective and found a significant increase in abundance of natural enemies, herbivore mortality and reduction in crop damage on farms with species-rich vegetation over those on farms with species-poor vegetation. The quality and quantity of non-crop vegetation near crop fields can significantly increase natural enemies and crop pest control (Gardiner et al., 2009). At the landscape scale, Geiger et al. (2010), found that pest control in multiple fields across nine regions of Europe was positively correlated with the percentage of the surrounding landscape using agri-environment management practices.

Floral resources selection

Conservation of beneficial arthropods and maintenance of ecosystem functioning in agricultural landscapes requires understanding and incorporating land use designs and management practices which provide the necessary ecological requisites of organisms (Landis et al., 2000). Given the need for more improved sustainability of agriculture, current agricultural landscapes will likely need to be redesigned to support biodiversity and ecosystem services. One of the prescribed strategies is to reintegrate natural or semi- natural floral habitat into agricultural landscapes or within agricultural fields as strips of flowering non crop habitat (Haaland et al., 2011).The addition of floral plantings has the ability to increase wild pollinator population across agricultural landscapes (Jönsson et al., 2015; Williams et al., 2015) and could increase pollination of high-value pollinator-dependent crops (Blaauw & Isaacs, 2014).

Ideally, floral resources should be established in such a way that they cater to both pollinators and natural enemies. A diverse array of floral resources can provide these species access to food, shelter, resting sites, alternate hosts and overwintering habitats, all of which increases their ability to provide pollination and pest control services (Kremen & Miles, 2012; Landis et al., 2000). It is also essential to evaluate floral species for their ability to provide needed resources to arthropods with different life histories (Fiedler et al., 2008). One method is to select floral mixes containing diverse floral traits such that they provide species with different abilities, dietary requirements and preferences access to the nectar. Flower mixes should also provide continuous bloom throughout the growing season, and include both perennials and annuals that may support greater pollinator species richness (Scheper et al., 2015; Williams et al., 2015). In addition to flower morphology for accessibility of floral resources, nectar-sugar concentration and nectar-amino acid concentration, flower reflectance and flower height/area are also of importance to pollinators/arthropods. (Fornoff et al., 2017). Also, an important goal of habitat management for pest control is that floral traits are more attractive to beneficial arthropods than to pests (Araj et al., 2006).

While both native and exotic species can be utilized, plants that are native to a particular region generally possess floral traits that are more suited to native groups of invertebrates, thereby playing an important role in maintaining multiple functional groups of insects (Gill et al., 2016). There is some evidence that native floral resources conserve insect biodiversity more so than do exotic floral resources (Salisbury et al., 2015). Apart from supporting beneficial arthropods, native floral resources can also support higher native herbivore populations which are an important component of food webs (Wilson, 1987).

Monitoring wildflowers on marginal lands

Remote sensing application for detecting many ecosystem structures and changes in vegetation has extensively relied on satellite imagery. However, the cost for real-time, high-resolution images and the frequency of data collection could affect the quality of the results produced (Horton et al., 2017). But, the rapid development of low-cost unmanned air vehicles (UAVs) and light-weight imaging sensors in the past few years has resulted in a significant interest in their use for remote sensing applications in several fields including vegetation mapping (Anderson & Gaston, 2013; Cruzan et al., 2016; Zhang & Kovacs, 2012). Small UAVs provide many benefits over conventional remote sensing methods as they require minimal infrastructure and relatively low operational costs. Furthermore, UAVs allow for collection of data in ultra-high spatial resolution and this near real-time image acquisition (Hardin & Hardin, 2010; Lelong et al., 2008; Rango et al., 2009) indicates that these platforms are ideal tools for mapping and monitoring. UAVs are becoming an important tool for developing sustainable agriculture methods (Walter et al., 2017). UAVs have been successfully employed to detect and monitor pest infestations (Lehmann et al., 2015; Näsi et al., 2015), analyze structure of vegetation (Cunliffe et al., 2016), monitor several agricultural crops (Calvario et al., 2017; Fang et al., 2016; Severtson et al., 2016), and monitor distribution of insecticides. In addition, UAVs appear to be useful for monitoring flowering invasive species (Müllerová et al., 2017) and trees (Horton et al., 2017). Michez et al., 2016 successfully detected and classified flowers of *Heracleum mantegazzianum* with high accuracy and Carl et al., 2017 analyzed *Robinia pseudoacacia L.* flowers to predict nectar and honey production and also honey bee populations within the plantation.

In this study, I quantified the effect of added floral strips on beneficial arthropod populations and developed a model to predict beneficial arthropod populations with the assistance of UAVs.

Research Objectives

(1) Quantify the effects of floral strip position (adjacent to woodland or agriculture) and irrigation (irrigated or no irrigated) on flower production and flower visits of arthropod pollinators on commercially available native floral mixes

(2) Demonstrate the use of a small-unmanned aerial vehicle (UAV) for monitoring of floral vegetation in agricultural landscapes

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CHAPTER 2

EVALUATING THE EFFICACY OF SOUTH EAST NATIVE WILDFLOWER MIXES IN AUGUMENTING BENEFICIAL ARTHROPODS.

[1]

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Abstract

Marginal agricultural land provides opportunities to diversify landscapes by producing biomass for biofuel, and through floral provisioning that enhances arthropod-mediated ecosystem service delivery. We examined the effects of local spatial context (adjacent to woodland or agriculture) and irrigation (irrigation or no irrigation) on wildflower bloom and visitation by arthropods in a wildflower habitat buffer design. Nineteen habitat buffer plots were established containing three commercial wildflower mix subplots, and a control subplot containing spontaneous weeds. Arthropods and flowers were visually observed in quadrats throughout the season. Regardless of the type of mix or the landscape context, counts of inflorescences were similar in all the treatments. We found irrespective of buffer location or irrigation, pollinators were observed more frequently early in the season and on experimental plots with wildflowers than on weeds in the control plots. Natural enemies showed a tendency for being more common on plots adjacent to a wooded border, and were also more commonly observed early in the season. Herbivore visits were infrequent and not significantly influenced by experimental treatments.

Keywords: agroecosystem design; conservation; floral provisioning; functional groups; habitat management; natural enemies; landscape restoration; sustainable intensification

Introduction

Numerous studies have shown that in intensely managed, simplistic agricultural landscapes the diversity of multiple biotic species has declined which can result in a loss of the ecosystem services they provide (Landis, 2017). In recent decades, considerable research has focused on mitigating these negative impacts, primarily via management of habitats to promote biodiversity and enhance services at the local scale. As local and landscape factors interact, Landis (2017) proposes that the loss of ecosystem services due to landscape simplification can only be addressed by a concerted effort to fundamentally redesign agricultural landscapes.

Marginal lands provide an opportunity for the provisioning of biodiversity and crop protection. In this context, marginal lands are areas where cultivation is possible and may have once occurred, but where conservation benefits strongly favor removal of these lands from active crop production (e.g., reviewed by Coffin et al., 2016). Over 300,000 hectares of marginal land characterized by cropland-forest edges near riparian buffers and potential grassed waterways within agricultural landscapes have been identified in the coastal plain of Georgia (Coffin et al., 2016).

Habitat management through the addition of native flowering plants to cropping systems has gained momentum among growers in the past few years to increase ecosystem service delivery. For example, maintaining flowering plants both within fields and along their edges successfully enhances two important arthropod-mediated regulating services in agroecosystems: biological control of annual crop pests by natural enemies (Blaauw & Isaacs, 2012; Lu et al., 2014; Tscharntke et al., 2008; Tschumi et al., 2016; Tschumi et al., 2015; Walton & Isaacs, 2011). Such regulating services increase crop yield, with an added benefit of reducing the need for costly and environmentally risky pesticide application. It is well known that natural enemies and pollinators require food resources such as pollen and nectar for enhancement of longevity, and fecundity (Lu et al., 2014). Therefore, continuous availability of floral resources in an agricultural landscape has the potential to promote healthy beneficial arthropod populations, thereby increasing their ability to deliver effective biological control and pollination services to annual crops (Garibaldi et al., 2014).

Habitat management success is context dependent, where local and landscape factors influence the benefits of additional habitat to a cropping system (Tscharntke et al., 2008; Werling et al., 2014). Two local factors to be considered in habitat management are irrigation and soil nutrients. Another contributing local factor is the type of habitat adjacent to crop fields (e.g., woodland or agriculture). Ingrao et al. (2017) found natural enemy abundance and pest control were higher within woodland habitat and adjacent crop field edges compared to within crop field interiors. Therefore, our study focuses on the response of arthropods and wildflowers to woodland or agriculture location context and irrigation in early establishment of buffer habitat. Our objectives were to (1) quantify flower visits of arthropod natural enemies, pollinators and herbivores on three native floral mixes in buffers plots on marginal land, (2) test buffer location (adjacent to woodland or agriculture) and irrigation effects (irrigation or no irrigation) on wildflower counts and counts of arthropods on flowers.

Materials and methods

Study sites

Nineteen conservation buffer sites were selected on marginal land across University of Georgia experimental farms (Tifton, GA, USA, Tift County; Figure 2.1A). Buffer plots were assigned to a 2 × 2 design of local spatial context and irrigation. For local spatial context, ten plots were located adjacent to woodland (“T”) and nine in open areas between 1 and 30 m from agricultural fields (“A”). Half of these plots received irrigation or no irrigation. Irrigation treatments were irrigated (“I”) weekly beginning 05 April 2016 and ending 18 August 2016 at a moisture level of 2 cm based on a rain gauge. The other half of the plots received no additional irrigation (“N”). In late winter, plots were sprayed with Roundup® (Monsanto, Melbourne, Australia) at 4.68 L/ha for weed suppression. A week later, a deep till rig (35.5 cm depth) was used to prepare the soil. A field cultivator was used to remove further weeds and smooth the soil for planting.

Each experimental buffer plot was 34 m × 10 m (340 m2), separated by distances of at least 150 m. Plots contained a 2 m × 30 m (60 m2) strip of Napier grass separated by a 2 m vegetation free alley on all sides (Figure 2.1B,C). Eight subplots, with final dimensions of 1.75 m × 2.6 m (~4.55 m2), were randomly assigned a wildflower treatment (Figure 1C). The area between wildflower subplots was sprayed with Roundup® at 4.68 L/ha, and maintained free of vegetation.

The eight wildflower subplot planting treatments included three subplots, each with a unique flowering species; one subplot with a combination of the three species; three subplots with distinct commercial mixes; and one subplot containing spontaneous weed growth as the control. The wildflower subplots containing seeds of *Monarda fistulosa* and *Monarda citriodora* (Lamiaeae), and a combination of the two had poor germination/establishment so only data from the three commercial mixes and the control subplots were analyzed. The commercial seed mixes were specific to the southeastern USA (Southeast wildflower Seed Mix): Eden Brothers® (Arden, NC, USA), High Country Gardens® and American Meadows®, (Shelburne, VT, USA). The different wildflower mixtures are hereafter referred to as control (C), floral mix 1 (M1), floral mix 2 (M2) and floral mix 3 (M3), respectively. Following manufacturer instructions, the wildflower seeds (22.67 g) were mixed with 5 parts sand and sown in the plots by hand broadcasting on 7 December 2015.

Arthropod and vegetation sampling

Vegetation and arthropod sampling was carried out simultaneously on the same day. Sampling was carried out on six dates from June to August of 2016. For vegetation sampling we counted the inflorescences of each species of wildflower occurring within a random area of 0.25 m2 (a pvc quadrat) in each of the subplot which had the floral mixtures. We decided on the minimal area for the quadrat by testing quadrats of various dimensions within each of the mixes. A quadrat of dimensions 0.5*0.5m accommodated the maximum number of flowering species within the quadrat. The arthropod counts also were carried out within the same quadrat area as the count of inflorescences. Each subplot was observed visually for three functional groups of arthropods, i.e., pollinators, natural enemies and herbivores for 3 minutes. All bees and syrphid flies visiting the flowers were grouped as pollinators, both spiders and insect predators (Reduviidae, Geocoridae, Carabidae, Coccinellidae, Dermaptera and Hymenopteran parasitoid wasps) were grouped together as natural enemies. Most of the Hemiptera (other than the known predatory taxa like Geocoridae, Reduviidae) and all orthopterans were counted as herbivores.

Statistical analysis

Linear Mixed-Effects Models (LMMs) were fit to the response variables using lmer within the statistical software R (Bates et al., 2015; Team R. C, 2016). Response variables, pollinator counts, natural enemy counts, and herbivore counts were natural log transformed to improve model fit. The random effects formula was specified to account for repeated measures of plots by nesting sampling sites within sampling date. For assessing wildflower counts, a generalized linear mixed model GLMM with distribution (i.e. family) set as Poisson fit best using glmer (removed pattern in plots of residuals). Fixed effect predictor variables were specified as the experimental design: local scale context treatment (i.e. buffer adjacent to agriculture or woodland), and irrigation treatment (irrigated or non-irrigated), wildflower treatment (control, M1, M2, M3), sampling date and interactions between wildflower and local scale context treatments and interactions between flowers and irrigation treatments. Total seasonal production of flowers (total number of flowers in the entire plot) were analyzed in relation to soil covariates and location by irrigation treatment design. Correlations between each of the soil covariates were assessed and variables with strong correlations were removed to eliminate multicollinearity. To standardize covariates, each was natural log transformed. In a second step, we fit a linear model containing the covariates (LBC, pH, K, Mg, Mn, and P), location treatment (agriculture or wooded margin) and irrigation treatment (irrigated or dryland), and ranked the inclusion of different combinations of covariates, treatments, and interactions using step AIC (with forward and backward selection). The best fitting model was reported, and adjusted multiple comparisons for significant main effects were evaluated using“lsmeans” with the Tukey method.

Results

Wildflowers

Overall, 4,151 wildflowers were counted in the plots which displayed a diversity of flowers over the season (n = 456 observations; Table 1); the number of flowers observed in wildflower plots on a sample date ranged from 0 to 67. Significantly more inflorescences were observed in the commercial mixes as compared to the control treatment containing weeds independent of local spatial context or irrigation treatment (Table 2, Figure 2a). Overall, the greatest number of flowering structures occurred earlier in the season (Figure 2b). Irrespective of the commercial mix treatment, *Coreopsis tinctoria, Gaillardia pulchella* and *Rudbeckia hirta* dominated among all the floral vegetation (Table 1). *Coreopsis tinctoria* appeared to yield more inflorescences earlier in the season while *Gaillardia pulchella* and *Rudbeckia hirta* flowered throughout the sampling period

Pollinators

A total of 474 pollinators were observed over the course of the sampling period (n = 456 observations) which ranged from 0 to 13 per sample. The buffer location context and irrigation also had no effect on pollinator floral visitation (Table 2). Significantly higher numbers of pollinators were observed visiting the wildflower treatment plots than control plots independent of local context or irrigation treatments (Table 2, Figure 3a). However, there were no differences between the three wildflower mixes and pollinator floral visitation (Table 3, Figure 3a). More pollinators were observed earlier than later in the season (Table 2, Figure 3b).

Natural enemies

A total of 619 natural enemies were observed over the course of the sampling period. Natural enemy floral visitations were higher in some instances in the three floral mixtures than in the control (Table 2, Figure 4a). In particular, higher natural enemy visitation rates were observed in M3 than in M1 and M2 (Figure 4a). There were no effects of location context and irrigation on natural enemy floral visitation (Table 2), but there was a marginally significant effect of date on floral visitation (Table 4). Natural enemy observations were lower on the 1 July than the 6 June and 8 August sampling dates (Figure 4b).

Herbivores

A total of 237 herbivores were observed throughout the sampling period. There were no significant effects of buffer location context and irrigation, wildflower treatments, date and location context and irrigation interactions with flowers on herbivore floral visitation (Table 2, Figure 5a, b).

Wildflower Production and Soil Nutrients

The best fitting model for predicting wildflower production contained the predictor variables: pH, Mg, and p (F1, 13 = 6.41, p = 0.004, Adj. r2 = 0.56). Total wildflower counts were non-significantly correlated with pH, coefficient est. = −3.20 (2.21), t-value = −1.45, p = 0.1697, significantly positively correlated with Mg, coefficient est. = 5.53 (1.41), t-value = 3.91, p = 0.002, and P, coefficient est. = 4.27 (1.42), t-value = 2.99, p = 0.010.

Discussion

Wildflower mixes have been designed to provide regionally specific native flowering plants that cater to and enhance native pollinator populations. Here, we tested three seed mixes native to the south eastern United States containing similar combinations of annual and perennial species in contrasting landscape contexts. We found each performed well in establishing and providing much higher numbers of flowers than spontaneous weeds. Although landscape context did not significantly influence the number of flowers produced, soil nutrient levels were an important predictor of overall wildflower production.

The increase in flowers produced in wildflower plots corresponded directly with increases in the number of pollinators observed in plots, and provide similar enhancement to pollinator numbers independent of location to agriculture or a forested border. Conversely, natural enemies were variable in response to wildflower plots, but there was a tendency for higher numbers in plots associated with a wooded margin. Herbivorous insect numbers were slightly higher on one mix that tended to produce more flowers, and similar to other functional groups, fewer were observed later in the season. Our results suggest improving pollinator numbers is dependent upon providing more flowers over the season, but improving natural enemy populations for conservation biological control programs is not as straightforward.

The location context had no effect on pollinator, natural enemy, and herbivore attraction to flowers. This may be especially important as woodlands are prevalent features in the agricultural landscapes of the coastal plain of Georgia and minimal buffer management would be desirable. Our results are also contrary to what has been found in other studies for pollinators and natural enemies (Bates et al., 2014; Blaauw & Isaacs, 2014). However, this could be due to a lag period in responses, as maximum effects of floral provisioning on pollinators can take multiple years following establishment (e.g., (Blaauw & Isaacs, 2014; Lu et al., 2014), which may be due to changes in the arthropod community composition or plant communities during establishment. Because of this lag effect, the response of pollinators, natural enemies, and herbivores to location context will likely change over time. Additionally, as pollinator and natural enemy populations are influenced by landscape context, broader landscape ecological composition may influence overall trends in local scale responses of arthropod species, with lower group diversity found in landscapes with less heterogeneity (Garratt et al., 2017; Liere et al., 2015). Thus, information about surrounding land cover and land use would be needed to predict responses of the taxa in different landscapes.

The wildflower mixes in our study were dominated by three species in the Asteracae family: *Coreopsis tinctoria*, *Gaillardia pulchella* and *Rudbeckia hirta*. These species were attractive to bumble bees, which were entirely absent from the control plots. Plants in the Asteracae family have been shown to be highly attractive to bumblebees (Carvell et al., 2006; Torres & Galetto, 2002). *Gaillardia pulchella* and *R. hirta* bloomed through the entire season and *C. tinctoria* bloomed early in the season, suggesting that positive temporal availability of floral resources were present. Further study is needed to determine whether dominant flowering plant nectar is accessible and has suitable nutrition for pollinators and natural enemies (Perović et al., 2018). Increasing flower presence with extra floral nectaries in flower strips may be one method to improve overall accessibility to nectar resources (Tschumi et al., 2015). In addition, the non-irrigated plots adjacent to agricultural land had the lowest number of flowers likely because they were completely exposed to sunlight and received no irrigation during the season. This suggests that irrigation may be needed in these locations to maximize the abundance of floral resources.

Pollinators were more abundant early in the season (mid-June) in all three of the native wildflower commercial mixes. Several crops in the region, flower early in the season and rely on pollinators (e.g., blueberry and watermelon) or produce higher quality fruit when pollinated (e.g., cotton). The early blooming pattern of high value crops coincides with higher numbers of pollinators highlights the significance of maintaining pollinators near these crops for potential improvements in crop production. Pollinator richness and visitation rates drastically decline to less than 50% of maximum value within fields at around ~1.5 km and ~600 m respectively from natural habitats (Ricketts et al., 2008). Therefore, placement of floral resources must be carried out in such a way that spatial connectivity is taken into consideration.

Natural enemy numbers in the floral mixes tended to be more variable and not as clearly influenced by wildflower treatments as compared to pollinator numbers. However, the overall seasonal pattern for natural enemies was decreasing over the season, which was similar to the bloom period of the wildflowers. Many predators are omnivores, and along with parasitoids, have competing needs for resources such as refuges, mating sites, hosts and alternative food resources. Natural enemies may be responding to a variety of cues from these areas, whereas pollinators are likely responding more to visual and chemical cues associated with flowers. Frank et al. (2008) also found variable abundances of natural enemies over time, and showed natural enemy abundance does not always coincide with floral bloom periods. These results indicate some plant species can provide season long benefit by attracting natural enemies even if they are not blooming and emphasizes the need to understand natural enemy-plant associations that may enhance pest control (e.g., Amaral et al., 2016).

We did not detect any definitive pattern of herbivores across the location context, irrigation, and wildflower treatments, and their mean counts were low. Encouragingly, pestiferous herbivores are expected to prefer crops to wildflower habitats (McCabe et al., 2017). It may also be that natural enemies were suppressing herbivore populations in our wildflower and control plots, but this will need further study. Our visual observations likely underestimated arthropod abundance in the wildflower habitat and in particular the herbivores that were only observed on flowers. Fielder and Landis (2007) found numerous natural enemies and herbivores on native flowers by using plant suction sampling.

Over the first year of buffer establishment we saw substantial pollinator attraction to native wildflower treatments, but natural enemy and herbivore attraction to wildflowers was no different from control plots with spontaneous weeds. Wildflower establishment was high over all 19 sites. Although we concentrated our study at the local scale, future studies will examine landscape effects on arthropod community patterns. Further study is also needed to examine the effects of buffer size and configuration on arthropod responses, and to quantify natural enemy pest control of annual crops. Interestingly, we found nutrients positively influenced wildflower production, and suggests site characteristics should be assessed prior to establishment and some investment in pH and nutrient level adjustments may be needed to maximize production of flowers.

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Table 2.1. The bloom period and the total counts of inflorescences observed. The symbols indicate the presence of the respective floral species in one of the planted mixtures (M1, M2 and M3).

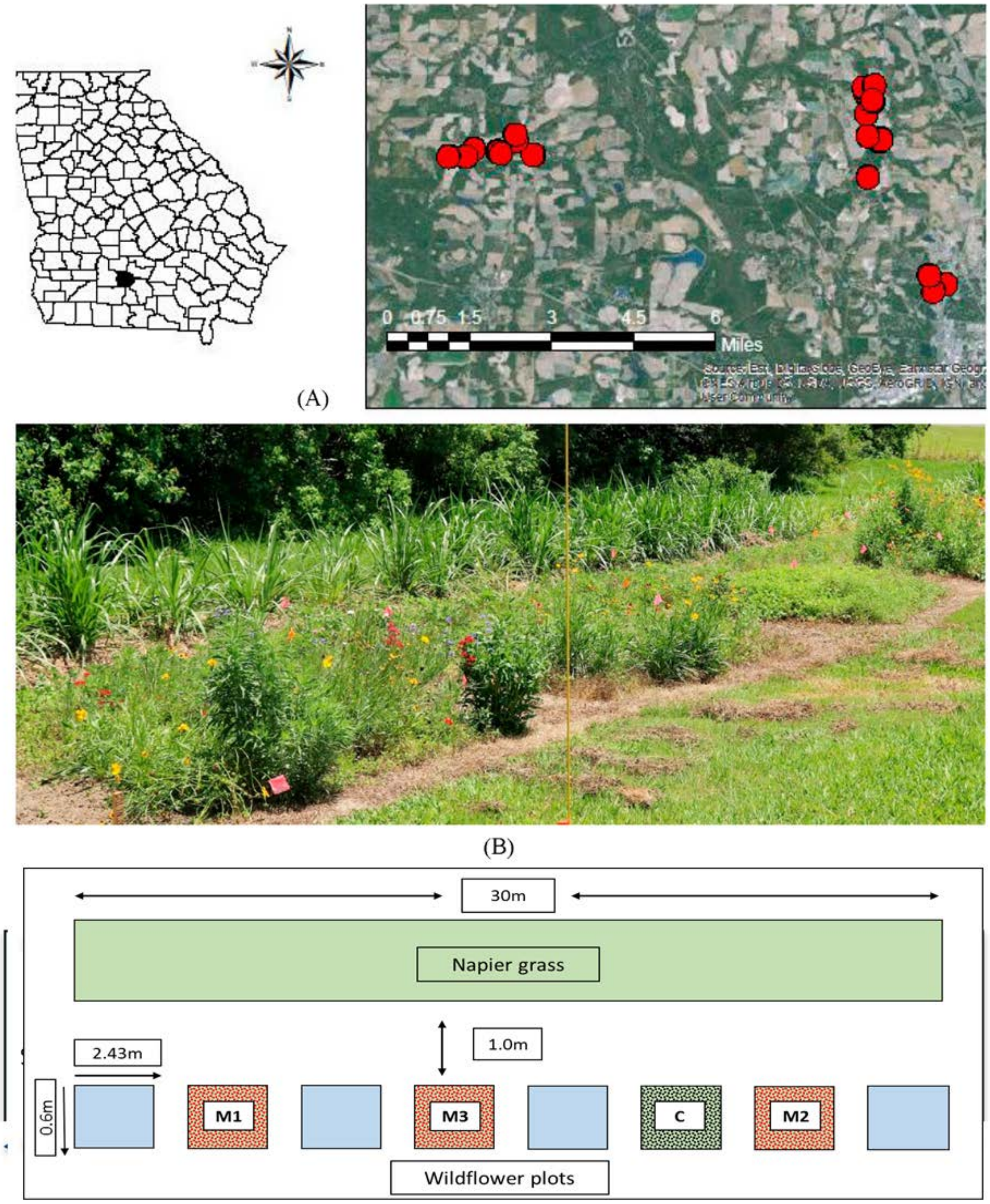
Wildflower species	**presence in wildflower mix**	**6-Jun**	**20-Jun**	**1-Jul**	**18-Jul**	**8-Aug**	**15-Aug**	Total flowers
Cynoglossum amabile	M2, M3	8	2					10
Eschscholzia californica	M1, M2, M3		3					3
Achillea millefolium	M1, M2, M3		6					6
Salvia coccinea	M1, M2, M3		4				6	10
Cosmos bipinnatus	M1, M2, M3			7				7
Echinacea purpurea	M1, M2, M3			3				3
Nemophilia maculata	M1,			2				2
Coreopsis tinctoria	M1, M2, M3	490	289	21	4			993
Phlox drummondi	M1, M2, M3	57		12				69
Rudbeckia amplexicaulis	M2, M3		29	13				42
Linum grandiflorum rubrum	M1, M2, M3		9		1	13		23
Centaurea cyanus	M1,	91	25	27	16			159
Rudbeckia gloriosa	M1, M2, M3		3	12	7	6		28
Oenothera lamarckiana	M2, M3		5	6	3	5		19
Cosmos sulphureus	M1,	8	15	21	15	2	4	101
Monarda citriodora	M1,	75	61	12	11	4		163
Coreopsis lanceolata	M1, M2, M3	63	93	19	32	12	2	221
Gaillardia pulchella	M1, M2, M3	161	177	103	405	218	325	1389
Rudbeckia hirta	M1, M2, M3	278	239	198	148	19	21	903
Total flowers		1231	960	645	642	279	394	4151

Table 2.2. Summary of results of type III tests of fixed effects from fitting GLMMs to the response variables observed in relation to local spatial context (i.e. buffer adjacent to agriculture or woodland), irrigation (irrigated or not irrigated), and flower treatments (control = no wildflowers planted, M1 M2 and M3 different commercial mixes). An interaction term is indicated for location context and irrigation with flower treatments as with “*”.

Response variables	NumDF	DenDF	F.value	Pr(>F)
Flowers				
Flower treatments	3	64	28.84	**<.0001**
Local spatial context	1	64	0.32	0.5734
Irrigation treatment	1	64	0.11	0.7470
Flower treatment*local spatial context	3	64	0.57	0.6384
Flower treatment*irrigation treatment	3	64	0.37	0.7751
Date	5	375	14.01	**<.0001**
Pollinators				
Flower treatments	3	64	6.03	**0.0011**
Local spatial context	1	64	0.11	0.7428
Irrigation treatment	1	64	0.49	0.4880
Flower treatment*local spatial context	3	64	0.20	0.8940
Flower treatment*irrigation treatment	3	64	0.30	0.8242
Date	5	375	8.85	**<.0001**
Natural enemies				
Flower treatments	3	64	3.27	**0.0268**
Local spatial context	1	64	1.31	0.2565
Irrigation treatment	1	64	0.65	0.4226
Flower treatment*local spatial context	3	64	1.74	0.1672
Flower treatment*irrigation treatment	3	64	0.37	0.7742
Date	5	375	5.30	**0.0001**
Herbivores				
Flower treatments	3	64	1.13	0.3379
Local spatial context	1	64	0.00	0.9818
Irrigation treatment	1	64	0.93	0.3362
Flower treatment*local spatial context	3	64	1.13	0.3385
Flower treatment*irrigation treatment	3	64	0.23	0.8723
Date	5	375	2.06	0.0703

Table 2.2. Mean (±1 SE) soil nutrient levels observed in plots in relation to local spatial context. Notes: adjacent to woodland (T) or agriculture (A); irrigated (I) and not irrigated (N). Lime buffer capacity (LBC) is a measure of the amount of soil acidity that must be neutralized in ppm by pure calcium carbonate to raise the pH by one unit

Local Spatial Context Treatments	**Mehlich 1 mg/kg (ppm)**							
	LBC	**pH**	**Ca**	**K**	**Mg**	**Mn**	**P**	**Zn**
AI	278 (22)	4.87 (0.09)	339 (37)	53.66 (10.23)	55.29 (6.30)	8.08 (2.19)	7.86 (1.06)	4.93 (2.05)
AN	211 (18)	4.71 (0.09)	205 (21)	34.96 (8.21)	33.08 (3.27)	4.34 (0.92)	9.42 (3.76)	1.48 (0.31)
TI	211 (33)	5.07 (0.20)	330 (61)	30.46 (8.78)	45.16 (8.98)	7.37 (2.53)	13.63 (6.22)	2.31 (0.93)
TN	271 (25)	4.74 (0.16)	487 (202)	32.93 (6.55)	38.28 (6.83)	7.61 (1.80)	90.78 (71.08)	4.97 (1.96)



(C)

Figure 2.1. Nineteen experimental wildflower plots distributed across experimental land at University of Georgia in Tift County, Georgia (**A**), photograph of experimental plot (**B**). Bottom panel (**C**) with plot design including the three wildflower mixes (red checkered boxes) and one control (green checkered box), with vegetation free alleys (2m) around all subplots (white). The blue boxes represent the flower mixes which did not establish well.

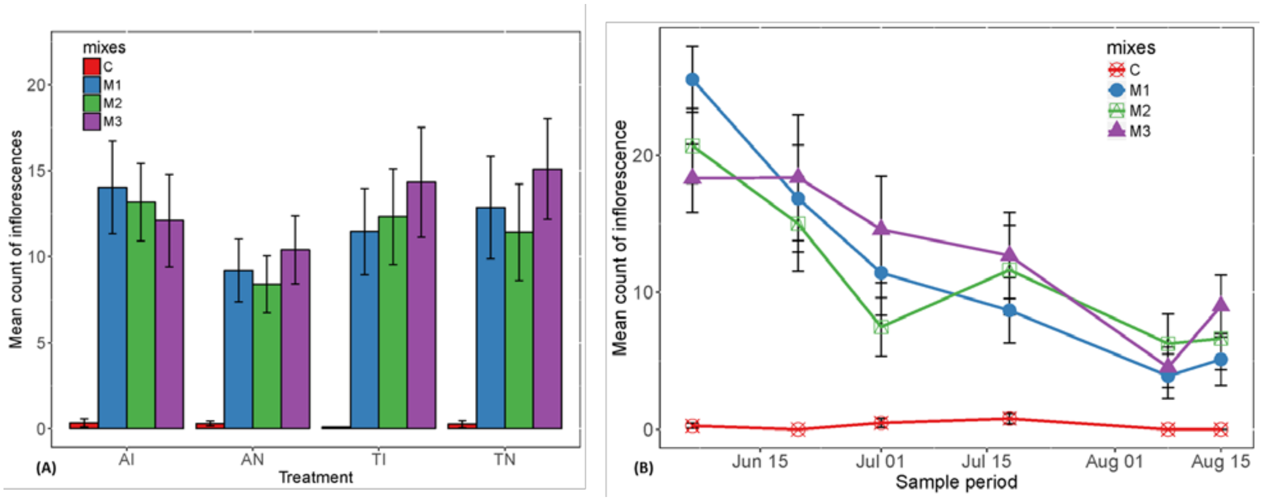


Figure 2.2. Mean (+1 SE) observations of (**A**) inflorescences among the mixes in relation to local spatial context, and (**B**) across time. Legend labels: C—control, M1—floral mix, M2—floral mix, and M3—floral mix).

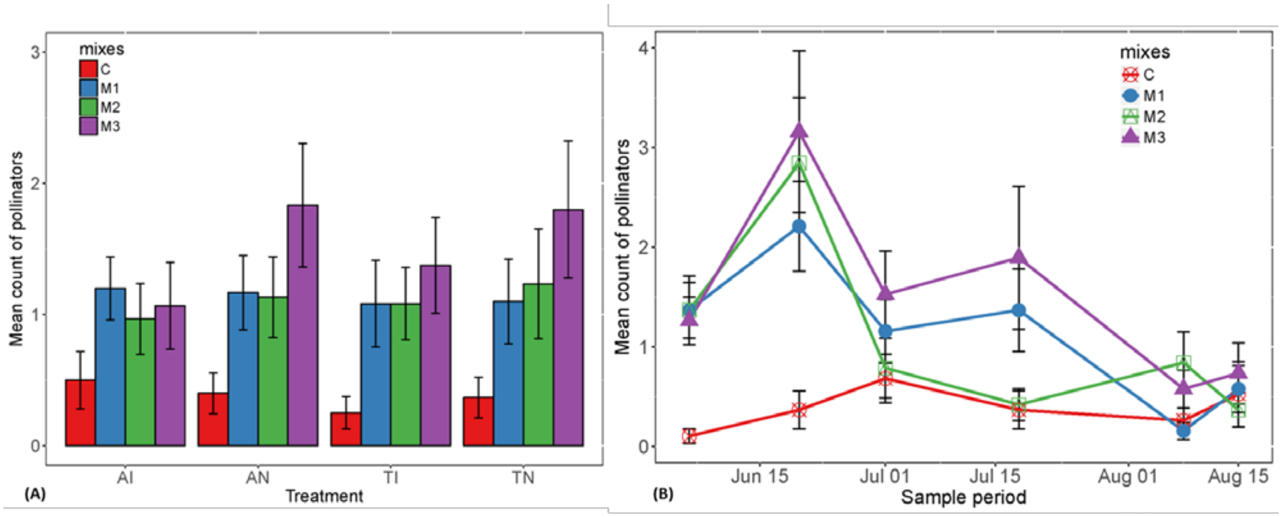


Figure 2.3. Mean (+1 SE) observations of (**A**) pollinators among the mixes and (**B**) mean (±1 SE) pollinators across the time among the different wildflower treatments. Legend labels: C—control, M1—floral mix, M2—floral mix, and M3—floral mix).

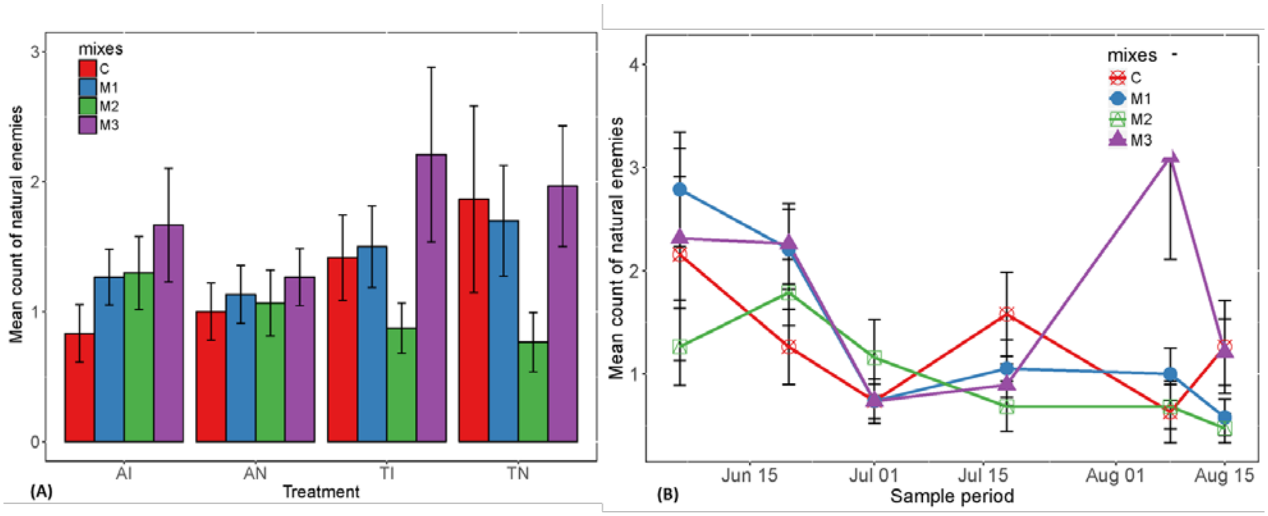


Figure 2.4. Mean (+1 SE) observations of (**A**) natural enemies among the mixes and local spatial context and (**B**) mean (±1 SE) natural enemies across time. Legend labels: C—control, M1—floral mix, M2—floral mix, and M3—floral mix).

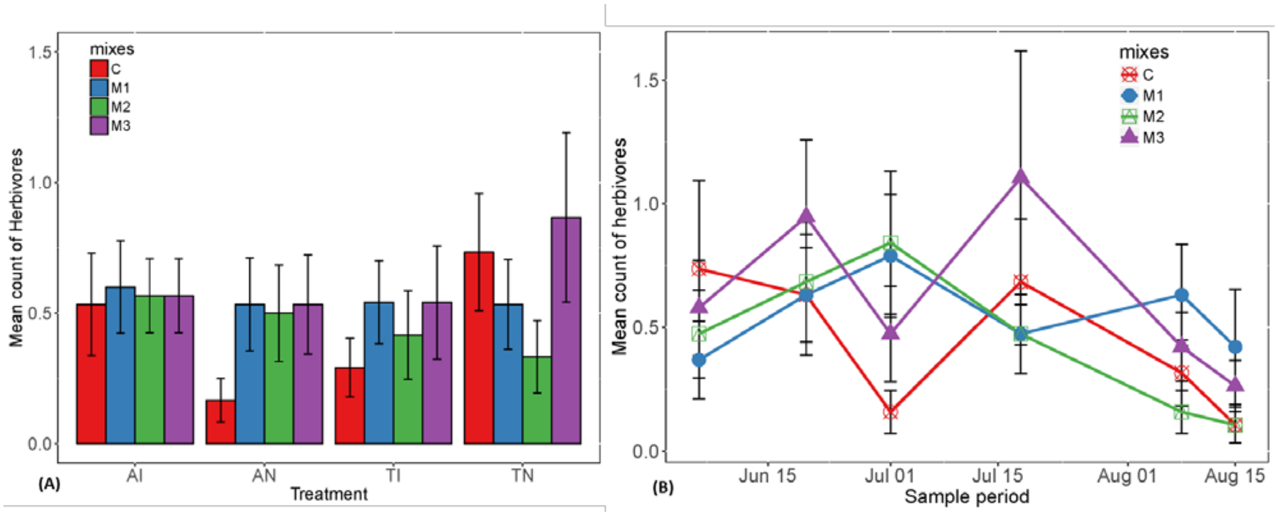


Figure 2.5. Mean (+1 SE) observations of (**A**) herbivores among the mixes and local spatial context and irrigation treatments and (**B**) mean (±1 SE) herbivores across the sampling periods among the different wildflower treatments. Legend labels: C—control, M1—floral mix, M2—floral mix, and M3—floral mix).

CHAPTER 3

REMOTE ESTIMATION OF BENEFICIAL ARTHROPOD POPULATIONS: IMPLICATIONS OF [2]A LOW COST DRONE SYSTEM.

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Abstract

Studies show that agricultural land requires investment in habitat management to provide non-cropping areas to support healthy beneficial arthropods and the ecosystem services they provide. In a previous small plot study, we manually counted blooms over the season, and found that plots providing greater numbers of flowers supported significantly higher pollinator populations over that of spontaneous weed plots. Here we examined the potential of deploying an inexpensive small unmanned vehicle (UAV) as a tool to remotely estimate floral resources and corresponding pollinator populations. UAV data were collected from previously established native wildflower plots in 19 locations on the University of Georgia experimental farms in South Georgia, USA. A UAV (Solo 3Dr)® equipped with a standard panchromatic camera was deployed to capture images of the flowers during the months of June and September 2017. Supervised image classification using ArcGIS® was carried out on the acquired images and classified to determine the floral area. The floral area obtained from the images positively correlated with the floral counts gathered from the quadrat samples. Furthermore, UAV-derived floral area significantly predicted pollinator populations, with a positive correlation indicating that plots with greater area of blooming flowers contained higher numbers of pollinators.

Keywords: UAV floral detection; image classification; floral provisioning; functional groups; habitat management; natural enemies, agricultural buffers

Introduction

Agricultural landscape diversification is an important strategy for ameliorating the loss of biodiversity and boosting ecosystem services, like biological control and pollination, provided by beneficial organisms (Gurr et al., 2017; Landis, 2017). In recent years, the concept of habitat management has been promoted as a feasible approach for diversifying agricultural landscapes. Habitat management encompasses several approaches which may occur within-crop, within-farm, or within-landscape. One form of habitat management is the utilization of wildflower strips sown at field margins (Tschumi et al., 2016a; Tschumi et al., 2016b) or within fields (Hatt et al., 2017) to attract beneficial insects, enhancing pollination and biocontrol of nearby crops. Numerous studies have evaluated and demonstrated the potential of wildflowers in agricultural systems for providing ecosystem services (Balzan et al., 2016; Martin et al., 2016).

Given the importance of wildflowers for the future of sustainable agricultural production, there is a need to develop monitoring tools for estimating the floral resources in a landscape. Apart from the traditional method of quantifying flowers through manual counts, recent advances have started utilizing digital imagery for quantifying floral counts. A potentially efficient method to quantitatively measure floral resources in digital imagery is through image segmentation and classification (Thorp & Dierig, 2011). Until recently, remote sensing for vegetation mapping in agriculture has relied extensively on satellite imagery or low resolution aerial imagery. These images are very effective for monitoring crop production over the season, and for understanding critical information about regional, national and global cropland trends (Fritz et al., 2015). However, satellite imagery is limited to certain times of year due to cloud cover, and also, the resolution of images at 1-250m is prohibitive for monitoring more fine scale, high resolution changes in the environment. Over the past few years, low-cost unmanned aerial vehicles (UAVs) carrying light-weight cameras and sensors, has resulted in a significant interest in their use for remote sensing applications in vegetation mapping (Anderson & Gaston, 2013; Cruzan et al., 2016; Zhang & Kovacs, 2012).

UAVs provide indirect estimates of biomass, grain yield (Swain et al, 2010), nitrogen status (Hunt et al., 2005), and the normalized difference vegetation index (NDVI) (Agüera et al., 2011). UAVs have been successfully employed to detect and monitor pest infestations (Lehmann et al., 2015; Näsi et al., 2015), analyze structure of vegetation (Cunliffe et al., 2016), monitor several agricultural crops (Calvario et al., 2017; Fang et al., 2016; Severtson et al., 2016), and monitor distribution of insecticides. UAVs allow for collection of data at very high spatial resolutions (<50 cm ground sample distance), and with little to no latency (Hardin & Hardin, 2010; Lelong et al., 2008; Rango et al., 2009). For these reasons, UAVs equipped with even low cost sensors appear to be ideal tools for mapping and monitoring floral resources.

Several image segmentation and classification methods have been developed for flower detection based on assessments of the different spectral bands from high resolution colored images. Biradar & Shrikhande, (2015), achieved an overall accuracy of 92% in classifying marigold flowers in green houses from images captured using a digital camera. Siraj et al, (2010) applied neural networks to segment the features of flowers. Because flowers have distinct colors and textures, traditional image processing methods such as color and texture analysis can be used to segment flower pixels, and correlate pixel flower percentages with flower numbers (Biradar & Shrikhande, 2015; Thorp et al., 2016).

Although UAV use for monitoring plants is still in the early stages, Mullerova et al. (2017) demonstrated that UAV imagery could be used to successfully differentiate between flowers of different invasive species. Michez et al., 2016 successfully detected and classified flowers of

Heracleum mantegazzianum (giant hogweed) with high accuracy. Analysis of UAV images yielded higher accuracy in detection of black locust (*Robinia pseudoaccacia*) blooms when compared to satellite imagery (Müllerová et al., 2017), and yellow flag iris (*Iris psedacorus*) in contrast with field surveys (Hill et al., 2017). Carl et al (2017) have utilized UAV imagery to analyze black locust flowers and estimate the food base for Hymenopteran species (bees and wasps), especially for the honey bee, *Apis mellifera*. Hence, application of UAVs supported by digital imaging techniques and classification of floral resources (Lino et al., 2011) could act as an important tool for monitoring and predicting the populations of beneficial arthropods such as pollinators. While the use of customized UAV systems with expensive calibrated sensors may work best for research applications, optimizing a lower-cost commercially available UAV system with ordinary panchromatic cameras is more practical for agricultural producers and consultants.

In this study I : (1) compared flower areas derived from UAV imagery with flower counts from traditional plant ecology methods (2) developed a method to analyze and classify flowers from the buffer plots from panchromatic UAV images; and, (3) predicted patterns of beneficial arthropod populations from the floral area obtained in the classification process. In so doing, I demonstrate the use of a low-cost commercial UAV for indirectly monitoring floral resources in agricultural landscapes.

Materials and Methods

Field Sites

The same nineteen conservation buffer sites with the three native floral mixes outlined in Chapter 2 (Figure 2.1) were used for this study.

UAV mission preparation

The workflow from image acquisition to data extraction is illustrated in Figure 2. Prior to data collection, high-resolution orthomosaics were created for each plot to serve as reference maps against which later imagery could be georeferenced. We established 6 ground control points (GCPs) per plot using a Trimble Geo7x GPS system (DOP<2cm) and placed a highly visible whisker and nail marker at each of these points, to serve as temporary geo-located monuments for the duration of the study. Black and white 18cm x 18cm laminated targets were centered on the GCPs prior to every UAV flight. On May 2-3, 2017, a DJI Matrice 100® with a ZenuseX3® camera was flown over each plot at a height of 9.14m, and overlapping imagery of each plot was collected. The imagery was processed using Pix4DPro with GCPs, and produced a very high-resolution (0.004m) orthomosaic reference image for each plot (average RMSE ~0.009) which was used to georeference later image mosaics.

Image Acquisition

Images were captured from the 19 plots to provide data on each of the subplots (Figure 2.1; C, M1, M2, M3) on two dates, in June and September, 2017. Dates represented known bloom peak of the commercial wildflower mixes in June and senesce in September (Xavier et al. 2017). The commercially available UAV, Solo-3DR® equipped with a GoPro Hero4 ® was used to capture standard RGB images of each control and wildflower sub-plot (Figure 2.1). Prior to each flight, ground control targets were placed over the GCP monuments located in the plot. The UAV was manually controlled using a navigation controller interfaced with a tablet computer, and flown at an altitude of 9.14m above the plot to capture images of the subplots. The images were captured with 70 % overlap between images.

Image processing and analysis

Imagery from the UAV flights was mosaicked using Photoscan professional® (Agisoft LLC). The image mosaics were then georeferenced on ArcGIS using GCPs visible in the imagery. The georeferenced image was then classified through a supervised maximum likelihood classification (Foody et al., 1992). The accuracy of each classification was validated through the Kappa index (Fitzgerald & Lees, 1994) calculated from a confusion matrix using ArcMap geographic information system (GIS) software (v. 10.5; Esri)®. The classified image was resampled to a resolution of 0.01*0.01 m. The resampled image was reclassified to group all the different floral types into one class to represent the floral area. The data extracted from the images were separated into two classes: floral area and vegetation area. The floral area obtained from the images was then compared with the manually counted flowers and the arthropod data to predict possible patterns in the arthropod populations.

Two approaches were evaluated to analyze the classified ortho-images and select an appropriate model for running regression analysis on the beneficial arthropods against floral resources. In the first method, we divided each subplot into five quadrats and calculated the UAV derived average flower area within these five quadrats and then correlated it with the manual count of flowers. In the second method, we selected one of the five quadrats from the image, which was also the quadrat where we had manually counted the flowers.

Vegetation and arthropod sampling

Vegetation sampling and arthropod sampling were carried out simultaneously with image acquisition. For vegetation sampling, numbers of flowers occurring within a randomly selected quadrat of 0.25m^2 were counted for each species of wildflower. Pollinator visits were quantified by visually observing the flowers within the same quadrat for 3 minutes. All bees and syrphid flies visiting the flowers were pooled as pollinators. Natural enemies were collected by suction sampling from the same quadrat using a reverse flow leaf blower for 30 seconds. Spiders and several groups of insect predators (Reduviidae, Geocoridae, Carabidae, Coccinellidae, Dermaptera and Hymenopteran parasitoid wasps) were pooled together as natural enemies.

Results

The number of wildflowers observed from the manual counts in the flower mixes was higher in June than in September. As with the previous study (Xavier et al., 2017) the subplots with the commercial mixes had more flowers than the control with spontaneous vegetation growth.

Of the nineteen established plots, the images captured from one of the plots in September were not usable as they could not be mosaicked together without distortion. Hence we analyzed the data for eighteen plots for the months of June and September. A total of 890 and 583 flowers were recorded from manual counts in June and September, respectively, a 35% decrease in number of flowers from June (Table 1).

The total mean flower area from the five different quadrats was 239.62cm^2 in June and 33.99 cm^2 in September, an 85% decrease in flower area in flower area from June. The mean flower area from selected quadrats within the plots was 391.92 cm^2 in June and 66.39 cm^2 in September, an 83% decrease in flower area from June (Table 1). The image classification protocol was more successful in detecting flowers in June than in September. The overall classification accuracy ranged between 89% and 97% in June and between 80% and 95% in September. The Kappa index in June ranged from 0.83 to 0.95 except for one plot with a low Kappa index of 0.64 (Table 2). In September, fifteen plots had a higher Kappa index from 0.77 to 0.91. However, three of the plots had a low index ranging from 0.64 to 0.73 (Table 2). The flower area obtained from the selected quadrat correlated better with the manual counts of flowers than the mean flower from the five quadrats (Figure 3).

A total of 198 and 37 pollinators were observed visiting in all the plots in June and September respectively, an 81% decrease in pollinators from June (Table 1). The floral resources had a significant impact on the pollinator visits in all the plots. There was a positive correlation between the number of pollinator visits and the number of inflorescences that were counted from the UAV acquired images (Table 3) (Fig 4). We also observed a very similar positive correlation between the floral area obtained from a selected quadrat and the number of pollinators recorded (Table 3) (Fig 5). Collectively we observed more pollinators when there were more flowers in the plots.

For natural enemies, a total of 573 and 1,150 were recorded in June and September respectively in all the plots, a 100% increase from the June count. Floral resources did not appear to have a significant effect on the natural enemy population (Table 3) (Fig 4). Natural enemy diversity (H) was also not significantly correlated with floral resources (Table 3) (Fig4).

Discussion

Habitat management to improve beneficial arthropod population, especially incorporating native floral resources in agricultural landscapes has gained momentum in recent years. Consequently, several commercial seed mixes have been designed and are available to support and enhance beneficial arthropod communities. Although floral resources are being implemented, there exists little quantifiable measurements of the association of floral resources and beneficial arthropod populations (Szigeti et al., 2016b). The use of UAVs has increased dramatically in recent years and appears to be a feasible approach in assessing floral resources in habitats. This study demonstrates the effectiveness of utilizing a low cost commercial UAV in quantifying floral resources in agricultural landscapes. UAV data collection coupled with the image classification system, successfully detected and estimated the floral surface area and provided a new indirect metric to estimate pollinator populations.

In this study, the planted flower mixes were composed of multiple species, colors and the UAV imagery was panchromatic consisting of only one band. We achieved moderate to high accuracy from our image classification approach. The overall accuracy of the classification was more efficient in June, but still measurable in September leading to a stronger overall correlation between the floral counts and the floral area obtained through the UAV imagery. Müllerová et al. (2017) reported that the accuracy of image classification depends largely on the period at which the phenological phase of the vegetation is most recognizable, which in this study is the flowers. All the plots in this study had a peak bloom periods in June as opposed to September and hence the best images were from June as shown by the Kappa scores. The slightly lower average accuracy of flower detection in September than in June was likely a result of a major weather event (i.e. Hurricane Irma) in September where pine debris contributed to the misclassification of certain pixels as flowers in September.

Research increasingly shows that native wildflower plantings support higher native pollinator populations (Balzan et al., 2016; Venturini et al., 2017; Williams et al., 2015). Two methods were utilized to quantify floral resource availability for pollinators. The model for predicting pollinator populations by using UAV acquired floral area within a selected quadrat exhibited a strong positive correlation than the manual floral counts from the selected quadrat. Although, both the methods yielded similar results, the traditional method of using quadrats was time consuming and required several observers, making the data more susceptible to observer bias (Szigeti et al., 2016a; Szigeti et al., 2016b). We recorded higher number of pollinators in the beginning of the season which also coincided with the peak of the floral bloom in the mixes. These results are similar to a previous study (Xavier et al., 2017) where pollinators were more abundant early in the season and declined through the rest of the season as the number of flowers decreased. The UAV imagery can be considered as a complimentary approach to monitor floral resources implemented within habitat management practices.

In contrast to the pollinators, our natural enemy population from our observations tended to be variable across the season, which was also consistent with the previous study (Xavier et al., 2017). We also found no significant correlations of floral area or counts with natural enemy diversity. In our study, we attempted to predict the response of natural enemies with one floral resource character, surface area of the flowers. Natural enemies respond to several other factors in addition to the presence of floral resources in the landscape (Hatt et al., 2018). The importance of complex natural habitat for natural enemies can vary widely depending on type of crop, predator identity or functional role, land management, and habitat structure (Tscharntke et al., 2016). As a first step in using the UAV approach, we pooled all the natural enemies as one group and analyzed counts from vacuum samples. This approach may limit our ability to detect responses to diverse habitats as demonstrated by (McCabe et al., 2017) where responses to wildflower strips depended on predator functional groups. Community and functional group analyses were beyond the scope of this initial study where we were primarily interested in using a UAV approach to indirectly predict pollinator populations. Future analyses will attempt to understand community responses to landscape context and floral resources.

The UAV approach to quantify floral resources has potential as a high resolution and relatively rapid and less laborious method of predicting pollinator populations over large spatial scales. Although our study demonstrated that UAV data are well suited for detection of floral resources, the processing of the data can still be difficult. For instance, images from one plot in September were not usable because of the geometric distortions caused while orthomosaicking the images. The workflow we implemented could further be refined by automating certain steps like the manual georeferncing of the plots to the GCPs. Our study provides insights for a practical application of utilizing UAVs as a flexible tool to quantify floral resource management and ecosystem service provisioning. Future research should be aimed at integrating the floral resource estimates with decision making tools for improving habitat structure in landscapes, thereby creating cropping systems that promote beneficial arthropod populations and their associated services.

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Table 3.1: Descriptive summary of the measured floral resources and arthropods (mean ± 1 SE), during the sample period.

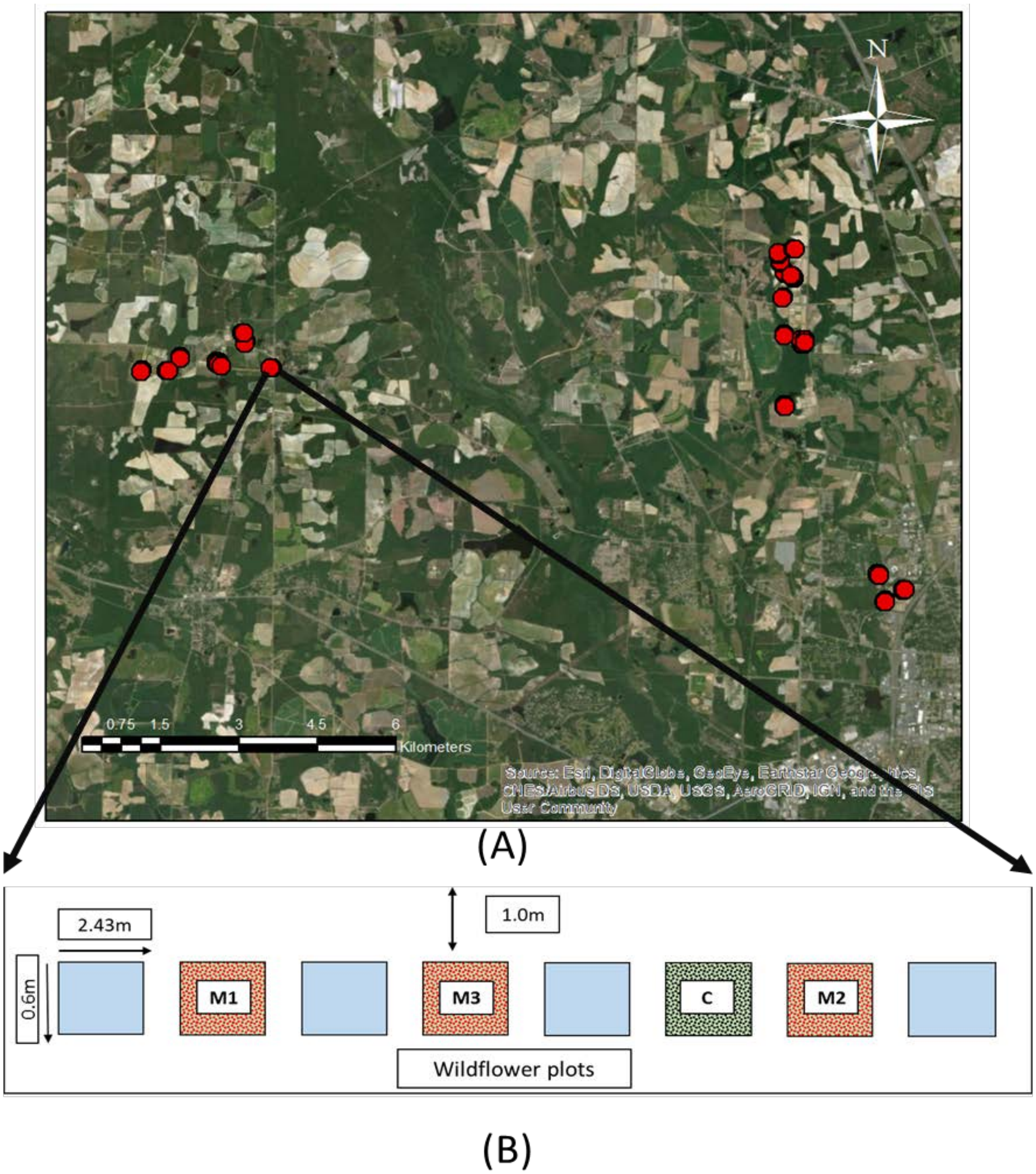
Measured variables	June	September
Floral area from 5 quadrats (cm^2)		
Mix 1	254.77	32.1
Mix 2	252.24	24.73
Mix 3	424.25	78.38
Control	27.01	0.72
Floral area from a single selected quadrat (cm^2)		
Mix 1	563.11	63.78
Mix 2	436.17	58.39
Mix 3	567.22	144.38
Control	1.12	0
Floral counts		
Mix 1	17.22	10.27
Mix 2	16.44	9.83
Mix 3	15.22	12.22
Control	0.55	0.05
Pollinators counts		
Mix 1	3.33	0.83
Mix 2	3.83	0.67
Mix 3	3.72	0.50
Control	0.11	0.06
Natural enemies counts		
Mix 1	8.28	16.27
Mix 2	6.11	18.11
Mix 3	11	17.33
Control	6.44	12.17

Table 3.2: The Root Mean Square Error (RMSE) recorded after geo-referencing of the plots. The Kappa index and overall accuracy (OA) values indicate the accuracy of the image classification protocol to detect floral area. Notes: adjacent to woodland (T) or agriculture (A); irrigated (I) and not irrigated (N).

	RMSE June	RMSE September	Kappa June	Kappa September	OA June	OA September
AI_01	0.035	0.032	0.837	0.885	0.894	0.932
AI_02	0.279	0.020	0.933	0.856	0.933	0.915
AI_03	0.047	0.030	0.871	0.851	0.910	0.917
AI_04	0.023	0.011	0.915	0.889	0.940	0.933
AI_05	0.282	0.023	0.646	0.775	0.768	0.867
AN_01	0.011	0.000	0.958	0.736	0.971	0.850
AN_02	0.061	0.045	0.958	0.803	0.971	0.883
AN_03	0.022	0.031	0.937	0.888	0.956	0.932
AN_04	0.057	0.062	0.876	0.894	0.914	0.933
AN_05	0.030	0.049	0.895	0.888	0.925	0.932
TI_01	0.054	0.028	0.937	0.645	0.956	0.800
TI_02	0.048	0.104	0.957	0.919	0.971	0.950
TI_03	0.047	0.018	0.894	0.866	0.929	0.932
TI_04	0.003	0.059	0.871	0.910	0.912	0.949
TN_01	0.055	0.033	0.874	0.879	0.911	0.933
TN_02	0.020	0.022	0.897	0.831	0.928	0.898
TN_03	0.030	0.108	0.917	0.872	0.943	0.933
TN_04	0.011	0.024	0.917	0.660	0.942	0.800

Table 3.3: Models utilizing floral resources as predictor variables to analyze the populations of beneficial arthropods.

Predictor variable	Response variable	$F_{(1,142)}$	Residual SE	R^2	*P*-value
Mean floral area	Floral counts	26.21	9.27	0.1499	$9.774e^{-07}$
Floral area (quadrat)	Floral counts	79.31	8.08	0.3538	$2.291e^{-15}$
Floral counts	Pollinator counts	84.73	1.80	0.3693	$4.029e^{-16}$
Floral area (quadrat)	Pollinator counts	87.49	1.79	0.3769	$<2.2e^{-16}$
Floral area (quadrat)	NE counts	0.02	14.26	-0.0068	0.88
Floral area (quadrat)	NE diversity (H)	1.11	0.46	0.0007	0.29



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3.1: (A) Wildflower plots distributed across research farms at University of Georgia, Tift County, Georgia. (B) The experimental plot design with the three commercial mixes (labelled M1, M2 and M3) and the control plot (labelled as C). All the wildflower plots were separated by alleys (2m wide) with no vegetation. The other subplots (in blue) had wildflower mixes which did not establish well.

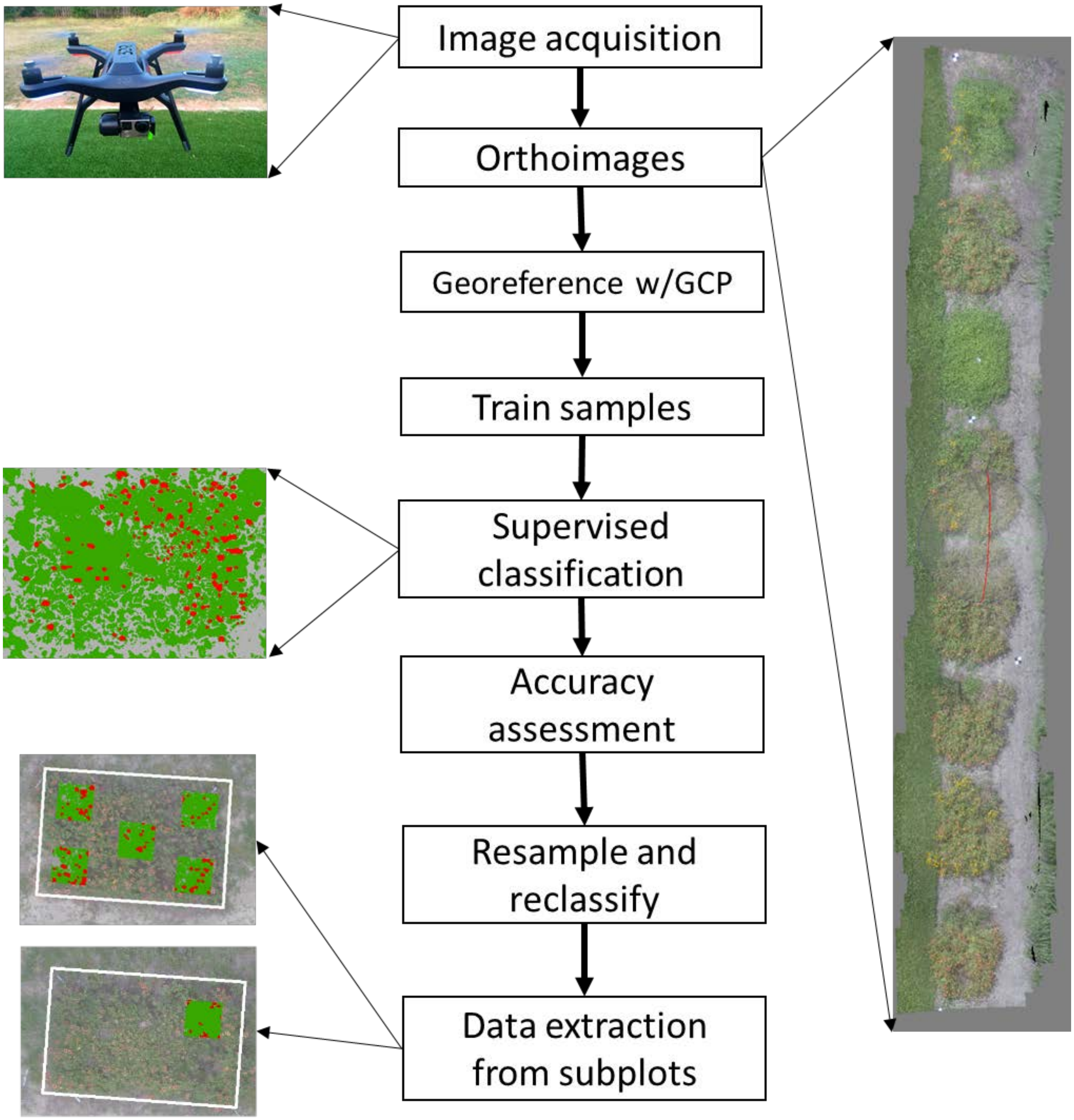


Figure 3.2: The workflow of the image classification protocol for extracting floral area. The images obtained from the UAV were processed through a series of steps to obtain the final data of the floral area from the plots.

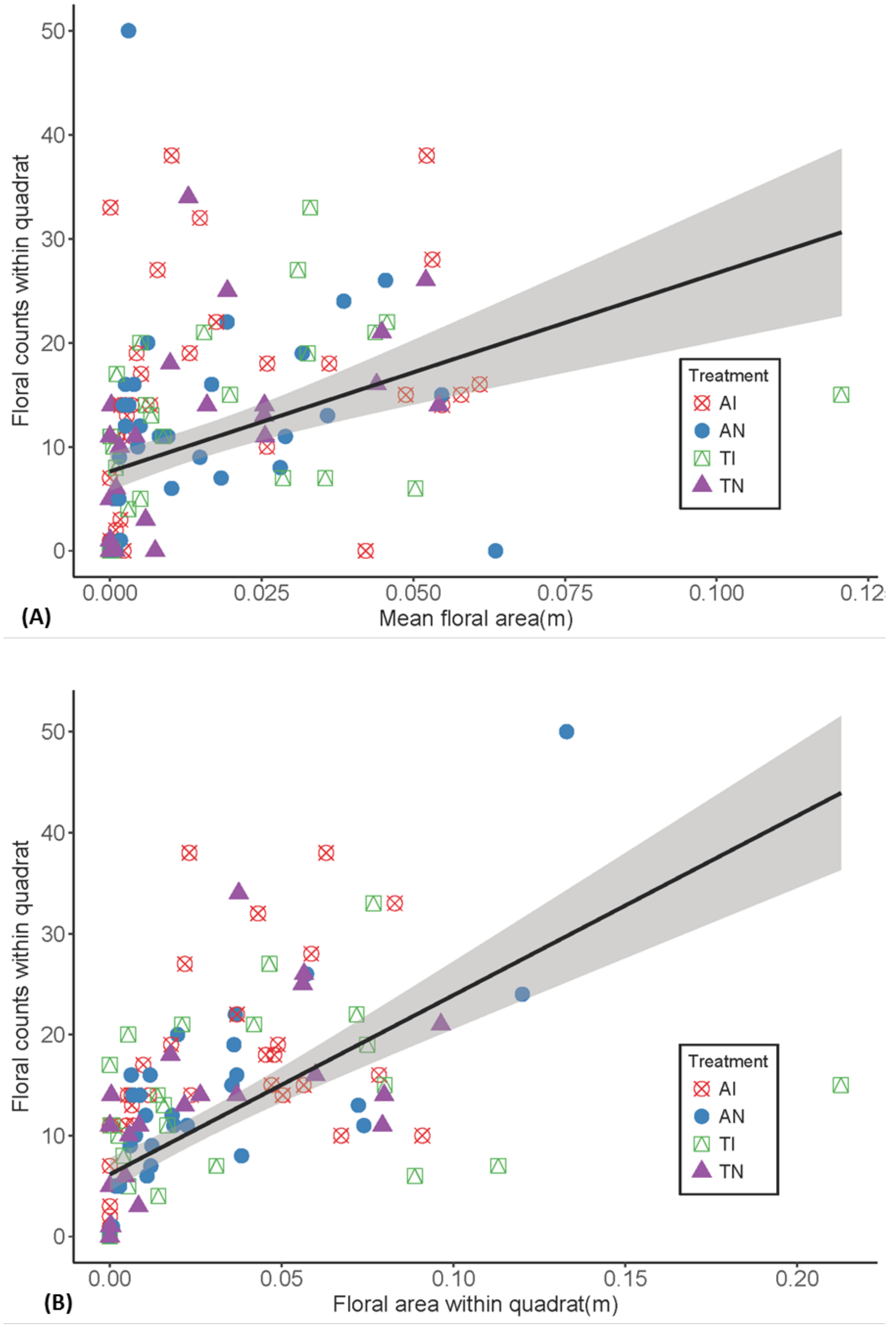


Figure 3.3: Linear regression show that both the mean floral area from the five quadrats (A) and the floral area within the selected quadrat (B) positively correlated with the manual counts of flowers obtained from the quadrat.

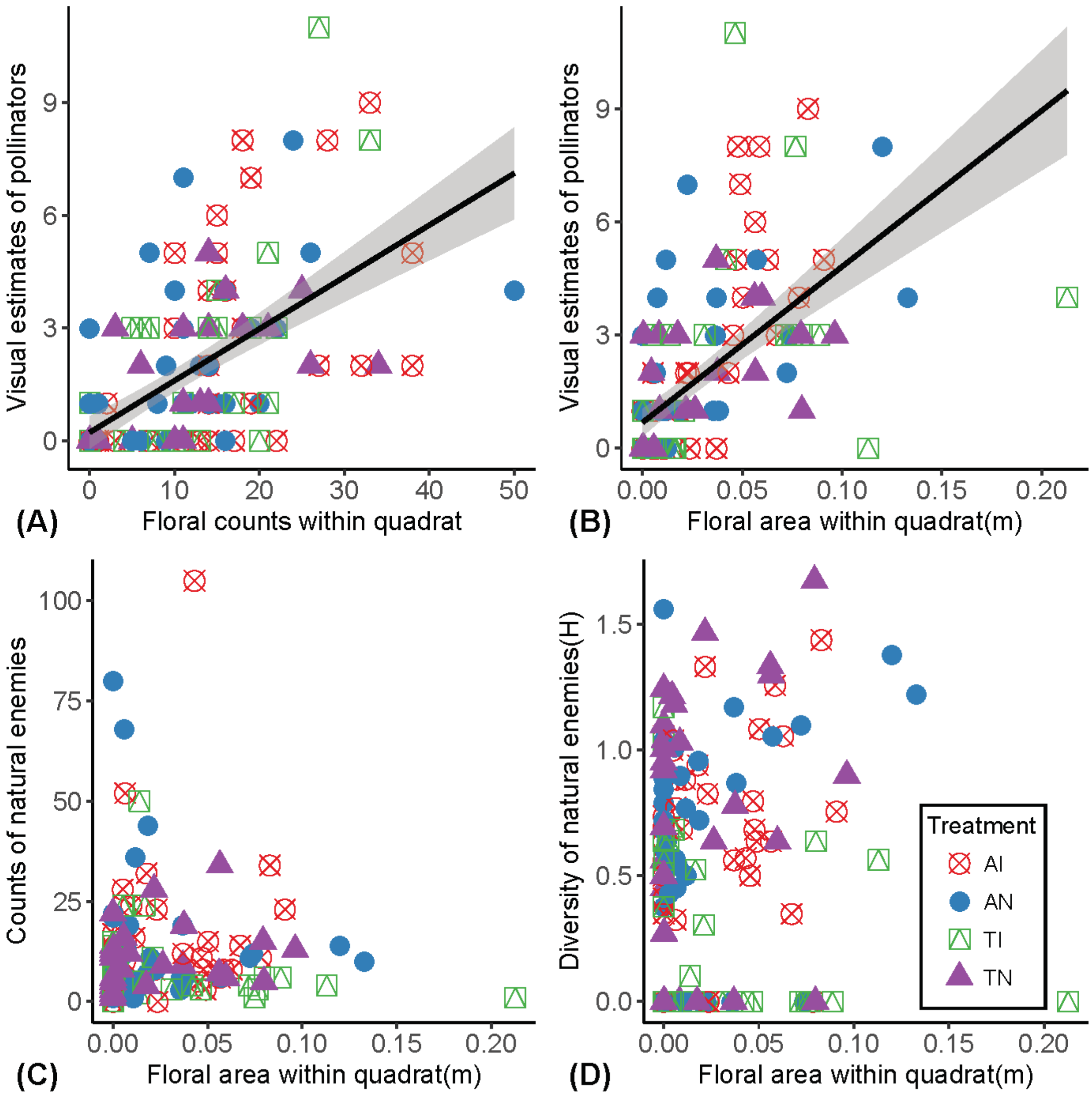


Figure 3.4: The visual estimates of pollinators responded similarly to both manual counts and the estimated floral area within the quadrat. Linear regressions with 95% confidence intervals of (A) pollinator counts as a function of floral counts within selected quadrat (B) pollinator counts as a function of floral area within selected quadrat. We found no correlation between the natural enemy counts (C) and natural enemy diversity (H) to the floral area within selected quadrat

CHAPTER 4

CONCLUSIONS

There is increasing evidence for the benefits that habitat management through floral resources can provide beneficial arthropods in intensively managed agricultural ecosystems. In this study, the potential of commercially available native wildflower mixes to enhance the population of beneficial arthropods in agricultural landscapes in South Georgia were examined. The research findings show that (1) all three floral mixes tested performed similarly in terms of wildflower production, irrespective of irrigation or landscape context (2) some species of wildflowers in the mixes were more dominant throughout the season (3) higher pollinator populations were directly proportional to the number of inflorescences recorded both manually and through the use of UAV imagery (4) natural enemy populations were variable and were not influenced by the presence of the inflorescences. Pollinators significantly increase crop yield and seed set in pollinator dependent crops and increase yield quality in some non-pollinator dependent crops. With the recent declines in managed pollinators, wild pollinators have gained more significance in agricultural landscapes for crop pollination (Garibaldi et al., 2013; Potts et al., 2010). Although, our results from both years show promising prospects for incorporating native wildflowers near crop fields to augment pollinator populations, there were a few limitations. All the mixes had lower flower production in September and we did not observe all the flowers listed in the mixes.

Natural enemy populations were highly variable over both years and, based on current analysis, were not significantly influenced by the wildflowers. Although several studies have shown a positive association between floral resources and natural enemies (Blaauw & Isaacs, 2012; 2015), there have been some studies with mixed responses (Chaplin-Kramer et al., 2011).

Natural enemies respond to different factors other than just floral resource abundance (Tscharntke et al., 2016). Future research is needed to further explore how to best incorporate floral resources for natural enemies so that habitat management can be translated into pest management within agroecosystems.

A method was also developed to remotely assess pollinator populations by utilizing floral area as an indicator. These results demonstrate that floral resources can be efficiently monitored with a high resolution, relatively low cost and less laborious UAV system which could be further used for predicting pollinator populations in landscapes. Similarly other studies have used UAV data to estimate floral resources from invasive species and trees. But there exists very few studies which utilize UAV data to predict ecosystem services such as pollination services.

Mapping multiple ecosystem services is a crucial step towards the application of the notion of ecosystem services in the agricultural landscapes. These mapping methods facilitate better understanding of local factors and can be used to target new management practices. Clec'h et al (2016) tested utilizing land cover data to map multiple ecosystem services, including pollination on a large scale. Although, our study provides data at a local scale, with further research into simplifying the workflow (through automation) we could implement the obtained data for predicting large scale ecosystem services. This data could also help to facilitate decision making tools to tailor multifunctional habitats in agroecosystems.

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