Field survey of native and non-native subterranean termites in southeastern United States forests

By

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Subterranean termites are ecologically and economically important insects that play major roles in organic matter decomposition and nutrient cycling. The Formosan subterranean termite, *Coptotermes formosanus* Shiraki, is an invasive species known to cause significant damage in urban areas through aggressive consumption of wooden structures and infestations of living trees. Little is known about the presence and impact of *C. formosanus* in forested ecosystems of the southeastern U.S. as the majority of studies have taken place in urban settings. This study investigates the prevalence of *C. formosanus* in localized forests, as well as the utilization of living trees by *C. formosanus* and native subterranean termite species (*Reticulitermes* spp.). Recently harvested timber stumps were inspected for subterranean termite presence on sites throughout Mississippi and Louisiana. Alate light traps were utilized for further *C. formosanus* detection. Three sites yielded *C. formosanus* alate catches, while 7,413 stump inspections produced 406 *Reticulitermes* spp. infestations.
DEDICATION

This thesis is dedicated to my parents, Charles and Carolyn Blount. They introduced me to the outdoors at an early age, which has lead to my continuous interest in forest environments and the field of natural resources. Throughout my studies they have provided tremendous encouragement and support, in turn helping me succeed. I would not be where I am today without them.
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TABLE OF CONTENTS

DEDICATION ................................................................................................................. ii

ACKNOWLEDGEMENTS ............................................................................................ iii

LIST OF TABLES .......................................................................................................... vii

LIST OF FIGURES ...................................................................................................... viii

CHAPTER

I. LITERATURE REVIEW ................................................................................... 1

   Introduction ....................................................................................................... 1
   Termites .......................................................................................................... 3
      Classification ............................................................................................... 3
      Social Behavior and Caste System ............................................................ 5
      Evolution and Eusociality .......................................................................... 7
      Digestion and Food Exchange ................................................................... 8
      Associations with Fungi ............................................................................. 10
      Communication and Foraging .................................................................. 11
      Swarming .................................................................................................... 12
      Ecological Importance .............................................................................. 13
      Economic Importance ............................................................................... 15

   Subterranean Termites Native to Mississippi .............................................. 15
   Formosan Subterranean Termites ............................................................... 16
      Presence in Southeastern U.S. Forests ...................................................... 19
      Presence in Mississippi ............................................................................ 20
      Competition with Native Subterranean Termites .................................. 21
      Infestations in Living Trees .................................................................... 22
      Feeding Preferences ................................................................................ 24

   Conclusion ....................................................................................................... 26

   Literature Cited ............................................................................................... 28

II. NATIVE AND FORMOSAN SUBTERRANEAN TERMITE
    (ISOPTERA: RHINOTERMITIDAE) UTILIZATION OF
    LIVING TREES IN FORESTED SETTINGS .................................................. 36
LIST OF TABLES

1. Summary of Stump Inspections and Subterranean Termite Infestations by Site ................................................................. 51
2. Mean Infested Pine Stump Diameters by Site Sorted by Diameter ............ 54
3. Distance from Inspection Sites to Nearest Railroad ................................. 64
LIST OF FIGURES

1. Location of Subterranean Termite Inspection Sites .........................................42
2. Layout of Systematic Line Plot Cruise Inspection .............................................44
3. Formosan Subterranean Termite Alate Light Trap ...........................................48
4. Subterranean Termite Total Stump Infestation Rates by Site ............................52
5. Subterranean Termite Pine Stump Infestation Rates by Site ............................52
6. Subterranean Termite Hardwood Stump Infestation Rates by Site ..................53
7. Frequency Distribution of Subterranean Termite Stump Infestations by Diameter Class .............................................................................................................53
8. Mean Subterranean Termite Stump Infestations per Hectare by Site ..............55
9. Map of Inspection Sites with Formosan Subterranean Termite Alate Catches .................................................................................................................................57
CHAPTER I
LITERATURE REVIEW

Introduction

Termites (Order: Isoptera) are some of the most voracious feeders in the insect world, providing both ecological benefits and economic distress in a variety of habitats ranging from arid deserts to tropical rainforests. In economic terms, termites are one of the most costly insects worldwide due to their extensive feeding preference for cellulose (Spear 1971; Su and Scheffrahn 1990). Termites are hemimetabolous insects, meaning they lack a pupal stage during metamorphosis. Sociality is another feature of termites, and a single colony can contain millions of individuals whom feed on a variety of plants and wood products. Termites provide a wide array of benefits to the environment including the cycling of nutrients, soil mineralization, decomposition of plant material, and termites serve as a major prey source for animals (Harris 1966; Black and Okwakol 1997). An absence of termites could drastically alter ecosystems as termites are the primary decomposers and nutrient recyclers in many settings (Wood and Sands 1978).

In recent years, the Formosan subterranean termite (*Coptotermes formosanus* Shiraki), a native of Asia, has arrived in the United States via transport of shipping cargo and is making a huge economic impact in urban areas through destruction of building materials. Formosan subterranean termites are much more damaging than native U.S.
termites due to *C. formosanus* colonies containing many more individuals and having greater foraging aggression (Su and Tamashiro 1987; Lax and Osbrink 2003). The distribution of *C. formosanus* is continuously spreading in states of the Gulf Coastal Plain due to the transport of infested materials (Lax and Osbrink 2003). California also has established populations of the termite (Atkinson et al. 1993; Haagsma et al. 1995). The economic woes of *C. formosanus* are being felt, but the environmental impacts are not yet clear.

One characteristic of *C. formosanus* that could have major ecological impacts is its ability to infest living trees. Formosan subterranean termites are frequently found in living trees within heavily infested urban areas, structurally weakening the trees, leaving them vulnerable to further physical damage (Osbrink et al. 1999). However the prevalence of *C. formosanus* in living trees within rural forests has not been reported, and what impact this invasive termite has on forested settings is not known. A previous Mississippi study found *C. formosanus* to be numerous in rural and forested settings outside of heavily infested urban areas. Alate traps were used in this study, and inspection of trees near successful traps led to the discovery of 14 *C. formosanus* infested trees (Sun et al. 2007). It is unknown how prevalent these living tree infestations are outside of urban areas.

Another potential ecological threat arising from the spread of Formosan subterranean termites is the displacement of native termite species. Studies show that *C. formosanus* are able to out-compete native *Reticulitermes* species (Su 2003). In some heavily infested neighborhoods of New Orleans, Louisiana, *C. formosanus* has replaced *Reticulitermes* spp. as the primary attacking termite species (La Fage 1987). Considering
natives and Formosan subterranean termites share similar food resources, competition is feasible and may lead to displacement of native species due to the more aggressive feeding habits of *C. formosanus*. The long term implications of native replacement by *C. formosanus* are not known. Formosan subterranean termite infestations within living trees and the displacement of native termites could have major ecological and economic impacts in the future. This literature review will give a broad overview of termites in general, with focus on native Mississippi *Reticulitermes* species and *C. formosanus*. The purpose of the review is to inform the reader about the impacts Formosan subterranean termites may have as their populations continue to increase and to justify the research I conducted regarding Formosan subterranean termites in forested settings.

**Termites**

*Classification*

There are approximately 2,700 species of termites throughout the world within seven families and two phylogenic classifications, lower termites and higher termites (Kambhampati and Eggleton 2000). Lower termites encompass the six oldest termite families: Mastotermitidae, Hodotermitidae, Kalotermitidae, Termopsidae, Rhinotermitidae, and Serritermitidae (Eggleton 2011). These termites rely on the aid of symbiotic protozoans in the gut to help digest cellulose (Krishna 1969). Speciation led to higher termites and the family Termitidae, which contains three-quarters of termite species. Higher termites have more advanced social specializations than lower termites and lack symbiotic protozoans in the hind gut, however gut fauna are still present...
Both lower and higher termites play equally important roles in ecosystems (Wood and Sands 1978).

There are three common classifications of termites in the United States: dampwood (Termopsidae and Kalotermitidae), drywood (Kalotermitidae), and subterranean (Rhinotermitidae) (Gleason and Koehler 1980). Dampwood and drywood termites live and nest in the wood on which they feed, and most species can survive without soil contact (Noirot 1970). Drywood termites infest wood with low moisture content, while dampwood termites require wood with very high moisture content (Oi et al. 2008). Subterranean termites are unique in that their nests require active contact with the soil which they tunnel through to locate resources (Suiter et al. 2002). Similar to dampwood termites, subterranean termites require moderate amounts of moisture in order to survive (Suiter et al. 2002). Of the three termite classifications discussed, subterranean termites are by far the most common classification found in the U.S. (Gleason and Koehler 1980).

Subterranean termites are the most economically important wood pest in the U.S and are found in every state excluding Alaska (Suiter et al. 2002). Of the 183 known economically important termite species, 147 are subterranean termites. The subterranean genus *Coptotermes*, which the Formosan subterranean termite belongs to, contains 28 economically important species, greater than any other termite genera (Su and Scheffrahn 1998). The importance of subterranean termites from both an economic and environmental standpoint is substantial.

There are many species of termites that have been successfully introduced into new environments where they are not native, and these exotic species can have
substantial economic impacts. These species primarily reside in the genera *Cryptotermes* (Kalotermitidae) and *Coptotermes* (Rhinotermitidae) (Gay 1969). *Cryptotermes* can easily be transplanted from one area to another due to their small colonies and ability to tolerate low-moisture conditions for extended periods of time (Gay 1969; Su and Scheffrahn 1998). *Coptotermes* are primarily spread by human movement of infested materials, such as soil in potted plants and various wood products. Both *Cryptotermes* and *Coptotermes* have been found to infest the woodwork of actual ships, making prevention and detection difficult (Gay 1969).

**Social Behavior and Caste System**

Termites are social insects, which live in colonies that can be comprised of millions of individuals. Termites are unique in that they are the only hemimetabolous social insect (Krishna 1969). Characteristics of the sociality among termites include cooperation in raising young, resource sharing, generational overlap, and a division of labor (Suiter et al. 2002). The division of labor is characterized by a caste system consisting of reproductives, workers, and soldiers (Gleason and Koehler 1980). Immature termites, referred to as nymphs, make up the majority of a colony in approximately a 1:1 sex ratio (Suiter et al. 2002). Nymphs can develop into any member of a caste depending on colony requirements (Krishna 1969). Juvenile hormones, genetic factors, environmental conditions, and pheromones all play major roles in caste differentiation (Miura and Scharf 2011), which takes place before the first molt (Lee and Wood 1971).
The reproductive caste can be divided into two main groups, primary and supplementary (or secondary). Primary reproductives, also known as kings and queens, are the initial founders of the colony and mate for life (Krishna 1969). The king undergoes little change during his lifetime, and his only role is to fertilize the eggs of the queen (Lee and Wood 1971). As a queen gets older, her abdomen can increase in size allowing her to produce more eggs (Lee and Wood 1971). Termite alates are primary reproductives with wings, which are used for dispersal during the swarming of the breeding season (Nutting 1969). The goal of the dispersal flight is to get clear of the parental colony (Eggleton 2011). Pheromone and nutrient exchange within a colony give cues to colony size and maturity, which is vital in determining how many alates are produced, if any (Nutting 1969). Secondary reproductives have no wings, and female secondary reproductives produce eggs to supplement the egg production of the queen (Gleason and Koehler 1980). On some occasions, egg production from secondary reproductives can exceed the egg production of the queen, causing the colony to grow at a substantial rate (Miller 2010). When the king or queen in a colony dies, it will be replaced by a secondary reproductive so the colony can continue (Krishna 1969).

Worker termites are sexually immature males and females that encompass the majority of the population within a colony (Suiter et al. 2002). In some species workers can be dimorphic, consisting of large and small forms (Lee and Wood 1971). Workers are blind, but can detect changes in light intensity (Suiter et al. 2002). The primary jobs of workers include foraging for food, building and repairs of colony structures, and tending to other termites (Krishna 1969). Food gathered by workers is the colony’s primary
energy source, thus large numbers of workers are crucial for colony survival (Lee and Wood 1971).

Soldier termites have one job, protecting the colony, especially the king and queen (Eggleton 2011). Soldiers often have modified mandibles, longer and more powerful than the mandibles of other castes. These modified mandibles help aid in colony defense and can be used to disembowel other termites and small insects (Krishna 1969). In some genera, such as *Coptotermes*, soldiers have chemical defenses they release from the frontal gland of the head in the form of a white, milky secretion (Stuart 1969). Soldier composition in a colony is generally between 1-10% for most termite species, with the highest percentage found during the few months prior to the swarming season (Haverty 1977; Liu et al. 2005). Formosan subterranean termite colonies are composed of approximately 10% soldiers (Lax and Osbrink 2003), much higher than the 1-2% composition rate in *Reticulitermes flavipes* (Suiter et al. 2002). Like workers, soldiers are normally sterile and blind (Krishna 1969), but still manage to aid the colony in a vital defense role.

**Evolution and Eusociality**

Termites date back to prehistoric ages as they are the oldest social insects, most closely related to cockroaches (Eggleton 2001; Korb 2008). In regards to termite genera, the imago-worker mandible has been vital in the construction of phylogenetic trees (Ahmad 1950; Krishna 1969). Scientists have recently established that termites are in fact a specialized form of cockroach, but with a more diverse diet and elaborate social system (Eggleton 2011). This has led to the proposal of dropping the order Isoptera, and placing
termites in the cockroach family Blattodea (Inward et al. 2007). According to most recent termite literature, the move to another order is very plausible (Eggleton 2011).

Eusociality is defined as ‘an evolutionary advanced level of colonial existence’ (Wilson and Hölldobler 2005). Thorne (1997) states that eusociality in termites likely evolved from small families of termites that kept flexibility in development and reproduction habits. Group defense advantages, nest inheritance by offspring, risk of dispersal for individuals, resource abundant habitats, slow development, monogamy, and generation overlap are all aspects of termite environments that likely drove termites towards eusociality (Thorne 1997). Since individual termites cannot live alone and depend on other members of the colony for survival, some scientists view termite colonies as a superorganism, containing numerous multi-celled individuals making up a single larger organism (Krishna 1969). Nests of termites can be viewed as a homeostatically regulated unit, with the internals being self-regulating and the wall of the nest being a defensive barrier. If part of the nest is destroyed, it can be regenerated similar to the lost parts of some organisms (Emerson 1956). Termites use the closed environment of nests to regulate their microclimate since their soft cuticle leaves them vulnerable to desiccation (Krishna 1969). Although there are other diploid eusocial taxa, termites are the only diploids to have a diverse caste system within structured colonies (Thorne 1997).

**Digestion and Food Exchange**

Termites feed on a wide array of matter including dead and decaying plant material, living stems and roots, dry grass and leaves, dead wood, humus, fungi, and even
soil (Lee and Wood 1971; Donovan et al. 2000). The cellulose within these materials provides termites their main source of energy and water, but lower termites do not possess the ability to produce cellulolytic enzymes, and therefore cannot metabolize cellulose by themselves (Moore 1969). Lower termites rely on various microbial gut symbionts, such as protozoa and bacteria, to help digest wood (Husseneder and Collier 2008). The hind gut is where the majority of absorption and digestion takes place (Noirot and Noirot-Timothee 1969), and protozoa can make up as much as 30-50% of the total weight of wood-eating termites (Paracer and Ahmadjian 2000). Symbionts receive shelter and food from their termite hosts, while at the same time degrading celluloses into products useful for termite metabolic processes (Moore 1969). Symbionts are also essential for survival in many lower termites (Honigberg 1970). During each molt, the symbiotic flagellate protozoans are shed along with the entire epithelial lining of the alimentary canal (Paracer and Ahmadjian 2000). However the protozoans can be regained through digestion of fecal matter from other colony members, a process known as trophallaxis (Krishna 1969). Higher termites are able to break down celluloses without the help of symbiotic microrganisms, although some species still harbor protozoa (Moore 1969; Honigberg 1970). Some termite genera, such as Reticulitermes, have their own unique intestinal host-specific protozoa. Because of this, it is possible to identify some termite species by the protozoa contained in their gut (Honigberg 1970). Cryptocercus roaches are the only other insect hosts known to contain similar mutualistic flagellates to those found in lower termites (Honigberg 1970).

Termites exchange food through two forms of trophallaxis: stomodeal and proctodeal. The worker caste is the principal donor of both feeding types, although in
some species other castes can be solicited for proctodeal food (McMahan 1969). Stomdeall feeding is present in all termite families and consists of a donor regurgitating food to a recipient. Proctodeal feeding involves the transport of hindgut fluid content from one termite to another and is exhibited in all families except Termitidae (McMahan 1969). The absence of proctodeal feeding in higher termites is related to the disappearance of the flagellates in their hind gut (Noirot and Noirot-Timothee 1969). The recipient of the hindgut matter normally initiates and terminates proctodeal feeding. The hindgut fluid contains flagellates used for cellulose digestion and wood particles as well as other digestive contents. Besides the exchange of nutrients and protozoa, trophallaxis also aids in colony mate and pheromone recognition as well as caste differentiation and elimination (McMahan 1969).

**Associations with Fungi**

Fungi have been shown to be beneficial to termites by breaking down cellulose and lignin making it easier for termites to digest, and some termite species are nutritionally dependent on fungi (Sands 1969). Termites are attracted to certain beneficial decay fungi, while other types of fungi can repel them (Sands 1969; Amburgey 1979). Some fungi can actually break wood down into products that are poisonous to termites (Sands 1969; Amburgey 1979). A study in Portugal found that subterranean termites may have a feeding preference towards wood already decayed by fungi (Nobre et al. 2009). Little et al. (2012) discovered that *R. flavipes* showed a feeding preference towards wood containing *Ophiostoma minus*, a fungi vectored by the southern pine beetle (*Dendroctonus frontalis*) (Klepzig et al. 2001). There have been documented cases of
*Reticulitermes* spp. constructing mud tubes across tree trunks in order to reach the fungus *Lenzites trabea* (Weesner 1970). It is clear that fungi can play an important and complex role in the feeding habits of subterranean termites.

**Communication and Foraging**

Termites use a variety of chemical and auditory cues in order to communicate about food resources (Stuart 1969; Evans et al. 2005; Inta et al. 2009). Individual termite colonies have their own unique odor, making it possible for termites to differentiate fellow colony members from external colonies (Stuart 1969). Worker termites lay down odor trails and use tactile means in order to inform fellow colony members about the location of food sources (Stuart 1969). Certain compounds produced by brown-rot decay fungi (*Gloeophyllum trabeum*) after wood decay are known to elicit trail following behavior in *Reticulitermes* spp. (Esenther and Beal 1979), and the compound produced by *G. trabeum* is chemically similar to the trail following pheromones produced by subterranean termites (Matsumara et al. 1969; Tokoro et al. 1992). In some species, soldier termites guard the foraging trails (Stuart 1969). Evans et al. (2005) discovered that drywood worker termites could use vibratory signals to determine wood size, which in turn could alter feeding activity of other termites on that particular piece of wood. Vibratory signals are also known to be used by soldiers as an alarm mechanism and can cause other members of the colony to cease foraging (Inta et al. 2009).
Swarming

Termite alates, winged primary reproductives, disperse from their colony to mate and establish new colonies (Nutting 1969). Pheromone and nutrient exchange within a colony give cues regarding colony size and maturity, two factors taken into consideration for alate production (Nutting 1969). Alates are produced in great numbers and disperse at around the same time, generally in large swarms (Eggleton 2011). Seasonal and climatic changes such as photoperiod, temperature, rainfall, and moisture content are what trigger these dispersal flights (Nutting 1969; Stuart 1969). High temperature and humidity along with low atmospheric pressure are known to trigger flights in China (Lin 1987). A 2-year study on *C. formosanus* swarming in Hawaii found no significant differences in climatological factors between flight days and non-flight days, and suggested environmental factors that affected swarming were at the microenvironmental level (Higa and Tamashiro 1983). Flight distance varies among species and can range from as little as a few meters upwards to several hundred meters (Nutting 1969). Distances can be much greater, as a *C. formosanus* alate recapture study found that termites were capable of flying approximately 900 meters across the Mississippi River when wind conditions were optimal (Messenger and Mullins 2005). Alates lose their wings shortly after the dispersal flight in a process coined dealation, and females in some species begin giving off pheromones to attract males. Through a series of chemical and tactile cues, males begin to seek out potential partners. After a partner is found, alates choose a nest site which varies according to species. Nest sites can include trees, woody debris, or even the soil. Both sexes can share the task of nest construction and selection, but in some species the task relies solely on the female (Stuart 1969). Once nest construction is complete, the
coupled alates begin to reproduce and copulate for life (Krishna 1969). Alate swarming activity is normally the first noticeable sign of subterranean termite infestation and expansion in homes and urban areas (Su and Scheffrahn 1990; Sun 2007).

The timing of subterranean termite swarming varies. *Reticulitermes* spp. swarming takes place during daylight hours with seasonal timing varying among species (Weesner 1970). In the southeastern U.S., *R. flavipes* swarming generally takes place in April or May, with secondary flights sometimes occurring in October and November. *R. hageni* swarms later in the year, usually in the months of August to December. Swarming activity of *R. virginicus* is most prevalent in May or June (Gleason and Koehler 1980). *Coptotermes* spp. swarm during the night and alates are attracted to lights (Weesner 1970). Within heavily infested areas of Mississippi and Louisiana, *C. formosanus* swarming begins in late April, peaking sometime during May or early June, and can continue until the end of July (Sun et al. 2007; Guillot et al. 2010; Lax and Wiltz 2010). Studies have shown that although thousands of *C. formosanus* alates leave a colony during swarming periods, only a few are successful in establishing new colonies (Spink 1967).

**Ecological Importance**

Although small, termites have major impacts and implications for ecosystems of all types. Termites are social insects, which generally have larger effects on ecosystems than other insects due to the size and extent of nesting systems (Wood and Sands 1978). Termites are important decomposers which can alter the ecology of native forests in many ways (Harris 1966). Decomposition can change the physical and chemical
properties of soil particles as well as the distribution of soil particles (Wood and Sands 1978). A loss of termites in an ecosystem can lead to nutrient cycling issues, such as a reduction in carbon and nitrogen mineralization (Black and Okwakol 1997). It has been reported that subterranean termites can account for 7%-22% of nitrogen input within a tropical forested ecosystem in Thailand (Yamada et al. 2006). Termites are important components of ecosystems due to their decomposition and nutrient cycling habits.

Termites affect soils in a variety of ways. Soil profiles are physically disturbed and overturned due to transport of particles from deeper in the profile to the surface for nest building (Lee and Wood 1971). Some termite species prefer certain sized soil particles for nest construction, thus potentially altering the particle size of the soil surrounding the colony (Lee and Wood 1971). Organic matter and plant nutrients are re-distributed in the soil through nest building. Many studies have reported termite nests exhibiting greater calcium, magnesium, and potassium content than surrounding soils (Lee and Wood 1971). Soil pH is also affected by termites, with pH levels around nests often being higher or lower than the pH levels of the surrounding area (Lee and Wood 1971). In some cases, the surface of soil horizons can be subjected to cementation, making water percolation and plant root establishment difficult. The cementation is due to the movement and repacking of soil particles by termites during construction of hard colony structures (Lee and Wood 1971). On the other hand, subterranean termite galleries can increase the porosity of soil, helping water penetrate more easily (Lee and Wood 1971). In mound building species, the mounds result in microrelief which can alter pedogenetic processes through the promotion of water surface runoff on steep sides of colonies. This runoff results in concentrated water spots near the base of mounds and
further leaching (Lee and Wood 1971). Overall, the benefits termites provide to the ecosystem surpass the cons of their pest status (Jouquet et al. 2011).

**Economic Importance**

Within the United States, monetary losses from termite damage are greater than fire and flood damage combined (Eggleton 2011), with the overall economic impact potentially as high as $11 billion per year when building repair cost is included (Su 2002). The most economically important termite in the United States is *R. flavipes*, primarily due to its wide distribution (Su and Scheffrahn 1990). However, the Formosan subterranean termite is another significant termite pest. It is estimated that Formosan subterranean termites cost the United States over $1 billion a year, with the city of New Orleans alone spending over $300 million a year. These costs include control and extermination of the termites, and damage costs (Lax and Osbrink 2003). Su (2002) states that termite expenses will continue to rise as the standard of living increases and more termite species are spread through human transport of materials.

**Subterranean Termites Native to Mississippi**

Mississippi is home to three species of native subterranean *Reticulitermes* termites. These species include *R. flavipes* (Kollar), *R. virginicus* Banks, and *R. hageni* Banks, with *R. flavipes* being the most abundant (Howard et al. 1982; Wang et al. 2003). Colonies of different species can inhabit the same area within close proximity to each other (Howard et al. 1982). A study in Mississippi showed *R. flavipes* was more likely to inhabit higher sites while *R. virginicus* was found more frequently on lower sites.
(Howard et al. 1982). Another Mississippi study found that termite numbers overall were less significant in an area with lower elevation and higher soil moisture. Some of these study sites were also underwater during winter months (Wang and Powell 2001). In a Florida study, *R. flavipes* were found in standing dead oak trees when the land was temporarily flooded (Su et al. 1993). This confirms that some native species can survive short periods of inundation.

*Reticulitermes flavipes* colonies were found to be non-randomly distributed at a density of approximately 4.42 colonies per hectare over a large forested area in south Mississippi (Howard et al. 1982). One objective of this study is to determine the distribution of the native colonies found during inspection. The majority of literature regarding native termites in Mississippi is focused on *R. flavipes*, with little literature on *R. virginicus* and even less on *R. hageni*.

**Formosan Subterranean Termites**

*Coptotermes formosanus*, the Formosan subterranean termite, is a highly destructive exotic termite species invading the Gulf Coastal Plain (Lax and Osbrink 2003). The Formosan subterranean termite was first described in 1909 on the island of Formosa (now Taiwan) and is native to Asia (Spink 1967; Su and Tamashiro 1987). The initial discovery of *C. formosanus* in North America occurred during 1913, when it was found in the Hawaiian Islands (Gay 1969). The first documentation of *C. formosanus* in the mainland United States came in 1965 when termites were found in wooden beams within a Houston, Texas shipyard. It is likely that *C. formosanus* arrived shortly after World War II via shipping materials (La Fage 1987). New Orleans, Louisiana was the
next victim with *C. formosanus* documented in four areas during 1966, and alates were captured the next year in Charleston, South Carolina (Beal 1967). DNA sequencing has shown that there have been at least two non-related introductions of *C. formosanus* within the U.S. (Austin et al. 2006).

Since the arrival of *C. formosanus* in the U.S., the termites have become one of the most destructive insect pests of wood products and the most damaging subterranean termites in areas where they occur (Osbrink et al. 1999). Formosan subterranean termites are indiscriminate in their feeding habits and have been known to attack telephone poles, boats, underground cables, books, metal products (Lin 1987). In Hawaii, *C. formosanus* is known to infest at least 47 species of plants, both woody and herbaceous, within 27 families (Lai et al. 1983). Wooden utility poles have been major targets for *C. formosanus* in some areas, causing decrease in service life and higher replacement costs (La Fage 1987). In New Orleans, the termites have endangered historic buildings as infestations are rampant within wooden structures throughout the city (Guillot et al. 2010).

The ability to construct arboreal nests is a noteworthy attribute of *C. formosanus*, as the only other termites capable of arboreal nests are found within Termitidae (Noirot 1970). Aerial nesting gives *C. formosanus* advantages that native termite species lack, such as the ability to survive long periods of inundation and increased availability of nesting sites. Multiple aerial *C. formosanus* colonies within high-rise buildings in Hawaii have reached populations of 100,000 individuals in just four years or less (Su and Tamashiro 1987). In Louisiana, established *C. formosanus* colonies have been found in isolated cypress trees growing in water (Liu et al. 2005). Osbrink et al. (2008)
investigated the effects sustained flooding from Hurricane Katrina had on *C. formosanus* populations in New Orleans. They discovered that even though some areas were underwater for 2-3 weeks, it did not affect alate catch numbers the following year. Foraging termite numbers were initially suppressed following the flood, but quickly rebounded the next year. Termites infesting hardwood trees such as oaks and cypress were shown to have better survival rates during periods of inundation than termites infesting pine trees (Osbrink et al. 2008). Arboreal nests are yet another characteristic of *C. formosanus* that makes it a formidable foe.

Formosan subterranean termite numbers have been spreading throughout the past decade and the termites are currently found in 11 states (Woodson et al. 2001). Long distance movement of termites is accomplished primarily by human transportation (Su 2003). The range of *C. formosanus* is being extended northward due to transport of infested materials. Railroad ties are often associated with transport of *C. formosanus*, and some infestations have been directly linked to an infested railroad tie (Chambers et al. 1988). Climate conditions could allow for *C. formosanus* to expand further north than they are presently found due to their ability to survive critically cold temperatures by burrowing deeper into the ground (Hu and Song 2007). In Hawaii it took *C. formosanus* around 50 years to naturally spread 40 miles (Higa and Tamashiro 1983). However the expansion in Mississippi is taking place at a much greater rate. In 1998 the United States government enacted Operation Full Stop with the goal of reducing the spread and numbers of Formosan subterranean termites. The United States Department of Agriculture was put in charge of this program and the program is still in effect to this day (Ring et al. 2001).
**Presence in Southeastern U. S. Forests**

Formosan subterranean termites are primarily considered a pest of wood products and structures, but potentially pose a chronic risk to forested settings within this region. Formosan subterranean termites have been shown to be detrimental to living trees in urban areas (Osbrink et al. 1999), but few studies have focused on *C. formosanus* in forested settings. *Coptotermes* spp. have been found to cause economic damage to standing timber in other countries such as eucalyptus in Australia, teak in Indonesia, and pines in Central America (Harris 1966). In Australian virgin eucalyptus forests, *Coptotermes* spp. have been estimated to be the cause of up to 92% of tree losses and approximately 64% of losses in younger forests (Greaves et al. 1967). It is also possible that *C. formosanus* may alter forest ecosystem function through competition with native subterranean termites. Formosan subterranean termites could alter the ecology of native forests in many ways since termites are important decomposers in forest ecosystems (Harris 1966).

Little is known about *C. formosanus* and their role in forest ecology, nutrient cycling, succession, and landscape scale processes as the majority of *C. formosanus* studies have focused on urban areas. The first major study regarding *C. formosanus* in Mississippi found that more alates were captured by traps along roads in rural and forested areas than in urban areas (Sun et al. 2007). The study suggested that perhaps greater resources are available for the termites in these areas in comparison to urban areas. In an urban environment, over 18 different *C. formosanus* colonies were found around one building during a four year period. The same study also found 14 colonies over a 12.75 hectare park-like setting in a single year (Aluko and Husseneder 2007),
much less dense than the 4.42 colonies per hectare found in forested settings for *R. flavipes* (Howard et al. 1982). How the urban colony numbers of *C. formosanus* compare to colonies in forested areas needs to be examined, especially since native *R. flavipes* colonies can be much denser in forested settings. Messenger et al. (2005) reported single colony foraging areas ranging from 83m² to 1,634m² in an urban park setting. However, the majority of colonies surrounding a building in another urban study were found to not forage beyond 30m from the colony (Aluko and Husseneder 2007). The discrepancy in foraging areas could be due to availability of food sources, with the termites around the building having a large amount of structural wood to sustain them. In forested environments, perhaps foraging areas may fall between the numbers in the previously mentioned studies. In a forest there will not be any large wooden buildings for multiple colonies to infest, while more trees will be present than in a park setting allowing termites to travel shorter distances between food sources. Alternately, colony establishment may be more successful in forested areas because of abundant foraging resources, lack of termiticide residuals, and absence of monitoring programs. Determining how prevalent *C. formosanus* colonies are in forests is one of the primary focuses of this study.

**Presence in Mississippi**

The Formosan subterranean termite has been documented in 26 Mississippi counties (Sun et al. 2007), with the most recent discovery in 2011 within Lee County (unpublished). The heaviest infestations of *C. formosanus* are found in the coastal counties of Hancock, Harrison, Jackson, and Pearl River (Sun et al. 2007). The major alate swarming periods in Mississippi occur during May and June, with one week
accounting for a major flight (Sun et al. 2007). It is possible that precipitation and humidity may play a role in determining when the major flight week takes place (Sun et al. 2007). Lax and Wiltz (2010) found a correlation between alate catches and distance to railroads. Transects based on ease of access and distance from roads have been used in the two major Mississippi *C. formosanus* studies (Sun et al. 2007; Lax and Wiltz 20010). Due to this, the need for traps in harder to access areas is vital in order to determine the abundance of *C. formosanus* in rural and forested areas. Additionally, traps and alate catches still tell us little regarding the impacts of *C. formosanus* on living trees.

**Competition with Native Subterranean Termites**

Intraguild competitors are one of the most important limiting factors for many termites due to the similar feeding and nesting habits between termites of different species (Lee and Wood 1971). There are several documented cases where one termite species overtakes another species’ colony (Lee and Wood 1971). Studies show that *C. formosanus* are able to out-compete native *Reticulitermes* spp. (Su 2003). Formosan subterranean termites and native *Reticulitermes* spp. utilize similar resources, but *C. formosanus* are more prolific feeders. Smythe and Carter (1970) found in lab studies that *C. formosanus* had higher survival and wood consumption rates than both *R. flavipes* and *R. virginicus*. Displacement of native termite species due to resource competition is very plausible in areas where *C. formosanus* are successfully established.

In some New Orleans’s neighborhoods, Formosan subterranean termites have already replaced *Reticulitermes* spp. as the primary attacking termite species (La Fage 1987). A mark and recapture study in a New Orleans park applied termiticides to dispatch
numerous \textit{C. formosanus} colonies. Within a month, \textit{R. flavipes} colonies were invading the vacated foraging territories of the treated \textit{C. formosanus} colonies (Messenger et al. 2005). It is apparent that the \textit{R. flavipes} colonies were already in the area, so it is very possible that \textit{C. formosanus} had previously displaced \textit{R. flavipes} from the foraging grounds. Osbrink et al. (1999) found native and \textit{C. formosanus} living tree infestations in close proximity, and the \textit{C. formosanus} infested trees greatly outnumbered the native infested trees. This is another scenario where potential native displacement had already begun.

\textit{Infestations in Living Trees}

Numerous studies have reported Formosan subterranean termite infestations in living trees within urban areas (Osbrink et al. 1999; Messenger et al. 2005; Guillot et al. 2010). Limited literature could be found regarding \textit{C. formosanus} infestations within forested areas of the United States. However, Sun et al. (2007) reported several infested trees in forested areas after conducting physical searches for colonies based on alate trap catches. The same study documented higher alate capture rates in forested areas than in urban areas (Sun et al. 2007). The impacts \textit{C. formosanus} have on standing timber and the extent of living tree infestations in forested areas still remains unclear.

The amount and size of available woody debris within a forest may affect the tendency of \textit{C. formosanus} to attack living trees. Woody debris is a major food source for native termites, which also sometimes infest living trees (Cooper and Grace 1987; Osbrink et al. 1999). Numerous components are known to influence the findings of termites in wood, such as moisture, soil type, and season (Howard et al. 1982).
Subterranean termites also have shown a preference for larger diameter wood (Wang and Powell 2001; Wang et al. 2003; Nobre et al. 2009), but Wang and Powell (2001) concluded that wood length alone is not a good indicator of susceptibility to termite attack. Due to these factors, the occurrence of termites in living trees may vary according to forest characteristics.

Formosan subterranean termites have been found infesting a wide variety of tree species within the United States. A South Carolina study discovered *C. formosanus* infesting 17 species of living trees (Chambers et al. 1988). These species included black cherry (*Prunus serotina*), southern red oak (*Quercus falcata*), white oak (*Quercus alba*), southern live oak (*Quercus virginiana*), crape myrtle (*Lagerstromia* spp.), elm (*Ulmus* spp.), American sycamore (*Platanus occidentalis*), flowering dogwood (*Cornus florida*), willow oak (*Quercus phellos*), southern magnolia (*Magnolia grandiflora*), laurel oak (*Quercus lauriflora*), water oak (*Quercus nigra*), hackberry (*Celtis* spp.), red cedar (*Juniperus virginiana*), American beech (*Fagus grandifolia*), eastern redbud (*Cercus canadensis*), and yellow poplar (*Liriodendron tulipifera*) (Chambers et al. 1988).

Loblolly pine (*Pinus taeda*) and bald cypress (*Taxodium distichum*) are two other species found to have multiple infestations in New Orleans (Osbrink et al. 1999). Many of these tree species are found throughout Mississippi and the current Formosan subterranean termite range, thus there is no shortage of living trees for *C. formosanus* to attack. In Africa, termites have been documented readily attacking introduced tree species while leaving native species relatively unharmed (Lee and Wood 1971). Conversely, invasive insects are well known to threaten native species of plants and insects (Pimentel et al. 1990).
2001.) In the case of *C. formosanus*, it is plausible that our native tree species may be at risk.

In New Orleans, Formosan subterranean termites were first found in pine stumps before they were found in living pine trees, years later (Spink 1967). “Least destructive sampling” (LDS), which consists of hacking away bark from the base of a tree using a hand tool, has been successfully used to detect infestations of *C. formosanus* in living trees (Osbrink et al. 1999). Unlike our native *Reticulitermes* spp., a lab study discovered that *C. formosanus* are likely to return to bait stations after mechanical disturbance (Gautam and Henderson 2012). These findings give validation to my study's methods which consists of mechanical inspection of recently harvested timber stumps.

**Feeding Preferences**

Feeding preferences of Formosan subterranean termites have been studied in lab settings with mixed results. One lab study tested 24 tree species and found that yellow birch (*Betula alleghaniensis*) was the highest preferred tree species, followed closely by sweet gum (*Liquidambar styraciflua*). Loblolly pine was not found to be a preferred species although it was consumed at the highest rate in American Wood Protection Association (AWPA) Standard E1 “no-choice” tests (Morales-Ramos and Rojas 2001). However, in an urban study, loblolly pine was found to have the highest infestation rate among live trees of various species (Osbrink et al. 1999). Another lab study reported strong colony growth in sweet gum, while loblolly pine colony growth was low (Morales-Ramos and Rojas 2003). With the low feeding preference and colony growth rate for loblolly pine in lab tests, there is somewhat conflicting evidence since loblolly pine was
consumed at the highest rate in no choice tests and infested at the highest rate in the urban study. Although loblolly pine was found not to exhibit high colony growth, pine straw mulch was correlated with excellent colony growth and progeny counts (Sun 2007). A study on *R. flavipes* found pine straw to be consumed at the highest rate in no-choice tests among seven different mulch types (Pinzon et al. 2006). If *C. formosanus* exhibits similar feeding habits toward pine straw, it could be significant for pine plantations in which the forest floor is composed of mostly pine straw.

A common tree species in southeastern pine plantations is sweet gum, which was shown to be a preferred species and have high colony growth in the previously mentioned lab tests (Morales-Ramos and Rojas 2001; Morales-Ramos and Rojas 2003). With the feeding preference for sweet gum and good colony growth in sweet gum and pine straw, it is possible that pine plantations may serve as valuable habitat for *C. formosanus*. This could have major implications for commercial forests since loblolly pine plantations comprise a large portion of the forest industry in the southeastern United States. To determine the potential threat *C. formosanus* poses to these plantations, feeding preferences among living trees in forested settings need to be further examined.

Studies in other countries have found subterranean termites more frequently infest and damage softwood tree species than woods of intermediate hardness (Lin 1987; Peralta et al. 2004). Pines are softwood and therefore accommodate this observation. Southern pine and sugar maple have been documented as preferred wood for numerous termite species (Smythe and Carter 1970), and tests show *C. formosanus* is no exception (Morales-Ramos and Rojas 2001). However, some woods have been found to be unsuitable for *C. formosanus*, such as cedar and redwood (Su and Tamashiro 1986).
Given a choice, termites will not feed on these species. Diets composed strictly of these non-suitable woods resulted in termite death within a month (Su and Tamashiro 1986). The cause behind non-suitable woods lies in the allelochemicals found within wood tissue, which can be toxic to termites or act as a repellent (Scheffrahn 1991). In some cases, this repellency can induce starvation (Scheffrahn 1991). Although a great deal of literature exists on *C. formosanus* and their feeding habits on various species of wood, the majority of these tests have taken place in lab settings. How this applies to forested settings is not known. An objective of this study is determine if Mississippi's subterranean termites do have feeding preferences among living trees in forested areas.

**Conclusion**

The invasive Formosan subterranean termite is now a firmly established pest throughout numerous Gulf Coastal Plain states, California, and Hawaii. Close to a billion dollars a year is spent on extermination, control, and repair costs due to this costly insect. There is an abundance of literature regarding *C. formosanus* biology, management, feeding preferences, and distribution in urban areas. However *C. formosanus* could be affecting the ecology of native forests and native termite species, and very little literature exists from these standpoints. In this study I hope to address these issues by examining the frequency of *C. formosanus* infestations in forested stands, the potential of *C. formosanus* to displace native *Reticulitermes* spp., the feeding preferences of *C. formosanus* in forested settings, and the spatial distribution of encountered termite colonies. I believe the information gathered from this study will be very helpful in
determining the potential impacts the Formosan subterranean termite may have on forested environments.
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CHAPTER II

NATIVE AND FORMOSAN SUBTERRANEAN TERMITE (ISOPTERA: RHINOTERMITIDAE) UTILIZATION OF LIVING TREES IN FORESTED SETTINGS

Abstract

Formosan subterranean termites, Coptotermes formosanus Shiraki, are well known pests of urban areas, but little is known about their presence in forested ecosystems of the southeastern U.S. Recently harvested timber stumps were mechanically inspected for the presence of Formosan subterranean termites on multiple sites throughout southern Mississippi and eastern Louisiana. A systematic line plot cruise with 100m x 200m spacing and 1/20ha plots was implemented, and all stumps with a diameter greater than 7.6cm were inspected. Additionally, alate light traps were placed on 8 sites to confirm presence of Formosan subterranean termites. No Formosan subterranean termites were found during mechanical inspection of tree stumps, however Formosan subterranean termite alates were captured on three sites. A total of 7,413 stumps were inspected, with 406 yielding native subterranean termite (Reticulitermes species) infestations. Although 6.27% of pine stumps and 1.86% of hardwood stumps were infested, termite presence within a site affected infestation rates more than stump type. Infestations of stumps by subterranean termites ranged from 0.94% to 14.97% depending
on site. The spatial distribution pattern of *Reticulitermes* species infestations was analyzed, however no significant distribution pattern could be found.

**Introduction**

Termites are ecologically and economically important insects that are common in many forest ecosystems. Subterranean termites (Isoptera: Rhinotermitidae) play important roles in cellulose decomposition, nutrient cycling, and soil mineralization across a multitude of environments (Harris 1966; Wood and Sands 1978; Black and Okwakol 1997). Subterranean termites can account for as much as 7%-22% of nitrogen input within forested ecosystems through nitrogen fixation in their guts (Yamada et al. 2006). A large amount of carbon dioxide is produced as a by-product of subterranean termite digestion, thus a reduction in carbon mineralization can result from dwindling termite populations (Black and Okwakol 1997). An absence of subterranean termites could alter ecosystems as termites are significant decomposers and nutrient recyclers in many forested settings (Wood and Sands 1978). Native subterranean *Reticulitermes* species are dominant wood decomposers and play an important ecological role within U.S. forests (La Fage and Nutting 1978). However, much less is known about the effects of the invasive Formosan subterranean termite, *Coptotermes formosanus* Shiraki (Family: Rhinotermitidae), on forested settings in the southeastern United States. *Coptotermes* species have been found to cause economic damage to standing timber in other countries such as eucalyptus in Australia, teak in Indonesia, and pines in Central America (Harris 1966). In Australian virgin eucalyptus forests predisposed to fire stress, *Coptotermes* species have been estimated to be the cause of up to 92% of tree losses and
approximately 64% of losses in younger forests (Greaves et al. 1967). The potential impacts of Formosan subterranean termites on forests in the southeastern U. S. are unknown, and it is important to quantify the effects Formosan subterranean termites may have on living trees in forested areas, as their presence could significantly alter the ecology of native forests.

Formosan subterranean termites are native to Asia and were first documented in the continental U.S. in 1965, where they were found in wooden beams inside a shipyard near Houston, Texas (La Fage 1987). Transportation of infested wooden shipping materials outside of numerous port cities led to further Formosan subterranean termite introductions into other southeastern states (Beal 1967). Movement of infested wood products such as railroad ties, landscape materials, and salvaged building materials also contributed to the Formosan subterranean termite’s current range (Chambers et al. 1988; Lax and Osbrink 2003). Formosan subterranean termite infestations have been documented in nine states along the Gulf Coastal Plain region of the U.S. and are also present in California and Hawaii (Haagsma et al. 1995; Woodson et al. 2001). Formosan subterranean termites have primarily been studied in urban areas within the U.S. due to their destructive capabilities on wooden structures; however, their presence in forested areas has yet to be quantified. Little regard has been given to the impact of Formosan subterranean termites on forest ecosystems within the U.S., despite the fact that they are well known to infest and damage living trees (Osbrink et al. 1999). Infestations of living trees are often common in urban areas where dense populations of Formosan subterranean termites exist (Osbrink et al. 1999; Guillot et al. 2010). These infestations can significantly weaken trees, leaving them more vulnerable to wind damage (Osbrink et
al. 1999). Structural damage from infestations can also decrease the marketability of trees (Harris 1966), and possibly increase the tree's susceptibility to disease due to increased health stress.

Formosan subterranean termites are known to infest at least 17 species of living trees in South Carolina (Chambers et al. 1988), many of which are common throughout the forests of the southeastern U.S. such as oaks (*Quercus* spp.), elms (*Ulmus* spp.), black cherry (*Prunus serotina*), flowering dogwood (*Cornus florida*), and red cedar (*Juniperus virginiana*). Additionally, more than forty species of plants are known to be infested by Formosan subterranean termites in Hawaii (Lai et al. 1983). With such a variety of plants and trees known to be susceptible to attack, the diversity of forests could potentially cater to Formosan subterranean termite expansion. Previous alate studies by Sun et al. (2007) indicated Formosan subterranean termite alate catches were higher in forested settings than in urban areas, but light competition in urban areas could have an effect on capture rates. Sun et al. (2007) also noted that Formosan subterranean termite alate catches increased yearly throughout the four-year study, indicating that populations are firmly established in localized forested areas in Mississippi. Formosan subterranean termites have shown feeding preferences for certain species of wood in lab tests, of which loblolly pine (*Pinus taeda*) was consumed at a very high rate in no-choice tests (Morales-Ramos and Rojas 2001). Living loblolly pines are also reported to be frequently infested in urban areas (Osbrink et al. 1999). Loblolly pine predominates 45 percent of commercial forest-land in the southern U.S. and contributes $30 billion annually to the economy (Schultz 1999). Considering the large industry for loblolly pine in the southeastern U.S., Formosan subterranean termites may be a threat to pine forests if their numbers continue to expand.
Inherent biological differences between native and Formosan subterranean termites may lead to subtle ecosystem changes such as alteration in nutrient cycles, forest succession, and other landscape scale processes in forested areas of the southeastern U.S. Formosan subterranean termite colonies contain many more individuals and have greater foraging aggression than native subterranean termite colonies, thus they are able to cause much more damage in a shorter period of time (Su and Tamashiro 1987; Lax and Osbrink 2003). The ability to construct arboreal nests enables Formosan subterranean termites to survive long periods of inundation and increases the availability of nesting sites (Osbrink et al. 2008), luxuries lacking in native species. As Formosan subterranean termite populations grow, forest ecology could be modified on many levels due to the biological and behavioral differences between Formosan subterranean termites and native subterranean termite species.

Differences in biology between native and Formosan subterranean termites may also allow Formosan subterranean termites to alter current native termite distributions in local forest settings. Formosan subterranean termites have been shown to outcompete native Reticulitermes species (Su 2003), and in some instances, completely replace natives as the predominant termite species (La Fage 1987). Formosan subterranean termites also exhibit higher survival and wood consumption rates in lab tests than Reticulitermes species (Smythe and Carther 1970). The Formosan subterranean termite has many advantages over its native counterpart and potentially threatens the distribution of native subterranean termites in forest settings.

The primary objective of this study was to determine the frequency of Formosan subterranean termite infestations in living trees within localized forested settings.
hypothesize that Formosan subterranean termites infest living trees in forested environments where the termites are established. Secondary objectives included determining the feeding preferences of Formosan subterranean termites in forested settings and investigating the degree of native subterranean termite displacement through competition with Formosan subterranean termites. I hypothesize that Formosan subterranean termites have feeding preferences related to tree type and size. I also hypothesize that Formosan subterranean termites may displace native subterranean termite species from foraging areas. A final objective of this study was to determine the spatial distribution of native *Reticulitermes* spp. infestations. I hypothesize that native subterranean termite infestations are non-randomly distributed across forested settings.

**Materials and Methods**

*Site Selection and Stump Inspection*

Eleven sites comprising 476.8 hectares throughout southern Mississippi and Louisiana were inspected during 2011 and 2012. A map of site inspection site locations can be found in Figure 1. There were nine sites surveyed in four Mississippi counties: Pearl River, Harrison, Jackson, and Lamar. Two additional sites were surveyed in St. Tammany Parish, Louisiana. According to a previous study by Sun et al. (2007), the four Mississippi counties inspected for this study were among the top five counties in the state for Formosan subterranean termite alate captures. Additionally, Formosan subterranean termites have been found in St. Tammany Parish, Louisiana since the late 1980’s (La Fage 1987; Messenger et al. 2002).
Figure 1. Location of Subterranean Termite Inspection Sites
Site criteria, which consisted of recent timber harvest and proximity to established Formosan subterranean termite populations, led to a non-continuous flow of site availability; therefore sites were inspected as they became available. Viable sites were found through cooperation with the Mississippi Forestry Commission and Weyerhaeuser timber company. Inspection took place within three weeks of timber harvest to avoid damaging standing timber and to limit the possibility of post-harvest colonization of stumps by subterranean termites. In some cases, tree harvest was still occurring during inspection. A 2.5% systematic line plot cruise (Avery and Burkhart 2002) was implemented post-harvest on sites that were 20 hectares and larger, while sites smaller than 20 hectares received a 5% cruise. Plots were 1/20th hectare in size and circular, with 100 meters between plots and 200 meters between transects. An example of the layout of the systematic line plot cruise utilized can be found in Figure 2. A global positioning system (GPS) unit (GPSMAP 60CSx®, Garmin Ltd., Olathe, KS) was used to record plot centers. This inspection method was chosen to insure adequate sampling across each site and to limit sampling bias.
Figure 2. Layout of Systematic Line Plot Cruise Inspection

All stumps greater than 7.6cm in diameter and located within plots were inspected with shovels and hatchets. The lower diameter limitation used for this study was based on previous Mississippi studies, which indicated that native subterranean termites primarily infest coarse woody debris with diameters above 7.6cm (Wang and Powell 2001; Wang et al. 2003). One-quarter of each stump was inspected for subterranean termite presence from the cut surface of the stump down to 15cm below the soil line. This method was successfully used to detect infestations of Formosan subterranean termites in living trees throughout urban areas, even when visual symptoms of infestation were not present (Osbrink et al. 1999). If termites were present in stumps, they were immediately identified as *Reticulitermes* spp. or *Coptotermes formosanus* using the morphological...
characteristic of head shape in the soldier termite caste (Gleason and Koehler 1980).
Stump diameter was recorded for infestations, which were subsequently labeled as hardwood or pine (softwood). Each infested stump was then marked and labeled on a GPS unit.

Sites

Inspections within Pearl River County, MS took place on two upland sites, A and K, which comprised a total of 104.4 hectares. Site A (N30° 46' 58" W89° 29' 56"), a 83 hectare clear-cut tract with remaining hardwood hollows, was inspected during early June 2011 at 5% cruise intensity. Site A bordered each side of Highway 53 near the Poplarville, MS airport. Lax and Wiltz (2010) reported alate captures within close proximity of this site. Site K (N30° 52' 5" W89° 24' 16"), also within Pearl River County, was a 21.4 hectare pine plantation. This site had recently received a fifth-row thin before inspection took place in March 2012. Since the tract was not clear-cut, cruise intensity was set to 5% to increase sampling accuracy. This tract was located on Gumpond Road near Poplarville, MS, which was also near previous trap locations of Formosan subterranean termite alates by Lax and Wiltz (2010).

A total of 215.3 hectares was inspected within Harrison County, MS among sites B, H, and C. Site B (N30° 31' 25" W89° 11' 47"), which was a 89.4 hectare upland seed tree clear-cut, had standing timber remaining on site. Standing timber consisted of mainly mature longleaf pines (Pinus palustris) and regeneration. This site was located north of Highway 53 near Lizana, MS and was inspected during July 2011. Site C (N30° 31' 43" W88° 53' 22") consisted of 117.4 hectares of clear-cut lowland and was located east of
Highway 15 near White Plains, MS. Site inspection took place during July 2011, and remaining timber on the site primarily consisted of isolated clusters of baldcypress \((\text{Taxodium distichum})\). Approximately one-third of the site was slightly inundated with water at the time of inspection due to recent heavy rainfall and the site being partially located on a floodplain. The final site located within Harrison County was site H \((\text{N30}^\circ 37' 3" \text{ W89}^\circ 12' 30'\)\). It consisted of 8.5 hectares of clear-cut lowland, north of Saucier-Advance Road near Lizana, MS. Inspection occurred during October 2011, and small hardwood trees remained scattered throughout the site.

Site D \((\text{N30}^\circ 36' 43" \text{ W88}^\circ 47' 17'\)\) was inspected in Jackson County, MS during August 2011. This site consisted of 25.9 hectares of upland clear cut pine plantation and was in the final stages of harvest during inspection. Pine timber located in hollows was left unharvested. The site was located south of Kito Lane Road, near Vancleave, MS, in one of the most heavily forested and rural areas of the study.

Three sites were inspected within Lamar County, MS, sites E, I, and J, which consisted of 72.1 total hectares. Site E \((\text{N31}^\circ 8' 23" \text{ W89}^\circ 30' 52'\)\) was a clear-cut location that comprised 13.4 hectares of upland mixed forest, with a few trees of various species remaining standing. It was located in close proximity to Dobson Road near Purvis, MS and was inspected during September 2011. Sites I \((\text{N31}^\circ 15' 13" \text{ W89}^\circ 37' 49'\)\) and J \((\text{N31}^\circ 15' 11" \text{ W89}^\circ 38' 20'\)\) were 19.4 and 39.3 hectares, respectively. Both sites were inspected during October 2011. The sites were located within a mile of each other, east of Columbia, MS, south of Highway 98 and north of A J Bond Road. These upland sites were both clear-cuts, which contained primarily pine with a few hardwoods occurring in low-lying areas.
Sites F and G were located within St. Tammany Parish, Louisiana. Both sites were located directly adjacent to Highway 36, between the towns of Abita Springs and Florenville. Site F (N30° 27' 10" W89° 59' 37") consisted of 39.3 hectares, whereas site G (N30° 25' 1" W89° 48' 45") totaled 19.8 hectares. Inspections took place during October 2011. The sites were flatland pine plantations that were recently clear-cut, with occasional hardwoods and isolated pockets of baldcypress standing in the lowest areas.

Alate Survey

Alate light traps were used during spring of 2012 to confirm the presence of Formosan subterranean termites near sites selected for physical inspections. Methods similar to Sun et al. (2007) were used to construct alate traps to ensure proper design. Traps were constructed using a 1.52m (5-foot) t-post, white polyvinyl chloride (PVC) pipe, 20 gauge 2.54cm (1-inch) poultry netting (Garden Plus), a solar powered light emitting diode (LED) light (model SPS2-P1-BK-T24, LG Sourcing Inc., N. Wilkesboro, NC), and a glue board (Trapper® LTD, Bell Laboratories, Inc., Madison, WI). Sections of PVC pipe were connected to form a 'U' shape, and the LED light was attached to one end of the 'U' (Figure 3.). The opposite end of the 'U' was attached to the t-post. A piece of 1.3cm (1/2-inch) plywood was screwed to the t-post above where the PVC was fitted, and a glue board was secured onto the plywood with binder clips. A 30.5cm (1-foot) section of PVC pipe was used for the bottom of the 'U', which positioned the LED light approximately 30.5cm (1-foot) from the glue board. To avoid non-target catches of vertebrates attempting to prey on captured insects, poultry netting was wrapped around the glue board and t-post to achieve cage dimensions of 16.5cm (9.5-inches) x 35.6cm
(14-inches). A wire top was fashioned to give easy access for glue board replacement. The t-post was driven into the ground to insure firm placement of the trap. A picture of a fully constructed alate light trap can be found in Figure 3. The LED light could be operated on either six or ten-hour periods, which began approximately 20 minutes after sunset. The six-hour period was used throughout the trapping season, since peak Formosan subterranean termite alate flight activity occurs at dusk (Bess 1970). In addition, the six hour time for running the lights allowed them to maintain a greater charge during days of heavy cloud cover where traps did not receive much sunlight.

![Figure 3. Formosan Subterranean Termite Alate Light Trap](image)
In Mississippi alates of Formosan subterranean termites have been documented to swarm as early as mid-April, with peak activity often occurring near the latter part of May (Sun et al. 2007; Lax and Wiltz 2010). Traps were placed on sites at the end of the first week in April, early enough to detect initial swarms. Glue boards were replaced every week for a seven week period, with a final collection date of May 26. This gave ample time to catch alates during their swarming periods according to the previous Mississippi studies (Sun et al. 2007; Lax and Wiltz 2010). All glue boards were dated and labeled by site when removed, wrapped in plastic wrap, and placed in a freezer for preservation. Alates were identified using the characters provided by Gleason and Koehler (1980).

A total of twelve alate light traps were placed on eight sites. The Lamar County sites (E, I, and J) were excluded from the alate trapping portion of this study due to travel constraints. Additionally, Lamar County had a low number of alate captures during a previous Mississippi study (Sun et al. 2007), relative to all other counties sampled. Site area determined the number of traps placed per site, with five sites receiving one trap each (<40.5 hectares), two sites receiving two traps each (83 and 89.4 hectares), and one site receiving three traps (117.4 hectares). Traps were placed at the approximated center of the sites. On sites with multiple traps, the location was partitioned according to area, with traps located in the approximate center of each partition.

**Spatial Distribution**

A geographic information system (GIS) program, ArcMap 10 (ESRI Inc., Redlands, CA), was used with the GPS coordinate data to determine the spatial
distribution pattern of native subterranean termite stump infestations. All infested stumps as well as the center of each plot were marked on a GPS unit during site inspection. Average nearest neighbor analysis (ANNA) was used on each plot that had at least 3 marked infestations. Plots that had less than three marked infestations were excluded during analysis due to insufficient point numbers. An ANNA analysis categorizes the distribution of point data as clustered, random, or dispersed by comparing the observed distances between points to the expected distances between points in a hypothetical random distribution.

**Statistical Analysis**

Correlations between mean percent pine, mean infested pine, and mean infested hardwood were calculated with Pearson correlation coefficients using the PROC CORR procedure in SAS 9.2 (SAS Institute, Cary, NC). Significance level for the Pearson correlation was set at $P \leq 0.05$.

**Results**

**Stump Inspection**

A total of 7,413 stumps were inspected, consisting of 6,072 pines and 1,341 hardwoods. No Formosan subterranean termites were found, however 406 infestations of *Reticulitermes* spp. were recorded, resulting in an overall stump infestation rate of 5.48%. These included 381 pine infestations (6.27% of total pines), whereas only 25 hardwoods were infested (1.86% of total hardwoods). Table 1. contains a summary of stump inspections and infestations across all sites. Individual site infestation rates ranged from
0.94% to 14.97% (Figure 4.). Infestation rates of 1.32% to 15.78% were recorded in pines (Figure 5.), and 0% to 7.84% in hardwoods (Figure 6.). Infested stump diameters ranged from 9.65cm to 61.72cm in pines and from 10.16cm to 59.44cm in hardwoods. The mean infested stump diameter for all stump types was 32.22cm, with a median of 34.24cm. A frequency distribution of infested stump diameters arranged by diameter classes can be found in Figure 7. For infested pine stumps, the mean diameter was 32.26cm with a median of 34.30cm (Table 2.). Infested hardwood stump diameters were slightly lower, with a mean of 31.24cm and a median of 26.16cm.

### Table 1. Summary of Stump Inspections and Subterranean Termite Infestations by Site

<table>
<thead>
<tr>
<th>Site</th>
<th>P</th>
<th>H</th>
<th>Total</th>
<th>Infested</th>
<th>Infested</th>
<th>% Infestation</th>
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<tr>
<td></td>
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<td></td>
<td></td>
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<td>78</td>
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<td>19</td>
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<td>0</td>
<td>1206</td>
<td>19</td>
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</tr>
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<td>1341</td>
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<td>406</td>
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Figure 4. Subterranean Termite Total Stump Infestation Rates by Site

Figure 5. Subterranean Termite Pine Stump Infestation Rates by Site
Figure 6. Subterranean Termite Hardwood Stump Infestation Rates by Site

Figure 7. Frequency Distribution of Subterranean Termite Stump Infestations by Diameter Class
Table 2. Mean Infested Pine Stump Diameters by Site Sorted by Diameter

<table>
<thead>
<tr>
<th>Site</th>
<th>Diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>18.96</td>
</tr>
<tr>
<td>D</td>
<td>23.05</td>
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<tr>
<td>H</td>
<td>25.6</td>
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<tr>
<td>A</td>
<td>27.98</td>
</tr>
<tr>
<td>C</td>
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<td>G</td>
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<tr>
<td>B</td>
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</tr>
<tr>
<td>I</td>
<td>40.92</td>
</tr>
<tr>
<td>J</td>
<td>41.32</td>
</tr>
</tbody>
</table>

Site F had the highest overall infestation rate of *Reticulitermes* spp. with 14.97% of all stumps being infested. Sites C and G followed, with infestation rates of 10.81% and 7.42%, respectively. Site I had the lowest infestation rate of all sites inspected at 0.94%. It was followed closely by site D at 1.33% and site K at 1.58%.

Several sites had low occurrences of hardwood stumps. No hardwood stumps were encountered during inspections on site K, and site B only had 3 hardwood stumps in inspection plots. Sites D and F also had low numbers of hardwood stumps at 16 and 33, respectively. Five sites contained hardwood stumps but had no hardwood stump infestations (sites B, D, H, I, and J).

For further analysis and uniformity, stump infestations by *Reticulitermes* spp. were converted to a per hectare basis using a per hectare conversion factor relative to the percent cruise conducted on the site. Overall, mean infestations per hectare across all stump types and sites was 27.41. Pine stump mean infestations per hectare across all sites was 26.36, with hardwood stumps at 1.05. The mean infestations per hectare for all
stumps on a per site basis ranged from 5.06 (site A) to 79.39 (site F) (Figure 8.). Sites A, B, and I had less than 7.16 infestations per hectare. Site C had the second highest infestations per hectare at 65.08, which was followed by site G at 38.72. The hardwood stump infestations per hectare for site C was 7.16, and it was the only site with a mean of more than 1.68 infested hardwood stumps per hectare.

![Figure 8. Mean Subterranean Termite Stump Infestations per Hectare by Site](image)

There was no significant correlation between mean percent pine and mean infested pine or mean infested hardwood. However, a significant correlation ($P = 0.0312; r = 0.67785$) was present between mean infested pine and mean infested hardwood, indicating that as pine infestations increased, hardwood infestations increased as well. Feeding preferences towards stump diameter could not be analyzed due to lack of data for uninfested stump sizes.
Alate Survey

A total of 14 Formosan subterranean termite alates were caught among three sites during the seven week trapping period. The location of sites with alate catches can be viewed in Figure 9. Two alates were detected on the May 11 trap check of site A in Pearl River County. On May 12, one alate was present on the site D trap in Jackson County. Alates were not present again until the May 25 check, when 10 alates were caught on site A and one alate was present on site G within St. Tammany Parish, LA. Both traps on site A caught alates during this study. Due to limited alate catches, no statistical analysis was performed.
Figure 9. Map of Inspection Sites with Formosan Subterranean Termite Alate Catches
Spatial Distribution

A total of 45 plots were analyzed in ArcMap10 using the ANNA function. The number of stumps infested by native subterranean termites ranged from 3 to 13, depending on the plot selected for analysis. There was a mean of 5.26 infestations across all plots analyzed. Upon completion of the analysis, all plots yielded dispersed distributions of native subterranean termite stump infestations. P-values ranged from 0.00 to 0.06460 while nearest neighbor ratios ranged from 1.39 to 11.95. Analysis results were skewed due to the low mean stump infestations per plot and pre-existing spatial pattern arrangements of harvested stumps in plantation forests. Increased infestations per plot would have provided more points to be analyzed, while plantation forests pre-disposed stumps to a uniform distribution.

Discussion

The activities and influences of Formosan subterranean termites in U.S. forests have been overlooked because of their prevalence and destructiveness in urban areas. In other parts of the world, Formosan subterranean termites are known pests of living trees, causing economic damage to standing timber (Su and Tamashiro 1986; Lin 1987). Despite the lack of attention regarding Formosan subterranean termites in U.S. forests, higher alate captures have been reported in forested settings than in urban areas (Sun et al. 2007). Within urban areas, Formosan subterranean termites are well documented to infest living trees (Osbrink et al. 1999; Guillot et al. 2010). Sun et al. (2007) discovered infested living trees in forested settings near traps with high alate captures. This indicates
that Formosan subterranean termites are established in localized forested settings, however the extent of forest infestations is not known.

Although no Formosan subterranean termite infestations were found in stumps of recently logged forested stands in Mississippi and Louisiana during this study, native *Reticulitermes* spp. infestations were found across all sites inspected. Subterranean termite infestations were more prevalent in softwood than hardwood stumps. This result agrees with results from previous studies which documented that subterranean termite prevalence was inversely proportional to wood hardness, with soft woods having higher infestation rates (Lin 1987; Peralta et al. 2004). In an additional study pine was found to have the highest infestation rate among live trees of various species (Osbrink et al. 1999). The results within this study are very similar to the previously mentioned studies. A Pearson correlation coefficient was utilized in this study for statistical analysis and revealed a significant correlation between the mean percent infested pine and mean percent infested hardwood stumps on a per site basis. As pine infestations increased, hardwood infestations also increased. This implies that termite presence on a site had a greater affect on infestation numbers than stump type did. The low frequency of hardwood stumps across many sites likely contributed to this result. No significant correlation was found between the percentage of pine on a site and the mean infested percentage of stumps of either tree type, so the amount of pine present on a site did not affect stump infestation rates.

Stump diameter may have also played a major role in infestation occurrence. Site F had the highest overall infestation rate and the most total infestations per hectare out of all sites inspected. The mean infested pine stump diameter (34.3cm) of site F was also the
median mean infested pine stump diameter across all sites. Sites that deviated from the 34.3cm median had much lower infestation rates than sites with a mean pine stump diameter closer to that of the median (Table 2.). The frequency distribution of stump infestations by diameter class in Figure 7. also illustrates the effect stump diameter had on infestations. It is possible that native *Reticulitermes* spp. may have a feeding preference towards certain stump diameters, however this study was not able to statistically test for preference because uninfested stump diameters were not recorded.

Although bark thickness was not measured in this study, there was a noticeably higher incidence of subterranean termite infestations in pine stumps with thicker bark plates. Subterranean termites were found inhabiting the cambium layer, which has higher nitrogen content than bark (Mattson 1980). However, thick bark may also provide more staging area for termites as they travel to the xylem to feed. Additionally, progeny were found within bark plates on multiple occasions indicating potential nesting grounds. The majority of *Reticulitermes* spp. were found either under the bark plates next to the stump xylem (cambium layer) or within the bark plates. Even though *Reticulitermes* spp. are primarily viewed as insects that heavily rely on dead or decomposing wood, this study reveals that they do commonly utilize the phloem of living woody resources. Pine bark appears to be a viable resource for subterranean termites in forested settings and future studies could further investigate the utilization of pine bark by subterranean termites.

Soil moisture levels may have played an important role in detection of subterranean termite infestations in stumps. Site F was a lowland tract with moist soil conditions throughout the site. This site also had the highest incidence of subterranean termite infestations. Site C had the second highest overall infestation rate, as well as the
highest hardwood infestation rate. Abundant soil moisture on site C, due to locally heavy rainfall, inundated low lying areas, which may have forced subterranean termites into the stumps to prevent drowning. In many of the flooded plots within this site, the majority of stumps were infested with termites regardless of stump type. The two most heavily infested sites shared the property of abundant soil moisture. Conversely, the four sites with the lowest occurrence of infestations (A, D, I, K) were upland habitats with relatively dry soils. The sites were well drained, with little to no standing water. Moisture content has previously been shown to influence findings of subterranean termites in wood (Howard et al. 1982), and in this study it appears soil moisture is positively correlated with subterranean termite infestations in stumps.

Although no Formosan subterranean termites were detected by physical inspection of timber stumps throughout this study, alates were captured on three sites. Site A had multiple alate captures among two traps, while only one alate was caught on each of the other two sites. Formosan subterranean termite alates have the capability to disperse distances of nearly 900m in open areas (Messenger and Mullins 2005), however other studies have shown flight distances of 100m to be more common (Higa and Tamashiro 1983). Although it is unknown if Formosan subterranean termite colonies were located on the inspection sites where alates were caught, it is likely that colonies exist within close proximity, when common dispersal distances are taken into account. Another factor to consider is the number of alates caught. Since two sites only had an individual alate capture, it is possible that these alates dispersed a greater distance than the site with multiple alate captures. Site A did have multiple alates on two traps, therefore it is likely these traps are closer to parent colonies than the traps on other sites.
It is also possible that Site A contained a larger colony or greater number of colonies than the other sites. Site D, which was located in a very rural location and completely surrounded by forest, was one of the sites with a single alate catch. The site was over 1.6km (1-mile) away from the nearest house or residential area, increasing the likelihood that the alate came from a colony in a heavily forested area. Perhaps Formosan subterranean termite populations are not currently high enough in forested settings for easy detection, but captures on sites such as this imply that colonies may be established in localized forested areas.

The spatial distribution of native subterranean termite stump infestations was concluded to be a dispersed pattern in all 45 plots analyzed using ANNA. However, due to the sampling methods used in this study, a truly accurate analysis of spatial distribution was not possible. Pre-existing stump distributions (due to plots occurring in plantations) heavily influenced ANNA results, as stumps likely already had a defined spatial distribution pattern. For example, pine plantation stumps would likely have a uniform pattern due to planting methods whereas stumps in an unmodified natural stand should have more of a random pattern. Stump distributions would need to be random to increase ANNA accuracy, but the majority of sites sampled were pine plantations. Another major limiting factor of ANNA accuracy was the lack of infestations (points) per plot, as analyzed plots only had a mean of 5.26 infestations. Spatially recording negative points for analysis would have greatly increased accuracy. In order to further increase the accuracy of ANNA, larger plots could have been used to help raise the number of infestations per plot, and sampling methodology would have to be modified to correct for...
spatial autocorrelation created by plantation forestry practices and systemic line plot cruises.

There are several plausible reasons as to why no Formosan subterranean termite infestations were found during this study. Although Formosan subterranean termites commonly utilize living trees in urban areas (Osbrink et al. 1999), urban environments contain far fewer trees than forests. The abundance of living trees and woody debris in forested settings gives subterranean termites a plethora of resources to choose from, unlike urban areas where trees are normally scattered or isolated and woody debris is minimal. This can make locating infestations much more difficult.

Proximity to railroads may have also played a role in the lack of Formosan subterranean termite findings. A previous Mississippi study investigated the relationship between alate trap catches and distance to railroads, and found a significant correlation during one year of a three year study (Lax and Wiltz 2010). Two of the three sites where Formosan subterranean termite alates were caught in this study were located within close proximity to railroad tracks. The distance from each site to the nearest railroad is shown in Table 3. Sites A and G were located 5.95km and 1.5km from the nearest railroad, respectively. However, site D was located 21.08km from the nearest railroad, which raises the mean distance from a railroad to 9.51km for sites with alate catches. The mean distance from railroads for sites with no alate catches was 12.51km. It is plausible that infested railroad ties and transportation of infested materials via railway could influence Formosan subterranean termite presence.
Table 3. Distance from Inspection Sites to Nearest Railroad

<table>
<thead>
<tr>
<th>Site</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>K</td>
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</table>

* = denotes alate trap catch

Additional research is needed to ensure that Formosan subterranean termite populations are not posing a threat to forested settings. More forested sites need to be inspected for presence of Formosan subterranean termites, with potentially stricter site criteria such as distance to railroads and major roadways, documentation of previous alate trap catches, and proximity to urban areas. Imposing requirements on inspection sites should increase the probability of finding Formosan subterranean termites in forested areas. However, due to the difficulty of locating potential sites, it may take several years to adequately complete the investigation. Continuation of alate monitoring within forested and rural areas is also very important as data collected can be useful in monitoring alate populations and range expansion. Further confirmation of Formosan subterranean termite establishment in localized forest settings would also raise the importance of determining feeding preferences and the likelihood of native subterranean termite displacement in forests, issues this study was not able to address.

At the conclusion of this study, Formosan subterranean termites infestations were not found in recently harvested timber stumps at the 11 sites inspected. However,
Formosan subterranean termites were in the general area of 3 sites, as evidenced by the alate trap catches. Due to lack of findings on inspected sites, feeding preference data for Formosan subterranean termites could not be collected, and native *Reticulitermes* spp. displacement is not a current problem within the study areas. Stump inspection data did reveal that *Reticulitermes* spp. accounted for vastly more infestations in pine stumps than in hardwood stumps, but stump type could not be shown to significantly affect the number of infestations per site. *Reticulitermes* spp. infestations were highest around the median mean infested pine stump diameter of 34.3cm. Infestations decreased as stump diameters strayed farther from the median, indicating a potential feeding preference towards stump diameter. However, methods utilized for this study did not allow us to statistically test for stump diameter preference. It is important to note that Formosan subterranean termites could be impacting forested stands in other locations, even though they were not located on the tracts inspected during this study. With rising populations, the invasive Formosan subterranean termite could still pose a major ecological threat to forested settings and native termite species, issues that need to be addressed with continued research.
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