The Problem, One Solution, and The Future
An Investigation of Current and Future Insect Pest Management

By

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CERTIFICATE OF APPROVAL

Honors Thesis

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Chapter 1: The Problem

Introduction

The rise in use of chemical insecticides from the 1940s through the 1970s is popularly credited with being a driving factor behind the concurrent ‘Green Revolution.’ During this period, agriculture expanded rapidly. Even and Gollin (2003) noted the vast increases in crop globally.

From high yield varieties of crops to advances in molecular genetics, the Green Revolution has systematically reworked the framework for how we produce and distribute food. There is little wonder, then, that the Green Revolution and its overuse of pesticides has also brought about great threats to human health. Aside from the environmental impacts (which are outside the scope of this work), the influences of insecticides on our health has potentially serious consequences. In this thesis, I detail some of the benefits and risks that we face as future policy makers to ensure that we use our toxic pesticides wisely.

Possible Human Health Issues

There is a dearth of information about the harmful consequences of exposure to pesticides on human health. A few studies revealed that short term exposure to pesticides is correlated with minor skin irritations while long term exposure is correlated with cancers (CDC systematic review, 2007). More studies on the positives and negatives of pesticide use are needed.

Broadly speaking, pesticides might affect the disadvantaged groups (socially, culturally, economically, culturally, linguistically.) that cannot fight or otherwise recompense themselves more negatively. For example, the poor, black citizens of Triana, Alabama were exposed to high levels of DDT leaching from a chemical dump upriver. The diet of this group of townsfolk was largely based on what they could catch from the neighboring Redstone River. The fatty fish they caught (catfish) was a source for bioconcentration of the DDT (EPA Superfund).

Other examples abound. All serve to caution us on the indiscriminant use of pesticides. As the citizens of Triana learned, thoughtful policies on pesticide use could have saved not only the contamination, but also the expensive and time consuming cleanup and rehabilitation efforts that followed.

Increased Resistance

Since DDT was widely implemented decades ago, a plethora of new pesticides have been developed to further combat a developing problem, the resistance to pesticides by insects. Similar to antibiotic resistance, insect resistance to pesticides is associated with the following phenomenon: a single or multiple doses of a pesticide to a pest that does not kill all the target insects. For one reason or another (slight variations in the genetic sequence) a few insects survive the chemical assault. The survivors reproduce and pass on their traits to their offspring that, in turn have that same resistance to the insecticide. Over hundreds of thousands of generations, insects will continue to pass on their resistant traits until the pesticide is rendered ineffective.

As John Ceccatti states in his 2004 review, “we humans have had to modify our own tactics to keep up with the increased resistance to pesticides found in many insects.” He notes with interest the mission of the Entomological Society of America (ESA) to minimize pesticide resistance in insects by requiring clear directions and use guidelines. This mission has environmental and economic benefits in the sense that fewer and smarter applications of pesticides are a simple, necessary step to mitigate the inevitable tide of insect resistance.

New Classes of Pesticides

Some of the greatest achievements in insect control have occurred because of research and the development of newer classes of insecticides. These insecticides are highly selective rather than broad spectrum as older insecticides were. This is important because older insecticides would kill the target species as well as non-target, often beneficial species. Thus, the net good accomplished by the insecticides was weighed down by a net loss. This net loss was not true of the newer insecticides. Furthermore, the new, targeted insecticides have limited persistence in the environment, break down with extended exposure to ultraviolet light from the sun and also have lower mammalian toxicities (Gentz 2008). Most of the new insecticides fall within the following chemical categories: pyrethroids which are derived from similar compounds found in chrysanthemums; neonicotinoids which are related to nicotine and target the nervous system of insects; and insect growth regulators which can stop the development of insects at the immature stage, thus preventing them from reaching sexual maturity and reproducing.

Today, the philosophy for insect management can be summarized as an ‘all of the above’ approach. There is no magic bullet. In the successive chapters, I will summarize an experiment dealing with biological control of pest species, as well as other and more varied approaches to controlling social insects. Finally, I will conclude with an idea for future studies that will contribute to the growing body of research into ecologically sensitive insect control.

Chapter 2: One Solution

<u>Introduction:</u>

The red imported fire ant, *Solenopsis invicta*: Buren, is a highly invasive pest species that originated in Amazonian habitats of South America. Its estimated arrival time and place in the United States was in the early 1930s in the Mobile, Alabama region. Thereafter, the imported fire ant spread across the southern United States limited only by cold temperatures or insufficient moisture. Since its introduction and range expansion into the United States, *S. invicta* has displaced a number of native ant species as well as and other arthropod species (Porter et al 1990). *S. invicta* has been most successful colonizing human-altered environments. It thrives in open lawn spaces such as golf courses, backyards, landfills and other suburban and urban habitats (Tschinkel 1988). Another reason for the rapid spread of *S. invicta* is its nature as a generalist, opportunistic predator and scavenger, consuming any food source it encounters (Vinson et al 1986).

As a consequence of its successful invasion of the United States, *S. invicta* has had significant socioeconomic impacts as well. For example, *S. invicta* has caused billions of dollars annually in sectors ranging from agriculture and infrastructure to household and recreation losses (Gutrich et al 2007). These costs include their aggressive nature, painful sting, and damaging tunnels to roadways in Florida and North Carolina (Miller et al. 2000; Thompson et all 2001; Vinson 1997; Williams et al 2001; Wojcik et al 2001; Banks et al 1990). Chemical control strategies have played a crucial role in the integrated pest management (IPM) techniques used to control the invasion of *S. invicta* (Vinson 1997; Williams et al 2001). Heavy use of chemical insecticides and herbicides have damaged farming practices and degraded the natural environment. To this end, organic farming has been encouraged to reduce the use of chemicals. Organic farming yields healthier soil and more biodiversity in soil microorganisms (Stoksad

2002). The same study showed the presence of more earthworms and other pest-eating arthropods. Moreover, organic farming techniques are nearly as productive as conventional farming for some crops. These facts suggest that the *S. invicta* invasion should not be approached using the old chemical warfare control methods. *S. invicta* is here to stay. It is important to consider whether this pest ant can be of some use *as* a predator or scavenger on other crop pests That is to say, is there some utility that can be extracted from *S. invicta*.

It is well documented that *S. invicta* colonies prefer warm, humid environments (Wojcik et al 2001; Vinson 1997). It is common knowledge that mosquitoes also inhabit warm, humid environments. Mosquitoes are vectors in the spread of diseases ranging from yellow and dengue fevers, to malaria, West Nile virus, and encephalitis (Gubler et al 1995; Lounibos et al 2000 Lounibos 2002; McNeil 1976; Soper et al 1943; Taylor 1951). Summerlin et al. (1984) observed *S. invicta* entering tree cavities and depositing sediments in order to dry out small collections of water to access populations of mosquito larvae in those niches. Furthermore, a recent laboratory study found that *S. invicta* preyed on mosquito eggs, larvae, and pupae on moistened paper surfaces (Duhrkopf et al 2011). This study showed the potential for *S. invicta* to prey on these mosquito life stages in the field in water as deep as four millimeters. Given this research and background, we hypothesized that *S. invicta* might play an important role in managing mosquitoes. Thus, we decided to investigate the potential for aquatic predation on the part of *S. invicta*. A series of laboratory experiments were designed to characterize the ability of *S. invicta* to forage for prey in aquatic settings, with particular attention to the genus *Culex* of mosquitoes which have been implicated in the spread of West Nile, encephalitis, and malaria (Hammon et al 1942; Sardelis et al 2001; Scholte et al 2003).

Methods:

General Setup: Three laboratory experiments were conducted at the University of South Florida St. Petersburg University Research Laboratory. Colonies of *S. invicta* were collected from north Pinellas County, Florida. Colonies were dug up using a shovel and placed into five gallon buckets. The upper six inches of the buckets' interiors were coated in talcum powder to prevent the workers from escaping. The buckets were then brought back to the lab where the colonies were extracted by steadily dripping water into each bucket at the approximate rate of one drop per second. This setup was left overnight. The following day, the floating colonies of ants were scooped up and placed into a large tupperware box (8 liter volume). The upper extremities of the interior of the container are also coated with talcum powder to prevent worker escape. The substrate used in each of these containers was a paper towel with approximately one hundred milliliters of fine sand sprinkled across it. One petri dish (diameter = 30 cm) was placed on end of this rearing habitat with a small hole in the lid to allow workers to ingress and egress. The bottom of the petri dish was also coated with a moistened piece of plaster of Paris to help ensure sufficient humidity levels within the artificial nest. Two small petri dish bottoms (15mm) were placed on the other end of this box, one filled with distilled water and the other with a twenty five percent sucrose solution. Nearby, a few frozen crickets were placed to ensure a source of protein for the colony. The colonies were maintained in this setting for thirty days to ensure acclimatization to the laboratory. Before the beginning of each experiment, each colony had food and water withheld for a period of seventy two hours to ensure hunger during the experimental frame (Cassill and Tschinkel 1999). Each of these stock colonies was divided into a number of sub colonies for each experiment. New field colonies were obtained and reared between successive experiments. Live crickets were purchased and frozen. The blackworms

(*Lumbriculus variegatus*) were obtained from a local fish store. The mosquito larvae were purchased from Carolina Biological.

Data Analysis: Data were analyzed using JMP Statistical Software. If data were not normally distributed, data were log-transformed. Parametric tests were used to determine differences between treatments and controls.

Experiment 1: The cricket experiment was established by splitting up a colony of fire ants into three sub colonies. Two small petri dishes (35mm diameter) were placed opposite the artificial nest. Three crickets were placed in one of the dishes and submerged with water to a surface depth of five millimeters. The second petri dish was filled just with water as a control. A small blade of grass (10 mm long) was bent as a bridge into each of the dishes to facilitate ease of access. Counts of the number of ants present at each petri dish were then taken at twenty-four, forty-eight, and seventy-two hour intervals. The data was analyzed with JMP Statistical software. This experiment was repeated twice more for a total of replicates nine sub colony replicates.

Experiment 2: Blackworms: One stock colony was divided into 4 sub colonies. The sub colonies were reared for one week under standard laboratory conditions of food and light. One sub colony, randomly selected, was designated the treatment group; the remaining 3 were control groups. The treatment group was provisioned with two petri dishes (diameter = 35mm) containing 10ml of water. Approximately 25 blackworms were submerged in one of the water dishes. Three other dishes contained water as controls. Counts of ants on the rim or in the dish were recorded at 5 min. intervals for 1 hr, at 24 hrs, 48 hrs and 72 hrs.

Experiment 3: Mosquitoes. . This experiment was set up using the same procedures as in the blackworm experiment. *Culex* larvae were submerged in water. Data was collected as in experiment 2 as well.

Results:

There was a significant difference in the number of ants foraging for submerged crickets relative to ants foraging for water (Fig. 1; T-test: $t = -22.59$; $p <.0001$). There was a significant difference in the number of ants foraging for submerged blackworms relative to ants foraging for water (Fig. 2; one-way ANOVA; $p <.0001$). There was a significant difference in the number of ants foraging for submerged mosquito larvae than for water (Fig. 4; T one-way ANOVA; $p <.0001$).

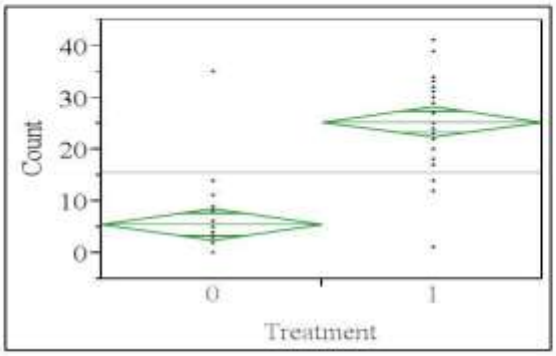

Figure 1: Foraging on crickets versus water. Differences were significant. 0 = water; 1 = submerged crickets.

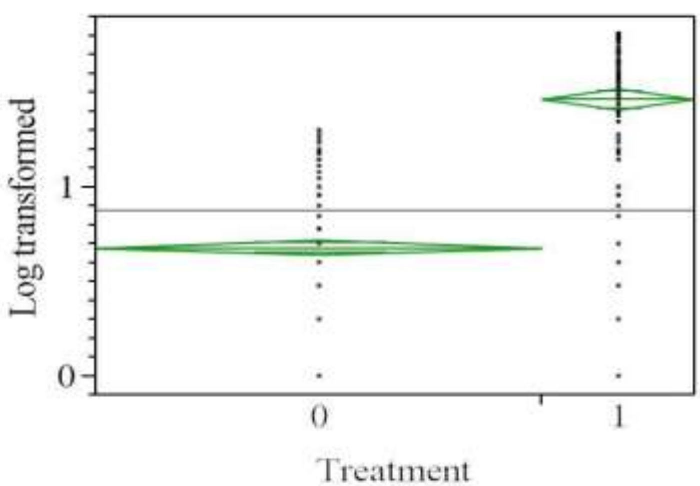

Figure 2: Foraging on blackworms versus water. Differences were significant. 0 = water; 1 = submerged worms.

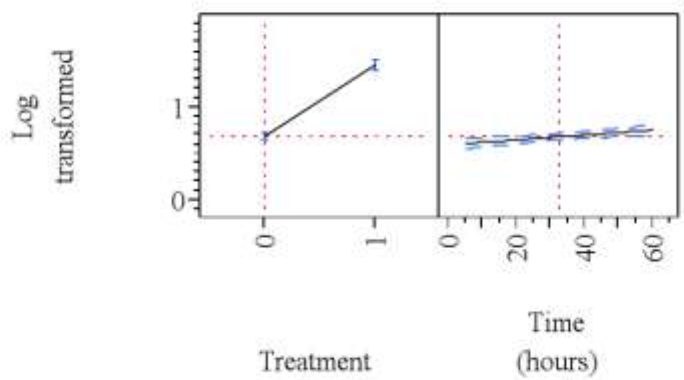

Figure 3: Measure of effect size of treatment versus time for blackworms. Both were significant. Treatment accounted for 98.6% and time for 1.4%.

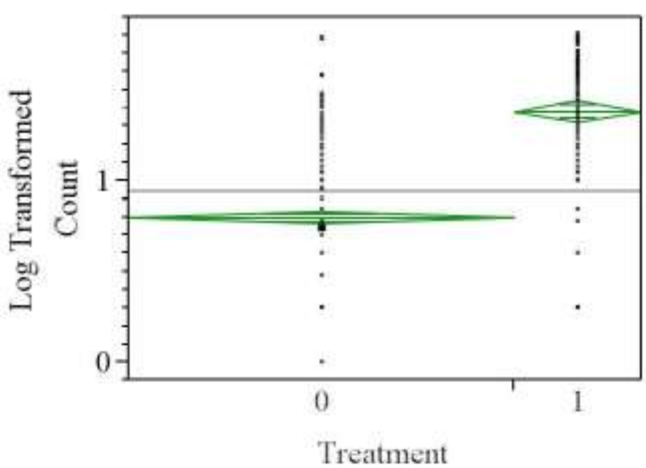

Figure 4: Foraging on mosquito larvae versus water. Differences were significant. 0 = water; 1 = submerged larvae.

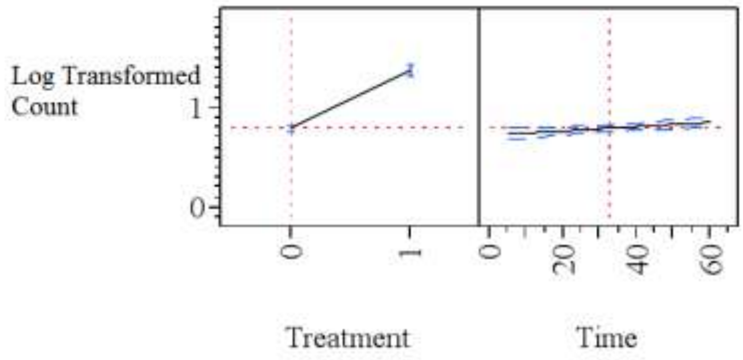

Figure 5: Measure of effect size of treatment versus time for mosquitoes. Only treatment was significant. Treatment accounted for 99.7% and time for 0.3%.

<u>Discussion:</u>

Our experimental results suggest that the fire ants are capable of foraging for submerged prey relative to the water control. These results are preliminary. Of note is the fact that fire ants clumped prey together, near the edge of the petri dish. In addition, ants cut bits of paper and placed it in the water to absorb it and then used the paper bits as a bridge to reach submerged prey. Nonetheless, the results suggest that fire ants are capable of preying on aquatic pests. Whereas they will not likely become a viable biocontrol option for mosquito larvae, imported fire ants might be useful in some circumstances for controlling pests of crops and gardens.

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Chapter 3: The Future

Introduction

The complexities of pest management strategies such as integrated pest management, push-pull techniques, and conservation biological control make it difficult to compare and contrast. Nevertheless, we attempt to do so here. Whereas each of the three strategies has-beens historically tested on its own, it is ever more important to examine in depth how they can work together in an interdisciplinary fashion. It is precisely this interdisciplinarianism inherent to the field of urban ecology that provides the remarkable insight on how such varied strategies can come together to better achieve their own goals.

In light of the conceptual framework described, we will explore the connection of pest management strategies to urban ecology. We begin by reviewing of the most recent and prevalent literature on integrated pest management (IPM), Push-Pull Strategies, and Conservation Biological Control. Next, we review the impact of social insects on urban and agricultural environments. Last, we integrate pest control, urban ecology and social insects to demonstrate the importance of collaboration among different scientific disciplines to effectively elucidate more effective and sustainable was of living with and managing pests.

Integrated Pest Management

The goal of Integrated Pest Management (IPM) is to increase crop production and reduce environmental degradation. Certainly, insects, rodents, nematodes, etc. do significant damage to crop production; thus- reducing the impact of these pests is the solution to increasing food stores (Trivedi 2011). However, we must do so in ways that mitigate chemical usage. By combining mechanical, biological, and chemical methods to reduce pest populations on crops, several common problems in agriculture can be addressed. Among these problems are pesticide resistance (Alam 2000), fungicidal resistance (Staub 1984), and non-target species impact

(Vaughn 2003). Similarly, pesticide residues on crops have caused concern among the consumer population (Arora 2006). It is precisely these problems which IPM can help solve.

The fundamental goal of IPM is to keep pest populations below economically damaging levels. This level is often arbitrary, though the exact point at which it is set is not entirely important. More so, IPM is based on the principle that rather than eliminating every pest organism, sufficient progress to limiting economic damage can be achieved by limiting the population of pest organisms *below* that level at which significant economic damage is deemed to be done (Trivedi 2011). There are several approaches to implementing IPM. Habitat analysis can provide a framework for manipulating IPM practices to better adapt to local environments with customized strategies. This individualism arise from modern monoculture agricultural practices which encourage severe declines in not only crop biodiversity but in native insect population diversity as well (Barlow 1983). Whereas natural systems tend to be self perpetuating, human dominated systems tend to do the opposite. Again, habitat analysis can help to maximize the abundance of natural predators and other beneficial organisms in agricultural settings (Kogan 1998).

Pest monitoring is another strategy fundamental to IPM. Mathematical and statistical modeling can supplement real world data to provide more accurate forecasts of where pests can be found and in what quantities. These models have streamlined IPM in the field (Das 2001, Singh 2004). While both habitat analysis and pest monitoring have largely been applied to large-scale agricultural projects to date, there is no reason the same could not and should not be done for urban environments as well. Improvements in IPM on such projects can also take a biological approach through long documented conservation and augmentation of natural enemies

(Thompson 1956), using only readily biodegradable pesticides such as arthropod toxins (Picket 1997), and the use of hormones as repellents or attractants (Cropping 1998).

With potential and realized benefits of IPM, what problems arise? Again, IPM is difficult to apply when it comes to both environmental and regional issues. To address this issue, one must understand the motivations behind IPM. There was enormous economic competitiveness among farmers to increase crop yields (Brewer 2012). The initial development of IPM through the 1950s and ‘60s saw a heavy dependence on the application and timing of insecticides at the same time as pest sampling and economic threshold levels were utilized to best determine where IPM should be considered (Pedigo 1986). These techniques revealed the effectiveness of IPM especially on a small and local scale and as long as it was applied in individual fields or small clusters of fields. Because management decisions were made at a local level, the incentive structure for implementing IPM centered on a market that valued costs and benefits (Pedigo 1986). The only exceptions to such practices at the time were government agencies and cooperative extensions of state universities which restricted pesticide use and provided consulting help on a broader scale. In addition, there was a general shift away from small scale farms to large scale agriculture (Kogan 1998). New methods in host plant resistance, crop biotechnology, and pesticides helped farmers plan better before the planting season, though the field was still the focus of most pest management strategies (Ratnadass 2012). Attributable to contemporary socioeconomic factors, this environment undoubtedly aided in the adoption of IPM and helped mitigate some environmental damage.

Ironically, pesticide use continued to increase and pose a greater threat to environmental risk (Pimentel 1992). Thus, arguments for sustainability and other environmental considerations began to take place in the IPM arena. Researchers concluded that extensive use of pesticides was inconsistent with the broader goals of IPM (Ehler 2006) and began to seek different incentives or policies to encourage farmers to use less damaging IPM methods. The objective was to highlight the use of biological controls in IPM more than the chemical controls on a larger, regional scale (a disincentive for farmers who own small farms) rather than on a smaller scale (where chemical control is much more cost effective on a per acre basis). The implementation of the more advanced IPM strategies required a greater knowledge of agroecology, community networks, etc than the average farmer had. Thus, new incentives that addressed sustainability was needed (Kogan 1998). Again, the advanced IPM on a larger scale tended to be cost prohibitive for farmers. The long term cost savings in limiting pesticide effects on non target organisms, biodiversity loss, and degradation of soil, water and air resources could not immediately be quantified (Pimentel 1992).

It has only been over the last few decades that IPM has begun to develop a more regional coordination to enhance pest management and for longer periods than when applied on a field basis (Zalucki 2009). Special considerations have recently been given to environmental health. For example, over ninety percent of surface and groundwater in the United States has been contaminated by pesticides (Gilliom 2006). These pesticides present a risk to aquatic invertebrates, fish, and humans, and largely enter the water through storm runoff from agricultural and urban areas (Gilliom 2007). Impaired air quality through emission of volatile organic compounds (VOCs) in urban areas has similar effects to that of low altitude ozone, damaging human health (Goodell 2011). In all these cases and more, advanced, environmentally minded IPM strategies have been developed and made available including vegetative groundcover reducing pesticides in runoff (Joyce 2004), sediment traps and vegetative ditch banks (Long 2010), improved pesticide applicators (Grafton 2005), and field margins to promote native wildlife and nutrient filtration (Kleijn 2006).

Large scale IPM can improve decision making. By coordinating individual farm decisions across a broad area, significant leeway to limiting pests below economically damaging levels can be made. The driving force of large scale IPM can come only from the recognition that working together. How then, can recognition and awareness be fostered and what are the approaches to addressing the ‘incentives dilemma’? The desire for community cooperation and relinquishing control of some field-based management decisions must be greater than the desire to control individual fields and farms (Brewer 2012). Various incentives such as the successful eradication of the boll weevil (Knipling 1979) can help reach this tipping point. Regional goals of agricultural benefits should include limitations to income risk through publicly supported financial supports, regulations lax enough to provide private investment, and enhanced environmental quality and countryside aesthetics will follow (Brewer 2012). Other public supports can also be in the form of extension work by state university systems and research promoted through government institutions. Combined with financial incentives, a strong motive should be created to implement these newer IPM techniques.

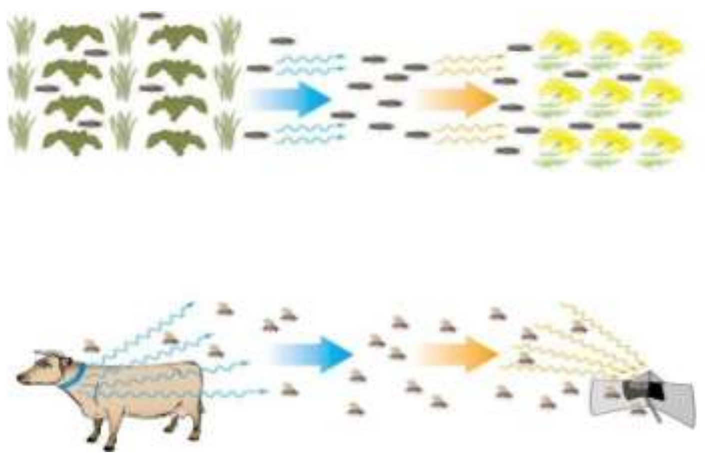
Conservation programs for farms can support these initiatives, too. Agricultural lands can be returned to a natural state to promote conservation and pest management (Firbank 2003). IPM can provide environmental benefits by reversing declines in biodiversity (Benton 2003). Economic benefits are still needed. However, the financial incentives for conservation are expensive to individual farmers and are unlikely to occur without sufficient reason (Firbank 2003). Conservation programs within IPM strategies must be flexible. For example, in the choice of conservation plots in urban to rural settings, some might prefer tree or shrub habitats to promote bird populations (Firbank 2003) whereas entomologists might seek inset preservation and management (Goodell 2011). In this way, species of interest (Firbank 2003), scale of implementation (Merckx 2009), and location (Tscharntke 2005) all have effects on successful implementation of IPM. The value of IPM to conservation is too important to abandon. Further efforts should be made to continue the nascent discussion.

In many ways, this discussion is reminiscent of the tragedy of the commons (Hardin 1968) wherein individual incentives can override the greater good. Smart implementation of IPM through financial incentives for farmers and cooperation between government agencies, state research bodies, and the farmers themselves can help address this potential tragedy of the agricultural commons. In expanding IPM from local to broader scales, longer lasting benefits can be extracted with benefits to both the environment and human health. Both public and private partnerships in conjunction with all interests involved can help provide a solution.

Push-Pull Strategies

Push-pull strategies (PPS) involve the behavioral manipulation of insect pests and their natural enemies via the integration of stimuli that make the protected resource unattractive or unsuitable to the pests (push) while luring them toward an attractive source (pull) from where the pests are subsequently removed (Cook 2007). PPS is a subset of biological control which itself is a subset of IPM. This section is designed to provide a brief review of the literature on the potential for this useful technique to reducing pesticide input, especially in urban areas.

Push-pull strategies are designed to ultimately reduce the number of a pest species on a target (protected) species of plant or animal. Being comprised of a double-ended mechanism, and combining with non-toxic methods to push and pull, PPS can have net positive effects on environmental conditions. Behavioral manipulation, chemical stimuli, and habitat diversification are all important principles of PPS (Cook 2007). Combined with an underlying knowledge of visual and semiochemical stimuli, PPS can be used in conjunction with biological control and conservation biological control as strategies within IPM. The following figure demonstrates effective PPS (Cook 2007).



Here, the ‘push’ can be visual distractions, non-host volatiles, anti-aggregation pheromones, alarm pheromones, oviposition deterrents, and antifeedants. The ‘pull’ can be visual stimulants, host volatiles, aggregation pheromones, sex pheromones, oviposition stimulants, and gustatory stimulants. Thus, a good understanding of pest biology and behavioral and chemical ecology can maximize pest control efficacy and efficiency while simultaneously minimizing environmental effects.

The visual cues can include changes in the host color, shape, or size to confuse the pest and minimize its negative effects. Such changes can be expensive, difficult, or both, to implement (Foster 1997). DEET (N,N-diethyl-3-methylbenzamide) is a popular synthetically produced chemical repellent that can be used more cheaply. However, there is question as to its environmental safety at higher concentrations (Nalyanya 2000). Odor masking strategies used in the push stage involve covering up the host volatiles with something that is repellent to the pest. These often take shape in various herbal extracts or oils such as eucalyptus or camphor and are generally regarded as non toxic and safe (Riddick 2000). The downside to them is that their effective timespan can be short as these essential oils can easily be broken down by sunlight

(Riddick 2000). Semiochemicals, behavior modifying chemicals, can also be used as part of the push. This category deals with the specific ratio of certain volatiles that are found in hosts. By modifying or altering the ratio of these volatiles, pests can be disoriented and repelled by the very plants that would have served as the hosts (Vallat 2005).

Anti-aggregation pheromones can be used. These pheromones are produced by pest species and are attractive at low concentrations but repellent at high concentrations, thereby serving as a control for intraspecific competition. These pheromones can be synthetically produced and dispersed to push pests away from the target (Shea 1995). Alarm pheromones are released by pest species when under attack by their natural enemies. Manufacturing and spraying these chemicals can elicit a response from pest species by reducing their distribution as part of the push strategy (Roditakis 2000). Antifeedants are other chemicals used in the push strategy. They operate by first being produced by certain plants such as neem and can be toxic to pest species at the concentration produced (Jermy 1990). Finally, oviposition deterrents, compounds that prevent or reduce egg laying behaviors, can be used as part of the push to help limit pest populations (Mensah 1996).

At the same time that pests are being pushed away from the target, they can be attracted to a ‘pull’ that further increases treatment efficacy. Pulls are essentially the converse of the push strategy. Whereas the push involved visual repellents, the pull involves visual stimulants. Similarly, attractive host volatiles, sex and aggregation pheromones, and gustatory and oviposition stimulants can enhance response from pests by attracting them away from targets (Cook 2007). The delivery of push and pull stimuli can take different forms as well. The most common are vegetative intercropping and trap cropping. Intercropping can include interspersing parts of the push strategy in and among the target while trap cropping usually takes place around the perimeter of the target and usually involves the pull strategy to achieve a total reduction of pests within and around the target (Khan 1997). As many components of the strategies involve compounds or pheromones as well as essential plant oils, effectiveness can further be increased by applying those pheromones in solution of those essential oils, for example, producing an anti aggregation pheromone within a neem oil (Khan 1997). In addition to simple mechanical trapping (Phillips 1992), PPS include production of antixenotic cultivars (i.e. tomatoes which can be bred to produce a sticky sap on the surface of their leaves) and plant induction (i.e. stimulating plants to produce salicylic acid; Cook 2007). All of these methods work together to deliver PPS directly to the pest.

The most modern PPS is being developed in the poor regions of eastern and southern Africa with thousands of farmers participating in trials to control stem borers in maize and sorghum (Khan 2004). Non host intercropping along with perimeter trap cropping and dispersing of different pheromones are being used. There is also the case of controlling lepidopteran pests such as *Helicoverpa* on cotton using similar techniques in India and Australia (Khan 2004). *Sitona lineatus*, a weevil that attacks leguminous plants in Europe, the Middle East, and the U.S. is also being treated using various semiochemical and other PPS methods. Pesticide use through implementation of PPS has been reduced by forty four percent in treatment of the Colorado potato beetle (*L. decemlineata*) (Martel 2005). Similarly, PPS has been developed successfully in the control of the pollen beetle in oilseed rape (Cook 2006). PPS has further been developed in recent years with work done in the horticultural field (through control of onion maggot and control of thrips on chrysanthemums), forestry (through control of bark beetles on conifers), and veterinary and medical pests (through control of the blood feeding muscid flies, and major disease vectors mosquitoes and midges) (Cook 2007).

The newest application of PPS, however, is the control of urban pests. These are the pests that infest human habitations such as homes, workplaces, schools, and hospitals. One example of urban PPS is in the control of cockroaches, which can transmit disease and produce allergens. The German cockroach (*Blattella germanica*) produced aggregation pheromones in its frass (Cook 2007). A recent PPS dealing with this involved both an insect repellent and a feces contaminated surface as an attractant combined with a food bait (Nalyanya 2000). This PPS was more effective than conventional chemical means of cockroach control. Further development of PPS with cockroaches is in progress using biopesticides as well as chemicals derived from catnip (*Nepeta cataria*) which has shown to be more effective than DEET treatments (Nalyanya 2000).

PPS thus has several advantages and relatively few disadvantages over chemical treatments. The implementations of PPS results in an increased efficiency of the individual push and pull components. Whereas techniques like trapping may work for some species, it will fail for others. In these cases, PPS effectively could combine trapping with something like semiochemical application resulting in a synergistically improved reduction in pest populations (Nalyanya 2000). PPS also provides almost exclusive validity for the use of antifeedants and oviposition deterrents. Whereas these have been used in IPM before, they are only significantly effective in their desired goals when combined with a sufficient pull strategy (Raffa 1998). Similarly, as PPS can concentrate remaining pest populations in confined areas, mechanical trapping then becomes more effective, too, and the need for chemical controls are reduced, further reducing cost, environmental impact, and damage to human health (Martel 2005). This reduction in chemicals further allows natural enemies of pests to propagate and these can then provide further control. The reduction in chemicals also results in less development in resistance among pests much as reduced use of antibiotics in humans results in smaller incidence of resistance development, further reducing costs (Duraimurugan 2005).

The disadvantages to PPS are more political in nature, and tend to be inherent to all pest control strategies, not just PPS (Cook 2007). The development of advanced PPS is often stymied by lack of knowledge and technology resulting in PPS that can cause more harm than good (Cook 2007). Also, the cost of registering different semiochemicals with government agencies can be prohibitive, especially in the developing world. Being a fairly new and sometimes high cost strategy, PPS can be somewhat limited in its adoption on a commercial scale (Cook 2007). This does not preclude the possibility, however, of greater adoption especially at the urban level with local and community gardens and backyard agricultural projects. In these areas in particular, PPS could be a powerful IPM tool in enhancing pest control while at the same time limiting the use of harmful chemical compounds. As technologies and the chemical means behind PPS are likely to improve, its implementation will likely do the same. Just as IPM has been in existence for fifty plus years but has only become prevalent in the last two decades, PPS will likely assume a greater role in pest management.

Conservation Biological Control

Conservation Biological Control (CBC) is another subset of IPM strategies that, much like PPS is fairly new and adaptable to modern times. Whereas it was first conceived of on a small, local scale, evidence is mounting to suggest that its implementation across a larger, landscape scale, including urban landscapes, can promote natural enemy diversity in order to help control pest species. In other words, the ultimate goal of CBC is to conserve those predatory arthropod communities in both rural and urban environments and the biological control services they provide (Tscharntke 2007). Current literature suggests that by implementing CBC on a landscape scale in conjunction with preserving local habitat quality is the most effective way to provide biological control (Tscharntke 2005).

Limiting the viewpoint to only the local scale can lead to an overestimation of natural predator diversity caused by small plot sizes, and enemy communities on a local level tend to be similar to one another due to limited spatial differences (Tylianakis 2005). These effects are mitigated at the landscape level as localized benefits are only realized when surrounding areas are also part of the conceptual framework when implementing CBC (Tscharntke 2005). Evidence shows that species richness is directly correlated to landscape scale and complexity (Schmidt 2007). This large scale method is not difficult to implement as intensive farming practices on a landscape scale can be supplemented by CBC to enhance the populations and diversities of generalist predators (Kleijn 2006). Thus, biological control benefits are further enhanced when correlated with this greater species richness and diversity as prey species experience higher mortalities (Tylianakis 2005).

It is important to consider that intensive agricultural practices often limit populations of natural predators more than is often accounted for by either farmers or scientists due to the limited body of research on such biological diversity. CBC management techniques should thus focus further on areas that are either close to the natural state or the precise opposite and very urbanized as the contrast between species diversity and richness will aid in research to better streamline CBC. Local management aimed at enhancing conservation objectives could be implemented in a broader scale in urban areas in particular as community organizations could unify their practices in these areas (Tscharntke 2007).

Reliable recommendations for applying CBC on a landscape scale are pending as research is still ongoing. Though local level CBC has been implemented, landscape level CBC is still in its fledgling state as the multitrophic interactions and responses are difficult to document and have not been properly studied (Tscharntke 2007). An example of these interactions is the newly studied entomopathogenic fungi which can interfere with arthropod predation at the landscape level (Roy 2006). This scale dependence would be dangerous to implement all at once until further study is completed.

Responses to CBC can differ within species groups and even within species (Tscharntke 2007). Greater knowledge of the role of landscape composition and configuration will continue to develop CBC techniques to enhance the diversity of biocontrol in sustainable agricultural and urban environments.

Social Insects of Urban Importance

Finally, in the context of IPM and its sub fields of PPS and CBC, we can begin to consider specific examples of new control techniques as they apply to urban pests. Social insects, such as termites, ants, and yellow jackets, cause significant harm to human health and infrastructure in urban areas. For example, these pests cause severe damage to structures, they are vectors for disease, they sting and bite, and they can alter urban ecosystems (Rust 2012). As human populations expand towards greater urbanization, efforts to control these pests will become ever more important and will likely follow the trend to minimize ecological impact while maximizing efficacy. What follows are descriptions of the basic biology of each of the three aforementioned pests as well as a summary of the problems they each cause along with current and future control methods that are emerging.

Termites are Isoptera. The genus *Cryptocercus* specializes in wood feeding. Indeed, this behavior is the root of their social nature (Higashi 2000). Termites are one of few organisms that can digest cellulose. Symbiotic bacteria, which produce the cellulase that termites need for digesting wood, is lost in every molting cycle and as such needs to be replaced. Bacteria are reconstituted when one member of the colony feeds on the waste products of another member.

Much like earthworms and ants, termites contribute to turnover of soil and are important ecological decomposers (Holt 2000). They become a pest only when certain species feed on structural lumber used by humans. Those pest species are further divided into two groups, the subterranean termites and the drywood termites. A recent estimate put the economic impact of termites at forty billion dollars worldwide (Su 2002). Like ants, termite colonies are comprised of three castes: reproductives, soldiers, and workers (Rust 2012). For many termites, these castes are permanent through the life cycle and do not change. Colonies of drywood termites tend to be limited to individual pieces of wood, however subterranean termites can forage to great distances and can number in the millions as they build out their foraging tunnels up to one hundred meters from the colony center (Su 2002).

Drywood termite infestations occur when mated pairs disperse from neighboring colonies. Dry fecal pellets are a common sign of infestation (Rust 2012). Treatments for drywood termite infestations depend on whether the colony is localized or if it has spread through the entire structure. In localized instances, treatments can include heating the wood, freezing the termites via liquid nitrogen, or other liquid and foaming chemicals. Whole-structure treatments usually involve fumigation with sulfuryl fluoride (Lewis 1996). Subterranean termite control can take the form of either soil termiticide barriers as exclusion devices or baiting to manage populations around the perimeter of structures (Rust 2012). The former is chemical in nature and uses different pyrethroids which kill via contact (Su 2002). The latter has recently implemented chitin synthesis inhibitors which balance time of action between too soon (contact kill) and too late (between generations) by preventing molting from one life stage to another (Su

2002). These baits can remain in the ground for upwards of twelve months thereby limiting labor costs somewhat. Nonetheless, use of these harmful chemicals can be damaging to human health and to that end, IPM work remains in progress for termite control.

The focus of termite IPM has been to limit use of chemicals by raising the level economically where they are necessary by encouraging population reduction through baiting measures that take advantage of termites' social nature. This idea is implemented through area wide projects parallel to the landscape level framework mentioned in the section on CBC. Instead of treating individual buildings for termites as they become a problem, it is proposed that termite control take place on a broader scale (Guillot 2010). A case study in New Orleans utilized a single pest control firm (rather than several picked by individual homeowners) that divided the city into different geographical blocks and applied treatments to those larger chunks one at a time. Pest species of termites have not been detected since the treatment period ended in 2005 (Guillot 2010) providing evidence for the need to implement these practices, especially in urban environments.

Several ant species have managed to adapt to urbanized environments and have taken advantage of their competitive edges over other species (King 2008). Ants affect urban residents by destroying structural materials, stinging and biting humans and pets, contaminating foods, mechanically vectoring disease agents, and tending aphids on ornamental plants (Rust 2012). Stings can cause medical emergencies via anaphylactic shock. On a less dramatic note, some species of ant such as the Pharaoh ant have been known to cause bronchial asthma (Kim 2007).

Ant control in the urban environment is largely through bait and perimeter treatments. The former is considered to be the most ideal due to ants' social tendencies to forage. An effective ant bait has four characteristics: delayed toxicity, effective over varied concentrations, non repellent, and ability to be formulated with different carriers (Stringer 1964). Often, though, these baits are toxic and are environmental hazards in their own right. In addition, baits are expensive and labor intensive to apply (Warner 2010). The perimeter treatment, on the other hand, is application of fipronil granules (Rust 2012). These, too, can cause ecological harm through storm water runoff into urban waterways. For these reasons, alternative strategies are in development.

Of these, biological controls appear to be the most promising, as documented by the case of the fire ant, *S. invicta*. The two most effective treatments used to reduce populations of fire ants are the application of *Pseudacteon*, the decapitating, or phorid fly, and a microsporidian pathogen, *K. solenopsae*. Both have contributed to a reduction in *S. invicta* by eighty five to ninety nine percent as compared to untreated areas (Vander Meer 2007). Thus, properly formulated IPM strategies can help to reduce pest populations through less chemically intensive and ecologically harmful means. When considering these IPM strategies, it is important to keep a historical perspective as well. Ultimately, the most common fate of invasive ants may be displacement by subsequent invaders. In the southeastern United States, for example, the Argentine ant appears to have been displaced throughout much of its introduced range by the black imported fire ant (*S. richteri*), and both were later displaced by *S. invicta* (Tsutsui 2002). These examples provide further support for pursuing area wide IPM through PPS and CBC.

Yellow jackets, hornets, and wasps (family: Vespidae) can also be problematic in urban areas such as dumpsters, schools, parks, and other recreational areas (Rust 2012). These organisms can be potentially more harmful to human health directly than ants due to a higher incidence (up to nineteen percent) of allergic and potentially fatal reactions in humans (Renaudin 2010). IPM for vespids includes olfactory confusion in foraging activity, direct nest treatment via thiamethoxam sprays and foams, and chemical baiting in and around urban centers of activity (Ebeling 1978). As with termites and ants, such strategies can be labor intensive, expensive, and environmentally harmful. Alternative strategies are limited and include interceptive trapping (immediately surrounding picnic areas with large quantities of baits, for example) or less damaging chemical treatments (lacing swimming pools with an algaecide to disable foraging workers (Rust 2012).

Overall, broad scale treatments (area wide, landscape level, etc.) are needed to mitigate effects of social insect pests in urban areas. IPM and its developing fields of PPS and CBC can help in this regard. Lower cost baits, both in formulation and application, which are less toxic, will also form part of the solution. In any case, further research needs to be conducted to reduce impact and increase sustainable methods of living.

Closing Thoughts

The focus for this thesis is to implement changes in policy relating to sea turtle protection and endangerment.

Though urban ecology might seem to be a complex and convoluted field, its interdisciplinary nature inevitably makes it the perfect candidate for dealing with pest problems. Integrated pest management, push-pull strategies, and conservation biological control have all been implemented to increase the efficacy and efficiency of treatments when it comes to agricultural pests at a localized level. Increasingly, it is becoming clear that such methods need to be applied at an area wide, or landscape level to better cope with the problems that some pests present. Such methods are in turn potentially of great use and import in urban ecological environments. As the impact and influence of humanity increases over the next decades, the effects of pests such as social insects will continue to greaten unless adequate measures are taken. It is in these cases that urban ecology ties together these sometimes disparate fields and provides solutions where others might provide confusion. Though much of the relevant research is still lacking or in a fledgling state, the future holds promise for the advent of a sustainable, or at least less harmful and less damaging interaction between humans and the natural world.

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