MAXWELL, JUSTIN TIMOTHY, Ph.D. Beekeepers' Gold: Reconstructing Tupelo Honey Yield in Northwest Florida Using Nyssa Ogeche Tree-Ring Data. (2012)
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This dissertation contains three manuscripts that have been either submitted to or accepted by peer-reviewed academic journals. I first examine the U.S. honey industry to determine how the industry is responding to the current multiple challenges facing U.S. beekeepers. I discuss how the industry might survive these challenges by transitioning to a multifunctional system and becoming more economically and environmentally sustainable.

I then examine a specific honey type—tupelo—in more detail using tree-rings to expand the honey record. Tupelo honey is derived from the nectar of Ogeechee tupelo (*Nyssa ogeche)* trees growing in northwest Florida and southern Georgia. I use *N. ogeche* tree-ring data to reconstruct and expand the honey yield-per-hive record and then place the current decline in a historical context. I also identify the climatic and hydrologic conditions conducive to optimal honey yields.

This project is the first to use dendrochronological techniques to expand and analyze honey yields. I use tupelo honey yield as an example of how climatic cycles may cause long-term fluctuations in crop productivity. The results demonstrate the utility of employing tree-rings to extend crop records to allow a broader understanding of yield variations inherent in agriculture and can be implemented for other crop yields.

BEEKEEPER'S GOLD: RECONSTRUCTING TUPELO HONEY YIELD IN NORTHWEST FLORIDA USING NYSSA OGECHE TREE-RING DATA

By

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CHAPTER I

INTRODUCTION

This dissertation has tree broad objectives: 1) to determine the potential of multifunctionality for the U.S. honey industry, 2) establish that *Nyssa ogeche* tree-rings crossdate and correlate with tupelo honey yield-per-hive, and 3) to determine if meso-scale climate oscillations influence tupelo honey yield-per-hive.

1.1 *Nyssa* Genus

The genus *Nyssa* consists of ten species, four of which are native to eastern and southeastern Asia and six native to North/Central America (Eyde 1963, Eyde 1966, Wen and Stuessy 1993). The name *Nyssa* was first cited in *Systema Naturae* (Linnaeus 1735) and is Latin for nymph. It is believed that Linnaeus assumed all species in the genus grew in aquatic habitats (Eyde 1966), which was later discovered to not be true of all the species in the genus. The common name used for the genus is *tupelo* and is derived from the Creek language, which is also known as Muskogee and was spoken by the Muscogee and Seminole people. The meaning of the word tupelo is roughly translated to swamp tree (Keyarts 1964).

Of the six species in North/Central America, five are found predominately in the United States: *N. sylvatica* Marsh (Black Gum), *N. aquatica* Linnaeus (Water Tupelo), *N. ogeche* Bartr. ex Marsh (Ogeechee Tupelo), and *N. biflora* Walt. (Swamp Tupelo). The two disjunct populations of the genus (North American and Asian) are not an uncommon pattern among other woody genera and it is accepted that the populations are most likely genetic remnants of Tertiary mesophytic forests that once extended throughout the majority of the Northern Hemisphere and were reduced by the Quaternary glaciation period (Li 1952; Eyde 1963). While this theory has been operative since the late 1800s (Gray 1878; Hu 1935), more recent studies have shown that the distribution has multiple origins (Hara 1952; Koyama and Kawano 1963; Li 1972). This theory has been confirmed, at least for the genus *Nyssa*, because the fruit for species in the genus are drupes of various sizes with unique endocarps, the innermost layer of fruit surrounding the seed, making the genus easily distinguishable by fruit alone (Eyde 1959; Eyde and Barghoorn 1963). The endocarps are also easily conserved, which combined with their distinct pattern makes the genus one of the best fossil records of any modern genus of trees (Eyde 1959; Eyde 1963; Wen and Stuessy 1993). The fossil record of *Nyssa* in the Tertiary strata also include, pollen, wood, and leaves leaving little doubt that the genus once existed in most of the Northern Hemisphere (Eyde 1963; Wen and Stuessy 1993). Many *Nyssa* species that exist in the fossil were found in Europe, North American, and Asia (Eyde and Barghoorn 1963) and are believed to be closely related to many of the current species, indicating that the current populations of *Nyssa* are the remains of a more widely distributed genus. In addition, Wen and Stuessy (1993) found a monophyletic group of two eastern Asian species and one North American species confirming that species on the two continents were closely related and thus were probably connected geographically in the past.

Nyssa has been the subject of major taxonomic debate for over two centuries with various authors recognizing several ecological variants (Burckhalter 1992). Most of these debates have involved the variants of *N. sylvatica*. *N. biflora* was recognized as a variant of *N. sylvatica* (*N. sylvatica* var. *biflora*) and shares many similarities; however, *N. biflora* is restricted to swamps along the southeastern U.S. coastline while *N. sylvatica* has a much larger range (see Little 1971). With the presence of moderate, but distinguishable morphological differences, *N. biflora* is now recognized as a separate species (Burckhalter 1992). *N. ursine* was initially considered (Small 1927) to be a separate species, but is now classified as a variant of *N. biflora* (Godfrey 1988; Burckhalter 1992). Other species of *Nyssa* have caused taxonomic problems too. A small shrub growing species, *N. acuminata*, caused confusion as some believed it to be a separate species and others thought it was a variant of *N. ogeche*. Currently it is classified as a phenotypic variation of *N. ogeche* (Eyles 1941; Little 1978; Burckhalter 1992). Similarly, while, *N. aquatica* and *N. uniflora* are now considered synonymous, the two were thought to be separate species in the past (Eyde 1964; Burckhalter 1992).

Nyssa species have also been used in tree-ring studies. The most widely studied *Nyssa* species, *N. sylvatica,* is particularly known for its longevity, the oldest known individual is 679 years old (Sperduto et al. 2000, Eastern OLDLIST 2010), making it an especially valuable species in the field of dendrochronology (Abrams 2007). *N. aquatica* has also been shown to crossdate (Earnhardt 1993; Brugam et al. 2007) — when annual tree ring widths significantly correlate between multiple trees — indicating that other species of this genus could be used in dendrochronology. No other species in the *Nyssa* genus, including *Nyssa ogeche*, have been used for tree-ring studies. General information can be gathered from the species that have been used in dendrochronology, *N. sylvatica* and *N. aquatica*, to determine the potential characteristics of other species in the genus and the likelihood that other species would crossdate. *Nyssa* species have diffuse-porous wood (Figure 1.1), which makes distinguishing ring boundaries difficult. Diffuse-porous wood occurs when vessels the trees use for water are distributed nearly equally throughout the growing season and are approximately the same size. Other hardwoods, such as oaks, will have larger and a higher number of vessels at the beginning of the growing season and then produce smaller and fewer vessels near the end of the growing season, making the ring boundary more distinguishable. While *N. ogeche* has not been used in a tree-ring study, using information from other species in the genus indicates that *N. ogeche* tree-rings could be difficult to distinguish but have great potential of crossdating.

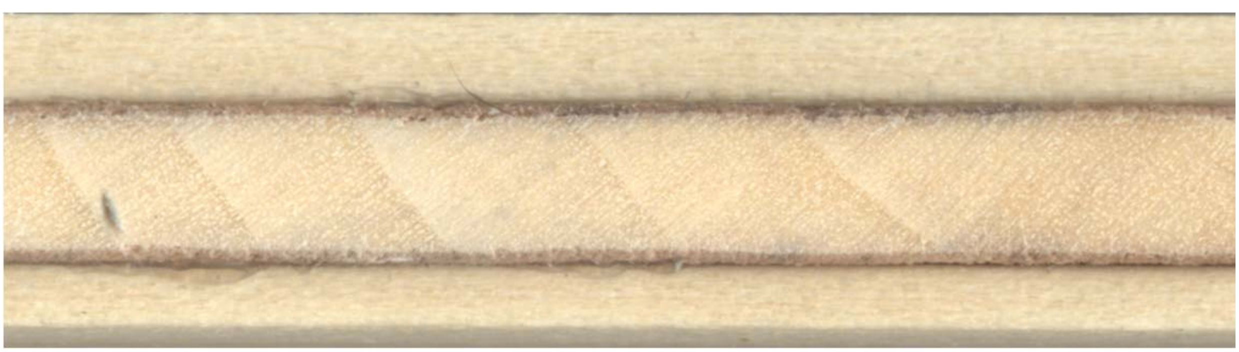

Figure 1.1: A cross-section view of a *Nyssa ogeche* core, showing the diffuse-porous nature of the species.

1.2 Ogeechee Tupelo (*Nyssa ogeche*)

Nyssa ogeche, also known as the ogeechee tupelo, white tupelo, bee tupelo, and ogeche-lime, inhabit a limited geographic range from southeastern Georgia to northwestern Florida (Figure 1.2). *N. ogeche* typically occur as a minor component in baldcypress-tupelo and water tupelo-Swamp tupelo forest types (Eyre 1980), although in their limited range they grow densely along river banks, especially along the Apalachicola River and may be nearly monospecific (Burckhalter 1992). Flowers are small and greenish yellow; they produce oblong-shaped fruit 3–4 cm long that turn red when mature (Sargent 1947). The leaves range from 10–15 cm in length, are pinnately veined, and are long and smooth (oblong and obovate) (VTREE ID 2010). Water is not an agent for dispersal of *N. ogeche* seeds (Kossuth and Scheer 1990) and consequently do not disperse as great of a distance as *N. aquatica*, which may explain the limited geographic range of ogeechee tupelo.

According to the Silvics of North America manual published by the United States Forest Service, little is known about the seedling and development stages of *N. ogeche,* but it is generally believed that if the surface soil is too dry new seedlings will not survive. Under favorable moist conditions seedlings can reach 0.6m (2ft) in one year of growth (USDA 1974). While regeneration is important for *N. ogeche*, epicormic branches (branches sprouting from stumps) are essential to regeneration. Along stream channels, *N. ogeche* reproduce almost exclusively in this manner (USDA 1974).

N. ogeche grow best on sites that are flooded for long periods, but not in areas where the water is stagnant. *N. ogeche* growing in areas further away from main streams channels that are often inundated with water tend to be dwarfed or shrublike, while those *N. ogeche* trees near stream channels grow in a more arborescent fashion (USDA 1990). *N. ogeche* are usually crooked, deliquescent trees of 7.6 to 10.7 m (25 to 35 ft) in height and rarely exceed 15.2m (50 ft). Stem diameter is usual 30 to 61cm (12 to 24 in) and the bark is irregularly fissured, broken in platelike scales (Sargent 1947).

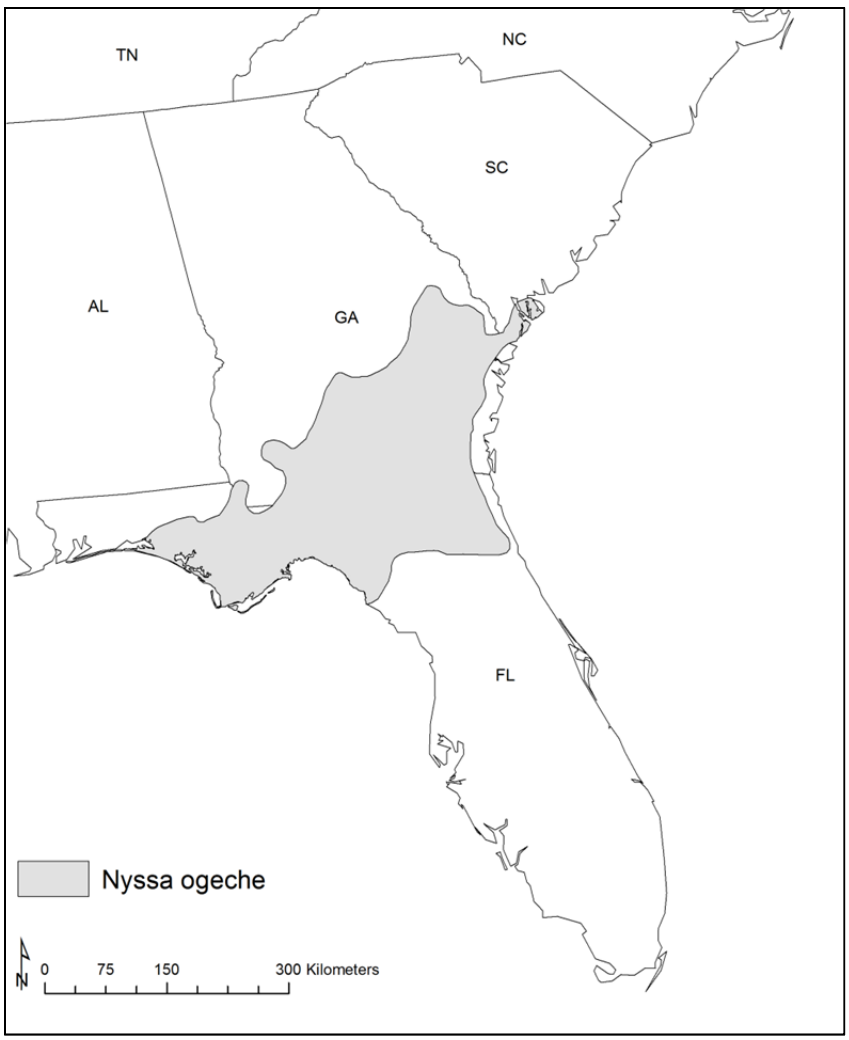

Figure 1.2: The natural range of *Nyssa ogeche*.

For a species to be ideal for a tree-ring study, the tree would need to have a single stem, be long-lived and sensitive to climate (Speer 2010). Based on the published information about *N. ogeche* there is no certainty as to whether this species meet these conditions. There is no information about how sensitive *N. ogeche* is to climate beyond that the trees grow best in swamp-like environments along stream channels. The published work also indicates that trees growing along stream channels are more likely to be more arborescent. Based on this information, I can assume that the *N. ogeche* trees will grow the best along the stream channels and because *N. ogeche* grow profusely along the Apalachicola River, sampling along this stream channel would be the most ideal location to determine how sensitive the trees are to climate. Typically trees that are at the outer edge of their growing limits are more sensitive to climate, indicating that the small shrublike trees further away from stream channels would be ideal for climate sensitivity (Speer 2010). However, because little is known about the species sensitivity and the shrublike trees have multiple small stems, the large single stem *N. ogeche* near stream channels is ideal for determining the initial climate sensitivity of the species.

1.3 Tupelo Honey

Commercially, *Nyssa ogeche* is primarily used for the production of the regionally specific heritage product Tupelo honey. Nectar from the flowers of *N. ogeche* bloom for a 3–5 week period in April and May and is collected by honey bees (*Apis mellifera* Linnaeus) and brought back to their hives where it is converted to honey (Laird 1963, Keyarts 1964, Bishop 2005). The timing of the *N. ogeche* bloom is ideal for tupelo honey production. Because bees are inactive during the winter, they are not as productive during early spring and need to be strengthened from other nectar sources (personal communication Donald Smiley, Wewahitchka, FL). Red maple (*Acer rubrum*) flowers bloom in late February to early March, which is ideal for tupelo honey production; when the *N. ogeche* flowers bloom the bees are at full strength and can maximize honey production (Donald Smiley, Smiley Apiaries, Wewahitchka, FL, pers. comm.). Once the bees have recovered from their inactivity and are at full strength, beekeepers must empty the hives of the red maple honey before the *N. ogeche* flower blooms to ensure the bees will produce a high-quality tupelo honey (i.e., the pollen count in the honey is mainly from *N. ogeche*).

Tupelo honey is among the few crops (*cf.* viticulture) whose production evokes an emotive response far exceeding its commercial prominence. This is because tupelo honey does not granulate and has other known health benefits (see Chapter 3). Thus, beekeepers can get a higher price for tupelo honey, which can encourage others to mislabel honey. As a result, the Florida agricultural commission has created regulations on labeling honey and instituted a certification process for specialty honeys to insure their authenticity (Sanford 1994). This is done by examining the pollen type present in the honey. When bees gather nectar they also bring back pollen for the nectar source species they visited. This pollen is transferred to the honey and can be seen when honey is examined microscopically. The shape of pollen is unique to one species and thus the source species of the pollen can be identified by examining the shape and size of the pollen. In the state of Florida, honey from one floral source must have a pollen count that is greater than

50% from one floral source. Thus to be called tupelo honey over half of the pollen in the honey must be from *N. ogeche* (Sanford 1994; Donald Smiley, Smiley Apiaries, Wewahitchka, FL, pers. comm.). *N. aquatica* is also used to produce tupelo honey, but local beekeepers argue that the highest quality of honey is produced from *N. ogeche* (Eyde 1963) and few beekeepers mix the two honey sources. Interestingly, beekeepers claim that honey derived from *N. aquatica* nectar is a lower-quality tupelo honey (Donald Smiley, Smiley Apiaries, Wewahitchka, FL, pers. comm.), despite the shared characteristics and lineage between the trees.

Once the beekeepers have determined that the hives have sufficient honey to extract, they remove the slots of comb and honey in the hive (Figure 1.3). They scrape the wax caps of the comb and then place the slots into a centrifuge, which is used to spin the honey out of the comb (Donald Smiley, Smiley Apiaries, Wewahitchka, FL, pers. comm.). The honey is then collected in large barrels and is later bottled in containers that are labeled properly and sold to customers.

1.4 United States Honey Industry

There are four types of honey bees worldwide: *Apis mellifera, Apis dorsata, Apis florea, and Apis cerana*, none of which are native to North America (Crane 1983). Of the honey bee species imported to the United States, *A. mellifera* is the most important in terms of honey production (Sheppard 1989a). The natural range of *A. mellifera* includes Europe, Africa, and Western Asia (Ruttner 1975; Crane 1983). Because of this large range, there are several (at least 26) sub-speices of *A. mellifera* (Sheppard and Meixner 2003; Delaney et al. 2009).

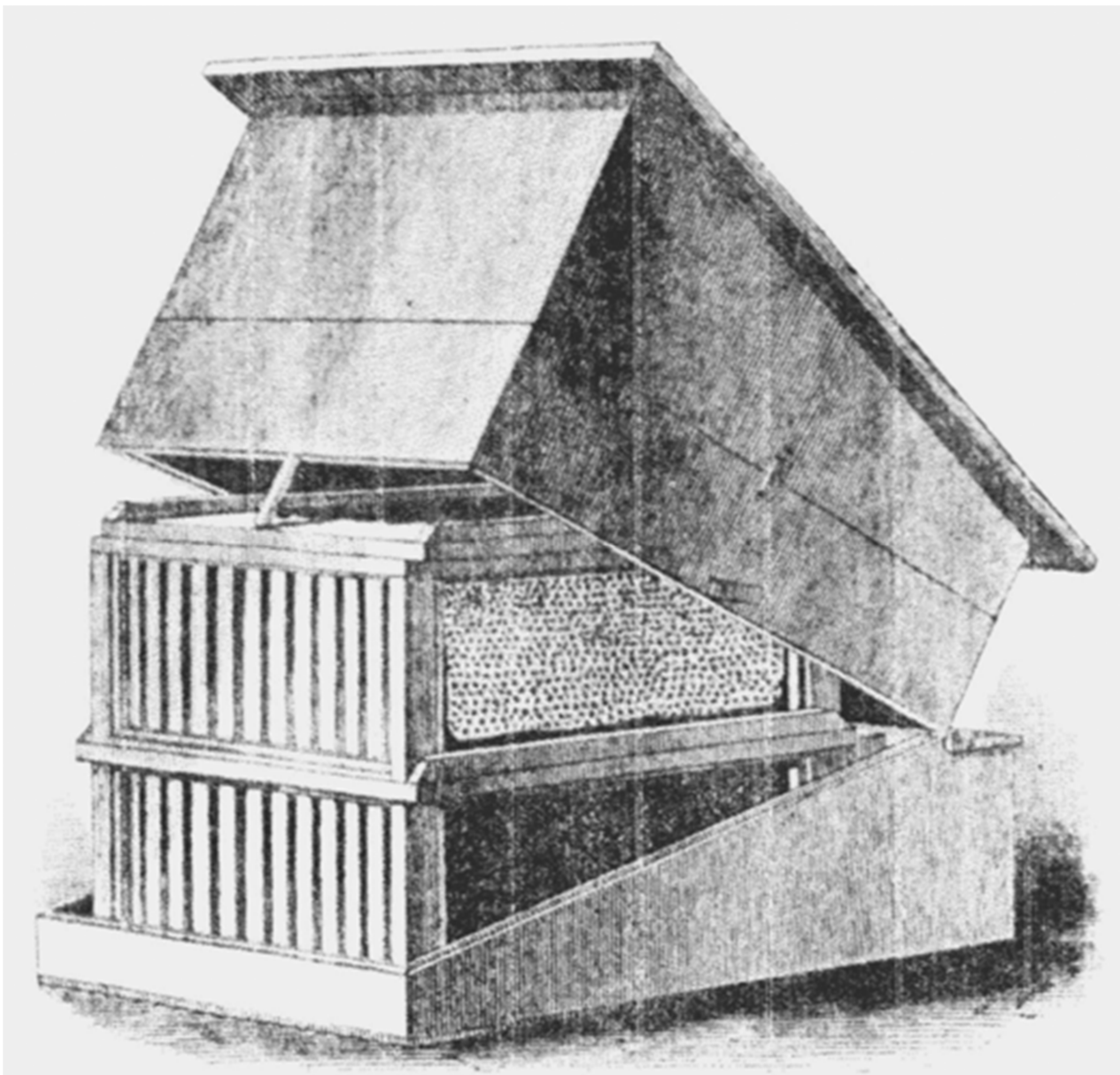

Figure 1.3: A beehive invented by Lorenzo Lorraine Langstroth in 1852. The current design of beehive is essentially unchanged. From Crane (1983): pg. 211.

Apis mellifera mellifera was the only honey bee in North American until the establishment of steamship services from Europe to the United States (Sheppard 1989a). The introduction of a more docile sub-species the Italian Bee (*A. mellifera ligustica)*, which is the most popular type of honey bee in the United States (Ruttner 1975), was one of the main subspecies introduced (Sheppard 1989a). The actual introduction of a pure *A. m. ligustica* breed is controversial. There were two different beekeepers selling *A. m. liqusitica* queens in 1860, one of which was considered a hybrid between *A. m. mellifera* and *A. m. liqustica*. Whether these accusations were true is unknown, however it was during the year of 1860 that *A. m. liqustica* became commercially available (Langstroth 1860, re-printed in Naile 1942).

The Carniolan Bee (*A. m. carnica*) was introduced in 1877 (Dadant 1877; Sheppard 1989b). The commercial production of the Carniolia Bee started in 1883. The bee did not generate as much favor in the United States as the Italian Bee despite that some considered it the most gentle behaving bee (Benton 1899), but did see popularity in Canada and the rest of the world (Ruttner 1975).

Many of the subspecies introduced in the United States were not commercially produced long. The Egyptian Bee (*A. m. lamarkii*) was imported to the United States in 1866, but was no longer commercial available by 1868 (Pellet 1938). Both the Cyprian (*A. m. cypria*) and the Syrian (*A. m. syriaca*) Bees were introduced in the 1880s, but after a few years were no longer sold in the United States or Canada (Sheppard 1989b). The Caucasian Bee (*A. m. caucasica*) was introduced in the early 1900s and gained popularity for their gentle temperament (Hill 1886). However, they were later determined to be less productive in honey production and the importation of *A. m. caucasica* declined. Lastly, the Punic Bee (*A. m. intermissa*) was introduced in 1891 and was considered a superior honey bee (Sheppard 1989b) for a few years then interest and favor declined. These five subspecies were viewed as inferior compared to the Italian and Carniolia Bees for various reasons including temperament and productivity (Sheppard 1989a; Sheppard 1989b).

In 1922 the United States restricted importation of adult honey bees with the U.S. Honey bee Act (Sheppard 1989a). The U.S. Honey Bee Act was created to prevent the spread of a parasitic honey bee mite that had been discovered in Europe (Delaney et al. 2009). Currently, the southwestern and southeastern United States are the two regions in the United States that produce queen bees commercially (Delaney et al. 2009). Of the eight subspecies that were introduced to the United States, the two regions only reproduced *A. m. carnica* and *A. m. ligustica* commercially in 2009 (Delaney et al. 2009). The other subspecies became feral because beekeepers no longer used them to commercially produce honey. The majority of feral populations were eliminated in 1987 because of a mite called *Varroa destructor*, thus the two subspecies used to commercially produce honey are the only two now present in vast numbers in United States.

There are many threats to the U.S. honey industry (see Chapter 2), including bee disease, global competition, and Africanized honey bees. These challenges are forcing the honey industry to adapt in order to survive. In the following chapters, I explore the potential for the U.S. honey industry to adapt to these challenges and examine what lessons can be learned from this industry that could be used in other agriculture industries. Further, I examine one specialty honey, tupelo, in detail and establish a relationship between *N. ogeche* tree rings and tupelo honey yield-per-hive. By establishing this relationship, I extend and expand the honey record to better understand the historic variation in yield-per-hive. Examining *N. ogeche* tree-rings also allows me to establish what conditions are ideal for tupelo growth and thus tupelo honey production.

CHAPTER II

THE POTENTIAL FOR MULTIFUNCTIONALITY IN THE U.S. HONEY AND APICULTURE INDUSTRY TO PROMOTE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY

This chapter is a manuscript that was submitted to *The International Journal of Agricultural Sustainability*.

2.1 Introduction

2.1.1 Background of the U.S. Honey Industry

Honey has been harvested in the United States since 1622 when ship records of voyages from England to Virginia documented one of the first shipments of honeybees (*A. mellifera*) to the new world (Oertel 1976; Crane 1983). The natural range of *A. mellifera* includes Europe, Africa, and western Asia (Ruttner 1975; Crane 1983). Thomas Jefferson wrote that to the American Indians honey bees often indicated that Europeans were in close proximity; native Americans referred to honey bees as the “White man’s flies” (Jefferson 1788, re-printed in Sheppard 1989a). Because honeybees are non-native to the U.S., only a few of the 26 sub-species of *A. mellifera* were shipped to the states. (Sheppard and Meixner 2003; Delaney et al. 2009). Beekeepers in the United States experimented with a number of the sub-species to determine which one was the most ideal in terms of efficiency in honey production and aggressiveness (Sheppard 1989a;

Sheppard 1989b). Based on the standards beekeepers want from a honeybee, the Italian bee (*A. m. ligustica*) was considered the most valuable (Ruttner 1975; Sheppard 1989a) and is still considered the best bee today for commercial honey production (D. Smiley, pers. comm., July 2010) In the process of identifying the best species for honey production many honeybees were shipped around the world, leading to the spread of disease, fungi, and pests (Sheppard 1989a; Sheppard 1989b). The modern honey industry operates much as it did in the 1950s (Dougherty 2009; Pundyk 2010). The lack of technological innovation combined with the spread of pests, viruses, and fungi causes alarm among beekeepers and those associated with the honey industry (Jacobsen 2008; Dougherty 2009).

Honey bee tracheal mites (*Acarapis woodi,* hereafter HBTM) were one of the first pests to affect honeybees, foreshadowing future trouble in the honey industry. HBTM was first observed between 1904 and 1919 when a bee die off reached epidemic levels in the Isle of Wight, U.K. (Clark 1985; Sammataro et al. 2000). In 1980, honey bees were imported that were infected with HBTM in Columbia, South America (Menapace and Wilson 1980). By 1984 HBTM was present in the southern United States (Sammataro et al. 2000) and two years after the discovery of HBTM in the United States there were reports of up to 90% of honeybee loss (Sammataro 1995).

HBTM remains a concern for honeybee health; however the mite responds to treatment better than the varroa mite *Varroa jacobsoni*, which has eclipsed HBTM and currently poses a threat to beekeepers in the United States and worldwide (Sammataro et al. 2000). *Varroa jacobsoni* was initially discovered in Java, Indonesia (Oudemans 1904) and was originally confined to the *A. cerana* honeybee species in Southeast Asia (Sasagawa et al. 1999). *Varroa jacobsoni* has five subspecies, one of which effects both *A. cerana* and *A. mellifera* (Anderson 2000). The *Varroa jacobsoni*, observed as a parasitic mite that parasitized both *A. mellifera* and *A. cerana*, was determined to have different characteristics than smaller *V. jaobsoni* mites that only parasitize *A. cerana* (Delfinado-Baker and Houck 1989) and thus were classified as a new species of *Varroa* called *V. destructor* (Anderson and Trueman 2000). Many chemicals were applied to exterminate *V. destructor* but the mite demonstrated resistance to these treatments (Baxter et al. 1998; Elzen et al. 1998; Pettis et al. 1998).

The varrao mites continue to challenge beekeepers. However, a mysterious phenomenon called colony collapse disorder (CCD) is now decimating honeybee populations at an alarming rate worldwide (Barrionuevo 2007; Cox-Foster et al. 2007; Oldroyd 2007; Stokstad 2007; Johnson 2010). CCD can be distinguished from mite-inflicted death because honeybee mortality occurs away from the hive with CCD. The hive is thus found empty with the exception of the queen and immature bees or brood, while honeybee death attributed to mites occurs around the hive (Oldroyd 2007; Cox-Foster et al. 2007). The cause of CCD is the subject of much debate. Speculation is associated with a number of causes, with the most likely causes identified as the Israel acute paralysis virus (IPAV) and the varrao mite (Cox-Foster et al. 2007). IPAV was found in the majority of affected colonies tested and was not found in most of the healthy hives (Cox-Foster et al. 2007). The varrao mite is believed to weaken the bees, making them more acceptable to pathogens and viruses. Thus, the presence of IPAV may be a consequence of a varrao mite infestation instead of the cause of CCD (Oldroyd 2007; Cox-Foster et al. 2007). More recent work suggests that the cause may be related to a combination of a fungus (*Nosema ceranae*) and a previously unknown virus infecting bees known as an invertebrate iridescent virus (Bromenskenk et al. 2010; Johnson 2010). Research continues on the new fungi-virus combination but mites are still suspected to be vectors in the infection of bees (Bromenskenk et al. 2010).

In 1956, a subspecies of *A. mellifera* from southern Africa called *A. m. scutellata* was introduced into Brazil to increase honey production in the region (Kerr 1967). The subspecies has hybridized with European subspecies and is known as the Africanized honeybee. The Africanized honey bee is more efficient at producing honey than is the native stingless bees of South America (Spivak et al. 1991). They are more defensive and are easily provoked to swarm in reaction to perceived threats to their hive, compared to the Italian honeybee (Smith et al. 1989; Sheppard et al. 1991; Schneider and DeGrandi-Hoffman 2002). The Africanized honeybees expanded both south and north. To the south, they reached their climatic limit in Argentina. They continue to expand north into the southern United States (Kerr et al. 1982). The rapid spread of the Africanized honeybee is attributed to their ability to invade European honeybees' colony, also called nest usurpation (Clarke et al. 2001; Clarke et al. 2002; Hall 1990; Schneider et al. 2004). Once hybridized, Africanized honeybee traits are dominant and hybrid honeybees behave similar to the African honeybee and they inherit their aggressive behavior (Sheppard et al. 1991; Schneider et al. 2004).

The global honey market also influences the U.S. honey industry. The price of imported honey impacts the price that U.S. beekeepers receive for their honey. Honey is often sold to honey packers who legally blend different types of honey from around the world to get the desired look and taste to sell in supermarkets (Pundyk 2010). Consumers often do not realize how the global market influences the origin of their honey. For example, China can produce honey cheaply because of the large number of beekeepers and cheap labor (Pundyk 2010). However, in 2002 residuals from the antibiotic chloramphenicol were detected in Chinese honey (Martin 2003; Michaud 2005). In response, the European Union suspended imported Chinese honey in 2002 and the U.S. instituted anti-dumping laws on Chinese honey (Michaud 2005). The anti-dumping laws issued by the U.S. were intended to help stabilize the cost of honey. However, imports from other countries, such as Mexico and Argentina, subsequently increased because they also produce honey cheaper than do U.S. beekeepers. Accordingly, they replaced China as leading import sources and still pose a problem to U.S. honey producers (Dougherty 2009).

2.1.2 Transition to Multifunctionality

The honey industry is currently experiencing a "perfect storm" of challenges. An IBSMWorld report summarized the status of the industry as declining based on the multiple challenges facing the industry (Dougherty 2009). The report suggests that the industry needs to restructure and focus on diversifying, which would promote growth. The objective of this study is to demonstrate that the U.S. honey industry has great potential to transition from a predominately productivist and non-sustainable system to a sustainable multifunctional system. I propose that the U.S. honey industry would not only generate economic sustainability from commodities by transitioning to a multifunctional system but also serve as an example of the potential economic benefits of non-commodity uses, such as environmental conservation.

While some of the challenges the U.S. honey industry are facing are unique, there are others, such as competing with cheaper prices from foreign imports that are common among other agricultural producers. Many researchers have argued that a transition from the conventional productivist agriculture regime, which focused on high production of primary goods, is shifting to a more post-productivist or multifunctional system (Marsden 1999; Marsden 2003; Wilson 2007). Post-productivism or non-productivism (see Wilson 2008) is the opposite of productivism and is characterized by farmers who deem environmental or cultural landscape conservation or aesthetics of the landscape important. However, this description has been criticized by many authors who note that this framework inadequately accounts for spatial scale or the geographic region and that structure and agency do not influence each agricultural system in the same way (Wilson 2001; Evans et al. 2002; Wilson 2004; Hollander 2004; Holmes 2006; Wilson 2007).

As a solution to this problem, many authors suggest refereeing to the shift as a *multifunctional spectrum*, which allows for multiple pathways to achieve transition (Wilson 2001; Lowe et al. 2002; Holmes 2002; Wilson 2004). The transition to multifunctionality, which promotes diversifying commodity and noncommodity uses of agricultural land, has been underway since the 1990s (Marsden 2003; McCarthy 2005;

Wilson 2008). Multifunctional agriculture provides a more holistic approach to agricultural developments from postproductivist or non-productivism agriculture (Wilson 2007). McCarthy (2005: 774) describes the differences and advantages of rural areas shifting from the traditional productivist framework to a multifunctional framework as: "it offers a positive characterization rather than a negative one; it recognizes the continued importance of commodity production in rural areas; and it is inherently sensitive to spatial and social differentiation, the fact that different rural areas clearly can and will produce very different, even unique, combinations of use values."

The transition of agriculture toward multifunctionality can be viewed as a spectrum consisting of weak, moderate and strong multifunctionality (Wilson 2001; Hollander 2004; Holmes 2006; Wilson 2008). An industry with strong multifunctionality is one that conserves cultural and social identity and the environment while providing capital for the economy, (Wilson 2008). Industries or actors can achieve a strong multifunctionality system in many ways. Typically strong multifunctionality promotes high environmental stability, a focus on local production (Goodman 2004; Wilson 2007), lower farming intensities (Evans et al. 2002), higher quality and greater variety of foods produced (Lang and Heasman 2004), and a mental shift in the perception of agriculture and farming (Clark 2003). The latter point implies producers and local stakeholders are open-minded about how the terms "farming" and "agriculture" are perceived by the community and that these terms offer non-commodity as well as commodity uses (Clark 2003; Wilson 2008). However, according to a survey in the UK by Burton and Wilson (2006), individual farmer motives are still in a production-oriented framework. They argue that agricultural transition must come from policy or at a macro-scale, rather than the individual or grassroots micro-scale. Based on the above characteristics of strong multifunctional systems, Wilson (2008) argues that it is unlikely for one system, especially from an individual physiological level, to obtain all the indicators in practice. Further, he suggests that strong multifunctional systems can be classified by a combination of the above indicators and they may vary between systems.

2.2 Methods

I used a report from IBSMWorld (Dougherty 2009) to assess the current economic state of the U.S. honey industry. This report discusses the value added by the industry and addresses key statistics such as the percent of domestic consumption, percentage of importation, and income generated by the industry. The report also discusses the strengths, weaknesses, opportunities and threats (SWOT) related to the industry. It identifies the status of the industry from an economic perspective and discusses where potential growth exists. To expand what economists and other professionals see as threats to the honey industry, I conducted an extensive literature review detailed in the introduction section.

For a qualitative perspective, I interviewed United States beekeepers who engage in the production of specialized honey. Specialized honey, as defined by the Unites States Department of Agriculture's National Agriculture Statistical Services, is produced in a region by a unique nectar source (T. Marshall, pers. comm., October 2010). I asked the beekeepers eight questions (Table 2.1) concerning the status of the honey industry. I then compared answers from the interviews with the IBSMWorld SWOT analysis to determine if there was a consensus between producers and economists. Based on these comparisons I discuss the potential of the U.S. honey industry transitioning to a *strong* multifunctional system and argue that it is uniquely designed to promote both economic and environmental sustainability. The company “Burt’s Bees” is examined as an example of a multifunctional system. This provides insight into one of the many pathways a company in the honey industry transitioned into a strong multifunctional system. The example does not imply that this is the best pathway to transition into a multifunctional system. Instead, it shows how transitioning impacted one company prominent in the industry.

Table 2.1: Questions Asked of Honey Producers

• In your opinion what is the state of the honey industry?
• What are the top 3 challengers faced by beekeepers at present, and any examples from your own experiences?
• What parts of the honey industry have the biggest potential for growth? Why? What needs to be done to help this to realize its potential?
• Who is your target market for your honey?
• Where or how do you sell your honey? Online, Supermarket, Honey packers, or other?
• For how long have you raised honey bees? Approximately how many hives do you have at present?
• Is there anything else that I should have asked you but didn't to help me understand the state of the honey industry?
• Who else do you think I should talk to about this topic?

2.3 Results and Discussion

2.3.1 IBISWorld Report and the Economist Viewpoint

The IBISWorld report (Dougherty 2009: 13) indicated that the honey industry is considered a declining industry, which it described as an industry in which "revenues grow slower than the economy, little technology and process change, declining per capita consumption of goods, stable and clearly segmented products and brands, and falling company numbers; large firms dominate." The U.S. honey industry faces competition from other sweetener products such as cane sugar and corn syrup which have decreased the demand for honey especially in the food and beverage manufacturing industry. Income from honey production has declined in four out of the last five years due to various factors including CCD, drought, and the global price of honey (Dougherty 2009). Conversely, industry-wide income increased in 2007 and 2008 because of pollination services. Almond trees, for example, are strongly dependent on honeybees for pollination (Morse and Calderone 2000; vanEngelsdrop et al. 2008; Gallai et al. 2009). Almond farms are expanding in California and those farmers need honeybees to ensure they have a crop to harvest. With CCD devastating many populations of bees in North America the almond producers have been forced to pay high amounts for pollination. Crop pollination is one bright spot for the industry. However even with crop pollination profitability has been decreasing the last five years because of the cost associated with treating bees for mites and replacing hives killed by CCD (Droughty 2009; Gallai et al. 2009). In addition, other crops benefit from honeybee pollination. The Florida beekeeper rents his bees in the off season to watermelon farmers in Georgia, which can increase the annual watermelon yield by 50% and generate additional income for the beekeeper. Imports of honey into the U.S. rose every year since 2005, indicating that there is a demand for honey but, other countries are producing honey cheaper. The Farm Bill of 2008, which forces honey to have the country of origin on the label may help the industry. The number of commercial beekeepers has declined and is forecasted to continue to decline. However, hobby beekeepers have increased and are also forecasted to increase in the near future (Dougherty 2009).

The report assumes that a cure or treatment for CCD will be discovered by 2013, but it does not give any potential treatments or a citation. If this hopeful event occurs, the honey industry would be more profitable because they would no longer have to replace as high of a percentage of hives annually. However, if bee numbers increase then crop pollination prices will decrease and it remains to be seen if a treatment is discovered how this will affect the industry's profitability.

Three main areas for growth in the U.S. honey industry are listed by the report. All three areas involve diversifying and would therefore create a more multifunctional industry. Crop pollination is one area that economists believe likely to experience growth. This is supported by Morse and Calderone (2000) who show the increase in pollination services over a ten year period and list the produce that with honeybee pollination will increase yield. Another area that the report indicates has potential for growth is creating niche markets for consumption. Currently the honey producers will often sell to large honey packers who then sell to a supermarket. By creating regionally specific honey (e.g., tupelo honey) the producer can offer a unique product and thus ask for a higher price. By selling to a niche market it could also allow the honey producers to sell more directly to the consumers instead of selling to a honey packer (D. Smiley, pers. comm., July 2010), maximizing their profits. The report also recommends that beekeepers produce organic honey as they can sell it for a higher price as well (Doughty 2009). Lastly, the report suggests medicine as a potential area for growth. Certain honeys such as manuka honey produced in New Zealand have demonstrated strong antibacterial and antioxidant properties. Research shows that impregnating this honey in surgical dressings leads to areas healing faster after surgery than conventional methods produced in Australia (Zumla and Lulat 1989; Pundyk 2010). Almost all honey possesses some level of antibacterial or antioxidant property which could be marketed to separate honey from other sweeteners (Pundyk 2010). Additionally, other parts of the hive or bees can be used in natural medicines such as propolis (bee glues) and royal jelly (food secreted from worker bees for the queen bee) because they have high levels of antioxidants (Nagai et al. 2001).

2.3.2 The Producers Point of View

I interviewed beekeepers in three regions within the U.S. (Figure 1) that are known as areas that produce both large amounts of honey and specialty honey. Honeybees gather nectar from certain flowers and plants through the entire growing season. Specialty honeys are created when bees gather nectar predominantly from one nectar source. Because plants have a limited climatic range that promotes healthy growth and nectar production, specialty honey types can only be produced within these natural ranges. Environmental conservation is important for specialty honey producers because they need the source species to be healthy to ensure long-term sustainability in their products. The three regions that I interviewed beekeepers were areas known for producing high quality specialty honey and thus are associated with a plant species that the local climate favors. Tupelo honey is produced from Ogechee Tupelo (*Nyssa ogeche*) in the panhandle of Florida and southeast Georgia, sourwood honey is produced form the Sourwood tree (*Oxydendrum arboretum*) along the foothills of the Appalachian

Mountains in Georgia and North Carolina, and sage honey is produced from a variety of sage shrubs that grow along the California coast and the Sierra Nevada Mountains (Figure 2.1).

I interviewed beekeepers with a wide range of experience, ranging from veterans with more than 20 years of experience to those that had only been keeping bees for fewer than three years. All beekeepers interviewed were full time, dependent on commercial sales of their products for their entire income. Most beekeepers sold the majority of their honey on-line through a website or at local festivals or corner stores. All beekeepers produced honey in bulk and sold to honey packers, but most only sold small quantities that did not produce the majority of their profit. Because of foreign competition, selling bulk honey profitably is challenging for a U.S. beekeeper. Many honey packers can get foreign honey for cheaper, creating a market that is almost impossible for U.S. beekeepers to be competitive in considering their associated structural costs.

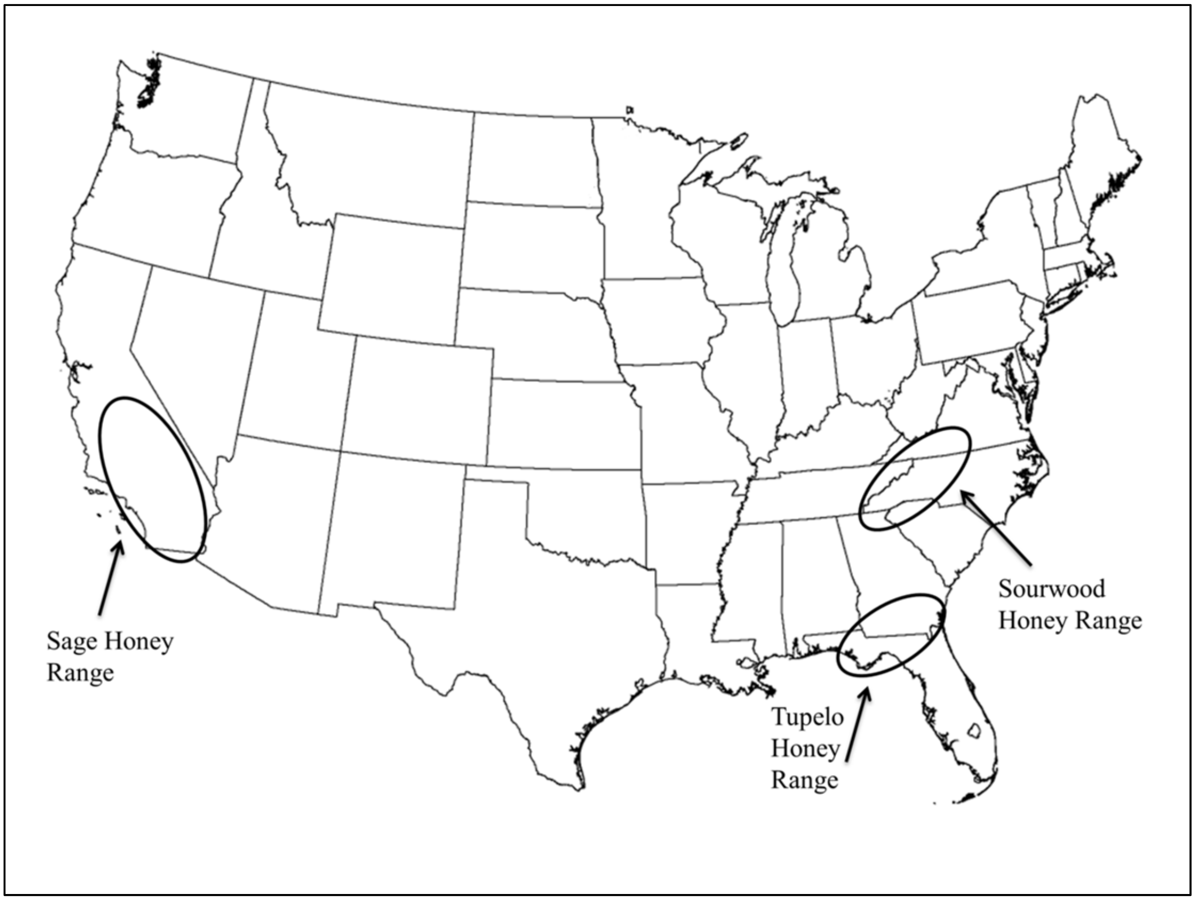

Figure 2.1: The beekeepers I interviewed were based in these three regions. The regions correspond to the honey source plant's natural range.

Specialty honeys can only be produced during the flowering season of the nectar source species. Honeybees need nectar to produce honey throughout the growing season to survive the following winter. Thus in certain regions, beekeepers can produce multiple types of honey throughout the growing season or blend honey to sell in bulk for a lower price. Some beekeepers produce multiple specialty honeys. For example, beekeepers in California can produce both sage and eucalyptus honey because both species are present in great numbers in California.

The responses from the 23 interviews I conducted showed that there are many similarities in the perceived opportunities and challenges between beekeepers around the country. The top challenge in all the interviews was the bee disease known as CCD. One beekeeper commented that "beekeeping isn't what it used to be; it's a lot harder now with the mites and especially this new virus. I wish someone would find out what going on with the bees and what's causing this virus, if it is a virus." This statement matches well with the report that CCD is the most threatening challenge to the industry. When I asked if the beekeepers had heard of any treatments to CCD, none of the beekeepers had and were treating for hive mites in hopes that would reduce the likelihood of colony collapse. One beekeeper mentioned that researchers still weren't sure what was causing it, which questions the statement of the report that projected a cure would be discovered by 2013.

The other top reported challenges that beekeepers face included weather, pesticides, locations for bee hive placement, and mislabeling of honey. Weather can influence honey yields both positively and negatively. The blooming of flowers of the sage plants and tupelo trees are particularly sensitive to weather. Tupelo flowers bloom from mid-April to early May; a warm winter will allow both the flowers to bloom and nectar to flow earlier. Combined with a dry warm spring, bees have a longer time to collect the nectar and transform it to honey, thus producing more honey. The opposite can happen if a cold winter or wet spring occurs (D. Smiley, pers. comm., July 2010). High sage honey yields depend on wet previous winters and summers. The relatively wet conditions allow the sage plants to produce more nectar and also prevent the likelihood of a brush fire (Zierer 1932).

According to beekeepers, pesticides influence honey yield directly, by killing bees. Because bees are insects they are often harmed by pesticides that are sprayed on nearby crops that bees will roam and pollinate and, on rare occasions, from crops the bees were contracted to pollinate. Additionally, in many areas that are producing specialized honey, especially Southern California and the Panhandle of Florida, there is increasing development. These developments limit the locations that are ideal for beekeepers have to place their hives. This is particularly true in Southern California with the sage and eucalyptus honey. In Florida, residential developments often employ companies to spray for mosquitoes, which if sprayed during the day can be harmful to honeybees.

Mislabeled honey is a challenge that is especially affecting those beekeepers that produce and sell honey in bulk. Honey from China could be labeled as honey originating in Australia (Pundyk 2010). However, there has been little work examining how specialized honey within the U.S. is often mislabeled. Because the U.S. Food and Drug Administration has decided that a standard of ID for honey is not a health hazard, it is not considered a high priority it is the responsibility of the State to form guidelines and restrictions on the labeling of honey (C. Webb, pers. comm., April 2011). Many states do not have a standard ID for honey and those states that do often have varying restrictions, resulting in honey being mislabeled as specialty honey to obtain a higher market price. Interestingly, many of the challenges listed by the beekeepers were either barely mentioned or not listed as an important challenge in the IBISWorld report. Weather was mentioned briefly, while pesticides, location for hive placement, and mislabeling of specialty honey were not mentioned, indicating that each beekeeper will experience unique challenges that are associated with the region they are producing honey.

Despite all the challenges that beekeepers are facing, most viewed the current state of the industry as favorable. Many observed that demand was at an all-time high and that the consumers were more educated about honey products, making it easier to market and sell honey. However one beekeeper argued that bee pest and disease is the only reason many beekeepers are enjoying high market prices for honey. CCD has made producing honey much more challenging and resulting in a decrease in the supply of overall honey, which would create more demand. While this may be true, many beekeepers feel that if honey supply was up and CCD was not an issue that they would still be able to sell large quantities of honey.

All beekeepers I interviewed had a similar opinion on the largest potential for growth in the honey industry: marketing honey as a healthy natural product. Many beekeepers are producing organic honey and specialty honeys that are marketed as a healthy natural sweetener. The National Agricultural Statistical Service has kept annual record of retail prices received for honey since 1989 and during that time specialty honey prices have increased 342% compared to the 158% increase of blended honey. This supports that there is an increase in demand for specialty honey from consumers and that consumers are willing to pay a higher price for organic specialty honey than for blended honey.

Diversifying products sold was another frequent response beekeepers gave for potential future growth of the honey industry. As the IBSMWorld report states, there are many products from the honeybee and its hive than can be sold commercially. Many of the beekeepers I interviewed reported selling wax candles and lip balm from bees wax and those sales had been increasing annually. I did not find a beekeeper selling propolis or royal jelly but many were aware of the products and considered it a possible commercial product in the future.

Most beekeepers felt that even with CCD, the U.S. honey industry is profitable and if a treatment is discovered that it could become quite lucrative. The areas with the biggest growth potential from the beekeepers point of view match nicely with the IBSMWorld findings. This would suggest that the industry will most likely morph to become more of a niche market for regional specific honey that is marketed as a healthy natural sweetener. Additionally, many beekeepers will start to expand their product sold to include wax products and potentially in future other products from honeybees. Diversification of products sold is an important step in becoming a multifunctional system and beekeepers and economist appear to agree that the U.S. honey industry has great potential in diversifying their commodities.

Many similarities between beekeepers around the U.S. exist. Local factors may influence honey production in one part of the country and not impact another region. For instance, Florida beekeepers stated that spoils from dredging the Apalachicola for increased ship traffic were deposited in the tupelo forests, which is not a favorable soil and thus contributes to declining rates of regeneration of tupelo trees (Stallins et al. 2010). Currently, dredging is banned from the Apalachicola River, but there is a push to reinstate dredging to provide shipping and transportation to upstream cities. This example reinforces important roles that physical, political, and cultural geography all play in honey production, and factors that need to be considered as they can vary throughout the country.

The responses from the producer matched the economists' point of view well with a few exceptions. Most of the exceptions are attributable to local situations, revealing that the transition to multifunctionality will vary based on the local physical, political, and cultural situations. These findings further suggest that there are many pathways for honey produces to achieve multifunctionality and that these pathways vary at the local producer scale. A honey producer attempting to transition into a multifunctional system will need to have a unique pathway that will include addressing challenges that are unique to them and may not be transferable to producers outside of the region.

Strong multifunctionality can also be achieved at the industry scale by promoting both economic and environmental sustainability. Economic sustainability can be achieved industry wide by promoting the production of regionally unique honey types or organic honey. In addition, the industry can encourage marketing honey for its medicinal properties. For example, the E.U. and U.S. are examining the possibility of using surgical dressings that are impregnated with honey as Australia does (Pundyk 2010) in the near future. The industry could also encourage beekeepers to diversify their commodities and sell more than just honey, such as bees wax, royal jelly, and propolis. Part of multifunctionality is offering noncommodity uses of agricultural land (McCarthy 2005; Wilson 2007; Wilson 2008). Honey production requires nectar from flowers of certain plants, which need to be healthy to produce the most nectar. Thus, many types of honey, such as tupelo and sourwood honey, promote conservation of the natural environment of the honey source plants.

Environmental sustainability is also achievable at the industry level and is perhaps the most underutilized potential the industry has. None of the beekeepers or the IBISWorld report mentioned environmental conservation as a potential opportunity for market growth in the honey industry. However, I discussed some sort of environmental threat with every beekeeper I interviewed, indicating that beekeepers are thinking of environmental conservation in terms of production sustainability. Most beekeepers want to ensure that their honey source species is in good health to promote higher nectar secretion and thus higher honey yields. However, environmental conservation has the potential to be both economically and environmental sustainable and is a major part of a strong multifunctional system. Putting aside agricultural lands for environmental conservation has been promoted (especially in the United Kingdom) since 2002 and is a strong part of creating a multifunctional system (Dobbs and Pretty 2004; McCarthy 2005). The honey industry is uniquely suited for environmental conservation compared to traditional agricultural products because protecting the local environment also ensures economic success. Further, the honey industry has the potential to be an agricultural industry that receives payments for conservation of agricultural land, but no known work has been done to address or promote this possibility. One possible reason for the oversight in this potential is that many beekeepers rent land that is near the desired honey source plant to place their hives. This makes it difficult for beekeepers to promote agricultural land conservation because other non-agricultural stakeholders own the land.

Promoting beekeepers to buy the land they use for honey production or offering incentives to those who conserve land and lease it to beekeepers could help the industry provide a non-commodity use and possibly generate more income for beekeepers. Burt's Bees is a large company that has been economically successful and I will show has transitioned into a strong multifunctional company and provides a great example of the potential for the U.S. honey industry.

2.3.3 Burt's Bees Example

Roxanne Quimby and Burt Shavitz started Burt's Bees in 1984. Burt Shavitz previously kept bees for about a dozen years. Together they diversified and started selling wax candles at craft fairs in 1984. They noticed that there was a market for wax candles and their annual sales reached $20,000 in 1984 dollars. By 1989, Roxanne and Burt were producing home care products that were home-made with many containing honey or bees wax. In 1993, Burt's Bees was incorporated and continued to grow, leading to the decision to expand and move to North Carolina where the business-friendly environment would encourage growth. By 1999, the company continued to add products and decided to start selling from a website allowing sales worldwide in addition to selling in stores such as Cracker Barrel. The company transitioned in 2002 to what Wilson (2007) terms a strong multifunctionality system when it used profits to buy tracts of land for conservation in Maine and started a working relationship with the Nature Conservancy.

The Burt's Bees pathway to a strong multifunctional company is more traditional where a farmer (or company) either purchases or sets aside a large tract of land to conserve.

However, this pathway requires either a sacrifice in the amount of farmland used in production or a large finical investment. This would not be a feasible option for the many smaller beekeepers that produce regionally specific honey. These beekeepers could conserve the environments they use for honey production and still achieve the same level of strong multifunctionality without the large finical investments or sacrifices making this area of the industry capable of achieve economic and environmental sustainability simultaneously.

2.4 Conclusions

There are many ways to transition into a multifunctional system, with Burt's Bees being one example. The company began by selling honey then continued to diversify the product it offered by adding wax candles and later personal care products. Another possible pathway is pursued by Donald Smiley who generates income selling regionally unique tupelo honey. A producer wishing to transition to a multifunctional system needs to address unique situations and challenges they may face. However, there is potential for the transition into a strong multifunctional system industry-wide. To obtain economic sustainability, a company could diversify the commodities it produces, such as using bees wax or produce organic or regional specific honey and market the healthy benefits. Selling honey to the medical field is another pathway to economic sustainability that will most likely present itself in the U.S. after testing is complete. Until then, marketing honey's antibacterial and antioxidant properties will benefit the industry and help separate honey from other sweeteners. The honey industry is uniquely designed to promote environmental sustainability because many honey producers depend on a healthy ecosystem for quality honey production, allowing the beekeepers to conserve the environment in an economically feasible manner.

In order to achieve strong multifunctionality, a producer must combine the suggestions above. That is not to say they need to implement all the suggestions, which I acknowledge would be difficult, but the more of the above suggestions a beekeeper achieved would allow a transition into a stronger multifunctional system. To better understand the producers' opinions about the honey industry and the local variation in the honey market, I will need to interview more beekeepers from different parts of the country in future research. The non-commodity uses that honey producers offer is an area that needs further examination. The potential for a program to reward those beekeepers who own and conserve the land they use for honey production or landowners who conserve their land and rent it to beekeepers needs to be examined. This study identified areas in which the U.S. honey industry could grow and provides suggestions as to how to achieve industry-wide multifunctionality.

CHAPTER III

RECONSTRUCTED TUPELO-HONEY YIELD IN NORTHWEST FLORIDA INFERRED FROM *NYSSA OGECHE* TREE-RING DATA: 1850–2009

This chapter is a manuscript that has been published in *Agriculture, Ecosystems and Environment* (2012) 149: 100–108. The use of "we" and "our" in this chapter refers to Dr. Paul Knapp and myself as we were co-authors.

3.1 Introduction

Ogeechee tupelo (*Nyssa ogeche*) forests of the Florida panhandle are the principal source of commercially produced tupelo honey. Tupelo honey has been produced in this region for over a century and the activities associated with harvest and production has contributed to a culturally distinct region (Hockersmith 2004). Skilled beekeepers transfer knowledge of tupelo-forest ecology and honey-production techniques to future generations, creating a culture that promotes self-reliance and the inherent acceptance of uncertainty (Watson 2010). The critically acclaimed movie *Ulee's Gold* (Nunez 1997) captured the iconic status of tupelo honey in northwest Florida and the fervent belief that no other honey rivals tupelo's color, health benefits, or distinctive flavor (Sawyer 1962). The tupelo-honey industry also serves as a locally important economic engine, generating \$2.4 million dollars in 2000 (Holland 2003; Watson 2010) and selling tupelo honey to over 25 states and more than 10 countries, including Japan, Switzerland, Germany, Australia, and England (D. Smiley, pers. comm., July 2010). Like all agrarian industries, success is dependent upon the health of the crop; in this case, the tupelo trees.

Tupelo honey is produced primarily from the nectar of *N. ogeche* (Figure 3.1), which grow in back-swamp areas that are typically flooded and rest below the natural levees of the stream. Tupelo honey is one of a limited number of unifloral honeys certified in the United States as it is unblended with other honey sources (Watts 1975; Hockersmith 2004), and is known for its flavor and health-related benefits. Tupelo honey does not granulate (Crane 1980), obviating the heating process for filtering common among multifloral honeys (Sawyer 1962). Thus, the honey retains its antioxidant properties, distinctive flavor, and greenish-gold hue. Further, tupelo honey's high fructose-to-glucose ratio may confer additional health benefits for individuals seeking sweeteners with lower glycemic indices. Tupelo's glycemic index of 54.1 +/- 8.2 (Lanier 2010) falls into the preferable "low" category for foods unlikely to raise blood sugar to unhealthy levels (http://www.diabetesguide.org/glycemic-list.htm).

Tupelo honey yield began declining during the mid-1980s, with a 30% decrease in honey yield-per-hive from 1990–2009 (NASS 2010). The decline has been attributed to environmental changes to bottomland hardwood forest dynamics (Stallins et al. 2010; J. Rish, pers. comm., December 2009) as *N. ogeche* trees require moist soil conditions, and the back-swamp environments along the Apalachicola River have experienced a trend towards drier conditions relative to the 1970s (Darst and Light 2008). The drier hydrologic conditions have resulted from a combination of a drier climate (Barber and

Stamey 2000) and an increase in upstream water demand (Feldman 2008), which has reduced flows of the Apalachicola River. In turn, drier conditions decrease the regeneration and recruitment of *N. ogeche* allowing other species to establish with comparable light requirements and increase interspecific competition (Stallins et al. 2010). The increase in competition combined with the drying environment may have lessened *N. ogeche* nectar production, thus reducing honey yield-per-hive (Stallins et al. 2010). Although drought conditions have influenced river flow and have been more frequent in the last decade (Barber and Stamey 2000; Verdi et al. 2006), deposition of dredging spoils, encroaching development, and the construction of dams are also contributing to the drier hydrologic conditions (Holland 2003; Stallins et al. 2010).

The decline in honey yield is also influenced by invasive pests including the Varroa mite (*Varroa destructor*) and the small hive beetle (*Aethina tumida*) that live in bee hives or on the bees and deteriorate the health of the infected honey bees (*Apis mellifera*). These honeybee pests have caused die-offs upwards to 50% of the colonies and may contribute to colony-collapse disorder, which has devastated U.S. honeybee populations (Barrionuevo 2007; Cox-Foster et al. 2007; Oldroyd 2007; Stokstad 2007; Johnson, 2010). However, the primary cause for the declining yield has been attributed to the aging cohort of *N. ogeche* stands created by the decline of favorable climatic/river flow conditions (Boyer and Greaves 2008; Stallins et al. 2010). To account for confounding factors that may reduce the direct linkage between tree-ring growth and honey production (e.g., honeybee disease and pests) we used honey yield-per-hive to ensure that declines in honey yield are primarily from environmental factors. Our study provides a means to examine if variations in tree-ring widths from tree species used in honey production will be influenced by the same factors as honey yields by using dendrochronological methods. Understanding changes and trends in tupelo radial growth could serve as a proxy to changes occurring in tupelo-honey production.

Figure 3.1: *Nyssa ogeche* in NW Florida. Photo by J. Maxwell.

Annual variations in tree–ring widths record environmental conditions influencing growth (Fritts 2001) and can be used successfully as a proxy to record historical events. For example, studies have used tree rings as proxy data for stream flow (Stockton and Jacoby 1976; Cook and Jacoby 1983; Woodhouse and Overpeck 1998; Cleaveland 2000; Meko and Woodhouse 2005), insect outbreaks (Swetnam and Lynch 1989; Speer et al. 2001), and wind/ice storms (Lafon and Speer 2002; Lafon and Kutac 2003; Knapp and Hadley 2011). Tree rings have also been used to reconstruct agricultural productivity, a subspecialty we identify as *dendroagronomy*. Originally, historical agricultural yields were used to test the accuracy of tree-ring climate reconstructions (Hawley 1941; Burns, 1983). Using tree rings to reconstruct agricultural yields was thus considered possible and has been used to reconstruct maize yield in central Mexico (Therrell et al. 2006) and the potential food reserves of prehistoric Mississippian societies in Georgia and South Carolina (Anderson et al. 1995). We show that variations in tree rings from species used in honey production are influenced by factors that affect honey yields and thus serve as a proxy for tupelo-honey yields. We posit that meteorological/river conditions conducive for tree growth are favorable for nectar flow that generates greater honey yields with interannual fluctuations in honey yield inferred from *N. ogeche* radial-growth variations. Specifically, we use *N. ogeche* tree rings a to: 1) place the recent decline in honey yield in a historical context by extending the record by 140 years; and 2) examine the reconstructed honey data to identify climatic and river conditions producing optimal honey yields.

3.2 Material and Methods

3.2.1 Site Selection and Location

We conducted fieldwork in cypress-tupelo forests along the Apalachicola River floodplains at two sites (Figure 3.2). These sites were chosen because local apiarists consider them to have a sufficient density of *N. ogeche* trees to produce honey and the sites are known for producing high-quality tupelo honey. Further, these sites are centered in the primary commercial area for tupelo-honey production along the Apalachicola River floodplains. For each site, we targeted old-growth trees to sample, which gave the best potential to extend the reconstruction of honey yield as far back into the past as possible. Little is known about the variation in nectar production between trees of different ages or sizes. We decided to target old-growth trees because according to local beekeepers, there is little or no difference between trees and our main objective was to extend the honey record as far back as possible.

3.2.2 Core Collection and Analysis

We followed methodology described in Fritts (2001) and Stokes and Smiley (1968) for the collection and preparation of samples and subsequent tree-ring chronology development. Two cores from each tree were extracted *at ~1.3 meters* on opposite sides *using an increment borer*. We cored 30 *N. ogeche* trees (60 cores) at Whites River (WRO) and 15 trees (30 cores) at Browns Lake (BLO; Figure 3.2) to create a combined chronology of 45 trees (90 cores). We sampled only *N. ogeche* that were absent of visible anthropogenic disturbances.

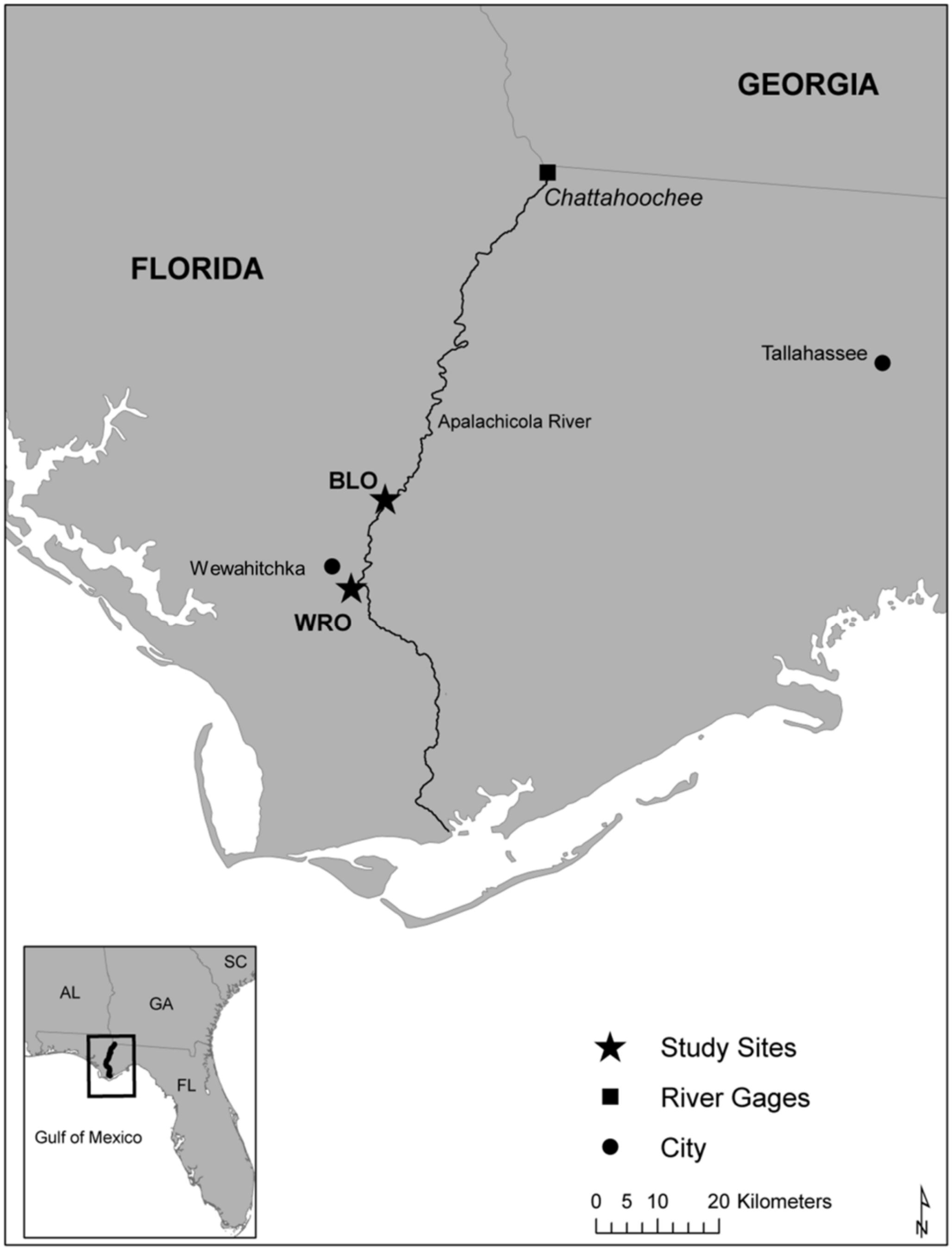

Figure 3.2: Sampled study sites and river stations in northwest Florida.

We crossdated the tree cores using the list method (Yamaguchi 1991). To ensure accuracy in the crossdating method, we statistically verified the dating of the cores using the program COFECHA (Holmes 1983). We measured the core samples with a Velmex measuring stage at 0.001 mm precision using J2X software (Voorhees 2000). The cores were standardized to remove biological-growth trends associated with tree growth using the program ARSTAN (Cook 1985). To preserve low-frequency (long-term) variation of tree growth that may be related to climate variation, a negative-exponential or negative-linear curve was used for standardizing the cores. When necessary, a Freidman super-smoother was used to reduce the influence of short periods of suppressed growth (i.e., short-term growth effects from canopy openings such as windfalls) while preserving long-term trends (Pederson et al. 2004). Once standardized, we combined the chronologies and used ARSTAN to generate a master chronology. Of the three types of standardized chronologies that ARSTAN generates (residual, standardized, and ARSTAN) we used the ARSTAN chronology as it offered the strongest climate-growth relationship.

3.2.3 Data

We selected honey yield-per-hive data from the National Agricultural Statistics Services to examine interannual variability in honey production for the state of Florida from1942–2009. Using honey yield-per-hive removes variation in honey yields caused by factors other than pollen/nectar availability, such as honeybee die-offs from pests or pathogens. Die-offs influence how many hives a beekeeper maintains annually—

influencing overall honey yield—but not honey yield-per-hive. Thus, this measure of annual honey yield standardizes honey production and allows comparison to annual *N. ogeche* radial-growth patterns.

We selected a suite of climatic and river-flow variables to examine influences on tree growth and honey yield. These variables were obtained for Florida Climate Division 1 from the National Climatic Data Center (NCDC) and included monthly mean temperature, total precipitation, and Palmer Drought Severity Index (PDSI; Palmer 1965) from 1895–2009. We also gathered monthly minimum and maximum temperatures from the closest weather station (located in Tallahassee) that had a greater than 95% complete record from the United States Historical Climatology Network. The Chattahoochee, Florida gage station (USGS 2011) on the Apalachicola River (Figure 3.2), provided monthly stream-flow data. The station is located upstream of the study sites and thus records fluctuations of the main fresh-water source in the region. The station has continuous, monthly discharge records (ft^3/sec) from 1922–2010 and gage height (ft) from 1928–2010.

3.2.4 Tree-Growth and Honey Models

To determine what river and climate variables influenced *N. ogeche* tree-growth we used both correlation and response-function analysis using the program DENDROCLIM2002 (Biondi and Waikul 2004). The program calculates correlation and response coefficients using 1000 random bootstrapped samples and determines significance at the $p < 0.05$ level and removes autocorrelation of climate variables. We examined interannual Pearson correlation coefficients between the ARSTAN *N. ogeche* chronology and the suite of climate and river variables to determine monthly variables optimal for use in DENDROCLIM2002. We also used DENDROCLIM2002 to examine the temporal stability of relationships between tree growth and climate and river variables by using evolution correlation and response functions. Because of evolution analysis requirements, where data must have enough intervals and degrees of freedom within the intervals to conduct analysis, we only used the current year when examining the temporal stability of relationships. We used a forward evolution interval with a 50-year base length. We created four models in DENDROCLIM 2002 based on our selection of the best variables: 1) monthly maximum temperature and monthly mean precipitation; 2) monthly minimum temperature and monthly mean precipitation; 3) monthly maximum temperature and monthly river discharge values (natural log transformed); and 4) monthly minimum temperature and transformed monthly river-discharge values.

To determine the driving forces behind honey yield, we used Pearson and Spearman correlation analyses between the USDA honey yield-per-hive and the suite of climate and river variables. We decided not to use DENDROCLIM2002 because the high-quality honey yield-per-hive record was too short to meet the requirements of the analysis. Additionally, we ran Pearson and Spearman correlation analyses between *N. ogeche* radial growth and the climate and river variables for the same time period as the honey yield-per-hive record. In this way, we compared the driving forces behind *N. ogeche* radial growth and honey yield to determine how differently or similarly they respond to the climate and river variables. The comparison will allow us to better understand the relationship between *N. ogeche* radial growth and honey yield and determine the validity of reconstructing honey yield using *N. ogeche* tree rings.

3.2.5 Reconstruction

We used a two-stage process of calibration and verification to develop a honey yield-per-hive reconstruction. To demonstrate reconstruction potential, we used correlation analysis between the tree-ring chronologies and the yield-per-hive. Honey yield-per-hive has been recorded by different entities of the USDA since 1942 for the state of Florida. The initial correlation between the entire Florida honey yield-per-hive dataset and the combined chronology was not significant. Examination of the honey-yield dataset identified that prior to 1988, data sets were reported voluntarily by beekeepers likely causing inaccuracies. Post-1988, the National Agricultural Statistics Services employed methods to improve honey yield-per-hive data accuracy using data from 1990–2009 gave a significant relationship of r = 0.546, p = 0.013 and thus we used the period of 1990–2009 for calibration and verification. The honey yield-per-hive record was divided between 1990–1999 and 2000–2009 with calibration and verification made on both periods. We used the latter period to develop a regression model for honey yield-per-hive using the *N. ogeche* tree-ring chronology derived from ARSTAN as the dependent variable. The predicted values from the regression model were verified against actual honey yield-per-hive values from 1990–1999. The same procedure was conducted using the earlier period and compared for verification to the actual honey yield-per-hive values of the later period. Multiple verification procedures were used to ensure the two calibration models were statistically significant including Pearson or Spearman correlation coefficients, the reduction-of-error statistic (RE; Fritts 2001), and the coefficient-of-efficiency statistic (CE; Nash and Sutcliffe 1971).

3.2.6 Monte Carlo Honey Yield-Per-Hive Analysis

The reconstructed values of honey are best interpreted in probabilistic terms because the estimation of annual honey yield-per-hive reconstructed from tree-rings has associated error. Thus, we used a Monte Carlo approach to create both exceedance values and empirical confidence intervals. Following methods identified by Touchan et al. (1999), 1000 random normal-distribution sequences of a length of 160 years (1850–2009) with a mean of zero and standard deviation equal to the standard deviation of the reconstruction model were created. We added the 1000 sequences to the reconstructed honey yield-per-hive to account for noise, giving us 1000 noise-added reconstructions. For each year of the reconstruction, we used the empirical cumulative-distribution function on the 1000 noise-added reconstructed values to generate exceedance probabilities. We used the 10-percent and 90-percent exceedance probabilities to construct 80-percent confidence bands for our reconstruction. The 80-percent confidence band was used to determine the probability that a given reconstructed year exceeded the lowest or highest observed year. In summary, we determined how exceptional a given year of reconstructed honey yield was by comparing the error of estimated yield with the observed record. If the error of a given reconstructed year exceeded the highest or lowest observed yield, then we can determine the probability of that year's yield exceeding the record-high or record-low observed yield.

3.3 Results and Discussion

3.3.1 Crossdating and Standardization

At WRO, 23 trees (45 cores) statistically crossdated in COFECHA and were retained in the chronology with an interseries correlation of 0.386, a mean sensitivity of 0.403, and covered the period AD 1747–2009. At BLO, 12 trees (21 cores) were retained in the chronology with an interseries correlation of 0.404, a mean sensitivity of 0.432, and covered the period AD 1818–2009. Mean sensitivity is a measure of interannual variability in the chronology and higher values are indicative of the species ability to detect minor environmental changes (Fritts et al. 1965). Mean sensitivities of these two chronologies are high compared to most other native tree species found in the eastern United States (ITRDB; Grissino-Mayer and Fritts 1997). Detrending the series in ARSTAN produced an EPS value ≥ 0.75 (Wigley et al. 1984) at 1850 for WRO (n =160) and 1870 for BLO (n =140). After detrending, the two chronologies were significantly related (r = 0.221, p = 0.02) thus justifying combining the two sites into one chronology and confirming accuracy in crossdating. We combined the two chronologies and then detrended the combined chronology in ARSTAN, which gave an EPS value of ≥ 0.75 at 1850 (n = 160).

3.3.2 Nyssa Ogeche Growth and Honey Yield Response to River and Climatic Conditions

3.3.2.1 *Nyssa ogeche* Climate Responses

The interannual correlation function revealed that the previous summer was important to *N. ogeche* radial growth. Previous June minimum temperature (+), July maximum temperature (-), July river flow (+), and July mean precipitation (+) were significantly correlated with tree growth (Figure 3.3). Additionally, previous February (+) was significant. Current-year August and October minimum temperature also had a significant positive association and current August mean precipitation had a significantly negative relationship with tree growth. The importance of the previous year climatic conditions to *N. ogeche* radial growth is different from co-occurring bald cypress (*Taxodium distichum*), which is current growing season precipitation and temperature (Stahle et al. 1985). While little is known about *N. ogeche* starch storage ability, *Nyssa aquatica* are able to maintain high root-starch concentrations and high levels of photosynthesis during flooding allowing the trees to grow faster or store starch (Gravatt and Kirby 1998). *Nyssa ogeche* grow better in persistently flooded sites (Whitney et al. 2004) and thus could result in the species being more likely to store starch during favorable growing conditions resulting in lagged effects of climate on tree growth.

The interannual response function returned no significant variables. The lack of significant interannual response functions could indicate a temporal shift in the response of *N. ogeche* radial growth to climate variables. To examine the temporal stability we examined the evolution correlation functions, which showed that the significant variables in the interannual correlation function were temporally stable except August mean precipitation. Additionally, the evolution correlation analysis also found that current March, May, and September river flow were significant and stable and that November river flow did not have a significant negative relationship until the window end year 1997 (i.e., 1929–1997) indicating that it has recently become an important variable to *N. ogeche* radial growth. Because the evolution response functions are multivariate models the results differ based on the variables included in the model.

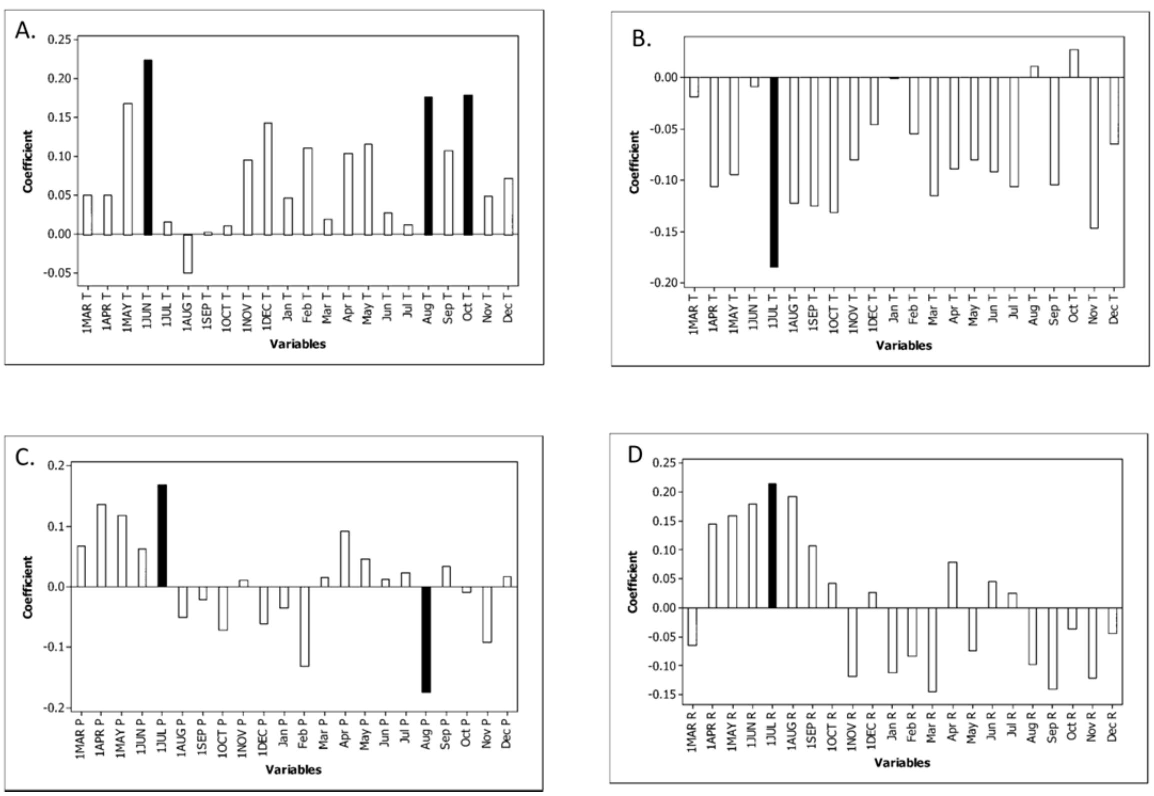

Figure 3.3: Correlation coefficients (*r*-value) with a) monthly minimum temperatures, b) monthly maximum temperatures, c) monthly mean precipatation, and d) Monthly river flow transformed by natural log. Black bars indicate significant relationships at $p < 0.05$.

We generated four models (Section 3.2.4) and found no significant response variables for Models 1 and 2. Model 3 generated significant response variables of: October minimum temperature with a positive relationship stable through time, and July river flow (Figure 3.4) and September river flow temporally unstable. Model 4 had one significant response variable of July river flow that was temporally unstable. July river flow was significant in both Models 3 and 4 and presents a temporal shift in response coefficients (Figure 3.4). The two models show that July flow was either significant or close to the 95-percent confidence level until the end year of 1993. The dramatic change in the distance between the response coefficient and the critical value suggests either changing hydrologic or climatic conditions or both may have contributed to the decline in honey production.

3.3.2.2 Honey Yield Climate Responses

Moderate current year spring temperatures are important to high honey yield-per-hive yields, with both March maximum and minimum temperatures having a significantly negative relationship with honey yield. Warm summers are also conducive to high yields, with June and July maximum temperatures having a significant positive relationship. Previous year spring and early summer minimum temperatures also significantly influence honey yield positively.

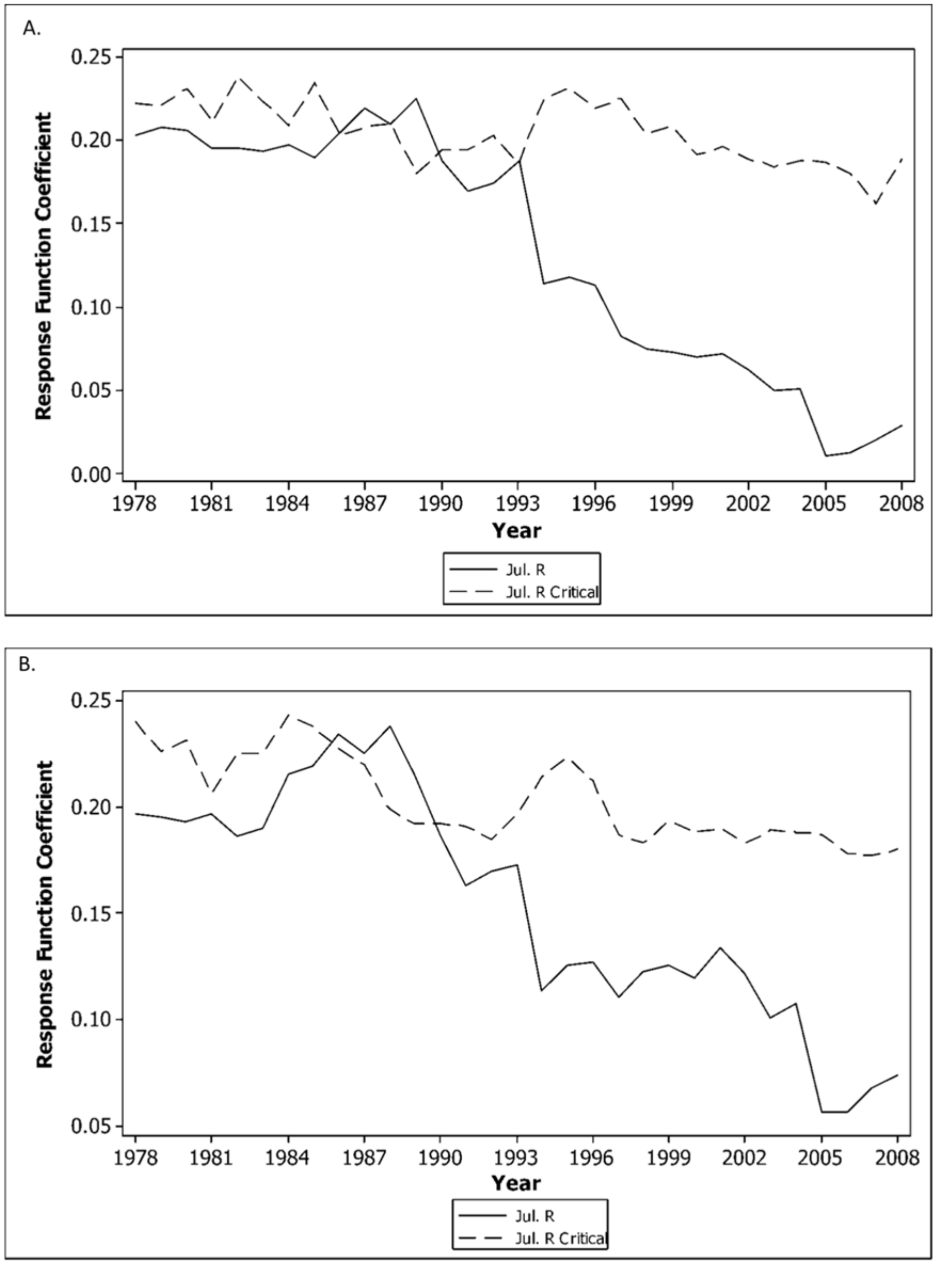

Figure 3.4: July river flow forward-evolution response-function coefficients for models with the variables of: a) Model 3, and b) Model 4 (see section 3.2.4). The solid line is the annual response function coefficients and the dashed line is the critical values for the annual response-function coefficients at the 95% confidence level. When the solid line is above the dashed line, the relationship is significant at the 95% confidence level.

The relationship between current-year temperatures and honey yield is unsurprising. Honeybees (*Apis mellifera*) are ectothermic organisms as they cannot self-regulate their internal temperature and rely on solar radiation to increase their body temperature to a level allowing flight. Thus, higher temperatures influence honey production positively because bee activity increases (Burrill and Dietz 1981). In honey-source plants, nectar is secreted by glands in the flowers (Moffett and Parker 1953) and the hydrolysis of starch to sugars during the flowering season favors nectar secretion (Porter 1978). Temperature affects the hydrolysis of starch and thus alters the level of sugars available in the nectar, which influences the amount of nectar available for bees to gather and transport to the hive. *Nyssa ogeche* flowers produce nectar for 3–5 weeks between late April and early May and thus meteorological conditions influencing bee activity and nectar secretion during this period affect tupelo honey yield. The importance of summer temperatures is more surprising because this is after the flowering season of *N. ogeche*. One possible explanation is that a warm spring could indicate a future warm early summer and thus both are significantly related to honey production.

Similar to the response of *N. ogeche* radial growth to climate, honey yield-per-hive is influenced by climate variables from the previous year. Because honey is dependent on the hydrolysis of starch to sugars, the storage of starch by *N. ogeche* during favorable growth years could also lead to a lagged influence of climate. Years that *N. ogeche* store starch could lead to an increase in the amount of nectar available for bees to gather the following flowering season.

To compare the responses of *N. ogeche* radial growth and honey yield to climate, we conducted the same test on *N. ogeche* radial growth from 1990–2009 as we did for the honey record. The Pearson and Spearman correlations revealed previous June precipitation and river flow and previous spring minimum temperature were positively related to tree growth. The results are similar to the DENDROCLIM2002 analysis of the entire record, with previous summer being important (i.e., previous June River flow (+) and precipitation (+)). Additionally, previous February minimum temperature had a positive and significant influence. Examining the shorter record of *N. ogeche* radial growth using a different test revealed that previous March minimum temperature (+) was important, but the test did not find current-year August and October minimum temperature or August mean precipitation to have a significant impact on growth. The difference are to be expected when examining a much shorter segment and using a different analysis. The response of *N. ogeche* radial growth and honey yield to climate was similar except honey yield is strongly influenced by maximum temperature of the current year and *N. ogeche* radial growth is influenced by previous year summer moisture availability.

3.3.3 Historical Honey Yield-Per-Hive Analysis

3.3.3.1 Reconstruction Modeling

The reconstruction of Florida honey using *N. ogeche* tree-ring data extended the data record by over a century (Figure 3.5). Using the significant period of 1990–2009, we followed procedures mentioned in section 3.2.4 and split the record for verification and calibration (Table 3.1). The regression models for the calibration period and the Pearson correlations between the actual and predicted values for the verification period were not significant at $\alpha < 0.05$. However, all tests had p-values < 0.1 and passed both the RE and CE tests. Both RE and CE values can range from $-\infty$ to 1.0 with any positive value considered acceptable (Fritts 2001). Positive values indicate the regression model better estimates values in the verification period than the mean of the observed data in the calibration (RE) or verification (CE) period (Cook 1992; Cook et al. 1999, Fritts 2001), demonstrating that the reconstruction model performed well. Because the RE and CE test returned positive values, we determined that p-values of < 0.1 were acceptable. The shorter length of the model could explain the non-significant values of the Pearson correlations, indicating that our model most likely under represents the relationship strength between *N. ogeche* tree rings and honey yield-per-hive. Graphically, the observed honey record matches well with the reconstructed honey and *N. ogeche* tree-ring records (Figure 3.6).

3.3.3.2 Monte Carlo Results

The reconstructed honey yield-per-hive (Figure 3.5) indicates the last two decades have been dominated by low-yield years relative to the 160-year record. Evaluation of the reconstructed values (Table 3.2) shows the two lowest-yield years of 1997 and 2007 and the highest-yield year of 1990 occurred near the end of the record suggesting that recent yields have been more variable. The highest yields were recorded in the middle to latter third of the reconstruction, with the top-ten high-yield years occurring during 1932–1990.

The lowest yields primarily occurred during the first third of the chronology with the period 1877-1898 being remarkable for the duration of low-yield years including four of the ten lowest years.

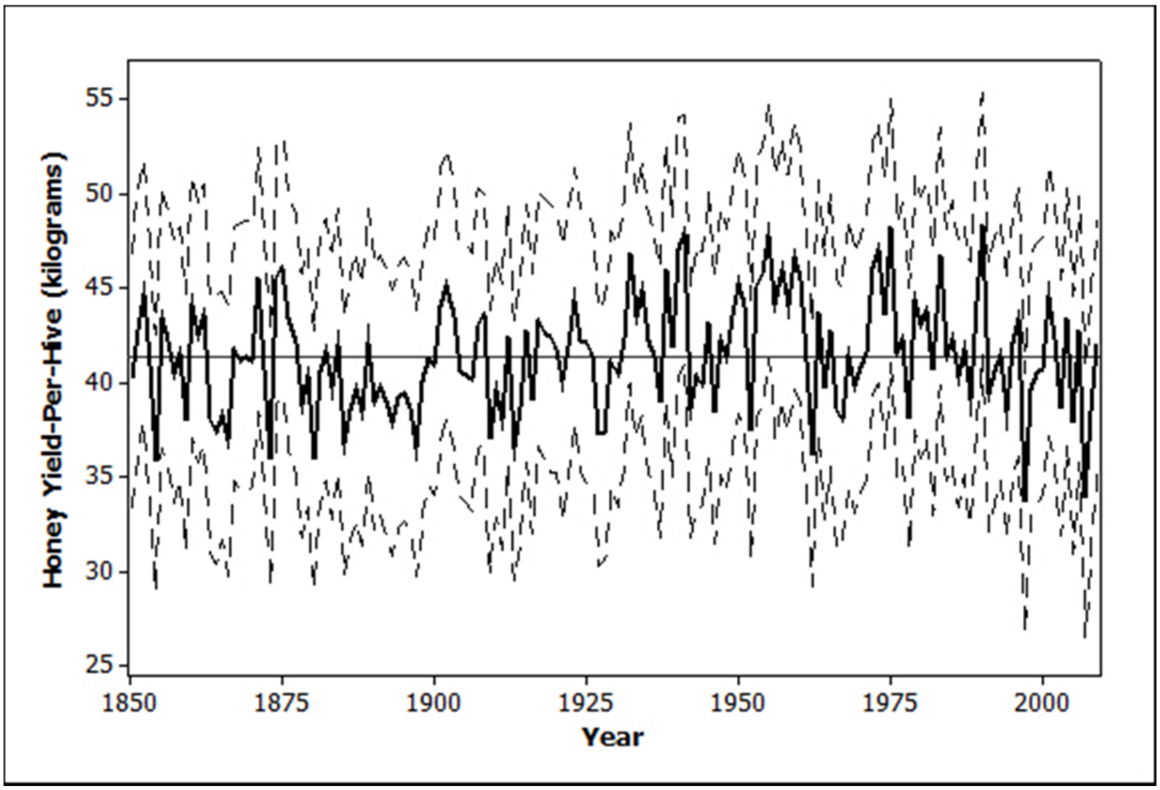

Figure 3.5: Reconstruction of honey yield-per hive AD 1850–2009. The solid line is the reconstruction. The top dashed line is the 90% confidence band and the lower dashed line is the 10% confidence band. Thus, the lines represent an 80% confidence interval for the reconstruction, meaning that 80% of of the error of the reconstruction will fall within the two dashed lines. The average annual honey yield-per-hive (41.4 kg) is represented as a line through the mean.

Table 3.1: Calibration and Verification Statistics

Calibration	R^2 (*p*-value)[a]	R^2adj[b]	Verification	*r* (*p*-value)[c]	RE	CE
1990–2009	0.30 (0.013)	0.26	----------	--	--	--
1990–1999	0.32 (0.086)	0.24	2000–2009	0.55 (0.098)	0.98	0.32
2000–2009	0.30 (0.098)	0.22	1990–1999	0.57 (0.086)	0.52	0.30

[a] The R^2 and p-value of tree-rings regressed on honey yield-per-hive for calibration period.

[b] Adjusted R^2 accounts for degrees of freedom.

[c] Pearson correlation between actual and predicted honey yield-per-hive.

The reconstruction of honey yield-per-hive with the 80-percent confidence bands (Figure 3.5) illustrates that the error in the reconstruction was temporally consistent, indicating that the model estimates are reliable throughout the reconstruction. Using the confidence bands, we calculated the probability that any given reconstructed yield not in the observed period (i.e., 1860–1989) exceeded the highest or lowest observed yield-per-hive (Table 3.3). For example, the highest observed yield year was 1993 with 51.3 kg per hive. This value has an empirically derived exceedance probability of 0.28 in the reconstructed year of 1975, indicating there is a 28-percent chance that the yield in 1975 exceeded the highest-recorded yield.

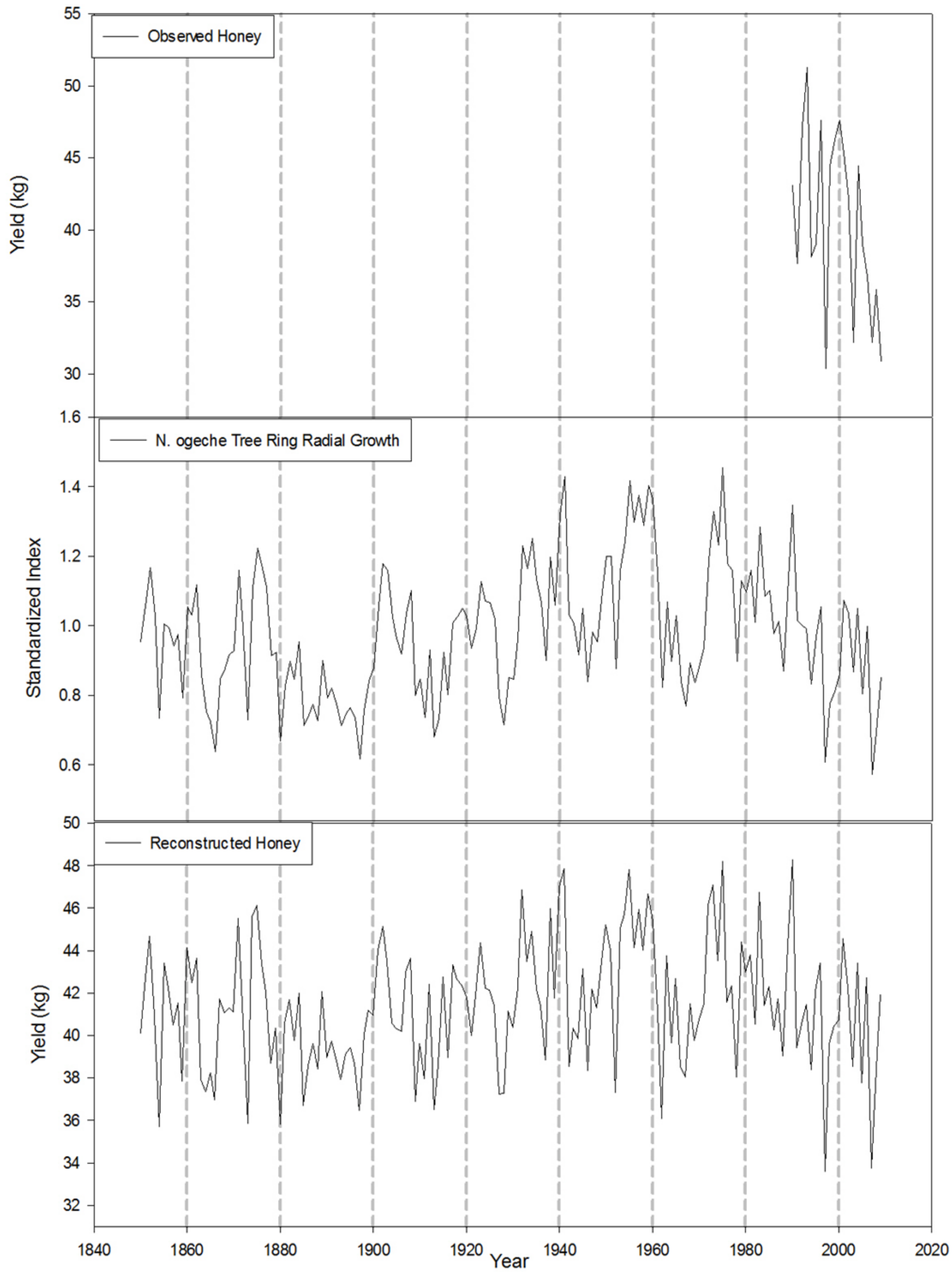

Figure 3.6: Time-series comparisons between observed honey yield, *N. ogeche* tree-ring radial growth, and reconstructed honey yield.

Table 3.2. Lowest and Highest Reconstructed and Actual Honey Yield-Per-Hive (in kilograms)*

Rank	High Yield	Low Yield
1	1990 (48.29)	1997 (33.62)
2	1975 (48.19)	2007 (33.75)
3	1941 (47.88)	1854 (34.34)
4	1955 (47.84)	1880 (35.83)
5	1973 (47.08)	1873 (35.87)
6	1940 (46.87)	1962 (36.09)
7	1932 (46.87)	1897 (36.46)
8	1983 (46.73)	1913 (36.52)
9	1959 (46.67)	1885 (36.72)
10	1972 (46.12)	1909 (36.88)
1	1993 (51.26)	1997 (30.39)

*Rows 1–10 are reconstructed years with the highest and lowest yield-per-hive listed. The bottom row represents the highest and lowest observed yield-per-hive.

Table 3.3. Reconstructed Honey Yield-Per-Hive (in kilograms) with probabilities from Monte Carlo.

Rank[a]	Year (AD)	Honey Yield-Per-Hive ($\hat{q}$)[b]	$p\ (q < q_c)^d$
High Yield Years: q_c = 51.26[c]			
2	1975	48.18	0.28
3	1941	47.88	0.24
4	1955	47.84	0.27
5	1973	47.08	0.21
6	1940	46.87	0.23
7	1932	46.87	0.21
8	1983	46.73	0.20
9	1959	46.67	0.20
10	1972	46.12	0.16
Low Yield Years: q_c = 30.39[c]			
3	1854	34.34	0.16
4	1880	35.83	0.15
5	1873	35.87	0.15
6	1962	36.09	0.15
7	1897	36.46	0.12
8	1913	36.52	0.14
9	1885	36.72	0.12
10	1909	36.88	0.12

[a] Rank in the reconstruction.

[b] Reconstructed honey yield-per-hive in kilograms ($\hat{q}$) for a given year.

[c] Highest and lowest observed honey yield-per-hive (q_c).

[d] Probability that reconstructed honey yield-per-hive was higher or lower than highest or lowest observed value.

The recent decline in honey yield based on probabilistic terms is rare, but with precedent as yield in 1854 had a 16-percent chance of being lower than 1997 (Table 3.3). The average yield during 1988–2009 was 40.7 kg/hive, (mean for 1850–2009 = 41.4 kg/hive), which was higher than the 1877–1898 average of 39.4 kg/hive. These findings suggest that lower, multidecadal-length yields have previously occurred. Regardless, the current decline is at least one of the most severe in the reconstructed record because of the *cumulative* effect of having multiple below-yield years. Higher honey-yield years were more likely to have occurred, with nine reconstructed years having at least a 20-percent probability of being larger than the highest-observed year. Examining reconstructed honey-yield years in probabilistic terms offers empirical evidence that the observed record (1990–2009) of honey yield has experienced both historically high- and low-yield years. The large variation in the observed annual honey yields suggests environmental conditions along the Apalachicola River have recently been exceptionally variable during the past two decades indicating that environmental conditions may have shifted to a more unstable regime. Additionally, the current decline in honey yield could indicate that environmental conditions have changed and are less conducive for high nectar secretion of *N. ogeche* and thus result in lower honey yields.

3.4 Conclusions

Our study demonstrated the feasibility of using tree-rings as proxy for extending agricultural yield records, especially for crops directly related to tree physiology.

Using tree-ring data from *N. ogeche*, we were able to expand the high-quality portion of the honey-yield record 140 years, which allowed us to identify the extent of temporal variability and place the recent decline in a historical context. The recent decline in tupelo honey yield-per-hive concerns northwest Florida beekeepers and could present significant economic challenges if the decline continues. Limited knowledge on the influences on tupelo-honey yield, make this decline difficult to assess, yet the reconstruction allows for interannual yield comparisons previously unavailable. Data from the reconstructed honey yield-per-hive suggests that a period of lower yields similar to the recent decline occurred in the late 1800s, although the two most extreme low-yield years occurred in 1997 and 2007. Thus, the recent decline is not unique in terms of duration, but perhaps in interannual variability.

We determined what climate and river variables influenced radial growth of *N. ogeche* to assist in examining the cause of the current decline in honey yield-per-hive. Climate during the previous year was important to both *N. ogeche* and honey yield indicating that starch storage during favorable years could be important to *N. ogeche* and allow for higher levels of radial growth and nectar secretion during years that are not as favorable climatically. The relationship between July river flow and honey yield has decreased, indicating that the environmental conditions have changed since the mid-1980s and may be responsible for the harvest decline. The changing relationship between

July river flow and honey yield could indicate that the current decline in honey yield may be different than previous declines and warrants more attention. However, a larger sample taken from the remaining area of the tupelo-honey producing region is required to determine if the shifting relationship found between the environment and *N. ogeche* tree rings are found at a few localized areas or for the majority of the cypress-tupelo forests along the Apalachicola River.

CHAPTER IV

CLIMATE VARIABILITY AND HONEY YIELD SINCE AD 1800: A HISTORIC PERSPECTIVE

This chapter is a manuscript that was submitted to *Geophysical Research Letters*. The use of "we" and "our" in this chapter refers to Dr. Paul Knapp and myself who are co-authors on the submitted manuscript.

4.1 Introduction

Agricultural records of commercial products are often temporally limited and may lack historic range-of-variations in harvest necessary to fully understand yield declines or increases. Salmon population declines in Alaska and the Pacific Northwest were shown to be responding, in part, to the Pacific Decadal Oscillation (PDO) indicating that populations would increase during a favorable phase of the PDO (Mantua et al. 1997). An analysis of the wine-quality records suggests that increases in wine quality are related to warming climatic conditions but may be temporary if continued warming temperatures exceed heat thresholds of the vines (Jones et al. 2005). Similarly, allocations of base flow of the Colorado River, the major water source for southwestern U.S. agriculture, were calculated using river discharges during a wetter climatic cycle and may be unrealistic during droughts (Fradkin 1996).   These studies suggest that multi-decadal variations in agricultural productivity, and the plethora of concerns they manifest, may be influenced by long-term mesoscale climatic oscillations that are often overlooked because of the time span in which they occur. In this study, we demonstrate how tupelo honey production in the southeastern U.S. exemplifies this issue of interdecadal variability.

Tupelo honey is created by honeybees (*Apis mellifera*) who gather nectar secreted in the flowers of *Nyssa ogeche* trees, which are most commonly found along the floodplains of the Apalachicola River, Florida. Honey yield declines during the past decade— including tupelo— (Stallins et al. 2010) have been attributed to colony collapse disorder (CCD). However, even when excluding the effects of CCD by using tupelo honey yield-per-hive data, reported yield has declined since the early 1990s. Tupelo honey apiarists have suggested other environmental factors may have contributed to the longer-term decline, including altered hydrologic conditions along the Apalachicola River (Stallins et al. 2010). *N. ogeche* grow best in permanently to semi-permanently flooded sites and repeat forest sampling documented a trend towards drier floodplain forest conditions (Darst and Light 2008) and an increase of flood-intolerant species compared to the 1970s (Darst and Light 2008). The altering hydrologic conditions are also resulting in declines in tupelo recruitment and regeneration along the Apalachicola River, which has been suggested to decrease the quantity and quality of *N. ogeche* nectar and pollen (Stallins et al. 2010). Decreases in pollen and nectar require more honeybees to generate equivalent honey yield-per-hive. While declines in honey production may be influenced by shifts at local-scale site conditions, consideration of multi-decadal length climatic cycles (e.g. the North Atlantic Oscillation, El Niño-Southern Oscillation, and Atlantic Multidecadal Oscillation) has not been identified as an operative cause for the recent decrease in yield. Here, we examine the influence of the Atlantic Multidecadal Oscillation (AMO) on honey production along sites on the Apalachicola River, Florida, thus illustrating how agricultural productivity can be affected by long-term climate variations. Specifically, we: 1) expand the tupelo honey yield-per-hive record to AD 1800 using tree-rings from *N. ogeche;* 2) determine if honey production is significantly correlated the AMO; and 3) place the current decline in a historic context using the expanded data set.

4.2 Methods

4.2.1 Site Section

We sampled 30–40 large (> 60cm) old-growth *N. ogeche* trees at four sites along the Apalachicola River floodplains in Northwest Florida (Figure 4.1). The banks and floodplains of the Apalachicola River are one of the few places *N. ogeche* density is sufficient for commercial production of tupelo honey (Eyde 1963) making this location optimal for sample sites. Each sample site was identified by local beekeepers as commercial-scale honey production locations. Only visually healthy trees absent direct anthropogenic damage were selected for sampling. Each tree was sampled from opposite sides at approximately 1.3 meters height using a 5.15 mm diameter increment borer (Stokes and Smiley 1968; Fritts 2001; Speer 2010).

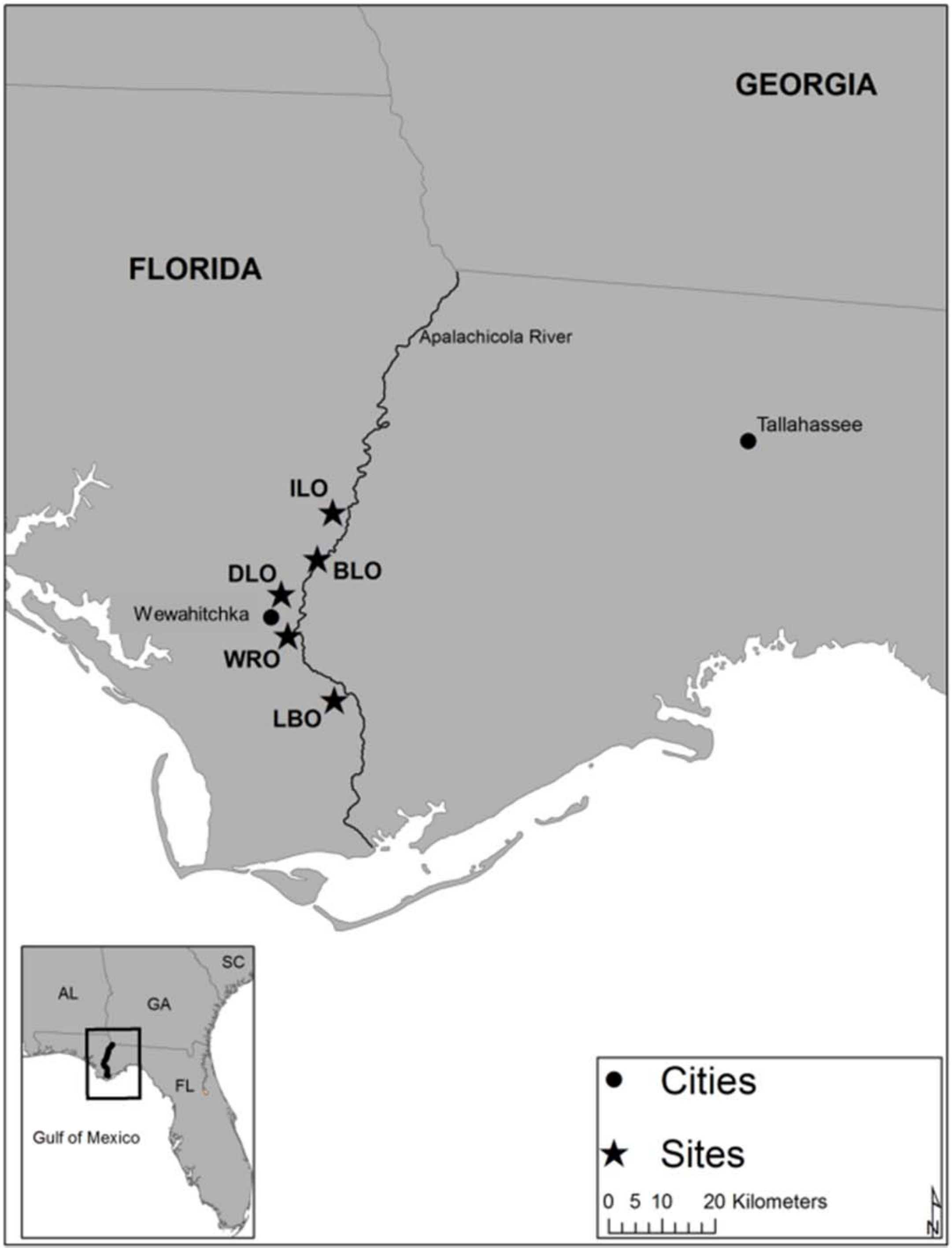

Figure 4.1: Location of tree-ring data collection sites (stars) and local cities (circles).

4.2.2 Laboratory Procedures

Collected cores were mounted and sanded using 15, 12, and 9 micron finishing film to reveal the ring structure. Sanded cores were crossdated using the list method (Yamaguchi 1991) and measured using a Velmex station in combination with the software program J2X (Voorhees 2000). Dating accuracy of each core was confirmed using the program COFECHA (Holmes 1983). The data from the four sites were combined and standardized using negative exponential trend fitting with the program ARSTAN (Cook 1985) to account for biological growth trend differences.

4.2.3 Statistical Analysis

We used the period 1990–2010 for the calibration and validation of the regression model, as this period contained the most accurate honey yield-per-hive data and represented the highest correlation between honey yield-per-hive and the *N. ogeche* tree ring chronology. We used the leave-one-out method (Michaelsen 1987) to calculate bivariate regression coefficients between the actual and predicted honey yield-per-hive and the reduction of error statistic (*RE*) (Fritts 2001). The reconstruction was successfully calibrated and validated with honey yield-per-hive being significantly related to *N. ogeche* tree-ring chronology and generating positive *RE* values for both the calibration and for the leave-one-out method (Table 4.1).

We used Pearson correlation analysis to determine if any climate index was significantly related to the reconstructed honey yield-per-hive and selected a composite list of climate indices gathered by NOAA's Earth System Research Laboratory. We examined the monthly values of the Pacific North American Index, the North Atlantic Oscillation, the Southern Oscillation Index, the Eastern Tropical Pacific SST (Nino 3), the PDO and the AMO. We calculated growing season (Mar.–Nov.) averages for each index and found that the AMO was the sole index significantly correlated to honey yield, and thus used it for analysis. We obtained honey yield-per-hive for the state of Florida from the National Agricultural Statistics Services branch of the United States of Department of Agriculture.

Table 4.1: Calibration and Verification Statistics

	r-value[a]	*p*-value[a]	RE
Calibration	0.556	0.0009	0.31
Leave-one-out	0.448	0.03	0.18

[a] Pearson correlation between actual and predicted honey yield-per-hive.

4.3 Results and Discussion

The extended honey yield-per-hive record dated to AD 1800 allowing us to place the current yield decline in a historical context. *N. ogeche* radial growth and tupelo honey yield-per-hive were significantly related (Figure 4.2). The current decline in honey yield-per-hive is precedented in the context of the 211-year reconstructed record. Honey production has oscillated between high- and low-productivity periods spanning multiple decades, with the longest low-yield period occurring during 1840–1880 CE (Figure 4.3). Both reconstructed honey yield derived from *N. ogeche* tree-ring data and AMO index values exhibited temporal autocorrelation and required adjusting the degrees of freedom using the methodology of (Pyper and Peterman 1998) prior to correlation analysis (r = -0.297; α= 0.050). Autocorrelation frequently occurs naturally with biological and climatic data yet is undesirable for mathematics and statistical analysis as it violates the assumption of data independence. However, removal of autocorrelation may either eliminate or mask actual relationships and thus could lead to false negative conclusions. The relationship between reconstructed honey yield-per-hive and AMO was inherently weakened when adjusting from autocorrelation, but since predictability is the objective of this paper, the unadjusted relationship ($r = -0.436$; $p < 0.000$; $n = 63$) is more suitable for our analysis.

AMO is negatively correlated with summer (JJA) precipitation (Enfield et al. 2001), and positively correlated with summer maximum and minimum temperatures in the southeastern United States (AMO and Tmax; $r = 0.375$; $\alpha = 0.003$; AMO and Tmin; $r = 0.309$; $\alpha = 0.015$). *N. ogeche* radial growth—and thus tupelo honey production—are positively correlated with previous summer precipitation and negatively correlated with maximum summer temperatures (Maxwell and Knapp In Press; Chapter III). Thus a positive (negative) AMO will coincide with a dry and warm (wet and cool) summer in the southeastern U.S. leading to a small (large) *N. ogeche* growth ring. The AMO is a multi-decadal oscillation that influences both current- and previous-year climate conditions and thus also impacts current-year *N. ogeche* radial growth.

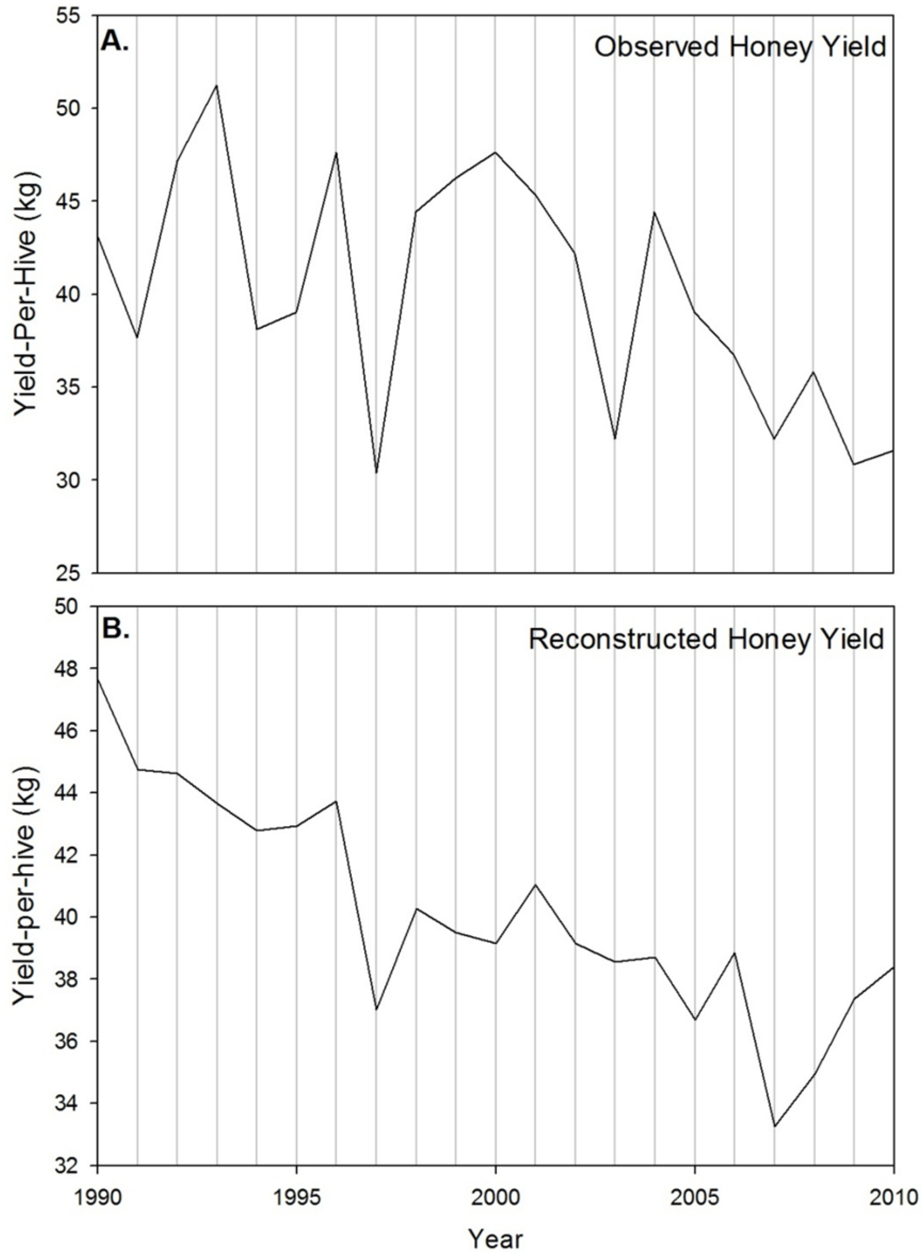

Figure 4.2: The graphical relationship between the: a) observed honey yield-per-hive recorded by the USDA; b) reconstructed honey yield-per-hive. The relationship is significant (r = 0.556; α = 0.009; n = 21) with the reconstructed data having a similar trend line to the observed data.

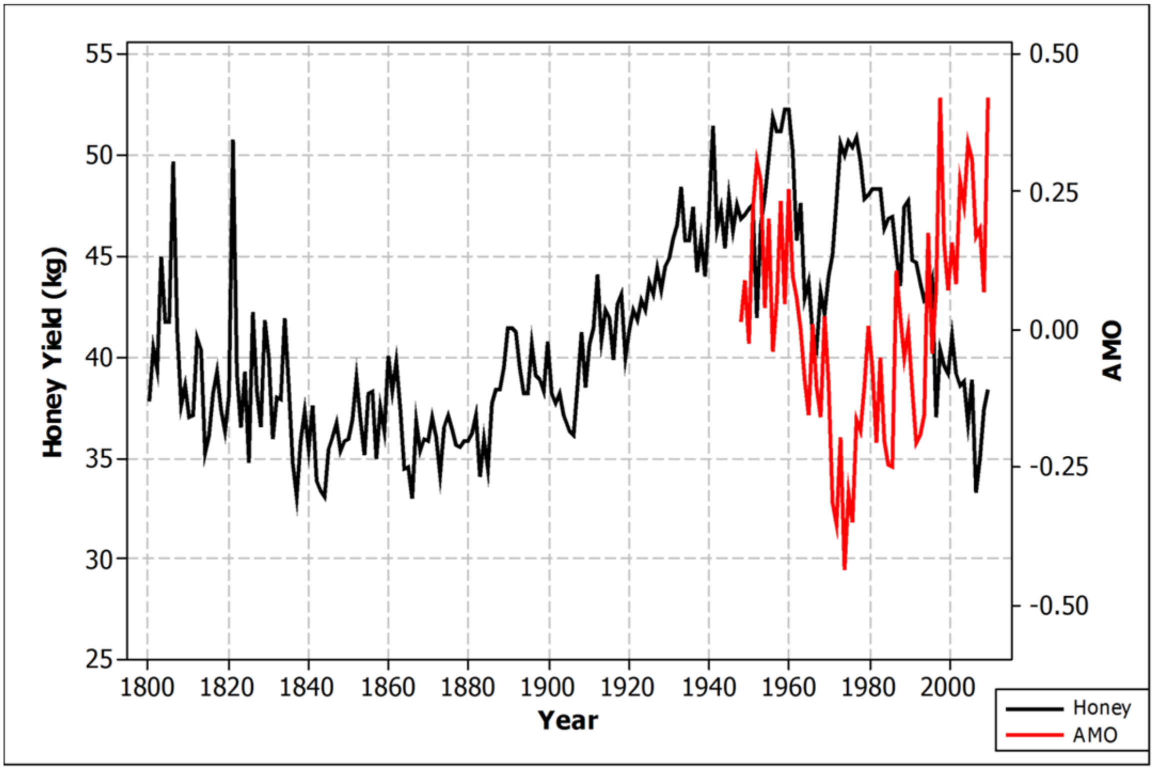

Figure 4.3: A time-series illustration of the relationship (r = -0.436; p < 0.000; n = 63) between reconstructed honey yield-per-hive (black) and the Atlantic Multidecadal Oscillation (red).

N. ogeche ring widths are positively related to previous summer minimum temperatures, while AMO is positively related to summer minimum temperatures (Maxwell and Knapp In Press; Chapter III), a finding in conflict with the negative relationship between AMO and *N. ogeche* radial growth. One possible explanation is that *N. ogeche* grow best during wet summers, which will reduce night-time cooling resulting in a positive relationship between previous summer minimum temperatures and *N. ogeche* radial growth. Because *N. ogeche* are influenced by multiple factors the conundrum of summer minimum temperatures is minimized as the other factors have a greater influence.

4.4 Conclusions

Our findings demonstrate the potential application of tree-ring data to quantify agricultural crop yields to examine natural variability in a multi-century historic context. The recent multi-decadal decline in tupelo honey yield may principally reflect a natural cause unrelated to CCD or hydrologic impacts. Given the duration of the decline it is tempting to ascribe a loss of productivity to more short-term and tangible causes and exclude the effects of a naturally occurring long-term climate oscillation. Several commercial agricultural crops are either derived directly (e.g., walnuts, almonds, grapes, and maple syrup) or indirectly from long-lived woody species that may also be affected by climatic oscillations. The methods used herein to reconstruct tupelo honey can be applied to develop similar harvest records for other agriculturally important species and place long-term production trends into a broader context.

CHAPTER V

CONCLUSIONS

This dissertation had three broad objectives: 1) to determine the potential of multifunctionality for the U.S. honey industry, 2) establish that *Nyssa ogeche* tree-rings crossdate and correlate with tupelo honey yield-per-hive, and 3) to determine if meso-scale climate oscillations influence tupelo honey yield-per-hive. A better understanding of the U.S. honey market may provide beekeepers with insight into what areas of the industry are most profitable. Examining tupelo honey yield from a multi-century time scale allows beekeepers to fully understand the natural variation in honey yield and assess current fluctuations in yield more accurately. The three objectives (Chapter II, III, and IV) were submitted to peer-reviewed journals.

I found that the multiple challenges the U.S. honey industry is facing (e.g., bee disease and foreign competition) has led to an interesting transition. Many beekeepers are now producing regionally specific honey and organic honey instead of mixed flora honeys sold in bulk, which foreign competitors can produce more cheaply. U.S. beekeepers are also more open to use their bees for pollination services and are producing other products than honey (e.g., bees wax products). The diversification of commodities is a classic sign of an industry transitioning into multifunctionality. The U.S. honey industry is unique in that honey is dependent on a healthy nectar source species and thus promotes environmental conservation. Environmental conservation is underutilized for the industry because it is one of the few examples where conservation can be both economically and environmentally sustainable.

Tupelo honey is a specialty honey that is renowned for its antioxidant qualities and its flavor. Beekeepers who produce tupelo honey exemplify many of the multifunctional traits I described about the industry. I examined the tupelo honey industry in more detail by using tree-rings from the source species, *Nyssa ogeche*. This is the first study to use *N. ogeche* in a dendrochronological study and I found that the species crossdates both within a site and among sites. Based on the two sites sampled on the Apalachicola River, Florida, *N. ogeche* tree-rings responded to previous summer variables along with current year variables, indicating that starch storage is important for the species. The relationship between river flow and radial growth has shifted and could indicate a change in the environment, which would be of concern for beekeepers. There was a significant relationship between *N. ogeche* tree-rings and honey yield-per-hive (r = 0.546, p = 0.013) allowing me to expand the honey record and examine the current decline in honey yield-per-hive in an historic context. I found that the current decline in tupelo honey-yield-per-hive has been exceeded in duration in the past but perhaps not in the intensity of the decline. The shift in the relationship between river flow and *N. ogeche* radial growth is problematic when combined with the intensity of the decline. A larger sample from more sites is needed to confirm the intensity of decline and determine the status of both *N. ogeche* environmental health and the tupelo honey industry health.

Using data from four sites comprising 127 core samples collected from 90 trees, I was able to expand the accurate honey record to 1800 CE. The expanded record shows that the current decline is precedented in both duration and intensity. The cyclic behavior of the honey yield record indicates that a meso-scale climate oscillation might be influencing honey production. Indeed, the Atlantic Multidecadal Oscillation (AMO) is significantly related to the reconstructed honey yield-per-hive (r = -0.436; p < 0.000; n = 63). Even with the adjustment in degrees of freedom to account for autocorrelation the relationship is near-significant (r = -0.297; p= 0.050). The AMO influences summer precipitation and temperature in the southeastern U.S. and thus impact *N. ogeche* radial growth.

AMO influence on honey yield exemplifies how large meso-scale climate oscillations can have local impacts on crop yield. It also demonstrates how short agriculture crop records can lead to misunderstandings of the natural variation of crop yield. The technique of using tree-rings to expand yield records can be used for other crops that are dependent on tree physiology (e.g., olives, maple syrup, walnuts, almonds, wine, and grapes). This approach could also be used for traditional agriculture products, albeit limited, in areas that have relatively undisturbed old-growth forest in close proximity.

The results from this study can be applied directly to beekeepers. If more U.S. beekeepers transition to a multifunctional system, the U.S. could establish a brand of unique high-quality honeys that would be more difficult for foreign competitors to produce, enabling beekeepers to sell their specialty honey for higher prices. The tupelo honey beekeepers can use the findings from this study to plan accordingly for oscillating phases of higher-and lower-production years. During years of higher production, beekeepers can either store honey to sell during lower production periods or ask for higher prices during lower producing phases. The conservation of the Apalachicola River basin is important for the production of tupelo honey and this study provided a quantification of the relationship between the environment, *N. ogeche* radial growth, and tupelo honey.

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