

ABSTRACT

Title of Thesis: EFFECTS OF THE INVASIVE *PHRAGMITES AUSTRALIS* ON THE PREDATION OF MOSQUITOES THROUGH CHANGES IN HABITAT COMPLEXITY

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Ephemeral stormwater ponds in the eastern United States are often invaded by non-native *Phragmites australis* which has been associated with numerous negative impacts on resident systems, including changes in hydrology, displacement of native macrophytes, and degradation of wildlife habitat. Few studies have documented the impacts of invasive *P.australis* on macroinvertebrate communities. Vegetated edges of stormwater retention facilities are often important developmental habitat for medically significant mosquitoes and the invertebrate predators that regulate their abundances. The displacement of resident macrophytes by *P.australis* could alter the physical structure of pond vegetation and disrupt the interactions between mosquitoes and their visual predators. The overall goal of my thesis was to evaluate differences in habitat complexity between native macrophytes, *T.latifolia* and *J.effuses*, and *P.australis*, and explore how those differences may impact predation of mosquitoes. I addressed this goal by conducting a controlled laboratory predation experiment and field surveys of four stormwater ponds.

EFFECTS OF THE INVASIVE *PHRAGMITES AUSTRALIS* ON THE PREDATION OF
MOSQUITOES THROUGH CHANGES IN HABITAT COMPLEXITY

by

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Chapter 1: Introduction

Storm water ponds

Management of urban stormwater runoff is of great environmental concern and is often alleviated with the employment of stormwater retention facilities, including constructed wetlands, constructed ponds, rain gardens, and ditches (Copeland, 2003; Copeland, 2006; Metzger et al., 2008). Although stormwater retention ponds can resemble natural ponds, they are different in that they are constructed, usually have more variable water levels, and must be maintained and properly managed to continue to provide the function for which they were intended. These mandatory and regulated ponds are designed to accumulate storm runoff in order to regulate water flow rates while also reducing impact on other water bodies by removing pollutants such as heavy metals, sediments, nutrients, and salts (Davis et al., 2001; Karouna-Renier & Sparling, 2001; Scher & Thiery, 2005). These ponds can be designed for permanent water detention for increased settling of pollutants or can be ephemeral to provide temporary water management when there is a water volume influx due to weather events (Center for Watershed Protection, 2009). Often varying species of aquatic plants aid in sediment retention and in filtering nutrients and contaminants in stormwater runoff (Hunt et al., 2006). The highly disruptive nature and high occurrence of water fluctuation of stormwater retention ponds makes them prone to infiltration by invasive and non-native plant species that develop strong rooted monocultures which outcompete other plants (Santana et al., 1994; Zedler & Kercher, 2004; Gingrich et al., 2006; Jodoin et al., 2007; Ehrenfeld, 2008; Metzger et al., 2008).

***Phragmites australis* invasion**

Phragmites australis (Cav.) Trin. ex Steudel is a perennial grass found along the borders of freshwater and brackish lakes, ponds, and rivers and widespread throughout wetland communities (IHM, 1996; Galatowitsch et al., 1999; Saltonstall, 2002; Silliman & Bertness, 2004). Although there is a native North American strain of *P. australis*, a genetically different strain from Europe and Asia has invaded and spread through much of eastern United States (Metzler & Rozsa, 1987; Hauber et al., 1991; Saltonstall, 2002; Saltonstall, 2003). The Eurasian strain of *P. australis* was introduced in the 1800's in multiple places along the east coast by European trade ships and rapidly spread across the Great Lakes regions and down through the Mississippi river delta (Simberloff, 2009; Marks et al., 1994; Hauber et al., 1991). *Phragmites australis* can rapidly invade new areas by reproduction through rhizomes leading to monotypic stands, its tolerance of brackish and freshwater conditions, and the rapid recovery after above ground growth damage (Meyerson et al., 2000). Its height, which can reach up to 5.5 meters, stem density, and high production of detritus reduce sunlight at the soil and water surface that decreases temperature and inhibits the germination and growth of other species and decreases decomposition within the stand (Meyerson et al., 2000). Its relatively large biomass deposits large quantities of detritus that can lead to soil accretion and wetlands loss (Rooth et al., 2003), causing prolonged water retention in stormwater retention ponds. These features have collectively led to quantifiable reductions in open water and plant diversity in both freshwater and brackish tidal wetlands and has displaced numerous resident wetland plants (Marks et al., 1994; Levine et al., 1998; Chambers et al., 1999; Meyerson et al., 2000; Chambers et al., 2003). Changes in water patterns and other

physical characteristics due to the accrual of sediment and detritus within large stands of *P. australis* reduce habitat heterogeneity (Buttery & Lambert, 1965; Shisler, 1990; Rooth & Stevenson, 1998) and can reduce the diversity of fish and terrestrial and aquatic invertebrate species (Chambers et al., 1999; Able & Hagan, 2000; Angradi et al., 2001; Able & Hagan, 2003; Raichel et al., 2003). These changes can also be observed in the availability of nutrients and habitats for fish and macroinvertebrates, refuge availability for prey, and ambush sites for predators (Canion & Heck, 2009; Yee, 2010). Therefore, due to structural, physiological, and spatial differences which can cause nutritional and architectural changes, the establishment and spread of *P. australis* as a major structural component within an aquatic system such as wetlands or stormwater retention ponds can have dramatic impacts on the respective ecological communities (Kovalenko et al., 2010; Pearson, 2009).

Habitat complexity conferred by plants

The effects of macrophyte communities on aquatic macroinvertebrates is well-studied (Heck & Wetstone, 1977; Dean & Connell, 1987; Carlisle & Hawkins, 1998; Crowder et al., 1998; Diehl & Kornijów, 1998) however most of the work is restricted to basic descriptions of species across different plant assemblages, even during significant invasion events. Perhaps the most interesting but understudied effects of plant invasions on aquatic macroinvertebrates might be their effects on predator populations and predator-prey interactions. Submerged and emergent plants provide refuge for prey and ambush sites for predators and often their role in mediating predator-prey dynamics is expressed in terms of increased habitat complexity (Rypstra et al., 1999; Landis et al., 2000; Sunderland &

Samu, 2000; Willems et al., 2005). Broadly speaking, habitat complexity is usually quantified by the number of different structural elements per unit habitat volume, which is usually characterized as plant density and configuration (McCoy & Bell, 1991). Since this definition is broad it forces researchers to define individual spatial scales of assessment: Microhabitat, habitat, and/or landscape. Within each level of spatial scaling there are elements of habitat complexity that theoretically shape the predator-prey dynamic. Although habitat complexity can be defined at multiple scales but perhaps the most important to the interactions of species is at the habitat level. On the habitat level these elemental complexities include plant species diversity, stand architecture, and characteristic of detritus/debris (Barbosa & Castellanos, 2005). Careful selection of spatial scales within the system of interest is crucial when attempting to identify elements of complexity that could affect predator-prey dynamics. Thorough definition and characterization of habitats and complexity structures are vital in order to understand the beneficiaries of the structures which is needed to explain variation of community structure among different habitats. This information can help predict consequences of changes in habitat for individual life histories and population and community dynamics including predation (Klecka & Boukal, 2014).

Habitat complexity that is conferred by plant density and configuration can alter the strength of predator-prey interactions in multispecies systems (Diehl, 1992; Swisher et al., 1998; Carter et al., 2010) and potentially destabilize the food web within that system (McCann et al., 2005). Vegetation can provide cover for ambush predators which delays prey detection and decreases predator cues (Howard & Koehn, 1985; Flynn & Ritz, 1999;

Horinouchi et al., 2009). Sit and wait or sit and pursue predators can use vegetative structure to improve their prey detection whilst also minimizing their presence (Cresswell et al., 2010). In addition, habitat structure provided by vegetation can change prey mortality rates in multi-predator environments like in the case of predators foraging in open water that facilitate predators in the vegetation (Swisher et al., 1998; Eklov & VanKooten, 2001; Grabowski et al., 2008; Horinouchi et al., 2009).

Habitat provides refuge

In some stormwater retention ponds, emergent plants are the only or dominant structural system available which can provide species with refuge from predation (Crowder & Cooper, 1982; Swisher et al., 1998; Yee, 2010). Refuges can either conceal the presence of prey or hinder the movement of predators (Savino & Stein, 1982; Dionne et al., 1990; Manatunge et al., 2000; Burks et al., 2001; Denno et al., 2005; Hauzy et al., 2010; Alexander et al., 2012). This would suggest that aquatic predators reside within a domain, for instance the bottom of or among the vegetation, which can be large or small but ultimately would affect the expected predation model for that system (Eklov & Diehl, 1994; Denno et al., 2005; Schmitz, 2007). This effect of habitat structure would depend on the ecology of both predators and prey, and the physical structure of the plants. These factors can include relative body size of predators and prey and spaces within the vegetative structure. If predators are unable to chase prey beyond the edge of the habitat structure, the refuge effect is maximized (Bartholomew et al., 2000; Bartholomew, 2002; Toscano & Griffen, 2013). This weakened predator effect on the prey community can result in positive effects on local species diversity (Diehl, 1992).

Mosquitoes

Mosquitoes are the world's most medically important insects and cause substantial morbidity and mortality worldwide. For example, it is estimated that there were about 219 million cases of malaria and 435,000 malaria-related deaths worldwide in 2017, making malaria the most medically important mosquito-borne disease on earth (World Health Organization, 2018). Malaria, caused by *Plasmodium* spp., a parasitic worm transmitted by mosquitoes in the genus *Anopheles*, is endemic in much of sub-Saharan Africa that suffers from underdeveloped infrastructure and high poverty (Miller et al., 2002). Unlike other diseases such as tuberculosis and schistosomiasis, the threat of malaria is determined by climate and ecology leading to high vector capacity within a region and not a direct consequence of poverty; however the presence of intense malaria within a region leads to greatly diminished growth of income per capita, roughly five fold, when compared to other, non-affected regions (Gallup & Sachs, 2001; Sachs & Malaney, 2002). Due to limited medical capabilities and poor mosquito control, mosquito-human contact and resultant malarial rates remain high in many areas in the region (Miller et al., 2002).

The United States has not been spared from pestiferous and disease vector mosquitoes. Pathogens such as West Nile Virus, St. Louis encephalitis virus, eastern equine virus, western equine encephalitis, and malaria have persisted due to wetland mosquito vectors, some of which maintain an enzootic cycle, but other generalist mosquitoes are primary vectors on mammals outside of wetland habitats (Rey et al., 2012). Malaria transmission from native *Anopheles* mosquitoes that inhabited wetlands plagued early settlements and large cities up until its eradication in 1951. Malaria was widespread throughout the

nineteenth century and was linked to over a million cases of illness during the civil war alone (Hong, 2007; Urban, 2010). This public health burden drove widespread policies to drain wetlands and diverse waterways to minimize mosquito breeding and treating outdoor environments by spraying pesticides. Today, wetlands still provide extensive habitat to a range of mosquito species around the country, including *Culex tarsalis* in the mid-west and *Culex pipiens*, and species of *Anopheles* in coastal areas in the southeastern part of the country, which demand extensive control programs. In the northeastern United States, many of the historical mosquito threats have been mitigated in highly populated cities due to extensive hydrological engineering. Nevertheless, a persistent concern has been the role that constructed storm water ponds may play in the maintenance of the country's most important mosquito-borne disease threat, West Nile virus (WNV). The principal vectors of WNV are urban *Culex pipiens* and *Aedes vexans* mosquitoes (Sardelis et al., 2001) that circulate and amplify the virus among preferred avian hosts, many of which are common in urban areas, including American robins, flycatchers, wrens, mockingbirds, and finches. Although *Culex erraticus* has tested positive for West Nile virus along with eastern equine encephalitis virus and St. Louis encephalitis virus (Rey et al., 2012), they don't seem to be competent vectors for disease apart from eastern equine encephalitis virus. After WNV's first detection in New York City in 1999, the virus spread dramatically westward across the continent, southward into Central America and the Caribbean, and northward into Canada. From 1999 to 2004, more than 7,000 neuroinvasive WNV disease cases were reported in the U.S. (Hayes et al., 2005) and was associated with reports of an extensive die-off among several bird species (Marfin et al., 2001). WNV is currently the most common vector-borne disease in North America with 2,097 cases reported to the CDC in

2017 (Center for Disease Control and Prevention, 2017). However, this number is almost certainly a gross underestimate since WNV is mostly asymptomatic or has flu like symptoms. *Culex* mosquitoes oviposit eggs on the surface of aquatic habitats as rafts, and a principal habitat is ephemeral ground pools that lack vertebrate predators, such as constructed storm water ponds.

Mosquito populations in urban areas are subject to the availability of habitat. As more container and waterbody environments are made accessible, populations will continue to increase. Understanding the natural predation process of these pests while in the fully aquatic, larval stage could help decrease the number of emerging adults and therefore decrease disease and mosquito control costs throughout affected areas. Exploring the interactions between other invertebrate species and mosquito larvae and the role of predation of mosquito larvae in varying habitats is crucial to the development of environmentally friendly strategies to biologically control mosquito populations (Bence, 1988; Focks, 2007; Marten & Reid, 2007; Mogi, 2007; Quiroz-Martínez & Rodríguez-Castro, 2007; Walton, 2007; Shaalan & Canyon, 2009). Furthermore, exploration into the relationship between invasive plant species and their role in the predator-prey dynamic within stormwater retention ponds would begin a dialogue into pest management that has not been widely investigated.

Stormwater retention ponds have been found to create a plethora of larval habitats for pestiferous and disease-vector mosquitoes due to their standing water levels and generally high nutrient concentration (Metzger et al., 2008) (Smith and Shisler, 1981; Dorothy &

Staker, 1990; Santana et al., 1994; Russell, 1999; Metzger et al., 2003; Su et al., 2003; Kwan et al., 2005; Gingrich et al., 2006; Wallace, 2007; Hunt et al., 2006; Metzger et al., 2008). Many mosquito species lay their eggs among vegetation in shallow waters around the edge of stormwater retention ponds, and those eggs will hatch within a 48-hour period (Gingrich et al., 2006). Considering the important implications to public health mosquitoes have as disease vectors, it is of great importance and interest to understand the environmental and ecological conditions that influence increased mosquito populations (Chaves & Koenraadt, 2010).

Predators

Predators play vital roles in community dynamics. Understanding functional roles of predators is important for understanding the consumptive and non-consumptive effects on prey (Sih et al., 1998; Schmitz, 2006; Schmitz, 2007). This role, however, may not be static but instead depend on the species with which it is interacting (Duffy, 2002; Hooper et al., 2005). According to Schmitz (2007), this context dependency might be the most difficult obstacle to overcome when attempting to develop predictive theories of species diversity and ecosystem function. To begin, predators can be categorized by hunting mode: sit and wait, sit and pursue, and active. Hunting mode, a predator's strategy and behavior used to capture prey, suggests the spatial and communal influence that predator has on the habitat or domain. These strategies can influence prey species behavioral responses based on cues of predation, body and foraging mode in prey, alter population densities, and lead to cascading effects on the heterogeneity and abundance of prey and plant species within the ecosystem (Schmitz & Suttle, 2001; Schmitz, 2003; Schmitz,

2006; Wirtz, 2012; Klecka & Boukal, 2013; Klecka & Boukal, 2014). Traits such as microhabitat use and behavior of both predators and prey may influence the effects of habitat structure on prey mortality (Burks et al., 2001).

Although the effects of competition parallel those of predation, studies show that in permanent bodies of water predation is more important to population dynamics (Wellborn et al., 1996; Focks, 2007; Marten & Reid, 2007; Mogi, 2007; Walton, 2007). Predators that live in/on/around pond water and consume mosquito larvae include a variety of taxa: Pisauridae, species of Notonectidae, Odonata, other Diptera larvae and adults, larvae and adult Dytiscidae, and larval Hydrophilidae (Stout, 1982; Juliano & Lawton, 1990; Lundkvist et al., 2003; Fischer et al., 2012). Ecological context can impact predation and in turn the prey population. Selectivity by predators of prey can be caused by predator-prey size combination and habitat overlap (Scott & Murdoch, 1983; Mogi, 2007). This suggests that mosquitoes will have different dominant predators in varying habitats with varying complexity.

Limited research shows the effectiveness of odonates as predators within different environments varies (Copeland et al., 1996; Lounibos et al., 1987; Breene et al., 1990; Louton et al., 1996; Fincke et al., 1997) however the natural overlap of habitat, long life cycle, and predation capacity make odonates valuable as potential mosquito control in aquatic environments (Shaalan & Canyon, 2009). Although the ecological literature on habitat complexity is vast, it has not been thoroughly applied to the role of hunting behavior within habitat use nor within the system of odonates and mosquitoes. The larger

the population of third and fourth instar mosquitoes, the more likely those mosquitoes would emerge into adults, contributing to larger adult mosquito populations within urban areas and ultimately leading to community health concerns.

Habitat complexity, mosquito predation, and stormwater retention ponds

Research has shown that with increased habitat complexity comes a decrease in predation (Orr & Resh, 1989; McCoy & Bell, 1991; Langellotto & Denno, 2004; Warfe & Barmuta, 2004). It is thought that more structurally complex systems provide more refuges or lower the encounter rates between predators and their prey (Heck & Crowder, 1991; Persson & Eklov, 1995; Warfe & Barmuta, 2004; Janssen et al., 2007; Yee, 2010). In more ephemeral stormwater retention ponds that do not have predatory fish, macroinvertebrate populations are often regulated by invertebrates. Within invertebrate dominant systems, structural complexity within an environment is thought to impact community composition, species interactions, and population dynamics (Sih et al., 1985; Crowder et al., 1998; Langellotto & Denno, 2004; Warfe & Barmuta, 2004). However, fewer studies have explored the role of structural complexity in mediating predator-prey interaction among aquatic insects (e.g., Orr & Resh, 1989; Yee, 2010), within stands of *P. australis*. Most constructed ponds invaded by *P. australis* are designed to be ephemeral, limiting the ability to support fish populations. A major consequence of increased numbers of poorly managed stormwater retention ponds is their potential to become invaded by *P. australis*, increasing water retention time, and becoming sources of pestiferous and disease-vector mosquitoes, which can have important wildlife, veterinary, and public health implications (Rey et al., 2012; Metzger et al., 2008). Understanding the effects of *P. australis* on the

interactions between invertebrate predators and their prey in storm water pond ecosystems is relevant to the approach for mosquito management in all communities.

Research goal and Project Activities

The overall goal of my thesis is to evaluate differences in habitat complexity between native plants, *T. latifolia* and *J. effuses*, and the invasive *P. australis* in stormwater retention ponds, and quantify how those differences impact predation of macroinvertebrates on mosquitoes. I address this goal by conducting a field survey that tests relationships among plant species, mosquito abundances, and predator communities. I focused on natural-bottomed stormwater ponds that have been invaded by *P. australis* and have both *T. latifolia* and *J. effuses* or one of these species around their edge. *Typha latifolia* is a broad leaf bulrush that is an obligate wetland species and *J. effusus* is a common rush that is found in wetland, riparian, and marshy areas. Both species are considered native to North and South America, Europe, Eurasia, and Africa. They are commonly found in stormwater ponds and other wetland regions that regularly co-occur with *P. australis* along the east coast of North America. I expect to see differences in habitat complexity, as measured by stem diameter and density, among these plant species. I then conducted a controlled mesocosm trial to test the effects of low, medium, and high densities of *P. australis*, *T. latifolia*, and *J. effusus* on the predation of the northern house mosquito, *Culex pipiens*, by damselfly nymphs in the Family *Coenagrionidae*, the most observed predator from the field study (Table 6). For this trial, I used bucket mesocosms with artificial plants that mimic *P. australis*, *T. latifolia*, or *J. effusus* at low, medium or high densities. *Culex pipiens* is commonly found in ground pool habitats and is the

principle vector of West Nile virus in the northeastern United States. Specifically, I will test if data from the field study and mesocosm trial are consistent with the hypothesis that *P. australis* reduces predation on mosquito larvae. If this hypothesis is true I expect to find higher mosquito abundances within *P. australis* stands in the field and lower predation in mesocosms with *P. australis* compared to stands in the field and mesocosms in the laboratory with two native plant species.

Chapter 2: Methods

Field Study

Study ponds

Ponds were selected to test differences in mosquito abundances and related biophysical and chemical predictors among the invasive *P. australis* and native *T. latifolia* and *J. effusus*. Ponds with natural non-cement bottoms, without fish within vegetative stands, and perimeter plants in water not more than 1 foot of water are most likely to provide habitat for mosquitoes (Clements, 1992). Therefore, preliminary surveys for these characteristics were conducted in the months of May through July in 2014. Four ponds that contained stands of all three study plant species around their perimeter and providing potential habitat for mosquitoes were selected for study. However, soon after the start of sampling, stands of *T. latifolia* or *J. effusus* in two ponds dried up, no longer providing habitat to larval mosquitoes, and thus were eliminated from the study. Two study ponds, Medical Drive (39°06'02.92" N, 77°12'20.22" W, Montgomery County, Maryland) (Figure 17) and Wellmoor Court (39°08'39.45"N, 76°48'17.59" W, Howard County, Maryland) (Figure 18) had all three plant types submerged in water during the duration of

the study. Freestate Drive (39°07'32.47" N, 76°49'27.32" W, Howard County, Maryland)(Figure 19) had *P. australis* and *T. latifolia* and Countrywood Court (38°54'50.62" N, 76°53'06.28" W, Prince Georges County, Maryland) (Figure 20) had *P. australis* and *J. effusus* for the duration of the study.

Mosquito and Predator Collections

In 2014, study ponds were surveyed during the time of year that mosquito abundances are highest, in August and early September (Kilpatrick et al., 2006). Surveys of Wellmoor Court and Medical Drive were performed once a week for a total of 5 collection dates. Surveys for Freestate Drive and Countrywood Court and performed on 3 collection dates. Predators were only identified and enumerated for the last three collection dates for Wellmoor Court and Medical Drive. Mosquito populations within *P. australis*, *T. latifolia*, and *J. effuses* were sampled in each pond using a standard 500 ml mosquito dipper. A total of 25 sample sites were randomly chosen in each pond on every collection date. The number of sample sites per plant type was proportionate to the area that the plant type composed. In some ponds on some collection dates, surveys were taken at fewer than 25 sample sites because dry conditions reduced the proportion of the pond habitat with at least one of the study plants. At each sample site, four evenly spaced dips were collected, dips were then combined into one 2 L sample and brought back to the lab where mosquitoes and predators were separated, identified, and enumerated. Late-instar (third and fourth instar) mosquito larvae were identified down to species and pupae and early-instar (first and second) larvae were identified down to genus using appropriate keys (Andreadis et al., 2005; Darsie & Ward 2005). All predators were identified down to family level using a key (Merritt et al., 2008).

Physiochemical Characteristics

Plant stand characteristics were sampled on two collection dates; once at the beginning and at the end of the sampling period. Three 1 m² quadrats were randomly placed in each plant stand in each pond. Within each quadrat the diameter of twenty stems (stem diameter) and the number of total stems (stem count) were enumerated and stem density per m² was calculated. Temperature, conductivity, total dissolved solids, and pH were measured from three randomly selected locations within each plant stand during each collection date using a Combo[®] pH/TDS/EC/Temp probe (Hanna Instruments).

Additionally, five 20 ml water samples were taken from randomly selected locations in each plant stand. Samples from the same plant stands were combined into one 100 ml sample from each plant type on each collection day and returned to the laboratory for tests of total phosphorous and total nitrogen using test Hach test kits (TNT826, TNT827, TNT843, TNT844, TNT845) on a Hach DR3800 spectrophotometer (Hach, Loveland, CO).

Mesocosm predation experiment

A predation experiment exposing *Cx. pipiens* larvae to odonate nymphs under varying plant type and density conditions was conducted over 10 replicate trials to test the effects of habitat complexity on a common predator-prey interaction. Odonate nymphs were collected in the months of August thru November 2015 from the stormwater pond at Wellmoor Court (39°08'39.45"N, 76°48'17.59"W, Howard County, Maryland) and a stormwater pond located on Perry Hall Blvd (39°22'40.50"N, 76°28'12.59"W, Baltimore County, Maryland) at least three days before each experimental run. All nymphs were randomly collected with a dipper from all vegetation types present within the ponds.

Individuals were measured for body length and kept in 250 ml Nalgene bottles with half 250 μ m sieved pond water and half distilled water in a 28°C environmental chamber set at a 16:8 L:D photoperiod that mimicked summer daylight. Only damselfly nymphs measuring between 9mm and 15 mm in body length and possessed two or more caudal lamellae were used in the experiment. To ensure nymph survival, a small wooden dowel was placed in each bottle as a perch and mosquito larvae were added for food. Mosquito larvae were removed from the containers 24 hrs prior to the start of an experimental run.

From late August to early September 2015, black containers provisioned with a 10% hay infusion were placed in a lot at the University of Maryland College Park to encourage oviposition of *Cx. pipiens* females. Rafts were collected daily and placed in 1 L Nalgene bottles containing rested tap water and ample food (Rat Chow) that were stored in an environmental chamber set at 28°C and 16:8 L:D photoperiod. When eggs hatched, resultant larvae were raised to third instar for identification. Larvae that were identified as *Cx. pipiens* were then used in experimental trials. In the months of October and November field caught *Cx. pipiens* were supplemented by *Cx. pipiens* from a F₁₋₃ colony kept in a lab at University of Maryland College Park. Field and colony *Cx. pipiens* were mixed before being randomly assigned to plant type and density treatments in the competition experiment.

Experimental mesocosms with varying plant type (*J. effusus*, *P. australis*, *T. latifolia*) and density (low, medium, high) were constructed from white 2 G buckets (24.13 cm x 24.13 cm) with inserted Styrofoam and dowel rods to mimic the six treatment combinations based on field conditions (Figure 21). To mimic stems of *J. effusus*, 0.3175 cm dowel rods were clustered together in 36 stem (low), 64 stem (medium), and 100 stem (high) clusters.

Low and medium clusters were arranged in one patch randomly located in the bucket whereas the high cluster was arranged in two randomly located patches side by side within the bucket. *P. australis* and *T. latifolia* treatment levels were mimicked using 1.27 cm and 2.45 cm dowel rods, respectively, arranged in 4 stem (low), 9 stem (medium), or 12 stem (high) clusters that were uniformly spaced around the bucket. Five replicate buckets of each treatment combination (3 plant types x 3 densities) was constructed, and individual buckets within each treatment combination were used in two of 10 replications to yield 90 observations. After a bucket was used the first time, all mosquitoes and predators were removed, and was thoroughly washed and rinsed before being used again.

The experiment was conducted over 10 replicate trials within a walk-in environmental chamber set at 28°C and 16:8 L:D photoperiod. For each trial, one replicate bucket of each plant type x density combination was randomly selected and randomly placed in a stationary grid. Each bucket was filled with 2.5 L of a 1:1 mix of 250µm sieved pond water and distilled water. Each bucket in a trial received 20 third-instar larvae, which were allowed an hour to acclimate and resume normal behavior. A randomly selected Odonate nymph was added to each bucket where they remained undisturbed for 24 hrs. After the 24 hr period, mosquito larvae were counted to calculate percent survival and damselfly nymphs were removed and kept for identification, which required dissection. Out of the 90 Odonate nymphs that were used, 42 and 58 were identified as *Enallagma* and *Ischnura*, respectively. Any trials that lost mosquitoes to pupation or Odonate nymphs to emergence were stopped and a new trial was run.

Statistical Analysis

Generalized linear models (PROC GLIMMIX, SAS 9.4, SAS Institute 2004) were used to test for relationships among mosquito abundances, physiochemical variables, and predator abundances from the field surveys. The appropriate error distributions were chosen for models based on preliminary data plots and descriptive statistics, with all mosquito and predator abundance response variables following a negative binomial distribution and all physiochemical response variables following a negative binomial, Gaussian, or Poisson distributions. Because the aim of my study was to test relationships with mosquito and predator species that often have different ecologies and public health impacts and with specific physiochemical predictor variables, I used univariate tests to focus on and quantify specific relationships. Ponds were analyzed separately because preliminary data plots and descriptions revealed substantial differences among ponds and because they were sampled on different collection dates. Collection date was included in all models as a random variable to control for natural variation among days. In the first set of models, I tested differences among plant stands in the densities of total mosquitoes (all larvae and pupae) and the two most abundant species that were identified to late-instar level. In all ponds, only 1 or 2 mosquitoes constituted most total late-instar specimens collected (Table 5), further justifying univariate analyses on these species. In the second set of models, I tested differences in plant (stem diameter, stem count) and water chemistry (temperature, conductivity, total dissolved solids, pH, total nitrogen, total phosphorous) parameters among plant stands. In the third set of models, I tested differences in the densities of total predators and the two most abundant families among plant stands. As with mosquito communities, individuals from 1 or 2 families constituted the vast majority of total

predators collected (Table 6) justifying univariate analyses on these species. In the final set of models, I tested the *a priori* effects of total predator abundances and the abundances of the two most abundant predator families on abundances of total mosquitoes and the two most common mosquito species. Plant type and its interaction with the predator predictor variable was included in all models. Because all predator abundance variables were overdispersed, I checked if $\log_{10} + 1$ transforming predator abundance predictors improved model fit based on AIC values, but none did.

General linear model (PROC GLM, SAS 9.4, SAS Institute 2004) was used to test the effects of habitat complexity on odonate nymph predation of *Cx. pipiens* in the mesocosm experiment. Effects of plant type, density, and *Odonate* genus, as well as all two-way interactions and the three-way interaction, were tested with *Cx. pipiens* survival as the response variable. *Cx. pipiens* survival met the parametric assumptions of normality and homogeneity of variances. Experimental trial was included as a random variable to control for variation in cohorts of mosquitoes, predators, or any other environmental factors among the 10 replicates.

For all analyses, experiment-wise $\alpha = 0.05$. Because of the large number of analyses on the field data, I applied a sequential Bonferroni correction to adjust experiment-wise α according to the number of tests in each set of models. Post-hoc tests among levels of significant variables were adjusted using the Tukey-Kramer method.

Chapter 3: Results

Field Study

Mosquitoes

Over the duration of the field season, I collected 6,969 total mosquitoes across all four study ponds, including 4,855 individuals at the late-instar (third and fourth instar) stage that were identified down to species level (Table 5). Although the assemblage of species varied among ponds, there was always two species that numerically dominated collections in each pond (Table 5). In Medical Drive, there were higher densities of total mosquitoes ($F_{2, 118}=12.32$, $p<0.0001$) and *Cx. pipiens* ($F_{2, 118}=17.24$, $p<0.0001$), the pond's second most abundant species, in *P. australis* than in *J. effusus* and *T. latifolia* (Figure 22).

Densities of *Culex territans*, the pond's most abundant species, did not vary among plant types ($F_{2, 118}=2.79$, $p=0.0655$). In Wellmoor Court, there were higher densities of total mosquitoes ($F_{2, 119}=9.90$, $p=0.0001$) and the most abundant mosquito, *Cx. erraticus* ($F_{2, 119}=28.15$, $p<0.0001$), in both *P. australis* and *J. effusus* than in *T. latifolia* (Figure 22).

Densities of *Culex territans*, the pond's second most abundant mosquito species, did not vary among plant types ($F_{2, 119}=4.31$, $p=0.0156$, non-significant with Bonferroni correction). In Freestate Drive and Countrywood Court, there were no differences in mosquito densities among plant types (F-values=0.00-11.13, p-values=0.0140-0.9776, non-significant with Bonferroni correction; Figure 23).

Predators

Over the duration of the field season, I collected 2,886 total predators in the ponds at Wellmoor Court and Medical Drive, which were identified down to the family level (Table 6). Although the predator composition varied among ponds, predators in the family *Coenagrionidae* and the family *Libellulidae* were the most abundant predators in both ponds (Table 6). Predators in the family *Coenagrionidae* constituted 69.89% (n=2886) of total predators and individuals in the family *Libellulidae* was the second most abundant, making up 14.87% (n=2886) (Table 6). Total predator ($F_{2, 70}=15.72$, $p<0.0001$), *Coenagrionidae* ($F_{2, 70}=12.46$, $p<0.0001$), and *Libellulidae* ($F_{2, 70}=15.61$, $p<0.0001$), densities all varied among plant types in Medical Drive. In Medical Drive, there were higher densities of total predators and *Coenagrionidae* predators ($F_{2, 70}=12.46$, $p<0.0001$) in *J. effuses* and *T. latifolia* when compared to *P. australis* (Figure 24). Predators in the family *Libellulidae* were found in higher densities in *T. latifolia* when compared to *P. australis* and *J. effusus* ($F_{2, 70}=15.61$, $p<0.0001$; Figure 24). Total predator ($F_{2, 68}=29.17$, $p<0.0001$), *Coenagrionidae* ($F_{2, 68}=25.65$, $p<0.0001$), and *Libellulidae* ($F_{2, 68}=4.21$, $p=0.0188$), densities also varied among plant types in Wellmoor Court. In Wellmoor Court, total predators and *Coenagrionidae* predators ($F_{2, 68}=25.65$, $p<0.0001$) were most dense in *J. effuses*, second most dense in *P. australis*, and least dense in *T. latifolia* (Figure 24). Predators in the family *Libellulidae* were found in higher densities in *P. australis* when compared to *T. latifolia* ($F_{2, 68}=4.21$, $p=0.0188$; Figure 24). There were no significant relationships between predators when considering plant type and mosquitoes among sample sites in either Medical Drive or Wellmoor Court (F-values=1.49-8.22, p-values=0.0055-0.2237, non-significant with Bonferroni correction).

Physical Stand Characteristics

In all study ponds, stem diameter and density clearly varied among plant types (Diameter: F-values=79.81-369.25, p-values= $p < 0.0001$; Density: F-values=5.04-131.90, p-values= < 0.0001 -0.0280; Table 7). In all ponds, *Juncus effusus* had the smallest stems, followed by *P. australis*, and then *T. latifolia* (F-values=79.81-369.25, p-values= $p < 0.0001$; Figure 25, Table 7). In Medical Drive, *J. effusus* had higher stem densities than *P. australis* and both had more stems than *T. latifolia* ($F_{2, 14}=63.39$, $p < 0.0001$; Figure 26, Table 7). In Wellmoor Court, *J. effusus* had more stems per quadrat than both *P. australis* and *T. latifolia* ($F_{2, 14}=92.75$, $p < 0.0001$; Figure 26, Table 7). *Juncus effusus* had more stems per quadrat than *P. australis* in the pond at Countrywood Court ($F_{1, 9}=42.05$, $p=0.0001$; Figure 26, Table 7). In the pond at Freestate Drive, *J. effusus* had more stems per quadrat than *P. australis* and *T. latifolia* ($F_{2, 11}=5.04$, $p=0.0280$; Figure 26, Table 7).

Water Characteristics

There were no clear trends between sampled water characteristics and plant types across ponds. Total nitrogen (F-values=0.02-4.18, p-values= 0.0573-0.8937) and total phosphorous (F-values=0.01-0.50, p-values=0.5286-0.9811) concentrations were not significantly different among plant types in any of the study ponds. In Wellmoor Court, *T. latifolia* stands had higher levels of conductivity than *J. effusus* and *P. australis* ($F_{2, 38}=43.80$, $p < 0.0001$; Figure 27). No other ponds showed a significant difference between plant type and conductivity (F-values=1.37-5.14, p-values=0.0157-0.2555, non-significant with Bonferroni correction). pH in *J. effusus* and *P. australis* stands were higher than those in *T. latifolia* at Wellmoor Court ($F_{2, 38}=29.37$, $p < 0.0001$; Figure 28). In Countrywood

Court, pH in *J. effusus* stands were higher than in *P. australis* ($F_{1, 19}=4.56$, $p=0.0459$; Figure 28). Medical Drive and Freestate Drive had no significant difference between plant type and pH (F-values=0.0, p-values=0.9600-0.9963). Total dissolved solids was highest in *T. latifolia* stands when compared to both *P. australis* and *J. effusus* at Wellmoor Court ($F_{2, 38}=50.38$, $p<0.0001$; Figure 29). No other ponds showed a significant difference between plant type and total dissolved solids (F-values=2.21-6.40, p-values=0.0048-0.1531, non-significant with Bonferroni correction). And lastly, water temperature within plant stands varied between ponds. In Medical Drive, water temperature was highest in *J. effusus* stands, with the second highest temperature within *T. latifolia*, and the lowest temperature in *P. australis* ($F_{2, 30}=28.60$, $p<0.0001$; Figure 30). In Wellmoor Court, *T. latifolia* had the lowest temperature when compared to both *J. effusus* and *P. australis* ($F_{2, 38}=83.53$, $p<0.0001$; Figure 30). Freestate Drive and Countrywood court showed no significance between temperature and plant type (F-values=0.07-4.56, p-values=0.0459-0.7981, non-significant with Bonferroni correction).

Mesocosm predation experiment

There were no effects of plant density ($F=0.58$; $p=0.5643$) (Table 8 **Error! Reference source not found.**) or damselfly genus ($F=0.88$; $p=0.3516$) on predation of *Cx. pipiens* in experiment mesocosms (Table 8). However, there is a significant difference between mosquito survival and plant type ($F=3.53$; $p=0.0351$) especially when genus of damselfly is considered ($F=3.24$; $p=0.0456$) (Table 8). Across all plant types mean mosquito survival was highest in *P. australis* and lowest in *J. effusus* ($p=0.0351$) (Figure 31). In the presence of damselfly nymphs in the genus *Enallagma*, mean mosquito survival was highest

amongst *P. australis* stems when compared to mosquito survival amongst *J. effusus* ($p=0.0453$) and *T. latifolia* ($p=0.0273$) (Figure 32). There also was significantly higher mosquito survival in the *P. australis* stems in the presence of damselfly nymphs in the genus *Enallagma* when compared to mosquito survival in *P. australis* ($p=0.0311$) and *J. effusus* ($p=0.0016$) with the damselfly nymphs in the genus *Ischnura*. This suggests predation rates are significantly lowest amongst the *P. australis* stems in the presence of damselfly nymphs in the genus *Enallagma* when compared to predation in both *P. australis* and *J. effusus* by damselfly nymphs in the genus *Ischnura*.

Chapter 4: Discussion

Habitat complexity is usually defined as the number of different structural elements per unit of habitat volume (McCoy & Bell, 1991). This can include elements such as plant density and configuration, and has been shown to impact macroinvertebrate diversity (Heck & Wetstone, 1977; Stoner & Lewis, 1985; Dean & Connell, 1987; Carlisle & Hawkins, 1998) and predation (Nelson, 1979; Folsom & Collins, 1984; Gilinsky, 1984; Gotceitas & Colgan, 1989; Lipcius et al., 1998; Swisher et al., 1998; Rypstra et al., 1999; Landis et al., 2000). However, few studies have examined the effects of different plant types and densities on the predation of mosquitoes in stormwater retention ponds (Gingrich et al., 2006; Hunt et al., 2006). The overall goal of my study was to evaluate the differences in habitat complexity between native *T. latifolia* and *J. effusus* and the invasive *P. australis* in stormwater retention ponds and quantify how those differences impact predation of mosquitoes. Each of these plants have different stem diameters, spatial

arrangement, and cluster patterns which make them unique. In a constructed laboratory trial, I found higher predation of *Cx. pipiens* in mesocosms that mimicked *J. effusus* and *T. latifolia* stems compared to *P. australis* stems from damselfly nymphs within the genus *Enallagma*. In surveys of four stormwater retention ponds in the field, I found that mosquito densities varied between *P. australis*, *J. effusus*, and *T. latifolia* but there was no consistent pattern among sites. I also found no relationships among predators and mosquitoes among individual sample locations within the two ponds where predators were also collected. Nevertheless, in one of those two ponds, *P. australis* has both the highest predator and lowest predator densities suggesting that predation rates may vary along plant boundaries. In the other pond, mosquito but not predator densities were lowest in *P. australis*, and *J. effusus* had both the highest densities of mosquitoes and predators. These findings demonstrate that although vegetation might mediate predation on at least some mosquitoes, numerous environmental and ecological factors are also likely to affect mosquito and predator densities in stormwater retention ponds such as detritus within vegetative stands (Murrell & Juliano, 2014; Yee et al., 2007). Detritus type and abundance can effect mosquito community populations and diversity (Connell, 1983; Schoener, 1983; Hairston & Hairston 1993; Léonard & Juliano 1995), resource competition (Yee et al., 2007), predator-prey behaviors (Juliano & Gravel, 2002), and species fitness (Lounibos et al., 1993; Walker et al., 1997) which would have large implications in stormwater retention facilities and the surrounding communities.

In the mesocosm study, I used damselfly nymphs from the genus *Enallagma* (Odonata: *Coenigrionidae*) and *Ischnura* (Odonata: *Coenigrionidae*). Damselfly nymphs are

abundant within permanent and semi-permanent ponds and can serve as dominant predators within gradients inaccessible to fish (Tonn & Magnuson, 1982; McPeck, 1990; Werner & McPeck, 1994; Skelly, 1996; Wilbur, 1997; Williams, 1997). In my field study I found damselfly nymphs from the family *Coenigrionidae* were the most abundant predator in all vegetation types in all ponds. Damselflies in the genus *Ischnura* and *Enallagma* are very common in ponds and can be found throughout the United States. Rate of consumption between species of damselflies vary (Mandal et al., 2008) and often are spatially and density of prey/predator dependent (Miura & Takahashi, 1988; Mandal et al., 2008). Damselflies in the genus *Ischnura* have relatively high consumption rates when compared to other odonates which suggests they are effective mosquito predators (Mandal et al., 2008). This could explain why the trials with *Ischnura* damselflies had higher mosquito predation in all plant type and density combinations when compared to the trials with the *Enallagma* damselflies. *Enallagma* damselflies had less predation success in *P. australis* when compared to *J. effusus* and *T. latifolia* which could be due to habitat structure. The difference in structure and density could have impeded the mobility (Diehl & Kornijów, 1988; Heck & Crowder, 1991) of the *Enallagma* damselflies which could have led to a change in predator strategy that was less successful (Savino & Stein, 1989). *Culex pipiens* is a principle vector of West Nile virus, the most common vector borne disease in America, and therefore of great public health importance. If species of damselflies have lower predation success on *Cx. pipiens* within *P. australis* in the field than increased *P. australis* invasion could lead to more instances of West Nile virus, especially in highly populated urban areas where stormwater runoff is regulated through implementation of poorly managed stormwater retention ponds. This is one of the first

studies to demonstrate how vegetation, specifically the invasion of *P. australis*, might affect crucial mosquito populations and ultimately the spread of West Nile virus by altering predator-prey interactions.

Despite this significant effect in the lab, there were few clear trends in the field. Not surprisingly, *P. australis*, *T. latifolia*, and *J. effusus* varied consistently in physical structure and density among all ponds, indicating that invasion by *P. australis* would likely substantially alter habitat complexity in the fringes of ponds where predators, including damselfly nymphs, and mosquitoes reside. Although the most dominant predator in both ponds sampled for predators were in the family *Coenagrionidae*, there was considerable variability in mosquito communities among vegetative stands between ponds. Though the most abundant mosquito species was consistently the most abundant between different vegetative stands within the same pond, no two ponds had the same dominant mosquito species. *Cx. territans* and *Cx. pipiens* were the only two mosquito species collected in high abundances in more than one pond although they were not always the most abundant mosquito present. It is likely that mosquitoes are affected by numerous environmental variables (Juliano, 2009). In this study I saw no clear trends between the propensity of mosquitoes within vegetation and any of the tested variables including temperature, conductivity, pH, total dissolved solids, or presence of nitrogen and phosphorus.

In the field, predators varied among vegetation types however there was no consistent relationship with plant types among sites and mosquitoes within sites. This suggests that

there is little evidence that predators are regulating mosquitoes in the field. It is possible that the fluidity of movement within a pond by mosquitoes and predators renders collection site a poor representation of residence. Mosquito distribution within ponds are most likely due to oviposition, which tend to be positively correlated with vegetation or algae density, temperature, and other chemical cues (Bentley & Day, 1989). Another factor impacting the distribution of mosquitoes could be feeding and predator avoidance behaviors which would move them specifically within submerged vegetation within the water column. Distribution of damselflies are impacted by physiochemical factors but also presence of fish, competition, and predatory interactions (McPeck, 1990). Predation performance in damselfly nymphs are not only specific to developmental stages, younger nymphs prey on smaller organisms (Lee, 1966; Collin & Resh, 1985), but nymphs within the last developmental instar stage consume less per day (Miura & Takahashi, 1988). In my lab study I tested the predation of a single damselfly within vegetation type and density combination however there is evidence that the presence of other damselfly nymphs can decrease consumption and high densities of prey can increase consumption (Miura & Takahashi, 1988). If habitat structure can influence predator-prey interactions, then it may also influence predator-predator interactions and hence the combined impacts of multiple predators. Although consumption rates of damselfly nymphs are low compared to other co-occurring aquatic predators (Aditya et al., 2004; Saha et al., 2007a; Saha et al., 2007b), and predator effects are not additive (Warfe & Barmuta, 2004), when compared with other taxonomic groups, damselfly nymph longevity, predatory ability, abundance, trophic position, and coexistence within habitats with mosquito larvae, make them an ideal agent for biological mosquito control (Chatterjee et al., 2007; Mandel et al.; 2008).

Figures and Tables

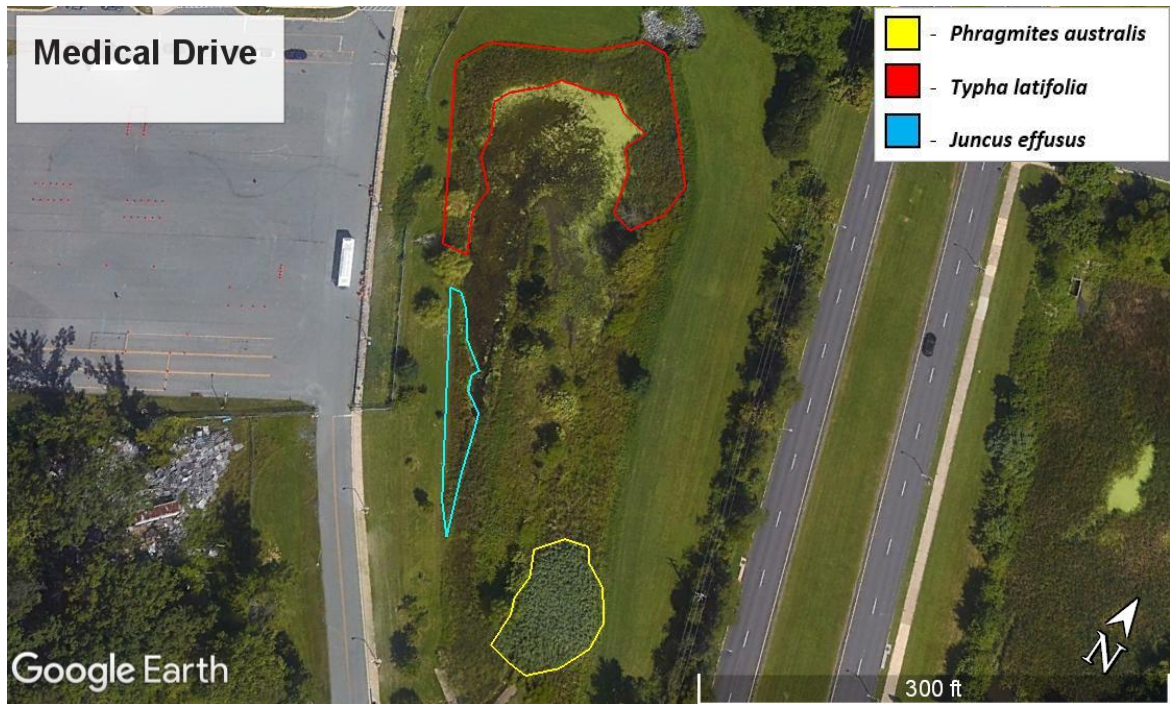


Figure 17: Aerial photo of the pond at Medical Drive ($39^{\circ}06'02.92''$ N, $77^{\circ}12'20.22''$ W, Montgomery County, Maryland) with the vegetative stands of *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* defined by color.

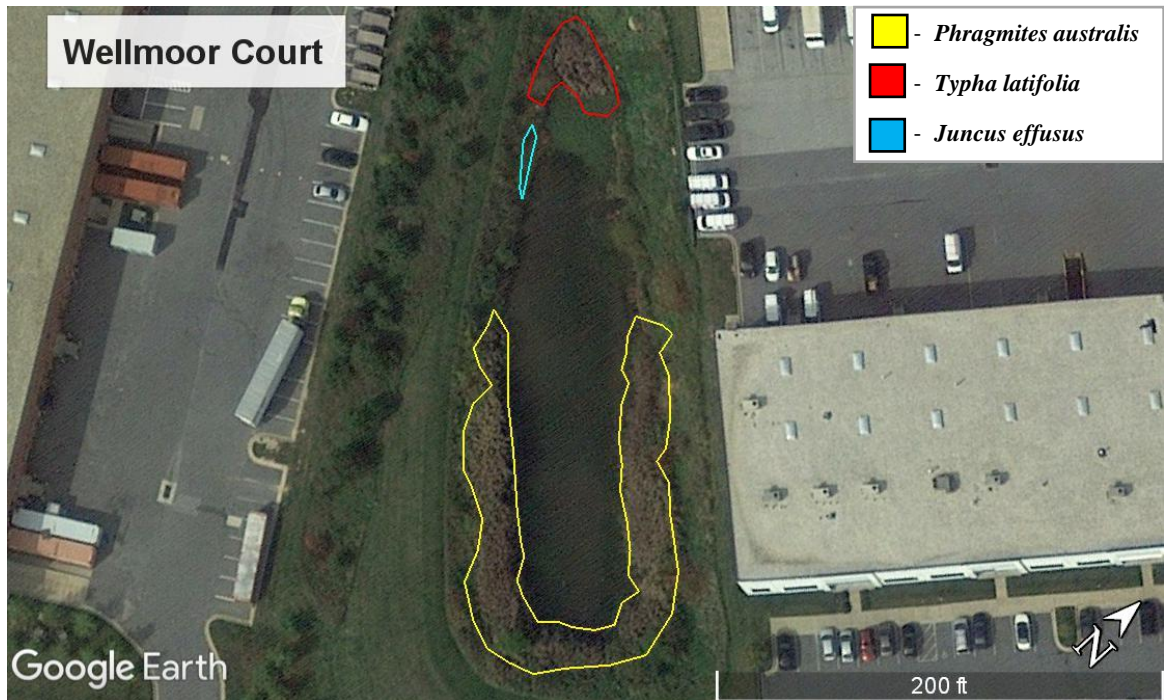


Figure 18: Aerial photo of the pond at Wellmoor Court (39°08'39.45"N, 76°48'17.59" W, Howard County, Maryland) with the vegetative stands of *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* defined by color.

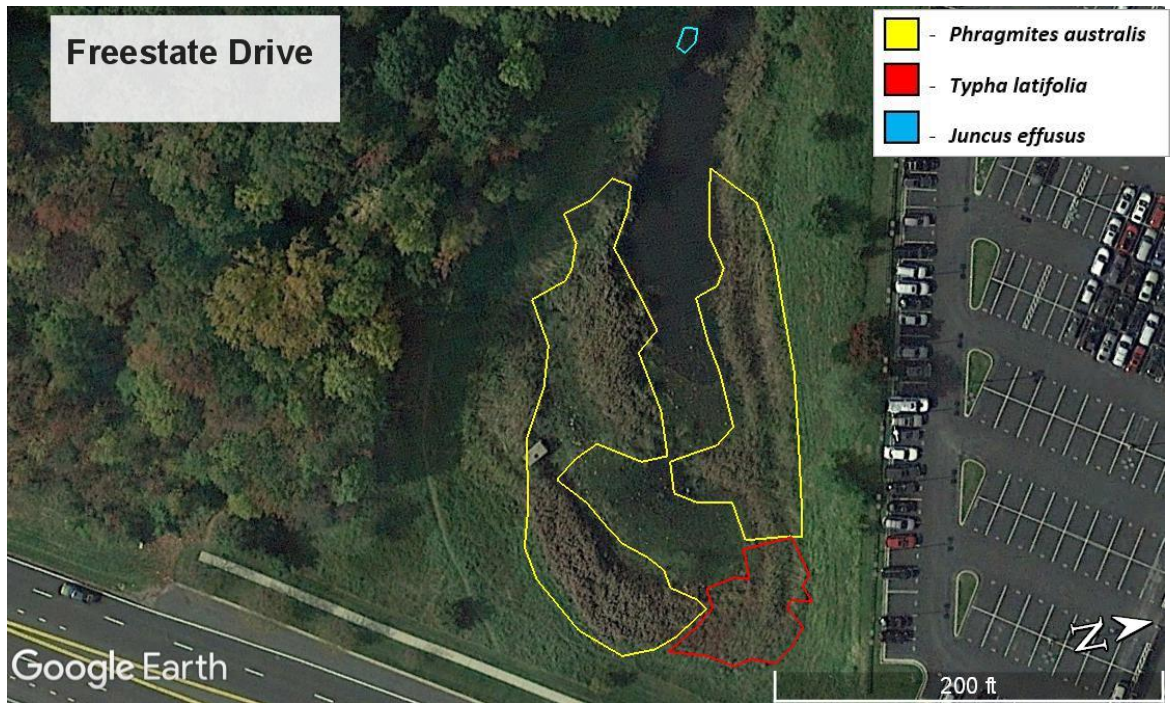


Figure 19: Aerial photo of the pond at Freestate Drive ($39^{\circ}07'32.47''$ N, $76^{\circ}49'27.32''$ W, Howard County, Maryland) with the vegetative stands of *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* defined by color.

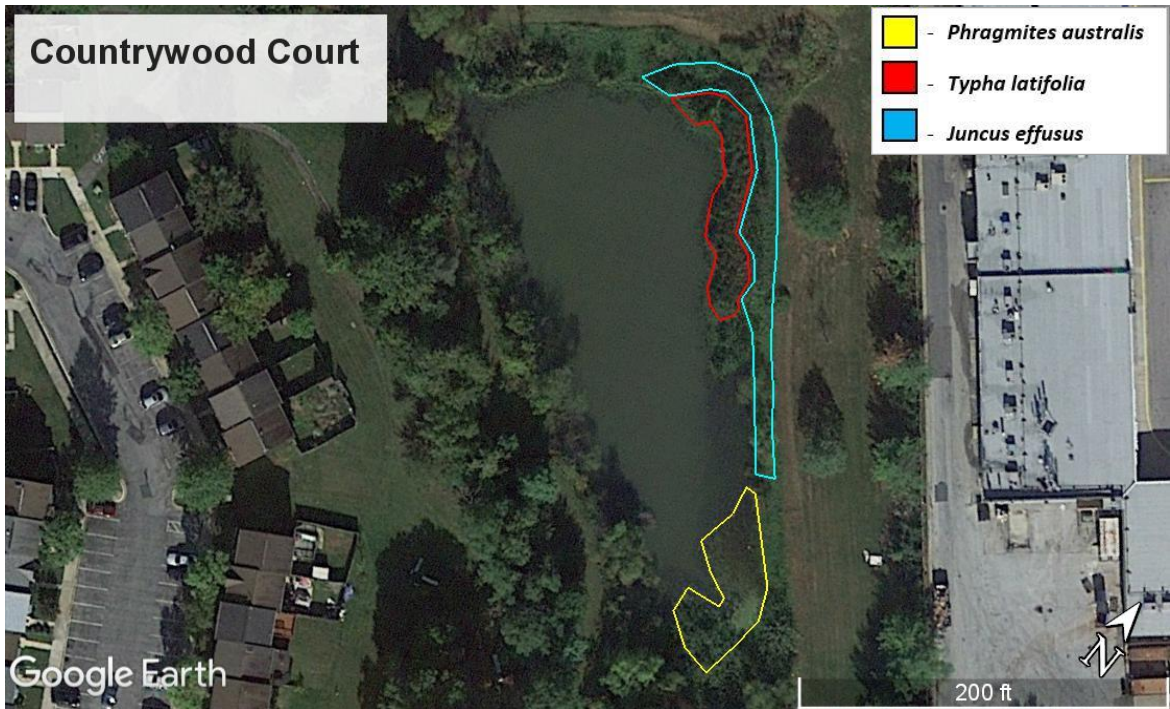


Figure 20: Aerial photo of the pond at Countrywood Court ($38^{\circ}54'50.62''$ N, $76^{\circ}53'06.28''$ W, Prince Georges County, Maryland) with the vegetative stands of *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* defined by color.



*Figure 21: Experimental mesocosms representing *J. effusus*, *P. australis*, *T. latifolia* with varying densities (low, medium, high) were constructed from white 2 G buckets with inserted Styrofoam and dowel rods to mimic the six treatment combinations based on field conditions.*

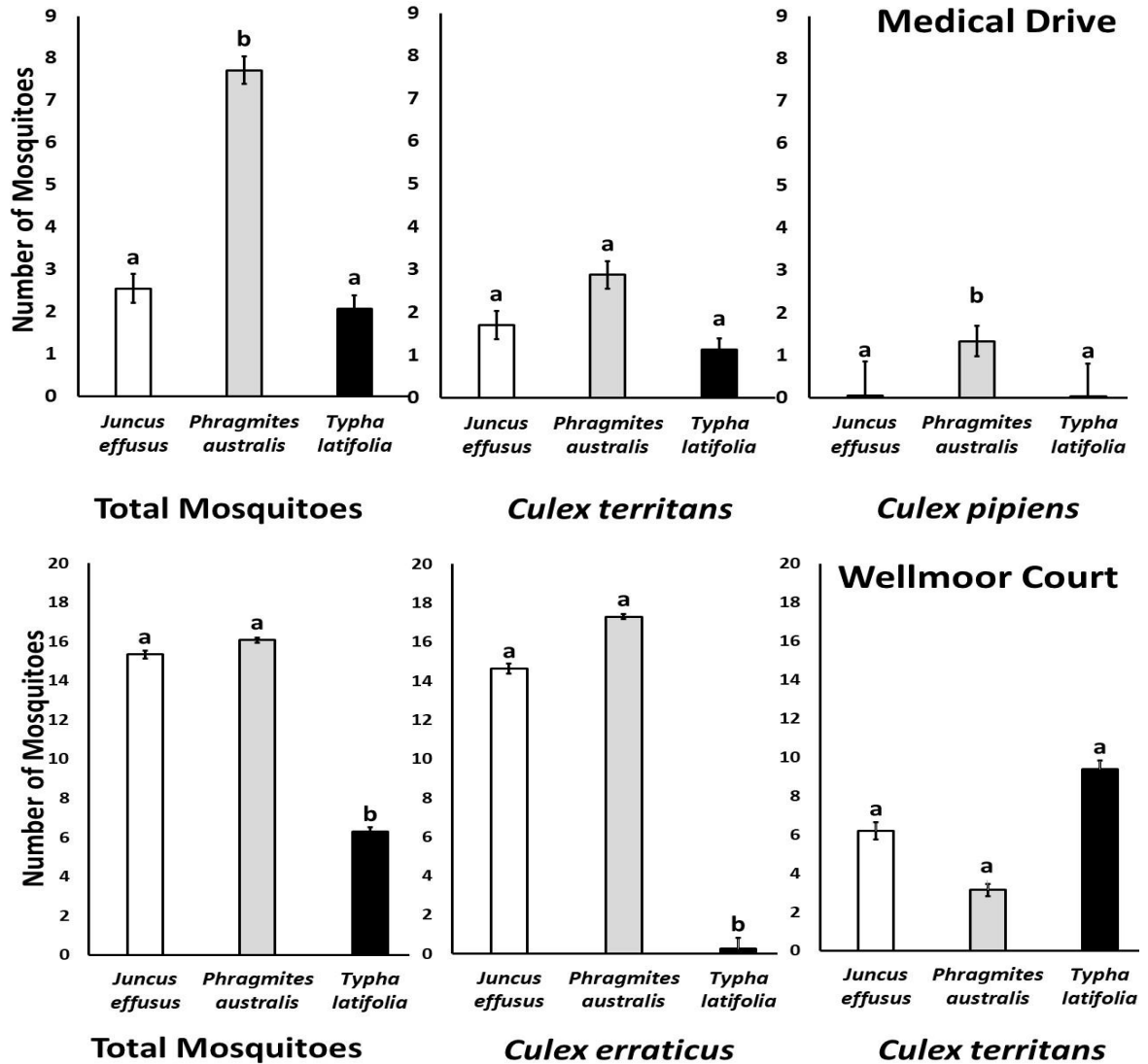


Figure 22: Mean number of third and fourth instar mosquito larvae within *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* at Medical Drive and Wellmoor Court study sites. The means of the total mosquito population and the two most abundant mosquito species sampled within each plant type were analyzed. Bars with letters above them show statistical significance at a 0.05% level of significance.

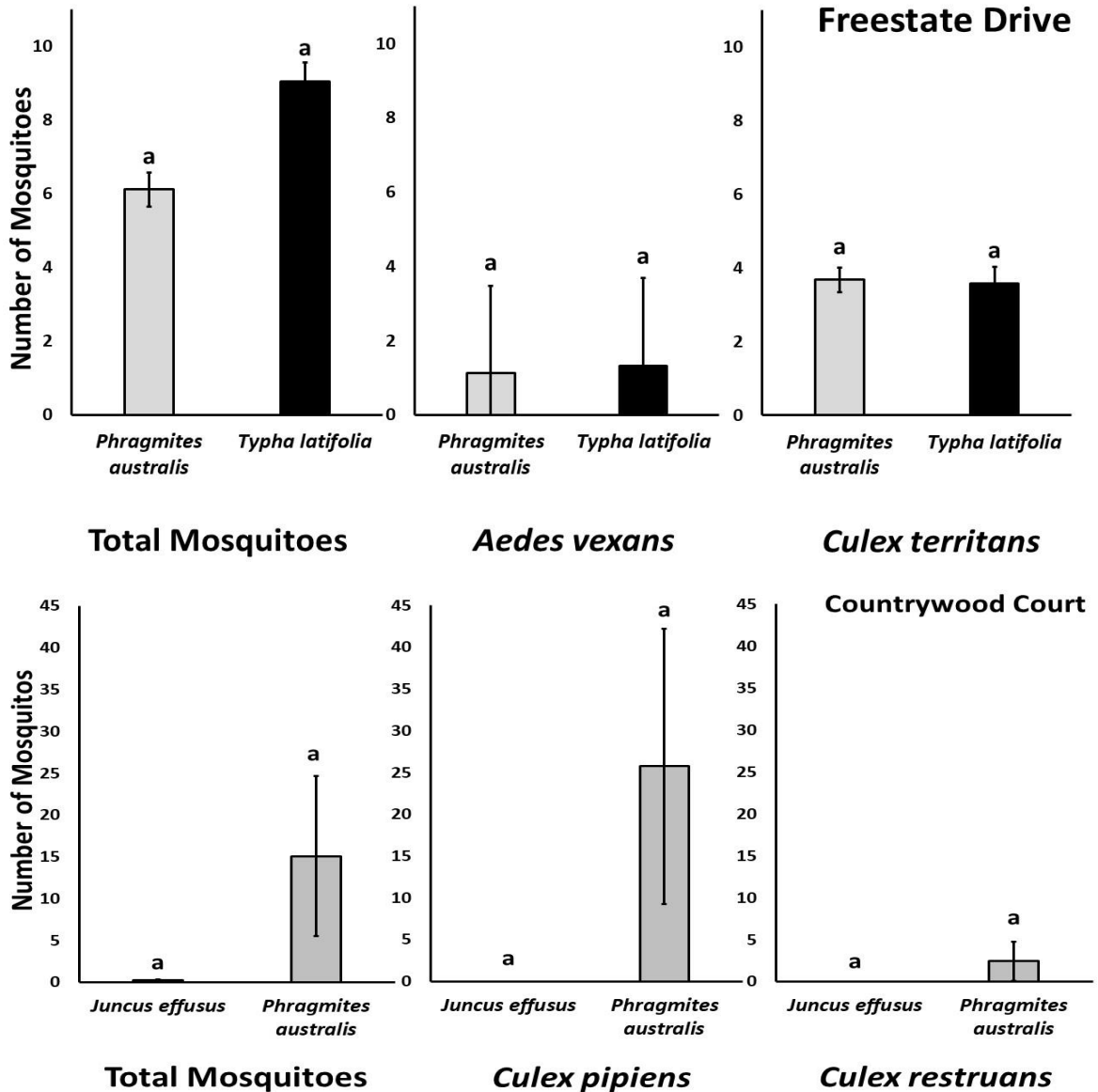


Figure 23: Mean number of third and fourth instar mosquito larvae within *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* across in the ponds at Freestate Drive and Countrywood Court. The means of the total mosquito population and the two most abundant mosquito species sampled within each plant type were analyzed. There was no statistical significance at a 0.05% level of significance between mosquito densities and plant type.

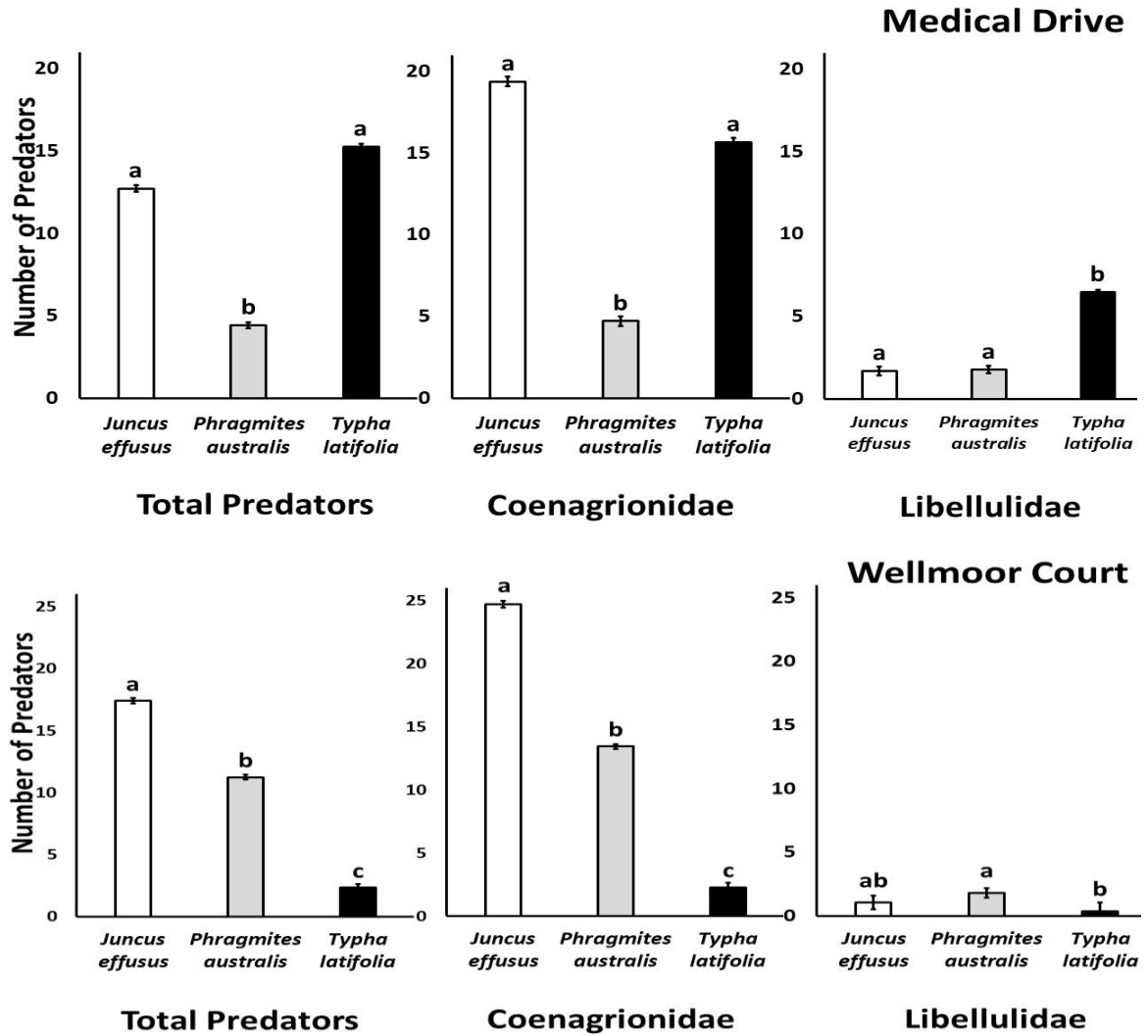


Figure 24: Mean number of predators within *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* within the ponds at Medical Drive and Wellmoor Court. Within each pond the means of the total predator population and the two most abundant predators sampled within each plant type were analyzed. Bars with letters above them show statistical significance at a 0.05% level of significance.

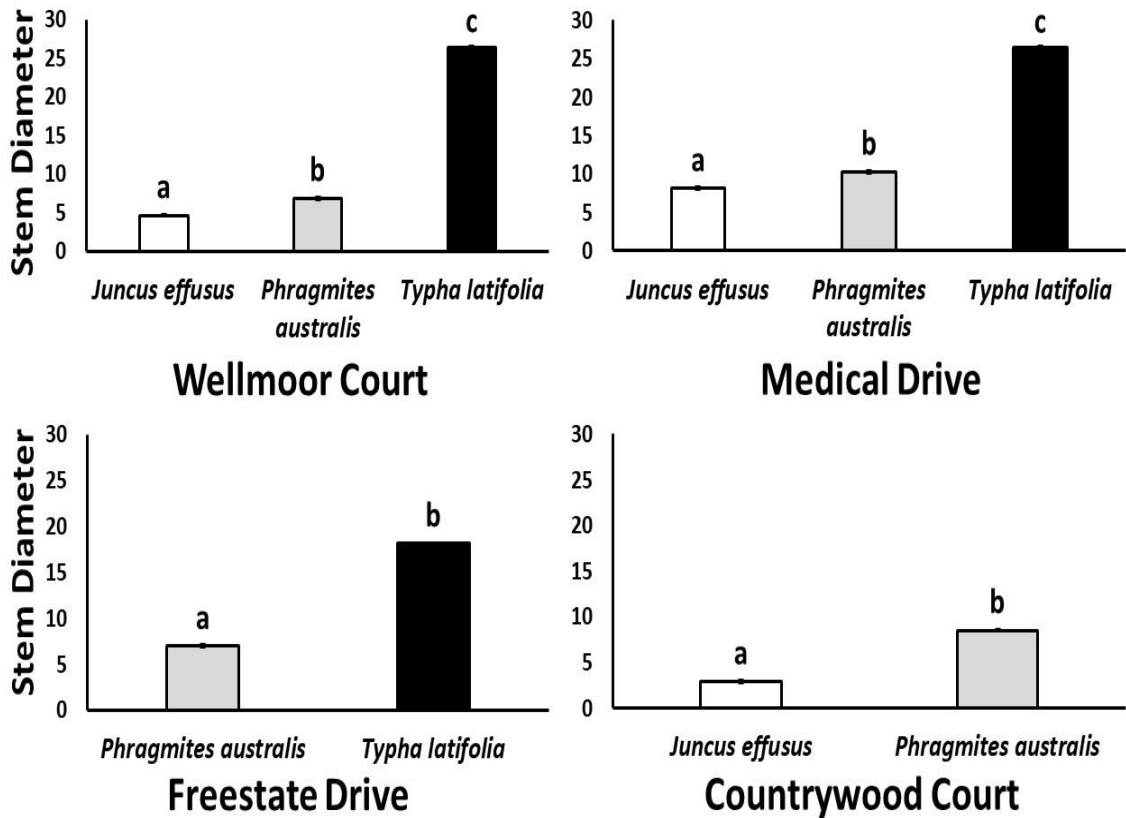


Figure 25: The mean plant stem diameter was compared between *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* within each pond. Bars with letters above them show statistical significance at a 0.05% level of significance. In all ponds *Typha latifolia* had a significantly larger stem diameter than *Phragmites australis*.

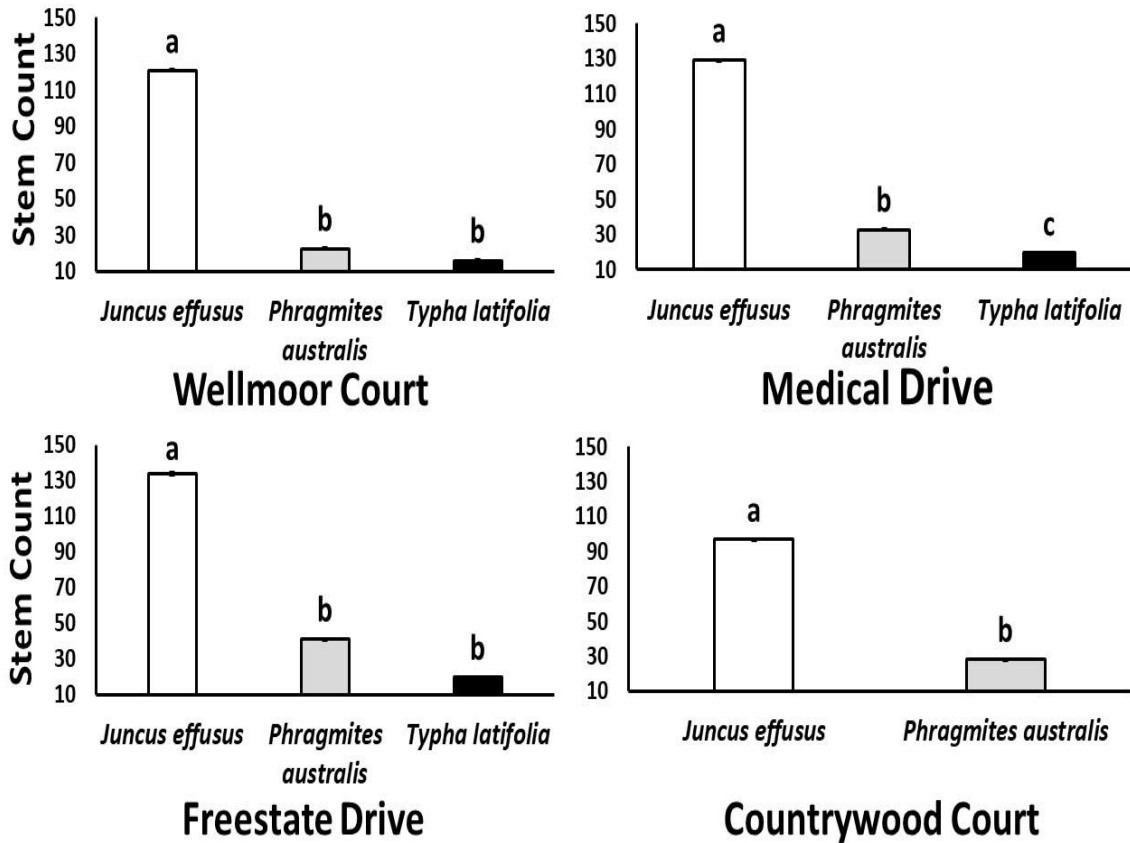


Figure 26: The mean number of plant stems within randomly placed quadrats were counted were compared between *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* within each pond. Bars with letters above them show statistical significance at a 0.05% level of significance.

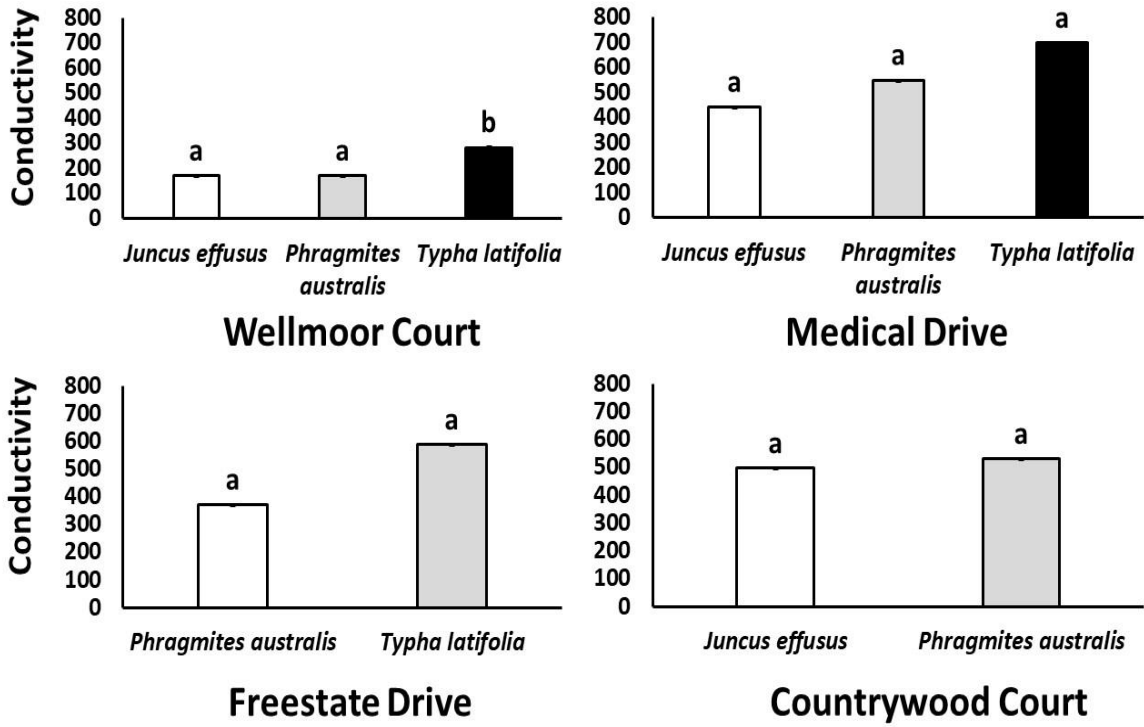


Figure 27: The mean water conductivity was compared between stands of *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* within each pond. Bars with letters above them show statistical significance at a 0.05% level of significance.

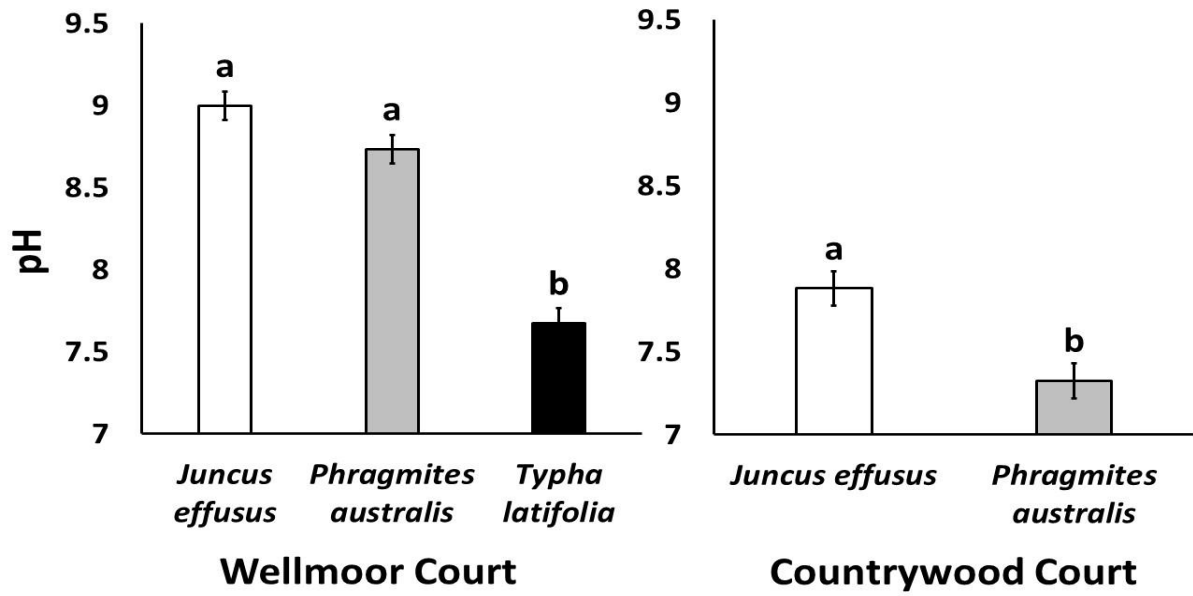
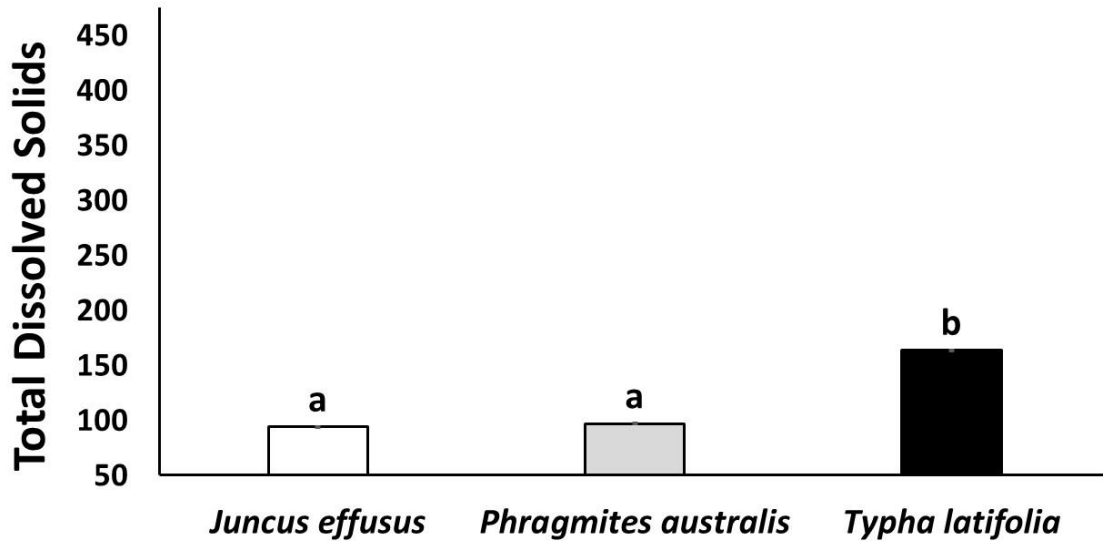


Figure 28: Mean levels of water pH was compared between stands of *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* within each pond. Bars with letters above them show statistical significance at a 0.05% level of significance.



Wellmoor Court

Figure 29: Mean values of the total dissolved solids within the water was compared between stands of *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* within each pond. Bars with letters above them show statistical significance at a 0.05% level of significance.

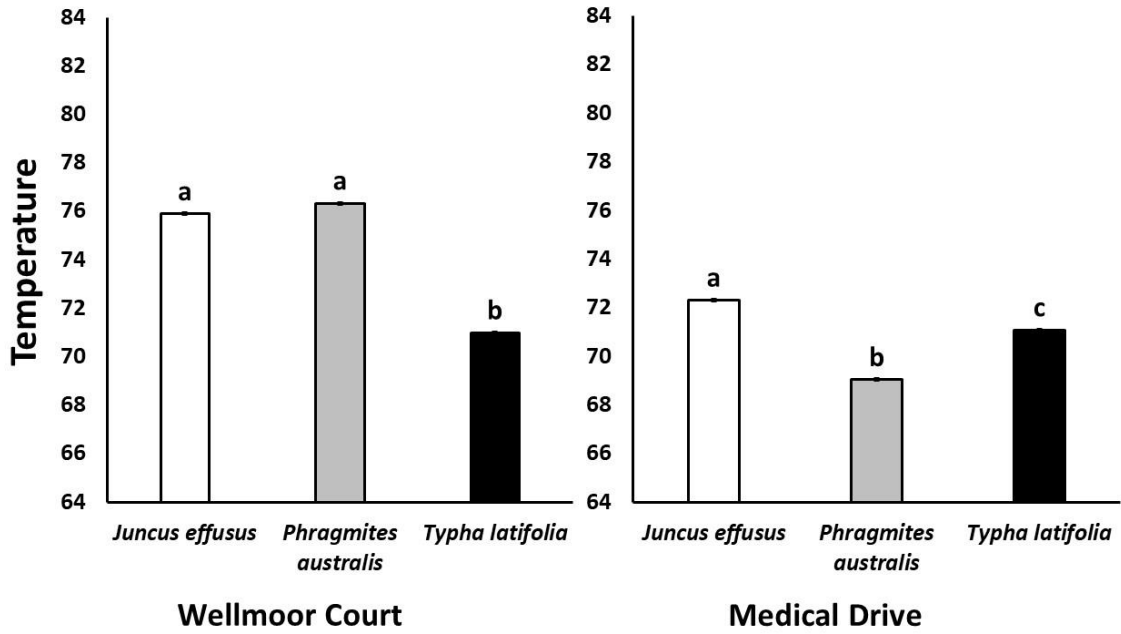


Figure 30: The mean water temperature was compared between stands of *Phragmites australis*, *Typha latifolia*, and *Juncus effusus* within each pond. Bars with letters above them show statistical significance at a 0.05% level of significance.

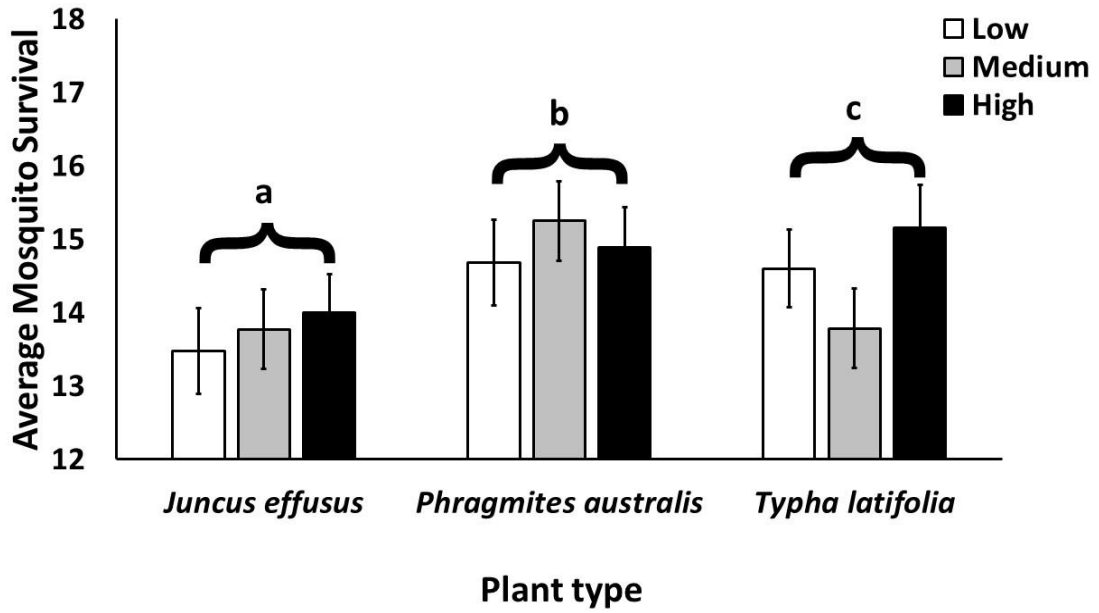


Figure 31: Mean mosquito survival was analyzed between each plant type when considering differences in plant density. Bars with letters above them show statistical significance at a 0.05% level of significance.

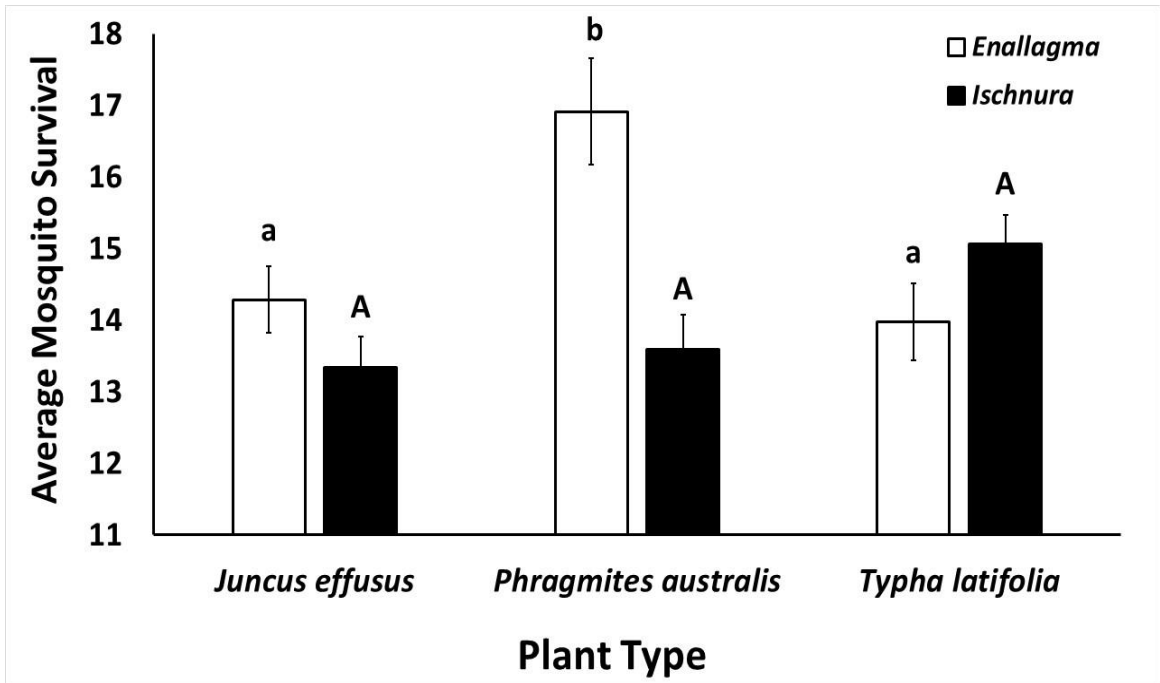


Figure 32: Average mosquito survival within each plant type was analyzed with consideration to the genus of damselfly nymph present in the trial. Bars with letters above them show statistical significance at a 0.05% level of significance.

Table 5: Mosquito Species Composition between the four ponds Medical Drive, Wellmoor Court, Freestate drive, and Countrywood Court. Complete third and fourth instar populations along with early instar and pupae data are presented although analysis was performed on third and fourth instar data only due to the ability to identify to species.

	Medical Drive	Wellmoor Court	Freestate Drive	Countrywood Court	Species Grand Total
LATE INSTAR MOSQUITO					
<i>A.vexans</i>	8	0	748	0	758
	(0.02015)	(0.00000)	(0.69841)	(0.00000)	(0.10877)
<i>An.quadrimaculatus</i>	0	40	0	0	40
	(0.00000)	(0.01545)	(0.00000)	(0.00000)	(0.00574)
<i>An.bradleyi</i>	0	42	1	0	43
	(0.00000)	(0.01622)	(0.00093)	(0.00000)	(0.00617)
<i>C. perturbans</i>	0	0	0	0	117
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.01679)
<i>Cx. territans</i>	245	570	224	0	1039
	(0.61713)	(0.22016)	(0.20915)	(0.00000)	(0.14909)
<i>Cx.erraticus</i>	43	1896	16	0	1955
	(0.10831)	(0.73233)	(0.01494)	(0.00000)	(0.28053)
<i>Cx.salinarius</i>	8	1	51	3	63
	(0.02015)	(0.00039)	(0.04762)	(0.00442)	(0.00904)
<i>Cx.pipiens</i>	68	6	25	618	717
	(0.17128)	(0.00232)	(0.02334)	(0.91016)	(0.10288)
<i>Cx.restruans</i>	0	0	0	58	58
	(0.00000)	(0.00000)	(0.00000)	(0.08542)	(0.00832)
<i>U.sapphirina</i>	25	34	6	0	65
	(0.06297)	(0.01313)	(0.00560)	(0.00000)	(0.00933)
LATE INSTAR TOTAL	397	2589	1071	679	4855
EARLY INSTAR AND PUPAE					
<i>Aedes Early instar</i>	0	0	2	0	
<i>Aedes pupae</i>	0	0	0	0	
<i>Anopheles Early instar</i>	215	480	14	19	
<i>Anopheles pupae</i>	0	3	0	1	
<i>Culex Early instar</i>	619	493	43	8	
<i>Culex pupae</i>	21	279	7	26	
<i>Uranotaenia Early instar</i>	0	0	0	0	
<i>Uranotaenia pupae</i>	3	0	0	0	
TOTAL POPULATION	1255	3844	1137	733	6969

Table 6: Predator Composition table for Medical Drive and Wellmoor Court. Complete predator population data presented on all predator species identified down to Family.

	Medical Drive	Wellmoor Court	Species Grand Total
PREDATORS			
<i>Anisoptera</i>			
<i>Libellulidae</i>	288	141	429
	(0.20616)	(0.09469)	(0.14865)
<i>Aeshnidae</i>	3	28	31
	(0.00215)	(0.01880)	(0.01074)
<i>Zygoptera</i>			
<i>Coenagrionidae</i>	1007	1010	2017
	(0.72083)	(0.67831)	(0.69889)
<i>Baetidae</i>	4	128	132
	(0.00286)	(0.08596)	(0.04574)
<i>Caenidae</i>	0	14	14
	(0.00000)	(0.00940)	(0.00485)
<i>Notonectidae</i>	2	21	23
	(0.00143)	(0.01410)	(0.00797)
<i>Belostomatidae</i>	4	13	17
	(0.00286)	(0.00873)	(0.00589)
<i>Veliidae</i>	8	43	51
	(0.00573)	(0.02888)	(0.01767)
<i>Hydrometridae</i>	0	22	22
	(0.00000)	(0.01478)	(0.00762)
<i>Mesoveliidae</i>	18	7	25
	(0.01288)	(0.00470)	(0.00866)
<i>Dytiscidae</i>	54	60	114
	(0.03865)	(0.04030)	(0.03950)
<i>Haliplidae</i>	2	2	4
	(0.00143)	(0.00134)	(0.00139)
<i>Hydrophilidae</i>	7	0	7
	(0.00501)	(0.00000)	(0.00243)
POPULATION TOTAL	1397	1489	2886

Table 7: Means and standard error, including ranges, for plant stem diameter and plant density measures of *P. australis*, *J. effusus*, and *T.latifolia* in all four ponds in the field.

Pond	Plant	Average Stem Diameter (mm)	Average Stem Density
Countrywood Court	<i>J. effusus</i>	2.9167 ± 0.1069 [3.7]	96.8039 ± 0.1858 [94]
	<i>P. australis</i>	8.5100 ± 0.05420 [7.2]	28.0643 ± 0.1976 [40]
Freestate Drive	<i>J. effusus</i>	2.5769 ± 0.1120 [2.3]	133.96 ± 0.4956 [352]
	<i>P. australis</i>	6.9661 ± 0.08833 [13.8]	41.0882 ± 0.3282 [52]
	<i>T. latifolia</i>	18.1176 ± 0.06520 [51]	19.6016 ± 0.3384 [25]
Medical Drive	<i>J. effusus</i>	8.1431 ± 0.1109 [10.9]	129.33 ± 0.1128 [97]
	<i>P. australis</i>	10.2691 ± 0.1080 [15.1]	32.8334 ± 0.1285 [34]
	<i>T. latifolia</i>	26.4405 ± 0.1009 [41.1]	19.3332 ± 0.1416 [22]
Wellmoor Court	<i>J. effusus</i>	4.6805 ± 0.1219 [8.3]	120.73 ± 0.1609 [140]
	<i>P. australis</i>	6.8828 ± 0.1120 [11.1]	22.4676 ± 0.1663 [59]
	<i>T. latifolia</i>	26.3772 ± 0.1017 [33.7]	16.0093 ± 0.1800 [12]

Table 8: ANOVA results of all plant type, plant density, dragonfly genus and their interactions on predation of *Cx. pipiens* in mesocosms that mimicked *P. australis*, *T. latifolia*, and *J. effuses* in a controlled laboratory experiment. Replicate trials of the experiment were conducted over time and date of trial of was included in the model as a random variable.

Source	<i>df</i>	<i>F</i>	<i>P</i>
Plant	2	3.53	0.0351
Density	2	0.58	0.5643
Dragonfly Genus	1	0.88	0.3516
Plant x Density	4	0.075	0.5594
Dragonfly Genus X Plant	2	3.24	0.0456
Dragonfly Genus X Density	2	0.92	0.4030
Dragonfly Genus X Plant X Density	4	0.48	0.7468
Error	63		

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