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Assessing And Modeling Mangrove Forest Dynamics Along The Temperate-subtropical Ecotone In Eastern Florida

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ASSESSING AND MODELING MANGROVE FOREST DYNAMICS ALONG THE
TEMPERATE-SUBTROPICAL ECOTONE IN EASTERN FLORIDA

by

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ABSTRACT

Mangrove ecosystems are among the world's most endangered biomes; nearly one-half of the overall coverage is threatened by human activity, invasive species, and global climate change. Mangroves play an important ecosystem role through detrital production and by providing: fisheries and wildlife nursery habitat, shoreline protection, a sink for nutrients, carbon, and sediment. In addition to human activity, the Florida mangroves (*Avicennia germinans*, *Laguncularia racemosa*, and *Rhizophora mangle*) are being threatened by the invasive Brazilian pepper (*Schinus terebinthifolius*). This study was performed along a 261 km stretch of the east coast of Florida from Sebastian Inlet to the northern extent of mangroves, near St. Augustine. It entailed two parts. The first examined the phenology and leafing rates of the four species and attempted to find if there was a relationship between growth and latitude or temperature. Although a correlation between peaks in temperature and phenology was observed for all species, no leafing pattern could be discerned. In terms of mangrove growth for branch diameter, a logarithmic model (y=a + b·log [Initial diameter]) best fitted the data for *R. mangle* and *L. racemosa* but neither latitude nor temperature appeared to be important. However, *S. terebinthifolius'* and *A. germinans'* branch diameter growth were best represented by a logarithmic model (y=a + b·log [Initial diameter]+ c·log x_2) that incorporated temperature and latitudinal inputs respectively.

In the second part, a simulation model was developed to focus on understanding the relationships between establishment and competition among the three mangrove species and the invading *S. terebinthifolius*. This model was run under various invasion and/or climate change scenarios to determine possible outcomes under global climate change with or without the presence of *S. terebinthifolius*. Conclusions were drawn that under all scenarios of invasion,

other than sea level rise as part of global climate change, *S. terebinthifolius* would dominate the landscape if allowed to invade and establish in areas in which it is not currently present although the amount of this response is dependent on the *S. terebinthifolius* response curves.

ACKNOWLEDGMENTS

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CHAPTER 1. INTRODUCTION

Global Climate Change

The concentration of atmospheric CO_2 has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 (IPCC 2007). The increase in this "greenhouse" gas and others including CH_4 and NO_2 are expected to result in a global climate change which has been hypothesized to result in an increase in temperature (Fig. 1-1) and changes in precipitation, in oceanic and atmospheric circulation, in the frequency, intensity, timing, and distribution of hurricanes and tropical storms, and lastly, changes in the rate of sea level rise (Michener et al. 1997, IPCC 2007).
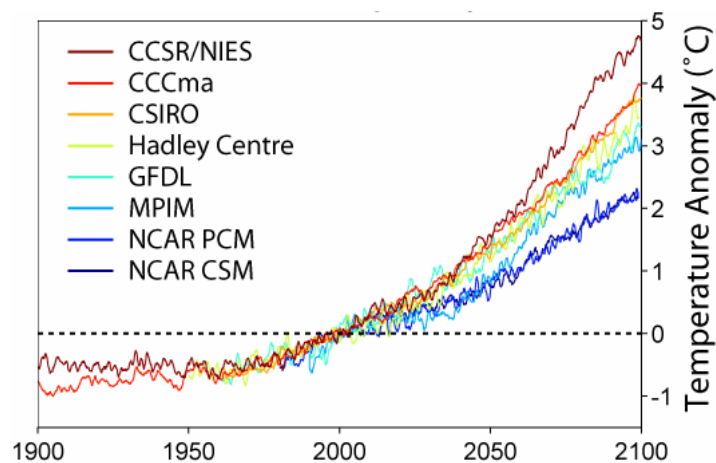
Figure 0-1. Global climate change warming predictions from eight general circulation models (IPCC 2007).

In 2006, the National Arbor Day Foundation updated their 1990 Hardiness Zone Maps as a result of recent changes in climate. These maps (Fig. 1-2) show the northern increase of the northern limits of Zone 10 (average annual low 40 °F – 30 °F) in just 16 years from South Florida to just above Cape Canaveral (National Arbor Day Foundation 2006). This division

between Zones 9 and 10 is often referred to as the division between the sub-tropic and temperate. The northern most extent of mangroves, occur just north of this division.
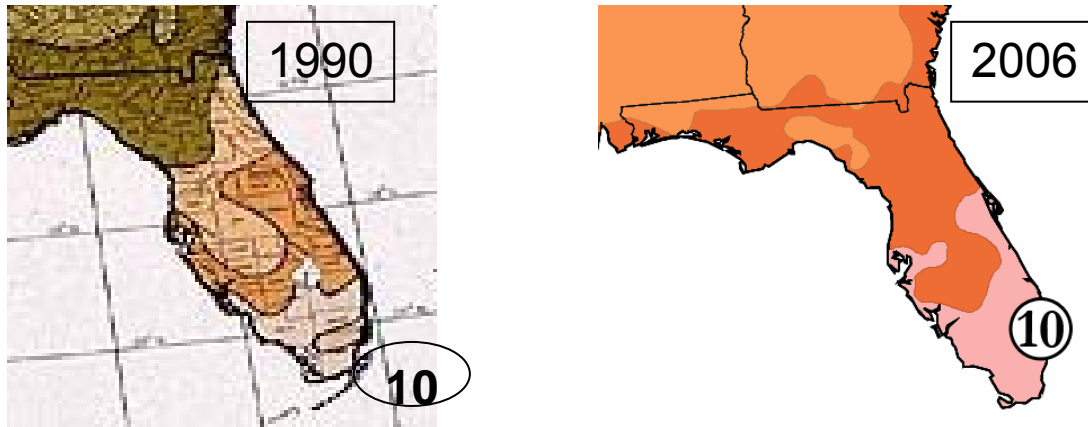
Figure 0-2. 1990 to 2006 change in the extent of Hardiness Zone 10 (Annual Low 30°F- 40°F) (National Arbor Day Foundation 2006).

Mangroves

Mangrove ecosystems are among the world's most endangered biomes with nearly one-half of the overall coverage of the biomes threaten by human activity, invasives, and global climate change (Field et al. 1998). They play an important role in the ecosystem by providing detritus, fish and wildlife habitat, shoreline protection, and by acting as a sink for nutrients, carbon and sediment. On average, 40% of the detrital materials in suspension in tropical estuarine waters have been found to be of mangrove origin (Lugo and Snedaker 1974). These ecosystems also have anthropogenic uses such as timber, charcoal, honey production, and a variety medicinal uses such as toothache relief (Davis 1942, Lugo and Snedaker 1974, Odum 1982, Tomlinson 1994, Ewel 1998, Hogarth 1999, USFWS 1999). In Florida, over 200 bird species can be found within mangrove communities as well as federally listed wildlife species such as the Florida panther (*Felis concolor coryi*), Key deer (*Odocoileus virginianus clavium*),

West Indian Manatee (*Trichechus manatus*), bald eagle (*Haliaeetus leucocephalus*), and Florida black bear (*Ursus amercianus floridanus*) (USFWS 1999).

The term "mangrove" expresses two distinctly different concepts (Odum 1982). One is that of a group of halophytic trees and shrubs which comprise 54 species in 20 genera, belonging to 16 families (Hogarth 1999). These plants are adapted to loose, waterlogged soils, to saline habitats with periodic tidal submergence, and usually have degrees of viviparity of propagules (Odum et al. 1982, Hogarth 1999). The second term for mangrove refers to the mangrove community or ecosystem which includes individual mangrove trees. The term "mangal" is often used to define this community. In this paper, the term "mangrove" will refer to the individual trees where "mangrove ecosystem" will refer to the community or mangrove forest.

Three species of mangrove can be found in Florida: the black mangrove (*Avicennia germinans*), red mangrove (*Rhizophora mangle*), and white mangrove (*Laguncularia racemosa*). The buttonwood tree (*Conocarpus erectus*) is often listed as a mangrove species, but it is not a true mangrove as it is not viviparous. Therefore *C. erectus* is often listed as a mangrove community associate (Hogarth 1999).

Mangroves are freeze intolerant and hence are restricted to subtropical and tropical environments. Worldwide, mangroves are delineated generally by the winter position of the 20°C isotherm for seawater (Duke et. al. 1998, Field et al. 1998, Hogarth 1999). In Florida, this 20°C isotherm occurs roughly along the 30° latitude, which along the Atlantic coast is located near St. Augustine (Kangas and Lugo 1990). The northernmost limit is thought to be the frost line (Davis 1942) though a combination of stresses including temperature, rainfall, and salinity may be the controlling influence limiting northern expansion (Lugo and Patterson-Zucca 1977, Chen and Twilley 1998). Of the three mangrove species in Florida, *A. germinans* is the most freeze tolerant (Odum et al. 1982, Chen and Twilley 1998) and can be found at higher latitudes (30° 01') usually

in monotypic stands (Tomlinson 1994). The northernmost extent of the *R. mangle* in Florida has been recently documented to be at the Fort Matanzas National Monument in St. Johns County (29° 42.94'N, 81° 14.35'W) though the species is well documented within Volusia County (Zomleffer et al. 2006). The northernmost limit of the *L. racemosa* is in Volusia County as documented in the ISB: Atlas of Florida Vascular Plants (Wunderlin and Hansen 2006). However, two *L. racemosa* plants located in northern Flagler County (29° 39.8'N, 81° 13' 00'W are part of this study.

Mangroves and Global Climate Change

Ecotones, which are transitional areas between ecological systems or types of vegetation (Nielsen 1993), provide scientists with the opportunity to study the dynamics of ecosystems and have been the focus for the early detection of climate change (Noble 1993, Risser 1995, Parmesan and Yohe 2003). From Cape Canaveral to the northern edge of the mangroves above St. Augustine, mangroves and salt marsh occur in a broad ecotone in which either mangroves or salt marsh vegetation exists (Kangas and Lugo 1990). Although it has been hypothesized that salt marshes successionally precede mangroves (Davis 1942, Egler 1952), both can co-exist with the edge between them changeable (Lugo 1980).

Along the ecotone, an increase in temperature is hypothesized to allow the mangroves, which are better competitors due to taller stature and increased productivity (Kangas and Lugo 1990) to outcompete the salt marsh vegetation and thus, move northward. This invasion or incursion of mangroves into the salt marsh was documented by Stevens et al. (2006) and Saintilan and Williams (1999). Similar northward movement of Florida native trees and shrubs has been predicted (Box et al. 1993, Box et al. 1999, Crumpacker et al. 2000, Iverson et al. 2004). This northward invasion is expected to occur as it has been hypothesized that as growing

conditions become warmer, southern species at the edge of their northern range will have an increased growth rate which is greater than northern species at the southern edge of their growing range (Loehle 1998). To use their faster growth to gain position, these southern species will need gaps, disturbances, or stand break up (Loehle 1998). An increase in the average winter temperature may be the most deterministic factor for range expansion of plants than that of the entire year (Shreve 1914, Box et al. 1999). A shift in the optimum habitat is expected to outpace that of the plant communities resulting in a "lag" of the northern migration of plant communities by at least 100 years. This lag time could be reduced through the human planting of propagules into the optimum, but not yet utilized, communities but may be overcome by species that are well-equipped for invasion (Iverson et al. 2004).

Along with increasing temperature, global climate change is hypothesized to result in sea-level rise (Edgerton 1991) which may negatively impact mangroves, especially *R. mangle* (Ellison 1993, Snedaker et al. 1994, Hogarth 1999). There are several hypotheses regarding the fate of mangroves as a result of sea-level rise. It is hypothesized that the rise in sea level may limit growth in *R. mangle* by the accumulation of acid-sulfide soils which retard growth (Ellison 1993, Ellison and Farnsworth 1997). Another hypothesis is that total submergence of worldwide mangroves may also be dependent on the rate of peat accumulation and rate of sea level rise (Parkinson et. al 1994). In general, a total collapse of the worldwide mangroves is not predicted as they have survived other periods of high rates of sea level rise (Woodroffe and Grindrod 1991). Regardless of the rates of sea level rise, loss of mangrove habitat will occur where landward migration is stopped by anthropological barriers and coastal development and by natural topography (Edgerton 1991, Parkinson et al 1994).

Brazilian Pepper (*Schinus terebinthifolius*)

An invasive exotic as defined by IUCN (2006) is an "alien species which becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity." Successful invaders have effective reproductive and dispersal mechanisms, a competitive ability superior to the native, few or no herbivores or pathogens, an ability to occupy vacant niches, and the capability to alter a site by either significantly changing resource availability or by disturbing regimes, or both (Gordon 1998). In addition, invasive species that become dominant in the community appear likely to change environmental conditions and resource availability over larger areas than they occupy or create a new community structure (Gordon 1998). The steps of invasion process are important processes which an invader must take before they are considered to be successful. They include transport, establishment, spread, and finally impact (Lockwood et al. 2007).

One of these successful invaders into Florida is Brazilian Pepper (*Schinus terebinthifolius*), also known as Christmas berry or Florida Holly. *S. terebinthifolius* is indigenous to subtropical Brazil, Paraguay, and Argentina and is believed to have been introduced to Florida as an ornamental plant in the 1840's (Jones and Doren 1997). It is listed by Florida rule as a Class I Prohibited Aquatic Plant which prohibits possession, collection, transportation, cultivation, and importation (FLDEP 2007). *S. terebinthifolius* thrives on disturbed soils (Jones and Doren 1997), but can also be found in coastal habitats ranging from pine rocklands to coastal mangrove forests (Weber 2003, Ewe and Sternberg 2005).

S. terebinthifolius has many detrimental environmental impacts including loss of habitat to threatened native plants and disruption of habit vital to the prey of the Florida panther (Cud et al. 2006). In contrast to the mangroves, whose leaves are an important part of the detrital food web, the leaves of *S. terebinthifolius* may have negative effects to migratory birds, including

robins (Morton 1978). Finally, leaf litter under trees, may serve as a refuge for other exotic, invasive organisms (Cuda et al. 2006).

Study Objectives/Questions

One purpose of this study was to study mangrove and *S. terebinthifolius* at the northern edge of their ranges. Questions addressed include:

1. Are there seasonal patterns to the timing (phenology) of buds, flowers, and/or fruits and do phenologies vary among species?

2. How does salinity vary from site to site, and how may sea level rise affect these salinities?

3. Do leaf production rates vary across species or sites and is there a phenological pattern in leaf production?

Another objective of the study was to determine the minimum temperature needed for mangrove growth. This could either be a daily threshold or base temperature or a yearly minimal growing degree days (DEGD). Yet another goal of this study was to determine a relationship between growth and temperature or between growth and latitude. The questions included:

1. How should growth be determined; by leaf production or by stem measurements?

2. If growth was determined using stem measurements, then what statistical model could be used to best represent this, and would other variables (e.g., latitude or temperature) also played a role?

The last objective was to use growth the relationship determined above to parameterize an existing mangrove model for use at its northern limit.

CHAPTER 2. GROWTH AND PHENOLOGY OF MANGROVE AND BRAZILIAN PEPPER NEAR THE NORTHERN EXTENT OF THEIR GEOGRAPHIC RANGES

Leaves and Flower, Fruit and Bud Phenology

The leaves of *R. mangle*, *A. germinans*, *L. racemosa* and *S. terebinthifolius* vary in size and texture and are considered to be "evergrowing," i.e., there is no pronounced period of senescence and produce and shed their leaves throughout the year (Parkinson et al.1999). The average leaf age is 330 days for *R. mangle* but can remain on the stem up to 17 months (Gill and Tomlinson 1971, Tomlinson 1994). Branch abortion of leaves is frequent in *L. racemosa* and often many dead and dying branches can be observed (Tomlinson 1994). The timing of leaf shedding and production rates are important inputs or organic matter in coastal ecosystems (Saenger and Moverley 1985). In Florida, more mangrove leaf abscission occurs in the wetter, summer months (Davis 1942, Gill and Tomlinson 1981, Tomlinson 1994) but rates may reflect a physiological state of a plant and be more a product of weather events than seasonal temperature (Williams et al 1981, Saenger and Moverley 1985). *S. terebinthifolius* exhibit leaf drop in October – November (Ewel 1978). Among the mangrove species, *R. mangle* produces the highest litterfall followed by *L. racemosa* then *A. germinans* (Odum and McIvor 1982). No comparable study of leave litter for *S. terebinthifolius* has been conducted.

As with leaf production, flower development can either be characterized as continuous or seasonal. While no distinct flowering period for *R. mangle* and *A. germinans* has been noted in Florida, *L. racemosa* has a distinct and heavy flowering period that occurs in the warmest months (Tomlinson 1994). Peaks have been noted in other mangrove species worldwide and

appear to correspond to the rainy season where soil salinities are the lowest rather than soil moisture content (Naidoo 1989). For *S. terebinthifolius* the main flowering period is in September – October (Ewel 1978). A second flowering period from March – May has been observed in less than 10% of plants (Jones and Doren 1997).

Viviparity is rare among higher plants and helps define mangroves (Hogarth 1999). Viviparous seedlings germinate on the tree before becoming detached. This can best be observed on *R. mangle* in which the embryo develops within a small fruit. As the embryo develops, the hydrocotyl elongates and bursts through the pericarp (Hogarth 1999). While still attached to the parent, the seedling develops into curved propagules 20-25 cm long (Tomlinson 1994, Hogarth 1999) and can weigh about 15 g (Hogarth 1999). Reproduction in *A. germinans* and *L. racemosa* follows a similar form but the developing hydrocotyl fails to penetrate the pericarp. This type of viviparity is known as cryptovivipary (Hogarth 1999). As with flowering, *R. mangle's* and *A. germinans'* seedling growth and production is constant while *L. racemosa* produces a heavy fruit set in the warmest, wettest months (Tomlinson 1994, Hogarth 1999). In *S. terebinthifolius* fruit develops November – April (Jones and Doren 1997) but drops from the trees before becoming a seedling (i.e. *S. terebinthifolius* is not viviparous). Once the seed or seedling fall, they generally float, and are often carried away from the parent by currents for some time before rooting (Hogarth 1999). Rabinowitz (1978) observed that *L. racemosa* required a floating period of eight (8) days before germinating, while *A. germinan*s required 14 days and 40 days for *R. mangle*. Donnelly (2006) found that *S. terebinthifolius' seeds* differ from mangroves in this respect as it does not require a period of soaking.

Materials and Methods

<u>Study Sites</u>

This study was conducted at ten sites along the east coast of Florida from February 2005 to May 2007 although not all sites were observed over for the entire study time (Fig. 2-1 and Appendix A). Sites Guano Park (GP) and the GTM NERR (Guana Tolomato Matanzas National Estuary Research Reserve) Research Headquarters (GTM) were located within the boundaries of the GTM NERR. The ten sites were selected based on species presence (Table 2-1), accessibility, and safety.

Due to unforeseen difficulties not all sites were observed throughout the entire monitoring period. Monitoring at Sebastian (SEB) began in February 2005 had to be discontinued in November 2006 after the site was severely altered by bulldozer work along the impoundment. Monitoring also had to be discontinued at Melbourne (MEL) but relocated to Rotary Park (ROT) due to personal safety concerns. In addition, monitoring Ulumay Park in Cocoa was discontinued and moved approximately 4 km east to Kelly Park (KEL) early in the study period as the mangroves at Ulumay became inaccessible. Lastly, monitoring of most *S. terebinthifolius* was halted because of removal of the exotic by county and park staff at the various locations. At the end of the study period, only Rotary Park (ROT) still contained the *S. terebinthifolius* marked for study. This led to a reduced sample size and number in the *S. terebinthifolius* counts.
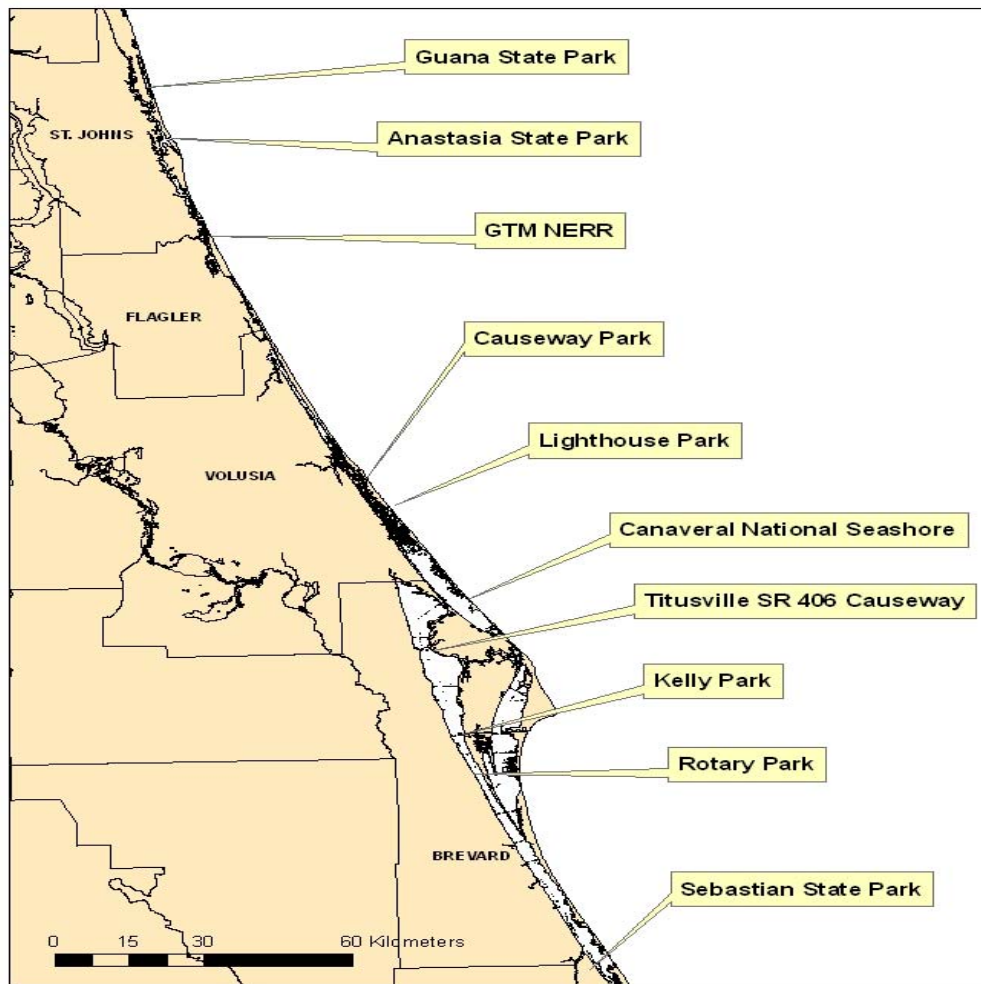
Figure 2-1. Site locations for tree measurements.

Table 2-1. Site ID (south to north), location, and species composition.

SITE	ID	Location	*A. germinans*	*L. racemosa*	*R. mangle*	*S. terebinthifolius*
Sebastian Inlet State Park	SEB	Sebastian	X	X	X	
Rotary Park	ROT	Rockledge	X	X	X	X
Kelly Park	KEL	Merritt Island	X	X	X	X
Canaveral National Seashore	CNS	Titusville	X	X		
Titusville 406 Causeway	TIT	Titusville				X
Lighthouse Park	LP	Ponce Inlet	X	X	X	
Causeway Park	CP	Port Orange	X	X	X	X
GTM NERR Research HQ	GTM	Marineland	X	X		
Anastasia State Park	ASP	St. Augustine	X			
Guana Park	GP	Ponte Vedra	X			

Measurements

At sites with the presence of all three mangrove species (*A. germinans*, *L. racemosa*, and *R. mangle*), two trees of each species were originally chosen as described above. As most mangroves are monoecious (Tomlinson 1994) selection of female or males trees was not a consideration. Although sex was not a consideration for *S. terebinthifolius* tree selection, in

hindsight it should have been a selection criteria as *S. terebinthifolius* is mainly dioecious (Jones and Doren 1997). At the other locations, the number of trees selected was chosen based on number of trees present at the site and the accessibility to the trees.

Each selected tree was marked with a metal tag bearing site ID, the first letter of the species name and tree number for that species (*e.g.,* ASP B1 designated black mangrove number one at Anastasia State Park). Three branches on each tree were randomly chosen and marked with loosely looped plastic cable ties for tracking of its leaves flowers, fruits and buds (Harper and White 1974, Christensen and Wium-Anderson 1977, Gill and Tomlinson 1971, Clarke 1994). For consistency, the same color scheme was used at each site: clear for stem 1, yellow for stem 2, and black (or blue) for stem 3. In addition, on each selected tree, three randomly selected stems were striped with a Sharpie pen for tracking diameter change (growth). The ink marks had to be reapplied approximately every two months due to fading through exposure to water, weather, or by absorption by the tree. The location of each stem marked either by cable tie or pen and investigator orientation was recorded in a field book for aid in its location (e.g., stem 3: back to water, upper left).

During each inspection, the number of leaves, fruits, buds, and/or berries were counted and recorded for each cable tie marked stem and the stem diameter at each ink marked stem was measured using a Vernier caliper. Also, during each site inspection, salinity was measured via a refractometer, time of day was noted, and site conditions such as weather, presence of other invasive species besides *S. terebinthifolius*, and water depth were noted and recorded. At each site, two Hobo® H8 Pro Series temperature data loggers, set to record temperature and relative humidity every 15 minutes, were attached to trees along the main stem at approximately 1.5 m above the substrate via plastic cable ties in different locations at the site. For example, at Lighthouse Point Park (LP) one logger was placed in a shaded area which contained the *R.*

mangle and most of the *A. germinans* while the second logger was placed in the exposed area which contained the *L. racemosa* and a few individuals of *A. germinans*.

Temperature was downloaded from the logger onto a Hobo® H9 Shuttle and offloaded into a computer using the BoxCar® Pro Version 4.3 computer program. The downloaded temperature was used by Hoboware® Pro software to calculate the degree growing days (DEGD) at each logger location. The DEGD of the site was assumed to be the average of the DEGDs of each site's loggers. The daily DEGD was calculated through Eq. (1)

$$DEGD = (T_{high} - T_{low})/2 - T_{threshold} \tag{1}$$

with T_{high} and T_{low} being the respective daily high and low temperatures and $T_{threshold}$, the minimum temperature for mangrove growth, set as 8.4 °C (Chen and Twilley 1998). In addition, tide stage (low, medium, high) was estimated using the tidal estimation program JTides (JTides 2005).

Statistical Analysis

To evaluate relationships between temperature (DEGD) or latitude to growth, eight statistical models were proposed that would best describe the relationship between diameter growth (y), initial stem diameter (x) and a site or temperature variable (c):

(1) null: y = a

(2) linear: y= a + b·x_1

(3) log: y = a + log (b)·x_1

(4) linear with sites: y = a + b·x_1 +c·x_2 (x_2 =sites 1-9 in Latitudinal S-N order)

(5) log with sites: y = a + b·x_1 +c·x_2 (x_2 =sites 1-9 in Latitudinal S-N order)

(6) linear with sites North or South: y = a + b·x_1 +c·x_2 (x_2 =1 – North or 2 - South)

(7) log with cites North or South:– y = a + b· x_1 +c·x_2 (x_2 =1 – North or 2 - South)

(8) linear with DEGD: y =a + b·x_1 +c·x_2 (x_2 =DEGD of each site)

(9) log with DEGD: $y = a + b \cdot x_1 + c \cdot x_2$ (x_2 =DEGD of each site).

The null model (model 1) evaluates the dispersion of the data around the mean value, and serves as a reference to assess the relative information of alternative models accounting for the potential effect of studied variables. Because initial size frequently affects growth rates (Hunt 1990), a linear or logarithmic relationship was used with initial diameter as covariable to account for this effect when evaluating the study variables. For models 6 and 7, the Interstate-4 (I-4) corridor, which is said to represent the division between the subtropic and temperate along Florida's east coast, was used to divide sites into north ($c = 1$) and south ($c = 2$) to see if growth could be delineated by this line. It was predicted that the best fit would be a logarithmic line with the incorporation of sites (either DEGD or latitude).

To determine the relative information of the models using the collected data, a Bayesian approach was utilized. Bayesian inference provides a quantitative measure of probability of a hypothesis being true given the data (Ellison 2004, McCarthy 2007). This is in contrast to frequentist inference which estimates the probability of the data being true given a particular hypothesis (Ellison 2004). The Bayesian analysis was performed by the computer program WinBUGS Version 14A. WinBUGS (Bayesian inference Using Gibbs Sampling) works by randomly sampling parameters from their posterior distribution, which is a degree of belief of the data (Ellison 2004,). Non-informed priors were used in this evaluation.

The results of the Bayesian analysis can be used to compare mathematical models (Ward 2008). Models that tend to lose the least amount of information tend to be the best predictors (McCarthy 2007). That loss can be quantified by the Kullback-Leibler (K-L) Information theorem which calculates the distance (fit) between two models (Burnham and Anderson 2002). Akaike used this theorem to propose a relationship between the expected information content of the model (K-L distance) and the maximized log-likelihood (i.e. the likelihood of the model)

(Burnham and Anderson 2002, Ellison 2004 McCarthy 2007). Akaike developed what has come to be known an Akaike's Information Criterion (AIC) which is represent by:

$$AIC = D_{min} + 2K \qquad (2)$$

where D_{min} is the smallest deviance of the model and K is the number of parameters (Burnham and Anderson 2002, McCarthy 2007). Using the AIC values, models can be compared to each other and that with the lowest AIC value is considered to be the model with the best fit (Ellison 2004).

The Bayesian alternative to AIC, namely the DIC (Deviance Information criterion), was proposed Spiegelhalter et al. (2003) and is given by:

$$DIC = D_{hat} + 2p_D \qquad (3)$$

where Dhat is the deviance when using the mean of the posterior distribution, and p_D is the effective number of parameters (McCarthy 2007).

Results

Growing Degree Days

The temperature as measured in annual growing degree days (DEGD), using Eq. (1), at the nine sites is provided in Fig. 2-2 for both a growing threshold (or base) temperature ($T_{threshold}$) of 4.1°C and 8.3°C. Note that based on using the threshold temperature of 8.3°C which is defined as mean temperature of the coldest month at the northern limit (Chen and Twilley 1998), no sites met the DEGD$_{min}$ (5782; dashed line Fig. 2-2) necessary for growth for *A. germinans* (Chen and Twilley 1998) but *A. germinans* was present at all sites. Additionally, no site met the DEGD$_{min}$ (7636); dotted line Fig. 2-2 for growth for either *R. mangle* or *L. racemosa* (Chen and Twilley 1998) but *R. mangle* was present at sites SEB, ROT, KEL, LP and CP and *L. racemosa*

was present at all sites expect ASP and GP. If the temperature threshold was lowered to 4.1°C

(half of 8.3°C), all sites would meet the minimum for *A. germinans* growth but still none meet

the minimum for *R. mangle* or *L. racemosa* (Fig. 2-2). A general latitudinal gradient of

temperature (solid line Fig. 2-2) can be observed with micro-climates accounting for variability

from the trend. The compiled temperatures are shown below while raw data appears in Appendix

B.
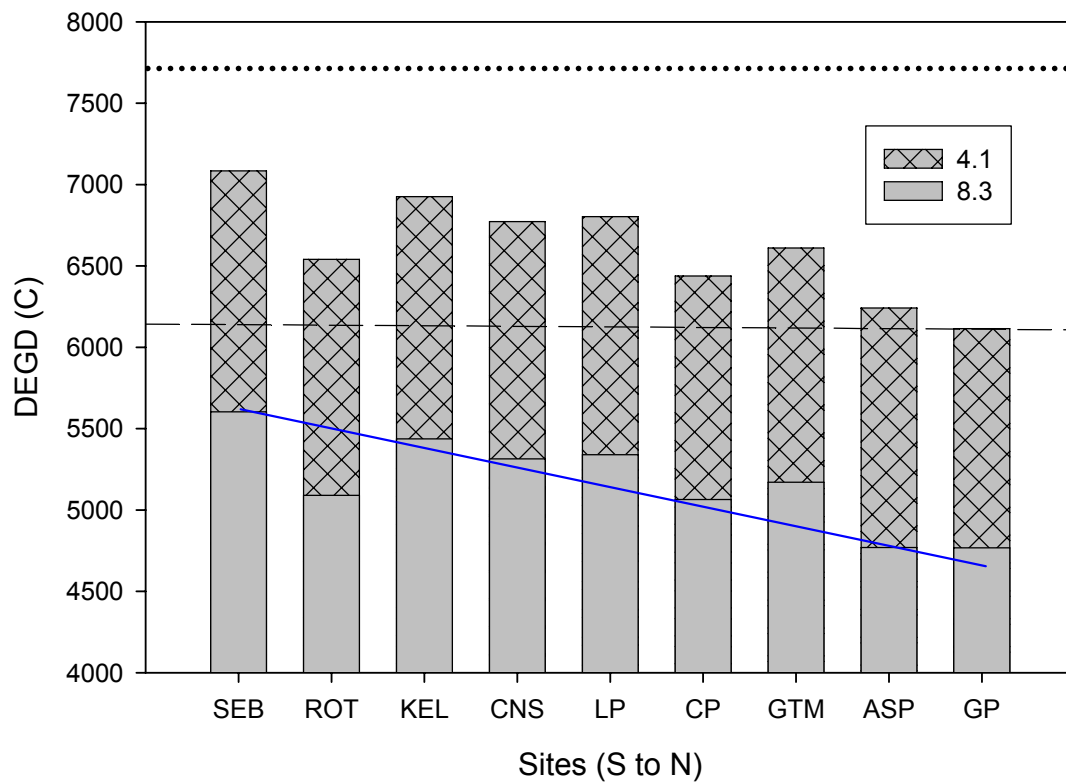
Figure 2-2. Annual Growing Degree Days (DEGD) at each site for $T_{threshhold} = 4.1$°C and 8.3°C.
The dashed line is the $DEGD_{min}$ for *A. germinans* while the dotted line is the $DEGD_{min}$ for both
R. mangle and *L. racemosa*. The solid line depicts the latitudinal gradient of DEGD.

Salinities

No pattern between salinity (Fig. 2-3) and temperature or latitude could be determined. Although most sites had a similar maximum range of around 35 ppt, the lower range varied between sites.
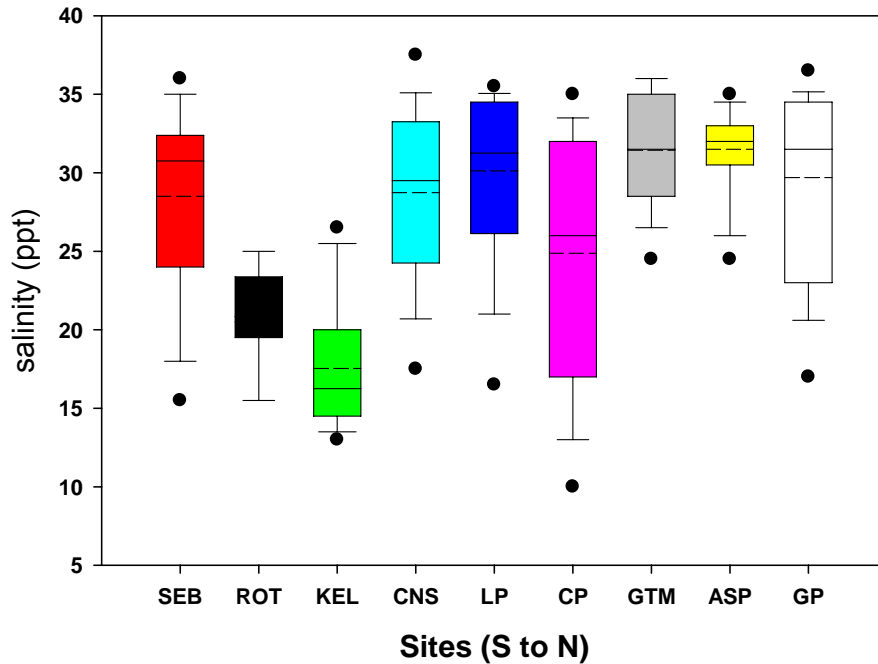
Figure 2-3. Salinity of sites. The solid line represents the median at each site and the dotted line represents the mean at each site. The dots represent outliers, i.e. points that are outside the 10th and 90th percentiles.

Leaves

In general leaf count increased over time but was highly variable Fig. 2-4. Many attempts were made to determine a relationship between leaf shedding and change in temperature or latitude but no relationship was observed. The raw data of leaf counts is presented in Appendix C. Field observations noted that some branches of *L. racemosa* completely aborted all its leaves and appeared to go dormant for at least three (3) months before resprouting.
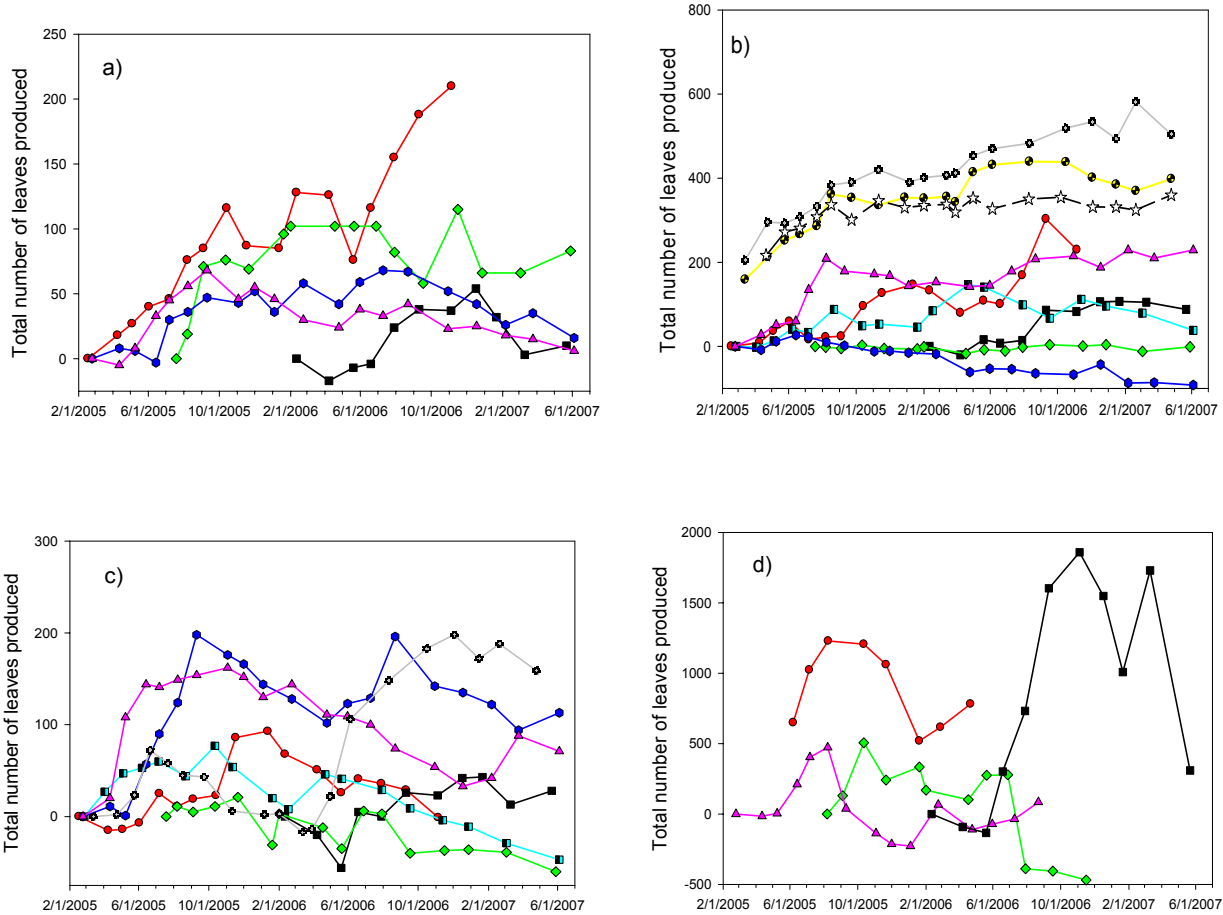
Figure 2-4. Number of leaves produced/month for a) *R. mangle*, b) *A. germinans*, c) *L. racemosa*, and d) *S. terebinthifolius*.

The production rate (Fig. 2-5), as determined by the area under the curves of Figure 2-4 a-d per month, shows an interesting pattern with the northern set of sites (GTM, ASP, and GP) having production rates of *A. germinans* at least 3x greater than the middle sites (CNS, LP, and CP) and 4x greater than the southern sites (SEB, ROT, and KEL). *S. terebinthifolius* also had high leaf production, although if many leaves had not been lost to removal efforts by park staff, counts would be higher. Although for *L. racemosa* production as shown in Fig. 2-4c appears to be bi-modal, total production is low relative to *A. germinans* and *S. terebinthifolius*. Total leaf in *R. mangle* was the lowest at almost all the sites.

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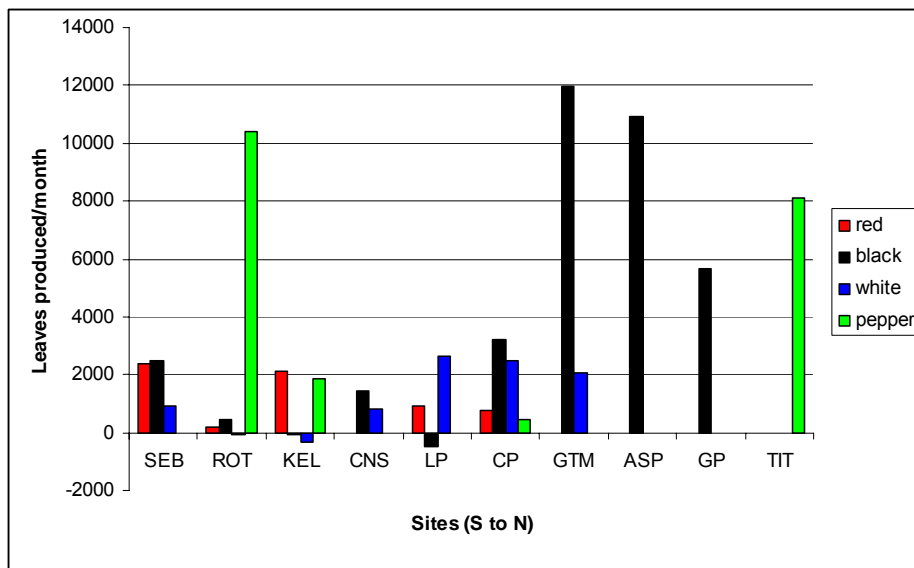
Figure 2-5. Leaf production/months across all sites and species.

Bud, Flower, and Fruit Phenology

The phenologies of flowering, fruiting, and flower budding, and corresponding average monthly temperature are presented in Figs. 2-6 through 2-9. Flowering for all mangrove species occurred at or near the peak in annual temperature while fruiting occurred just after the peak in temperature. As *R. mangle* fruits and seedling were counted as one, the fruit count is cumulative including new individuals as well as those which had been previously counted less those that had fallen. *S. terebinthifolius* (Fig. 2-9) follows a different flower, fruit and bud regime in that peaks in each occur one to two months after the peak in annual temperature. Compiled phenologies are presented below while the raw data appears in Appendix D.
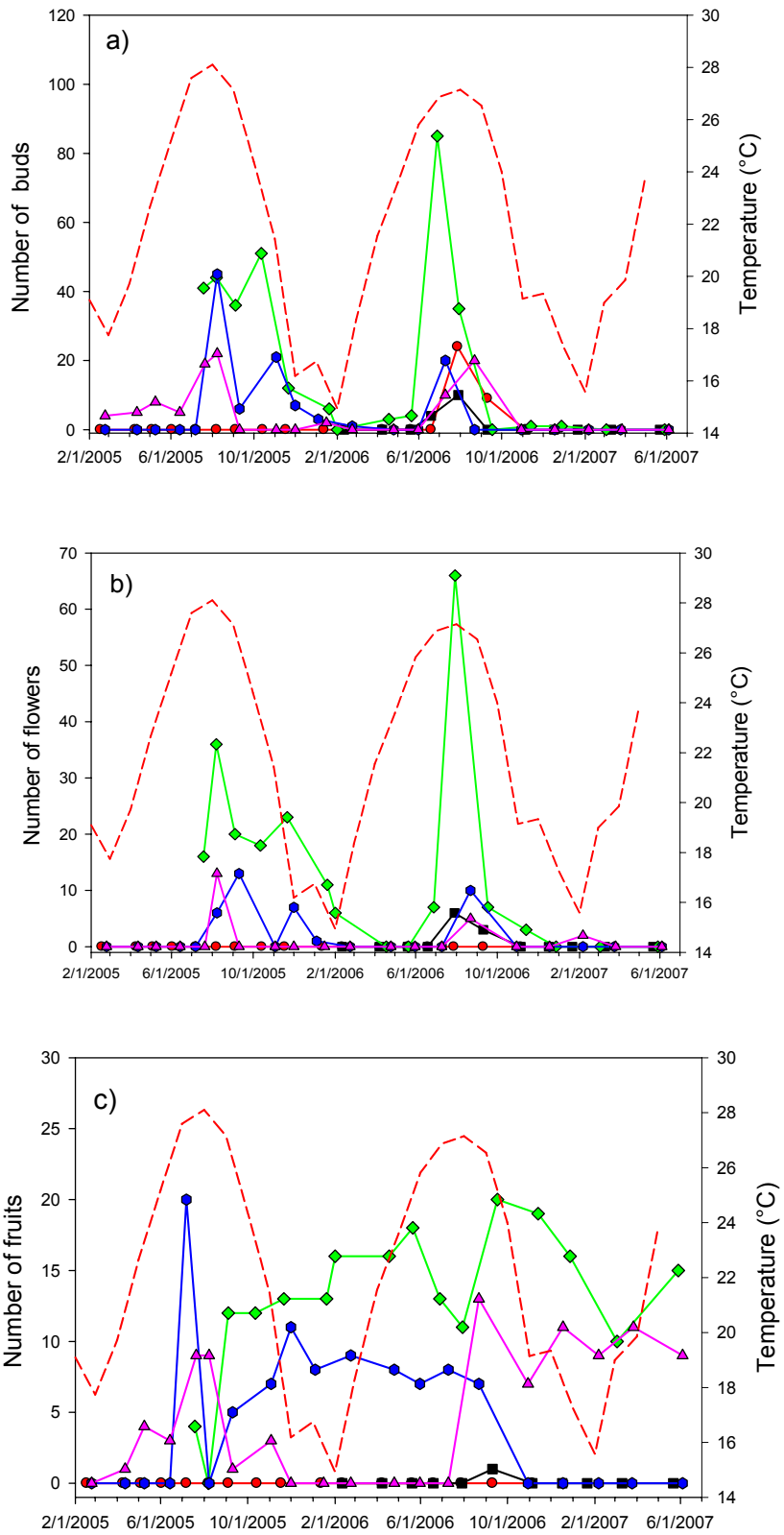
Figure 2-6. *R. mangle* a) buds, b) flowers and c) fruits.
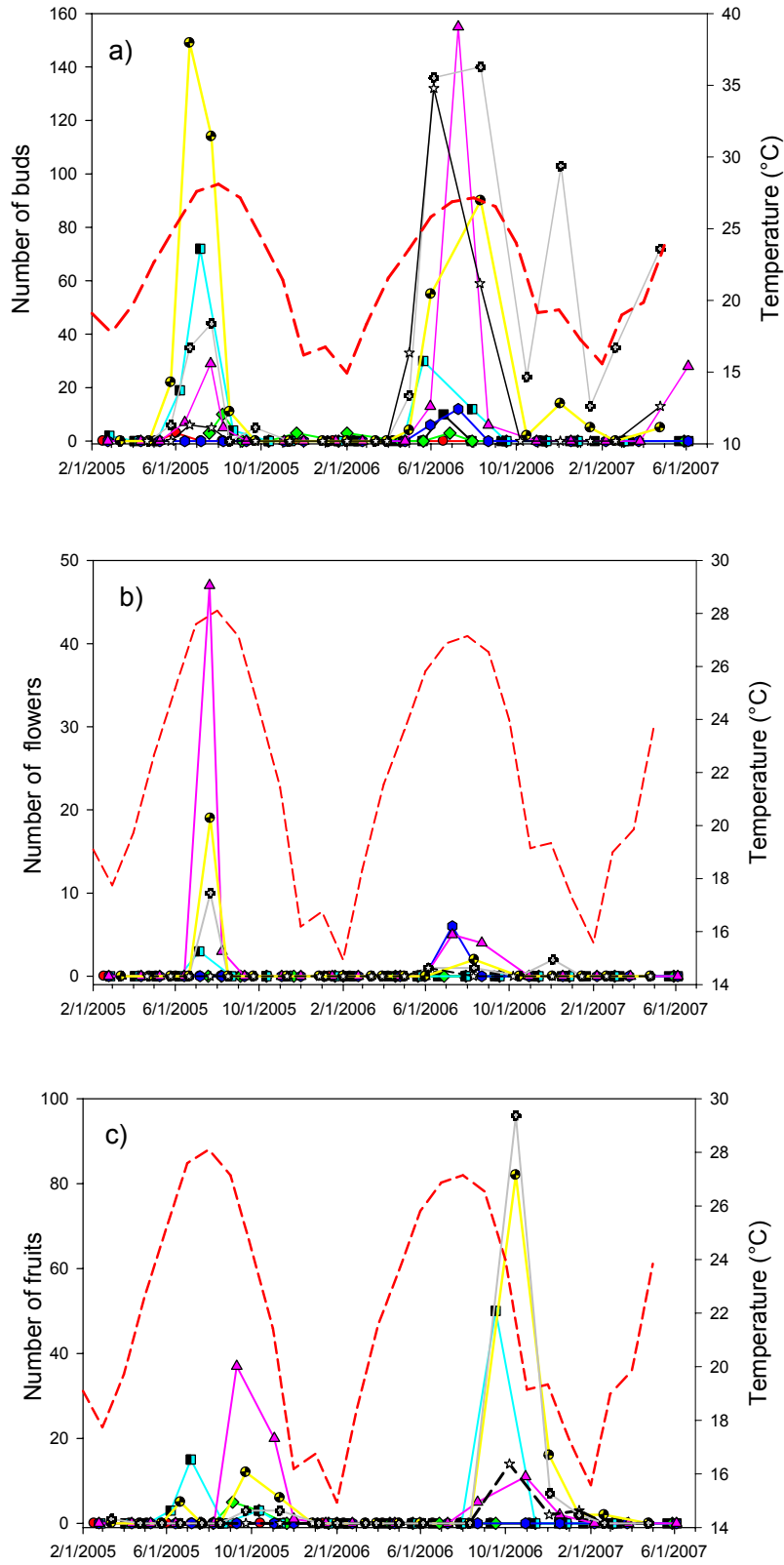
Figure 2-7. *A germinans* a) flowers, b) fruits and c) buds
Note that GTM fruits (b) and CP buds (c) are half of actual count.

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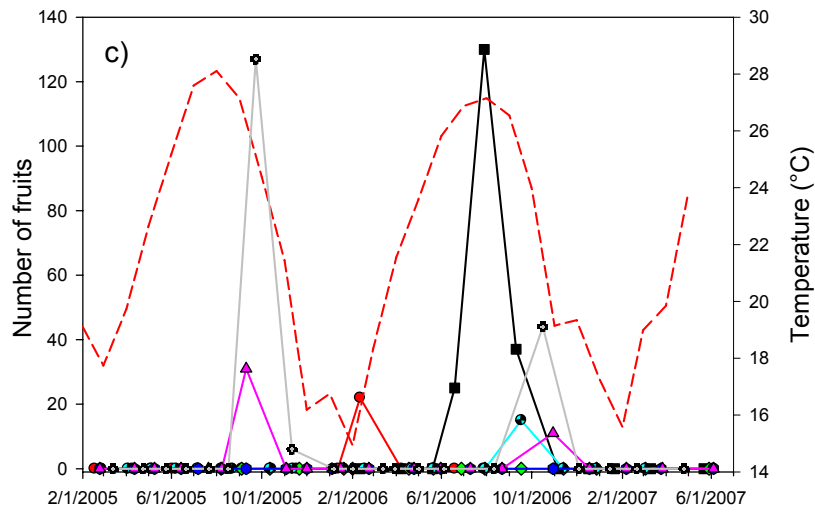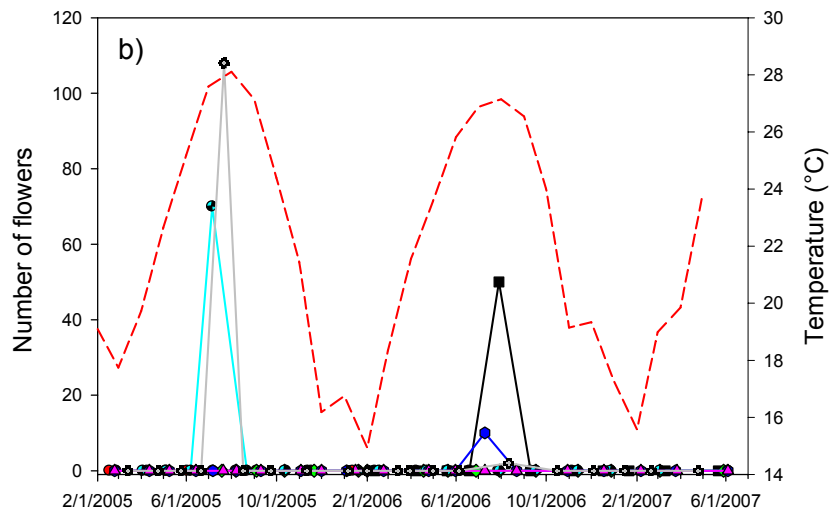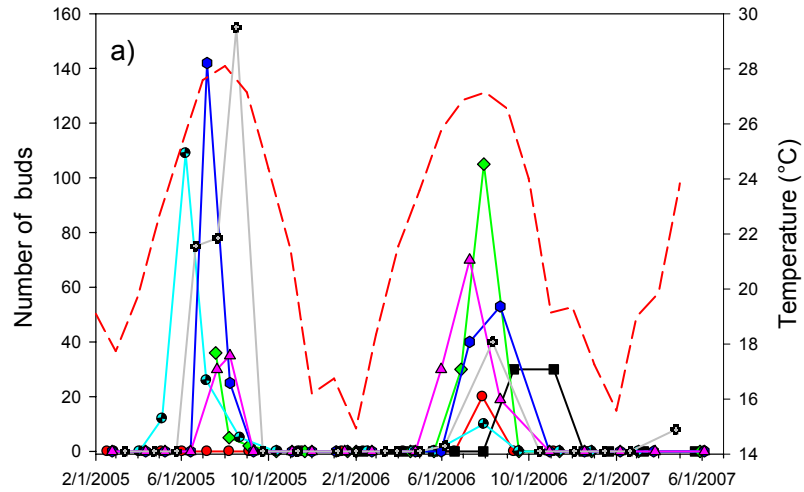
Figure 2-8. *L. racemosa* a) flowers, b) fruits and c) buds.
Note that GTM fruits (b) and buds (c) are half of actual count.
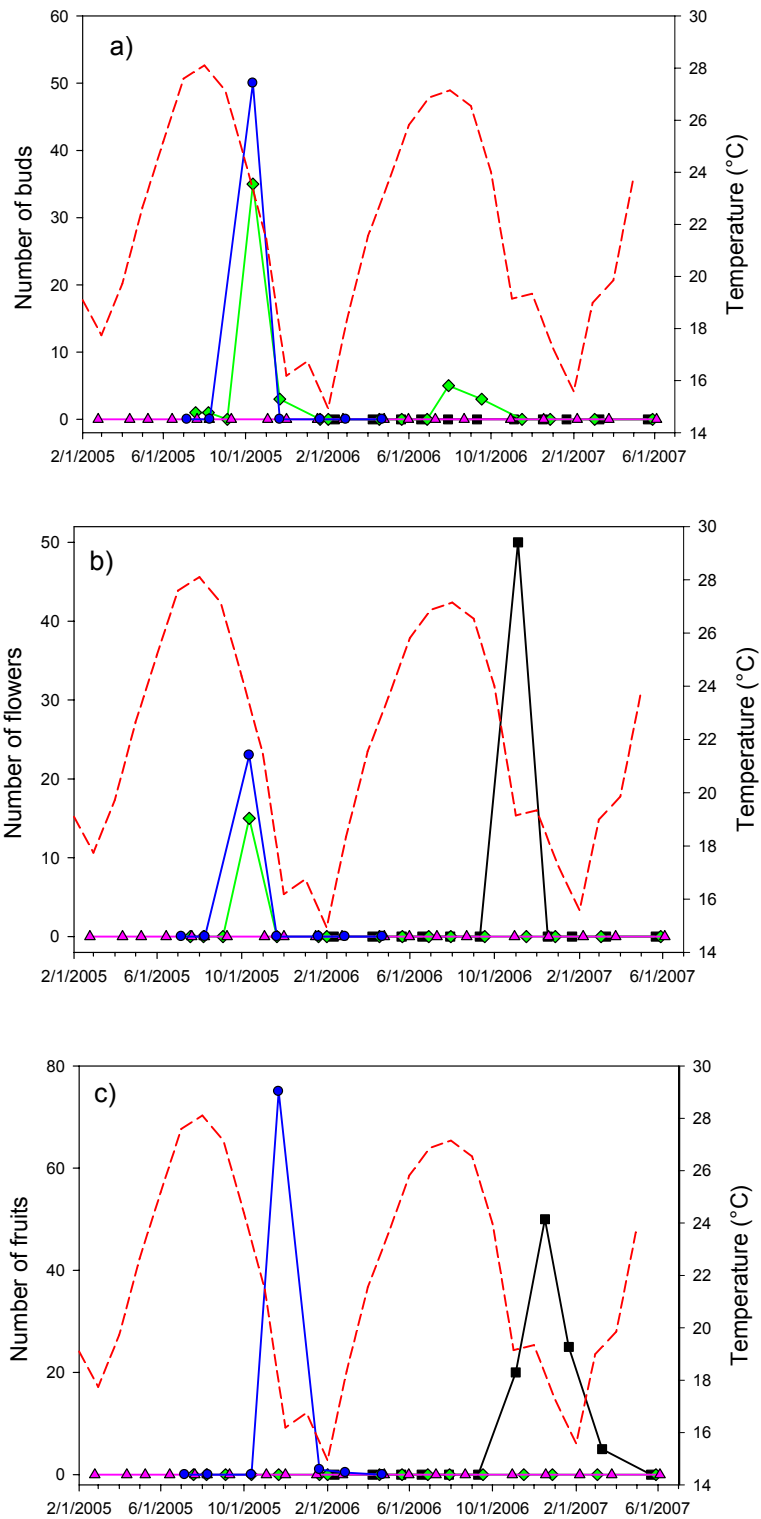
Figure 2-9. *S. terebinthifolius* a) flowers, b) fruits, and c) buds. Note that the number of flowers, fruits and buds for all sites is half of actual count for ROT. For TIT, the number of flowers is one-tenth of actual count and number of buds is one-twentieth of actual count.

Growth

The growth of each stem during measurement interval was determined by Eq. (4) (Hunt 1990)

$$growth = \sqrt[n]{\prod_{1}^{n}\left(D_j / D_i\right)^{(1/\text{int})}}$$

(4)

where D_j and D_i are consecutively measured stem diameters, *int* is the number of months between inspections, and n is the number of inspections per site. The average growth of each stem was the geometric mean over all intervals.

As expected, growth was a function of initial stem diameter with smaller stems growing at a faster rate than larger stems (Figs. 2-10). The best models as calculated by WinBUGS (Tables 2-2 through– 2-5) are shown in Fig. 2-10. The raw data of stem diameter and growth is presented in Appendix E.
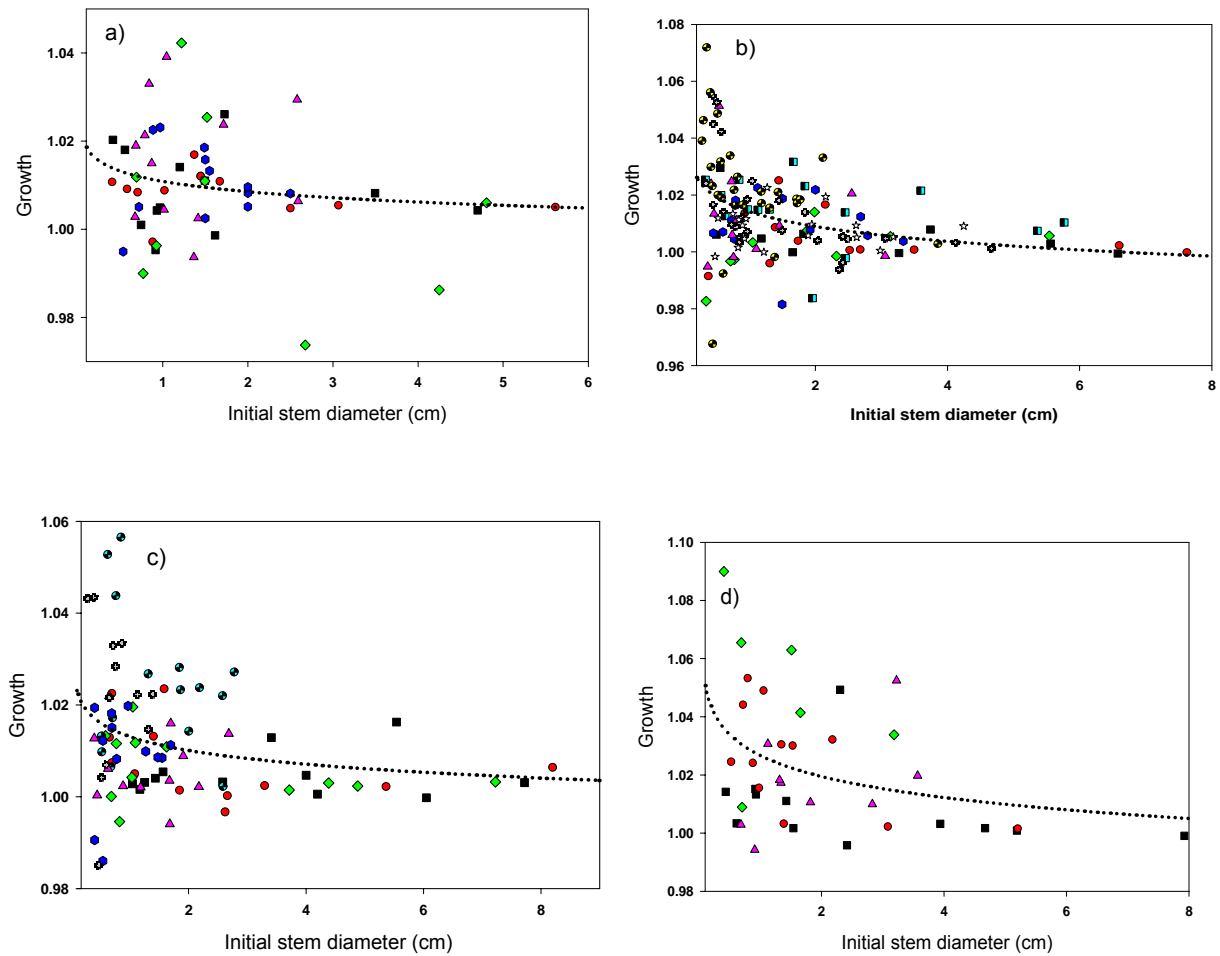
Figure 2-10. Growth v. initial stem diameter over study areas for a) *R. mangle*, b) *A. germinans*, c) *L. racemosa*, and d) *S. terebinthifolius*.

Growth of *R. mangle* and *L. racemosa* were best fit by a logarithmic model that did not incorporate sites (Tables 2-2 and 2-4). For *A. germinans* and *S. terebinthifolius*, the best fit was a logarithmic model which incorporated sites in latitudinal order for *A. germinans* and DEGD for *S. terebinthifolius* (Tables 2-3 and 2-5). The interval of credibility for the variables of a, b and c for the best models are given in Table 2-6.

Table 2-2. *R. mangle* DIC values.

model	sites	DIC	Δ DIC
$a + b \cdot \log(x_1)$	none	-303.68	0.00
$a + bx_1$	none	-303.31	0.37
$a + bx_1 + cx_2$	DEGD	-301.60	2.08
$a + bx_1 + cx_2$	ALL	-301.59	2.08
$a + b \cdot \log(x_1) + cx_2$	N/S	-301.50	2.18
$a + b \cdot \log(x_1) + cx_2$	DEGD	-301.38	2.30
$a + b \cdot \log(x_1) + cx_2$	ALL	-301.38	2.30
$a + bx_1 + cx_2$	N/S	-301.24	2.44
a	none	-286.4	17.28

Table 2-3. *A. germinans* DIC values.

model	sites	DIC	Δ DIC
$a + b \cdot \log(x_1) + cx_2$	ALL	-786.19	0.00
$a + bx_1$	none	-784.90	1.29
$a + b \cdot \log(x_1) + cx_2$	N/S	-784.43	1.76
$a + b \cdot \log(x_1) + cx_2$	DEGD	-782.61	3.58
$a + bx_1 + cx_2$	ALL	-780.56	5.63
$a + bx_1$	none	-778.97	7.22
$a + bx_1 + cx_2$	N/S	-778.77	7.42
$a + bx_1 + cx_2$	DEGD	-776.67	9.52
a	None	-769.5	16.69

Table 2-4. *L. racemosa* DIC values.

model	Sites	DIC	Δ DIC
$a + b \cdot \log(x_1)$	None	-477.36	0.00
$a + b \cdot \log(x_1) + cx_2$	ALL	-476.13	1.23
$a + bx_1 + cx_2$	ALL	-475.87	1.49
a	none	-475.600	1.761
$a + bx_1$	None	-447.53	29.84
$a + b \cdot \log(x_1) + cx_2$	DEGD	-445.49	31.87
$a + b \cdot \log(x_1) + cx_2$	N/S	-445.49	31.88
$a + bx_1 + cx_2$	N/S	-444.82	32.54
$a + bx_1 + cx_2$	DEGD	-444.83	32.53

Table 2-5. *S. terebinthifolius* DIC values.

model	sites	DIC	Δ DIC
$a + b \cdot \log(x_1) + cx_2$	DEGD	-177.64	0.00
$a + bx_1$	none	-173.19	4.44
a	None	-171.6	6.04
$a + b \cdot \log(x_1)$	none	-172.81	4.82
$a + bx_1 + cx_2$	N/S	-170.99	6.65
$a + bx_1 + cx_2$	ALL	-170.65	6.99
$a + bx_1 + cx_2$	DEGD	-170.56	7.08
$a + b \cdot \log(x_1) + cx_2$	ALL	-170.46	7.18
$a + b \cdot \log(x_1) + cx_2$	N/S	-170.40	7.24

Table 2-6. Interval of credibility for best models
in Table 2-2 through 2-5.

Species	variable	2.5%	mean	97.5%
R. mangle	a	1.004	1.010	1.016
	b	-0.013	-0.003	0.006
A. germinans	a	1.016	1.008	0.999
	b	-0.011	-0.006	-0.002
	c	0.000	0.001	0.002
L. racemosa	a	1.008	1.012	1.017
	b	-0.010	-0.005	0.001
S. terebinthifolius	a	0.992	0.621	0.249
	b	-0.022	-0.007	0.007
	c	6.54E-06	7.75E-05	1.49E-04

Discussion

Degree Growing Days (DEGD)

Chen and Twilley (1998) reported that the minimum temperature for mangrove growth

($T_{threshhold}$) was 8.3°C. Using this threshold and the temperature data collected at each site led to a

calculated DEGD at each site (Fig. 2-2) which was below $DEGD_{min}$, which is the minimum value

required for growth (Chen and Twilley 1998). Even by lowering the $T_{threshhold}$ by half to 4.1°C,

the $DEGD_{min}$ was only met for *A. germinans* at all sites. Neither *R. mangle* nor *L. racemosa* met

their $DEGD_{min}$ under the revised $T_{threshhold}$. As mangroves were observed growing at $DEGD_{min}$

lower than provided in Chen and Twilley (1998), $DEGD_{min}$ or the $T_{threshhold}$ needs to be revised to

account for growth at lower temperatures. This may be accomplished through garden

experiments which can accurately measure either the minimum temperature for growth ($T_{threshold}$)

or the minimum annual growing degree days ($DEGD_{min}$) needed for the same growth.

Seasonal Patterns of Leaf Senescence

Mangroves have been described as "evergrowing" and produce leaves throughout the year (Parkinson et al. 1999). These data (Fig. 2-4) support this description as there was continual growth the throughout the year. Although, Davis (1942), Gill and Tomlinson (1981) and Tomlinson (1994) all noted leaf abscission occurs in the wet, summer months, no discernable abscission period was observed on any of the species in this study, which instead supports random abscission (Williams et al. 1981, Saenger and Moverly 1985). Heavy leaf fall and branch abscission was noted in *L. racemosa* as described by (Tomlinson 1994). This branch abscission led to the heavily fluctuating leaf count numbers observed in Fig. 2-4c. Field observations noted that some branches of *L. racemosa* completely aborted all its leaves and appeared to go dormant for at least three months before resprouting.

The highest rates of leaf production (leaves added) were found in *A. germinans* and *S. terebinthifolius* with *L. racemosa* and *R. mangle* the lowest. These seem to be in agreement with Odum and McIvor (1982), who reported that among the mangrove species, *R. mangle* produces the highest litterfall (leaves lost) followed by *L. racemosa* then *A. germinans.*. As will be further discussed in Chapter 4, the alteration of species composition as a result of global climate change and/or invasive species can lead to large changes in detrital composition.

Bud, Fruit, and Flower Phenology

The timing of the flowering and budding for both *R. mangle* (Fig. 2-6a,b) and *A. germinans* (Fig. 2-7a,b) showed distinct periods of productivity that appeared to be correlated with peaks in average monthly temperature. This is in contrast to Tomlinson (1994) who reported that no distinct period of flowering has been noted for either *R. mangle* or *L. germinans* in Florida. Tomlinson (1994) reported that *L. racemosa* has heavy distinct periods of flowering

in the summer months. In this study, a peak in flowering for *L. racemosa* was observed over the first summer observation period (Fig. 2-8 b) but not over the second. In that second summer period, heavy budding was observed but not followed by the flowering.

The phenology of the flowers of *S. terebinthifolius* (Fig. 2-7b) was found to be in agreement with Ewel (1978) who stated that the main period of flowering is September – October. In this study, two sites flowered in October but the ROT site was not observed during the first summer period while the sites KEL and TIT were heavily modified and not observed during the second summer period (Appendix F).

No distinct period of fruit development was observed for *R. mangle* (Fig. 2-6c) which is in agreement with Tomlinson (1994) who found that growth of *R. mangle* fruit is continuous without a period of dormancy. As stated previously, the counted fruit was not marked after counting so it could not be determined by the data which fruits were new or preexisting from previous counts. In contrast to Tomlinson (1994) and Hogarth (1999) who state that fruit production of *A. germinans* is constant, a distinct period of fruit production one to two months following the peak in monthly temperatures (Fig. 2-7c) was observed. *L. racemosa* (Fig. 2-8c) also showed a distinct period of fruit production but occurred one to two months post temperature peak but this is in agreement with Tomlinson (1994)

Only two sites (ROT and TIT) had *S. terebinthifolius* trees which fruited. The fruiting occurred November – March (Fig. 2-9c) which corresponded to lowest average monthly temperature. This is in agreement with Jones and Doren 1997 who reported that fruit germinates November – April. Jones and Doren (1997) also reported that less than 10% of trees have a second germinating period from March – May but this second period was not observed on the studied trees.

<u>Growth rate models</u>

Growth, adjusted by initial stem diameter, was best described by a logarithmic function for all three mangroves and *S. terebinthifolius*. Differences among the species were based on presence/absence of a term for site location (latitude) or temperature (degree growing days). For *R. mangle* and *L racemosa*, the best fit was logarithmic, in which, the site variable was not included. For *A. germinans*, a logarithmic line was also the best fit (Table 2-3) but with the incorporation of sites as delineated from south to north. *S. terebinthifolius* (Table 2-5) also showed that a logarithmic line, which incorporated sites was the best fit but with the temperature (DEGD) as the site variable. These results could mean that the growth of both *R. mangle* and *L. racemosa* within the study area does not vary by either temperatures or latitude. On the other hand, the results could show that the growth of *A. germinan*s varies by latitude, while the growth of *S. terebinthifolius* varies by temperature.

Chapter Conclusions

Some general conclusions can be drawn from this portion of the study. For DEGD, more research is needed to determine either a better $T_{threshhold}$ and/or a lower $DEGD_{min}$ for all mangrove species to encompass growth at lower temperature and latitudes. For leaves, buds, fruit, and flowers, no definitive pattern could be observed for leaf senescence and temperature in both mangroves and *S. terebinthifolius*, while distinct peaks in fruiting, flowering and budding were observed in all mangrove species which roughly followed peaks in temperature. The peaks in flowering, fruiting and budding for *S. terebinthifolius* lagged behind the temperature peaks by about two to three months.

Lastly, one of the original goals of this study was to develop relationships between temperature or latitude and growth to parameterize and refine an existing model for use at the northern limit. This goal was not met as:

1. Only two of four species showed site specific growth. This may be because trees of different sizes were used, shorter in the north than south, which may have led to the statistical models showing that the northern *A. germinans* grew faster than the southern.

2. The developed relationships were not readily transported into the developed model, the growth relationship determined above were not used to parameterize the model.

Therefore, existing data and relationships were used in the model rather than the developed relationships.

CHAPTER 3. SIMULATING ESTABLISHMENT AND COMPETITION OF MANGROVE AND BRAZILIAN PEPPER ALONG THE NORTHERN EXTENT OF THEIR GEOGRAPHIC RANGES

Introduction

Gap Models

Gap models are the most commonly used models to predict species responses to climate change as growth is calculated as a function of species specific parameters and abiotic factors such as temperature (Bugmann 1996, Bugmann and Fischlin 1996, Shugart and Smith 1996, Zolbrod and Peterson 1999). In forestry, a gap is an open space created by the death of a canopy tree and is the localized site of regeneration and subsequent growth (Platt and Strong 1989). Gaps represent a functional unit that maintains diversity and determines successional changes in forest ecology. They can also shape landscape patterns of vegetation distribution for larger spatial and temperature scales and are important for seedling establishment to sapling development (Koch 1997, Twilley et al. 1999). Gap models track the growth of each individual tree in a plot on the basis of species-species life history traits and limitations of resources (Chen and Twilley 1998).Two important competitive interactions in gap models include shading of shorter trees by taller trees and competition of a limiting resource (Liu and Ashton 1995, Twilley et al. 1999)

Although mangroves dominate much of the tropical shoreline, few ecological models of mangroves have been built (Liu and Ashton 1995, Chen and Twilley 1998). The model FORMAN was developed to simulate demographic processes and the effects of soil

characteristics on mangrove forest dynamics in a 0.05-ha plot (Chen and Twilley 1998, Twilley et al. 1999). FORMAN represents individual tree growth of the three mangroves species (*A. germinans, L. racemosa,* and *R. mangle*) on an annual basis within a forest gap. Attributes of each individual tree, including diameter and height, are summed for each species in the plot at each time interval in the model (Twilley et al. 1999). The attributes are used to track demographic (density and dominance) and some functional responses to distributions of resources and stress (Twilley et al. 1999). In FORMAN, optimal growth is constrained by life histories and realized growth is limited by salt stress, nutrients, temperatures, and available light (Chen and Twilley 1998, Twilley et al. 1999).

S. terebinthifolius invasion

Modeling of an exotic invasion is often performed by comparing species with similar growth rates where the species with the faster growth rate is considered to be the invader (Loehle 2003). In the case of environmental change, such as global warming, the species with the slower growth rates is the one which adversely impacted. The rate of invasion is proportional to the rate of openings either through canopy tree death or disturbance.

Disturbances, which create canopy gaps, aid in the invasiveness of *S. terebinthifolius* since it has a very high growth rate of 0.3-0.5 cm/year in the open canopy (Jones and Doren 1997, Lugo 1998). Under varying salinities, these higher growth rates allow increased competition over native vegetation for light (Ewe and Sternberg 2005). *S. terebinthifolius* also provides little in the way of wildlife habitat (Jones and Doreen 1997) and appears to have the ability to cause and benefit from soil development and elevation changes in the shallow systems it colonizes (Gordon 1998). Two distinct populations have invaded South Florida and hybridized to the form observed in Florida today (Williams et al. 2005).

One obstacle to the invasion may be salt stress and thus it may be confined it to the higher-elevation edge of mangrove forest habitat (Mytinger and Williamson 1987, Lugo 1998, Ewe and Sternberg 2005). Though *S. terebinthifolius*, has been found to have some salinity tolerance (Ewe and Sternberg 2007), its invasiveness threat may increase if salinity decreases (Mytinger and Williamson 1987). This salinity tolerance may give a competitive advantage over freshwater natives with sea-level rise (Ewe and Sternberg 2007) but the impact to the mangrove ecosystem during sea-level rise has not yet been determined (Ewe and Sternberg 2007).

Methods and Materials

<u>Model Construction</u>

The modified FORMAN model named MANGRO (Fig 3-1; Appendix G) was built using the software package Stella Version 9.0 by High Performance Systems, Inc. Stella uses an icon-based graphical interface where icons represent functions. The tree diameter is represented by a stock (rectangle) which accumulates or loses based on flows, where inflow represents growth and recruitment while outflow represents tree death. A circle or converter in MANGRO holds values of constants and performs algebraic functions. The arrows or connectors show the flow of information of data between converters. Lastly, stacked converters and stocks represent arrays.

MANGRO was developed using the FORMAN gap model (Chen and Twilley 1998) and modified to include *S. terebinthifolius*. In MANGRO (Fig. 3-1) the growth of each individual tree is calculated based on the interaction of the environmental growth parameters and competition for light. At each time step, the diameter of each tree is sorted to determine the LAI of all trees above a given tree (middle routines) which in turn is used to determine the available light (AL) for that tree in its own routine. Additional inputs include salinity, degree growing

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days, and nutrients. Model output includes the number and diameter of live trees at each time

step.
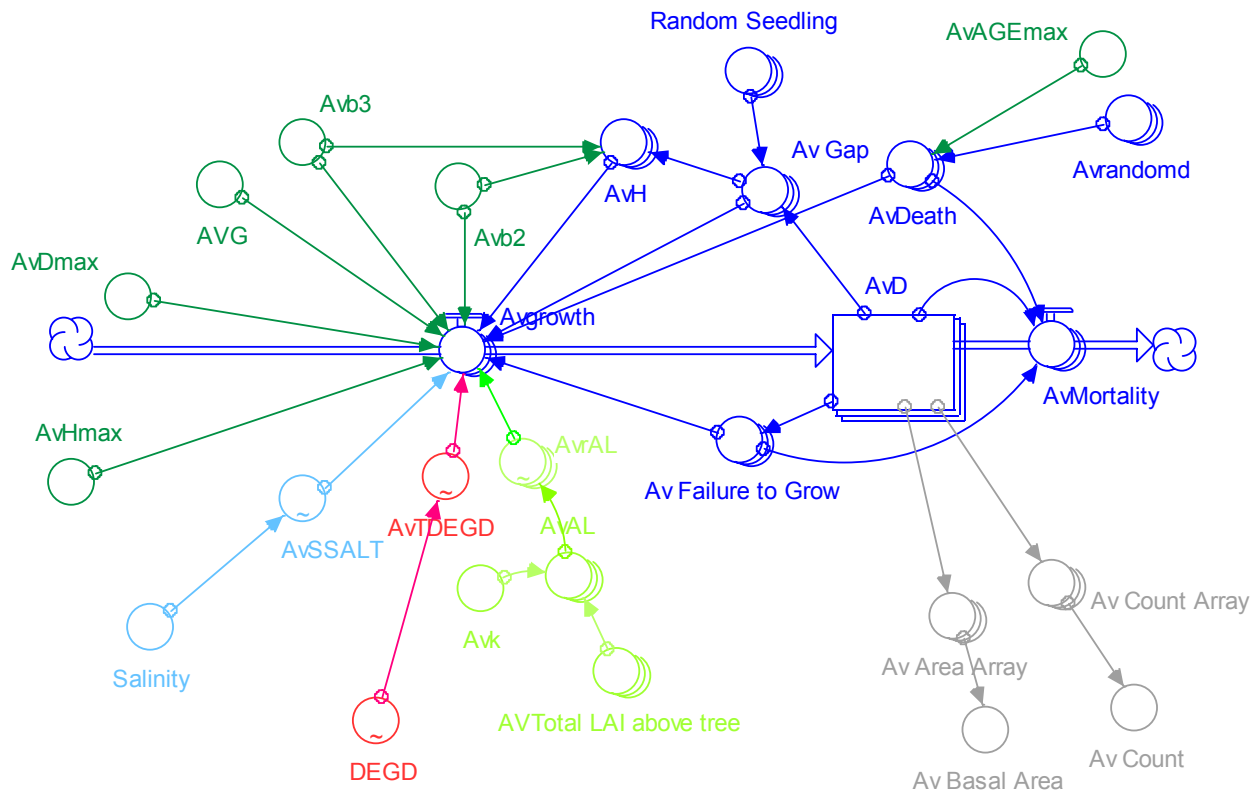
Figure 3-1. MANGRO subroutine for *A. germinans* with Stella diagram (light blue = salinity, red = temperature, light green = light, dark green = constants (Table 3-1), blue = basic functions, and gray = output).

The main equation of the model was based on the differential equation of diameter as

originally presented in FORET (Shugart 1984)

$$\frac{dD}{dt} = \frac{GD(1 - DH / D_{max} H_{max})}{274 + 3b_2 D - 4b_3 D^2} \tag{5}$$

where D is the diameter of the tree, H is the height of the tree and is determined by:

$$H = 137 + b_2 D - b_3 D^2 \tag{6}$$

and G, D_{max}, H_{max}, b_2, and b_3 are species specific constants as defined in Table 3-1. Chen and Twilley (1998) provided the constants for the three mangrove species while for *S. terebinthifolius*, D_{max} was provided by Morton (1978) and H_{max} was provided by Rockwood and Geary (1991): b_2 and b_3 were determined by the following equations (Botkin 1993, Shugart 1984)

$$b_2 = 2\left(\frac{H_{max} - 137}{D_{max}}\right) \tag{7}$$

and

$$b_3 = \left(\frac{H_{max} - 137}{D_{max}^2}\right). \tag{8}$$

Additionally in Table 3-1, AGE_{MAX} and G were estimated for *S. terebinthifolius*.

Eq. (5) was further refined by Chen and Twilley (1998) to include environmental multipliers for available light-r(AL), salinity-S(SALT), and temperature -T(DEGD) to become

$$\frac{dD}{dt} = \frac{GD(1 - DH / D_{max} H_{max})}{275 + 3b_2 D - 4b_3 D} \bullet r(AL) \bullet S(SALT) \bullet T(DEGD) \tag{9}$$

each of these multipliers are explained below and presented in Fig. 3-2.

To determine the available light multiplier r(AL), first, the LAI (leaf area index) was determined by

$$LAI = c \cdot D^2 \tag{10}$$

where c is a constant (c=0.00019283295; Shugart 1984)) and D is the tree diameter at each step as calculated by Eq. (5) above.

In MANGRO, the LAIs, as determined by Eq. (10), were summed for all trees that were taller than that of the specific tree. This sum was then used by Beer's Law (also known the Beer-Lambert Law; Nell 1993) to determine the available light (AL) to that tree

$$AL = exp\ (-k \cdot \Sigma\ LAI\ above\ the\ tree) \tag{11}$$

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where k is the light attenuation constant (k = 0.525; Green and Clark 2000).

Finally, the available light (AL) for that individual tree was used to calculate the available light multiplier by

$$r_s(AL) = 1 - \exp\left[-4.64(AL - 0.05)\right] \tag{12}$$

$$r_i(AL) = 2.24\left(1 - \exp\left[-1.136(AL - 0.08)\right]\right) \tag{13}$$

where, r is the reduction rate for photosynthesis for shade tolerant (r_s) and shade intolerant (r_i) species, and AL is the available light at the crown of the tree (Eq. (11)). Eq. (12) was used to calculate the light reduction for the shade tolerant *R. mangle* and *A. germinans* (Chen and Twilley 1998). For *L. racemosa*, which has been found to be more competitive at higher light levels than either *R. mangle* or *A. germinans* (Chen and Twilley 1998), an intermediate light reduction equation (r_m) was used

$$r_m = \left[r_s(AL) + r_i(AL)\right]/2 \tag{14}$$

The available light curve for *S. terebinthifolius* (Fig. 3-2b) was derived from Jones and Doreen (1997) who reported that *S. terebinthifolius* seedlings are shade tolerant but while in exposed, open areas, growth rates are among the highest of any vegetation at 0.3-0.5 m per year.

In FORMAN, the soil portion of JABOWA/FORET was replaced by the salinity (S(SALT)) multiplier and a nutrients multiplier N(NUT). Nutrients were not being addressed in this paper and thus the N(NUT) multiplier was not included in MANGRO. Salinity was calculated by

$$S(SALT) = \frac{1}{1 + \exp(d(U_i - U))} \tag{15}$$

where d and U_i are constants defined in Table 3-1 and U is the salinity at the site (g/kg or ppt). At salinities less than 50 ppt all three mangrove species have the same salt tolerance. While at salinities above 50 ppt, *A. germinans* has the highest salt tolerance followed by *L. racemosa* with

R. mangle having the lowest salt tolerance at these higher levels (Chen and Twilley 1998). The salt tolerance curve for *S. terebinthifolius* (Fig. 3-2c) was derived given that *S. terebinthifolius* can not tolerate salinities in excess of 35 ppt (Ewe et al. 2007).

Temperature is expressed in terms of degree growing days (DEGD) with the multiplier of T(DEGD) given through the following equation:

$$T(DEGD) = 1 - (DEGD_{min} / DEGD)^2 \qquad (16)$$

where

$$DEGD = \sum \left[(T_{max} + T_{min}) / 2 - T_{threshhold} \right] \qquad (17)$$

(also given as Eq. (1)) and where $T_{threshold} = 8.7$ C (Chen and Twilley 1998). The DEGD curve of *A. germinans* (Fig. 3-2a) was used for *S. terebinthifolius* as it has a northern distribution similar to that of *A. germinans*.
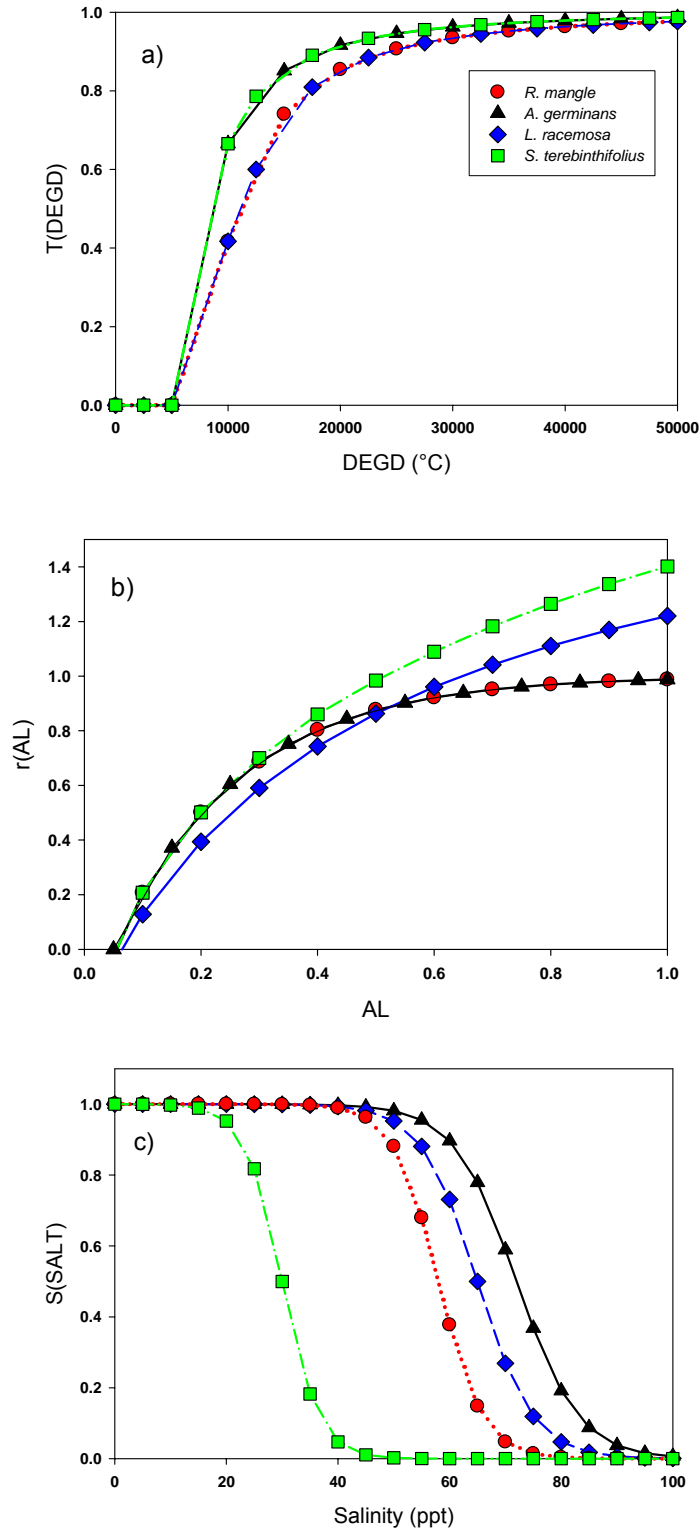
Figure 3-2. Mangrove and *S. terebinthifolius* growth multipliers for a) temperature, b) available light, c) salinity (Jones and Doren 1997, Chen and Twilley 1998, Ewe and Sternberg 2007).

Table 3-1. Constants used in MANGRO.

Para-meters	Description	A. germinans[1]	L. racemosa[1]	R. mangle[1]	S. terebinthifolius[.3]
G	Growth constant	162	243	267	150
D_{max}	Maximum dbh (cm)	140	80	100	100
H_{max}	Maximum height (cm)	3500	3000	4000	1500
AGE_{max}	Maximum age (year)	300	200	250	200
b_2	Constant in height to dbh relationship	48.04	71.58	77.26	27.26
b_3	Constant in height to dbh relationship	0.172	0.447	0.396	0.136
a	Constant in leaf weight to dbh relationship	38.90	38.90	27.55	
b	Constant in leaf weight to dbh relationship	1.62	1.62	1.79	
$DEGD_{min}$	Minimum growth degree days	5782	7636	7636	5782
U_i	Constant for salt effect on growth (g kg^{-1})	72.0	65.0	58.0	
d	Constant for salt effect on growth	-0.18	-0.2	-0.25	
c_1	Constant for nutrient effect on growth	-0.5	-1.0	0	
c_2	Constant for nutrient effect on growth	2.88	4.42	1.33	
c_3	Constant for nutrient effect on growth	-1.66	-2.5	-0.72	

[1]Chen and Twilley 1998, [2]Morton 1978, [3]Rockwood and Geary 1991

Study Objectives

As gap models can be used as a predictive tool, the objective of this chapter is to modify

FORMAN to include *S. terebinthifolius*, and to use the developed model to explore various

growth and invasion regimes. The model will also be used to simulate the effects that global

climate change may have on the mangrove system at its northern range with and without the

invasion of *S. terebinthifolius*.

Model Scenarios and Questions Addressed

Bare Ground (Run 1)

What will occur if all four species are allowed to grow from bare ground at high and low temperatures? It is assumed that S. terebinthifolius will dominate but A. germinans and L. racemosa will have strong presence with a weak presence of R. mangle.

The Bare Ground simulation (Run 1) (see Appendix H for a list of all run parameters) was used to model seedlings of all four species growing on bare ground. Four runs of this simulation were performed. Run 1a simulated "high" temperature (DEGD = 9500) with the seedling of all four species having an equal chance of establishment (15%) while Run 1b simulated "high" temperature but without *S. terebinthifolius*. In these runs, all mangrove species had an equal chance of establishment (20%). The next two runs (Run 1c and 1d) were similar to those above but run at a "low" temperature (DEGD =7500).

S. terebinthifolius invasion runs

What may occur if *S. terebinthifolius* establishes at sites that currently have only *A. germinans* (GP or ASP) or at sites that currently have only *A. germinans* and *L. racemosa* (GTM). Does varying the chances of seedling establishment aid the native mangrove from becoming dominated by *S. terebinthifolius*? The assumption is that *S. terebinthifolius* will dominate if established but lower chances of seedling establishment will help in native resistance to invasion.

The *S. terebinthifolius* invasion 1 simulation (Run 2) was constructed to model an invasion of an established *A. germinans* system by *S. terebinthifolius*. This is a colder site

without the current presence of *S. terebinthifolius*, such as what presently exists north of St. Augustine (GP site). In these simulations, *S. terebinthifolius* was introduced after 20 years of *A. germinans* growth from bare ground. Three runs were performed each with varying chances of seedling establishment. In Run 2a, the seedlings of both species had an equal chance of establishment (20%). In Run 2b, seedlings of *S. terebinthifolius* was given low chance of establishment (50*% A. germinans*/10% *S. terebinthifolius*) while in Run 2c, S. *terebinthifolius* was given a high chance of seedling establishment (10% *A. germinans*/50% *S. terebinthifolius*).

S. terebinthifolius invasion 2 (Run 3)

See *S. terebinthifolius invasion Runs* above for scenario questions

The *S. terebinthifolius* invasion 2 simulation (Run 3) modeled an invasion of an *A. germinans*/*L. racemosa* ecosystem (dominated by the former) by *S. terebinthifolius*. This would be a site such as the GTM site located near Marineland. Four runs of the simulation were conducted with Runs 3a and 3b at a "mid range" temperature (DEGD = 8500) and Runs 3c and 3d modeled at a "high" temperature (DEGD = 9500). These simulation runs modeled a *S. terebinthifolius* invasion after 40 years of mangrove seedling establishment from bare ground. During the first 20 years only *A. germinans* was allowed to seed and grow. Over the next 20 years *L. racemosa* seedlings were introduced. In Run 3a and 3c, there was an equal chance of seedling establishment (20% *A. germinans* year 0-150; 20% *L. racemosa* year 20-150; 20 % *S. terebinthifolius* year 40-150). In Runs 3b and 3d there was an increased chance of seedling establishment for *S. terebinthifolius* (10% *A. germinans* year 0-150; 10% *L. racemosa* year 20-150; 40 % *S. terebinthifolius* year 40-150).

Global Climate Change (Warming) (Run 4)

How will warming as part of global climate change affect the mangrove's range or invasion by *S. terebinthifolius*? Warming under global climate change should allow growth of all three species of mangroves to exist were there is currently only one or two. Warming should also slow invasion of *S. terebinthifolius* by adding additional species as competition for light.

The Global Climate Change (Warming) simulation (Run 4) was constructed to simulate the northern movement of species due to global climate change, specifically, global warming. Two runs of this simulation were performed, one with *S. terebinthifolius,* the other without. In both simulations, the temperature (DEGD) was increased linearly from a DEGD of 7500 to 9500 (°C) over a 20 year period. This is to simulate the temperature regime of GP, the northern most site, warming to become like that of SEB, the southernmost site. After 20 years of growing *A. germinans* seedlings from bare ground, the seedlings of *R. mangle*, *L. racemosa*, and *S. terebinthifolius* were allowed to establish (15% chance for all species) under a temperature (DEGD) regime which increased linearly from 7500 to 9500 (°C) over a 20 year period. In Run 3a, which included all four species, each was given a 15% chance of seedling establishment, while in 3b, which excluded *S. terebinthifolius*, each was given a 20% chance for seedling establishment.

Global Climate Change (Sea Level Rise) (Run 5)

How will sea level rise as part of global climate change affect the mangrove's range or invasion by *S. terebinthifolius*? The hypothesis is that mangroves will not be affected but *S. terebinthifolius'* growth may be curtailed as salinities increase.

The Global Climate Change (Sea Level Rise) simulation (Run 5) was used to model sea level rise through the linear increase of salinity from 20 ppt. to 35 ppt. over a 20 year period. As oceanic salinity is considered to be at approximately 40 ppt., the sea level scenario simulates the inflow of this saltier water into the more brackish marshes. Four runs were conducted similar to that described in warming above, but with two runs (Runs 5a and b) at "high" temperature (DEGD = 9500) and two runs (Runs 5c and d) at "low" temperature (DEGD = 7500). As in the warming scenario described above, each of the two runs Run 5a/b and c/d varied by the presence/absence of *S. terebinthifolius*.

Global Climate Change (Warming and Sea Level Rise) (Run 6)

How will a combination of warming and sea level rise as part of global climate change effect the mangroves' range or invasion by *S. terebinthifolius*? It is presumed that an increase in temperature will allow growth of all mangrove species in areas not previously populated but the compounding effect of sea level rise will curtail invasion by *S. terebinthifolius*.

The Global Climate Change (Warming and Sea Level Rise) simulation (Run 6) was used to model warming and concurrent sea level rise through the linear increase of temperature from a DEGD of 7500 to 9500 and salinity from 20 ppt. to 35 ppt. over a 20 year period beginning at year 20. Two runs were conducted one with *S. terebinthifolius* and one without the invader.

Freeze (Run 7)

If a freeze occurs at a site which contains all four species, how will this affect the dominance level? It is hypothesized that a freeze will heavily affect *R. mangle* and *L. racemosa*

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but with little effect on either *A. germinans* or *S. terebinthifoliu*s. Post freeze recovery may allow for a greater presence of *S. terebinthifolius*.

The Freeze simulation (Run 7) was constructed to simulate a freeze (or a very cold year) at year 20 of the model run. This simulation followed that of the bare ground simulation described above but included a drop in temperature from DEGD of 9500 to 7500 in year 20 followed by an return to 9500 in the following year. Two runs were conducted one with *S. terebinthifolius* the other without. In Runs 7a and 7b, all species had an equal chance of seedling survival. No specific freeze induced mortality was included for the seedlings other than the inability to grow at DEGDs less than the species specific $DEGD_{min}$.

Results

The results of runs of MANGRO are presented in Figs. 3-3 through 3-11. In the Bare Ground simulation (Runs 1a and 1b; Fig. 3-3) which simulated growth of seedlings with equal chance of establishment at high temperature (DEGD = 9500), *S. terebinthifolius* dominated over much of the model run but decreased over time as *A. germinans* increased in basal area. In the presence of *S. terebinthifolius* (Run 1a), both *R. mangle* and *L. racemosa* hold steady near 10% coverage. Without *S. terebinthifolius* (Run 1b; Fig. 3-3)), *A .germinans* dominated the landscape, after an initial surge by *L. racemosa*. *L. racemosa* and *R. mangle* coverage was limited but had had ~20% coverage for each. In Runs 1c and 1d (Fig. 3-4) which also simulated seedling growth as in Runs 1a and 1b, this time at a low temperature (DEGD = 7500), *S. terebinthifolius* continued to dominate over *A. germinans* (Run 1c). *R. mangle* and *L. racemosa* failed to grow as the $DEGD_{min}$ of 7636 was not met. Without *S. terebinthifolius* (Run 1d), only *A. germinans* established.

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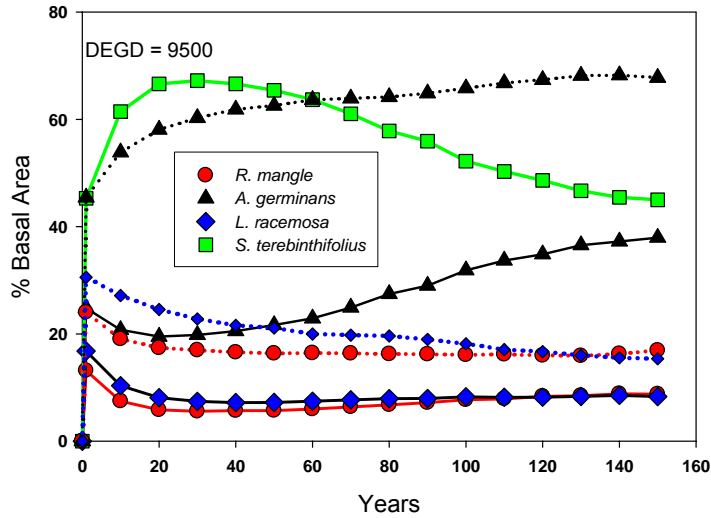
Figure 3-3. Bare Ground, high temperature (DEGD = 9500).
Dotted lines are runs without *S. terebinthifolius*.
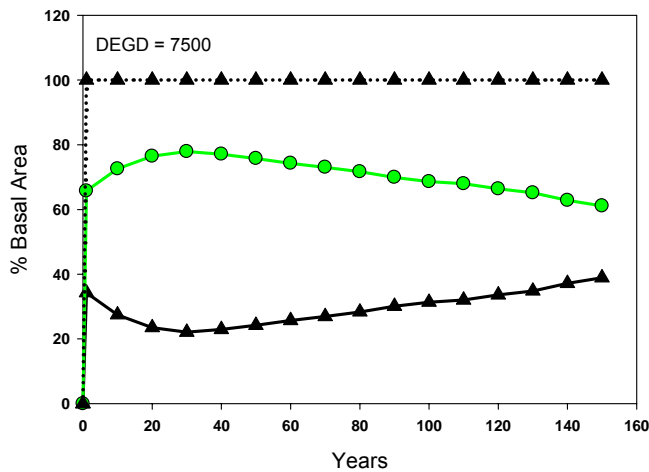
Figure 3-4. Bare Ground, low temperature (DEGD = 7500).
Dotted lines are runs without S. *terebinthifolius*.

In the *S. terebinthifolius* Invasion 1 scenario, (Runs 2a-c) (Fig. 3-5), *S. terebinthifolius*

was introduced after 20 years of *A. germinans* seedling growth and became the dominant

vegetation regardless of which species had the higher chance of seedling establishment. As was

expected, if *S. terebinthifolius* (Fig. 3-5 dotted lines) had a higher chance of seedling

establishment it become dominant earlier than if *A. germinans* has either a equal chance of

establishment (Fig. 3-5 solid lines) or a higher chance of establishment (Fig. 3-5 dashed lines).
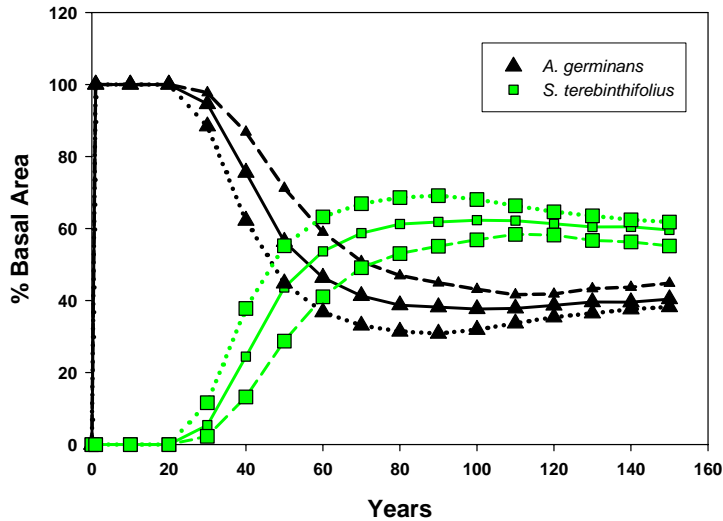
Figure 3-5. S. terebinthifolius invasion of *A. germinans* ecosystem. Solid, dashed, and dotted lines respectively represent equal, low, and high probabilities of *S. terebinthifolius* establishment.

The *S. terebinthifoliu*s Invasion 2 scenario (Runs 3a and 3b) (Fig. 3-6) simulated an invasion at year 40 of an *A. germinans*/*L. racemosa* ecosystem, dominated by the former, at a medium temperature (DEGD = 8500). *L. racemosa* basal coverage was extremely limited at both at an equal chance of seedling establishment for all species (20/20/20) and at a high chance of *S. terebinthifolius* establishment (10/10/40). At either seedling establishment regime, *S. terebinthifolius* became the dominant species. At a high temperature (Fig. 3-7), *S. terebinthifolius* still dominated the landscape under both seedling regimes, but *L. racemosa*, had a greater coverage than it had under the medium temperature. Under either temperature regime, *A. germinans* was slightly dominated by *S. terebinthifolius*.
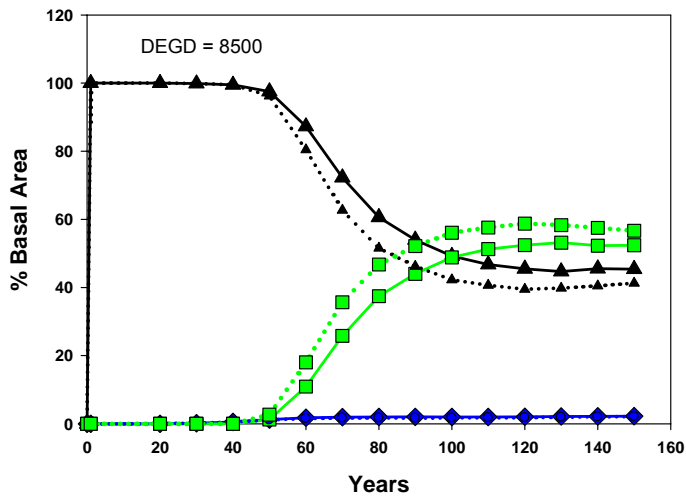
Figure 3-6. Invasion of an *A. germinans/L. racemosa* ecosystem by *S. terebinthifolius* at medium temperature (DEGD = 8500). Solid lines represent an equal chance of seedling establishment and dotted lines represent a high chance of *S. terebinthifolius* establishment.
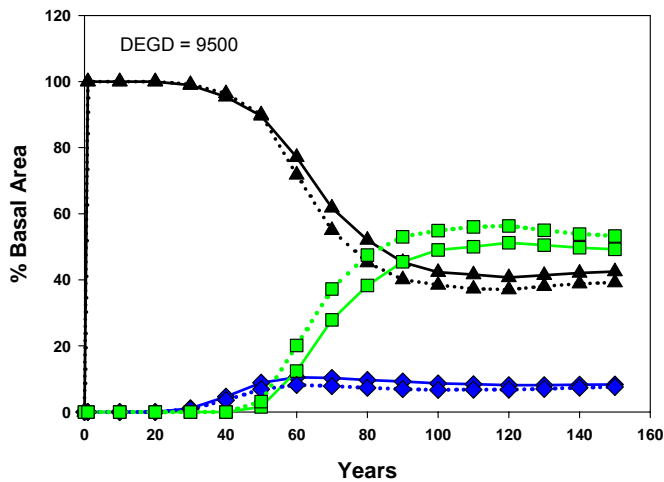
Figure 3-7. Invasion of an *A. germinans/L. racemosa* ecosystem by *S. terebinthifolius* at high temperature (DEGD = 9500) Solid lines represent an equal chance of seedling establishment and dotted lines represent a high chance of *S. terebinthifolius* establishment.

The Global Climate Change (Warming) scenario (Run 4) increased the temperature (DEGD) from 7500 to 9500 over a 20-year period (years 20 to 40) with and without the presence of *S. terebinthifolius* (Fig. 3-8). *S. terebinthifolius* began to dominate at about year 50 but declined and possibly equilibrated with *A. germinans* in about year 150. Without *S*

. *terebinthifolius*, *A. germinans* became the dominant vegetation although *L. racemosa* and *R. mangle,* which were not present under the cooler temperature regime, now covered about 15% of the landscape.
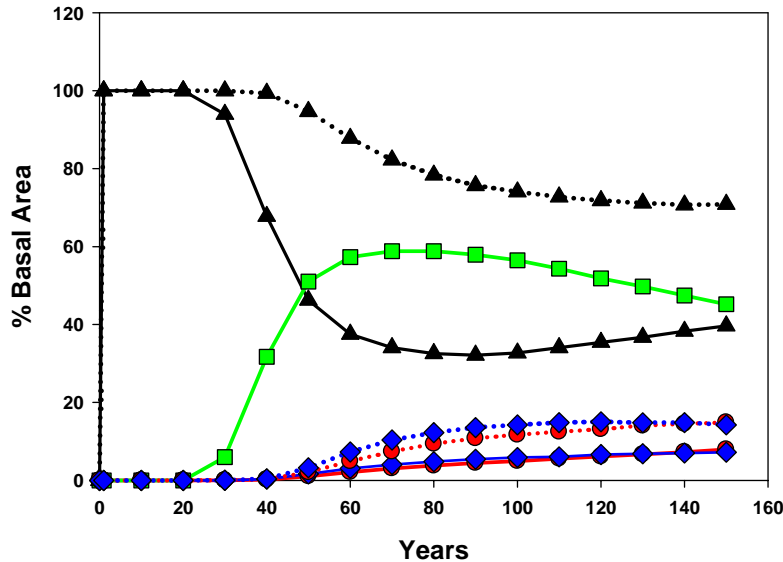
Figure 3-8. Climate change depicted with a warming trend. Dotted lines represent simulations without *S. terebinthifolius*.

The Global Climate Change (Sea Level Rise) scenario (Run 5) (Fig. 3-9) simulated sea level rise through an increase in salinity from 20 ppt. to 35 ppt. over a 20-year period (years 20-40). *S. terebinthifolius* reached its maximum growth at about year 20, then as salinity rose, *S. terebinthifolius'* growth slowed until salinity reached 35 ppt. at which *S. terebinthifolius* began to lose its dominance over the landscape. At approximately year 65, *A. germinans* became the dominant vegetation. Without *S. terebinthifolius*, *L. racemosa* had a slight decrease in its basal coverage than with it while *A. germinans* basal coverage slightly increased. *R. mangle* also showed a slight increase. Results of the run at low temperature are not presented here as results are similar to Fig. 3-4.
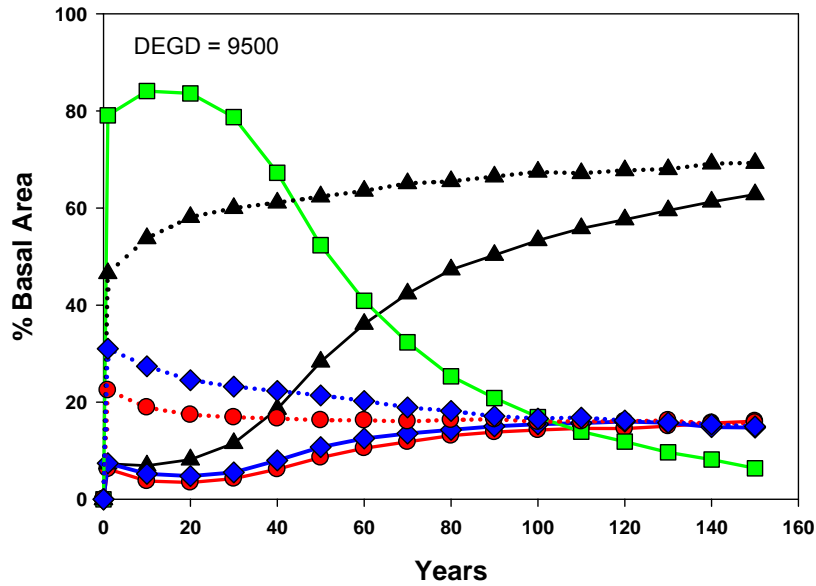
Figure 3-9. Climate change (sea level rise). Dotted lines represent simulations without *S. terebinthifolius.*

The Global Climate Change (Warming and Sea Level Rise) scenario (Run 6) (Fig. 3-10) simulated concurrent warming and sea level rise. In years 20-40, *S. terebinthifolius* began to grow but growth was slowed due to rising salinities and kept at very low area through the remainder of the study. The decline in growth of S. terebinthifolius along with the increase in temperature allowed basal coverage of *L. racemosa* and *R. mangle* to exceed *S. terebinthifolius.* *A. germinans* dominated that landscape during all phases of the simulation.
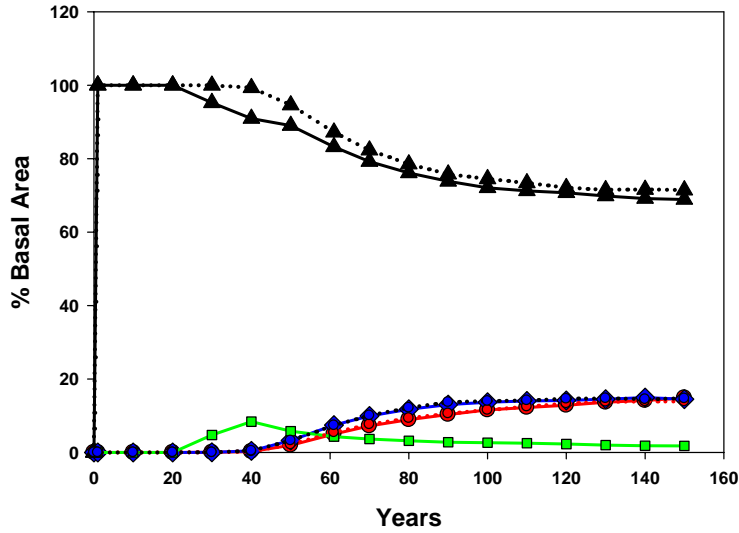
Figure 3-10. Climate change (Global warming with sea level rise).
Dotted lines represent simulations without *S. terebinthifolius*.

Lastly, the Freeze scenario (Run 7) (Fig. 3-11) simulated a freeze at year 20 of a

mangrove ecosystem with (Run 7a) and without (Run 7b) *S. terebinthifolius*. The freeze did not

have as much of an effect with *S. terebinthifolius* present as it dominated the landscape and was

not affected by the freeze. The freeze killed off both *L. racemosa* and *R. mangle.* The former of

which at the time of the freeze had greater coverage than *A. germinans*. Post freeze recovery of

R. mangle and *L. racemosa* was hindered by competition for light from the more established *S.*

terebinthifolius, or, in its absence, *A. germinans*.
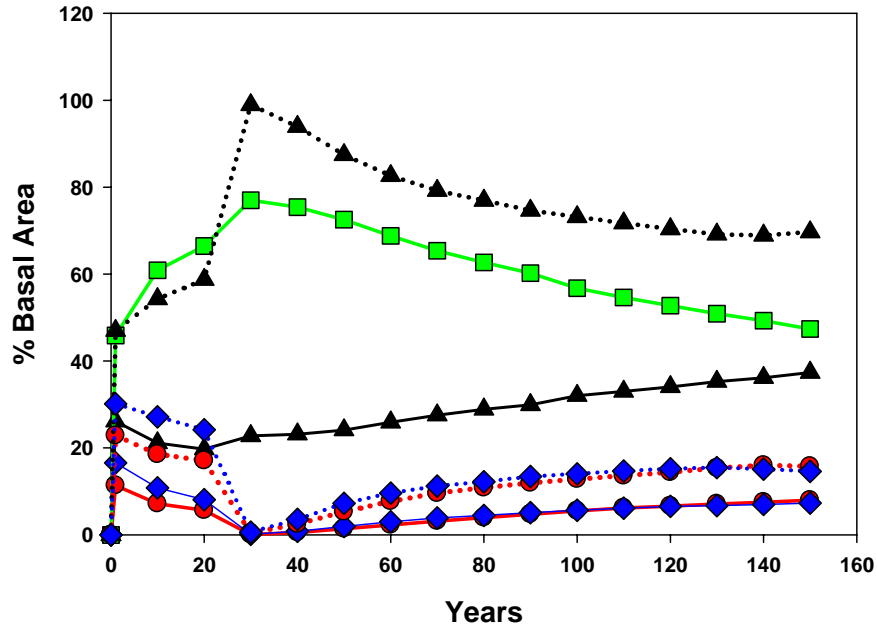
Figure 3-11. Seeding of bare ground with a freeze at year 20.
Dotted lines represent simulations without *S. terebinthifolius.*

Sensitivity Analysis

A sensitivity analysis was performed on *S. terebinthifolius*' salinity and light curves (Fig.

3-2 b,c). For salinity, two analyses (Fig.3-12) were performed utilizing Scenario 5, sea level rise;

one run with 20 ppt as the "drop off point" and the other 40 ppt.
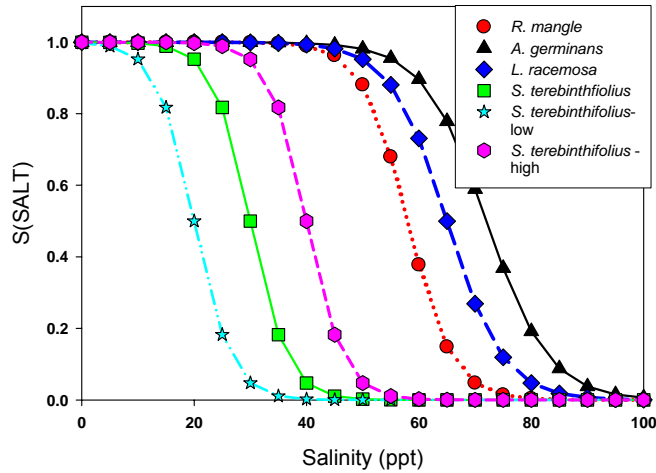
Figure 3-12. Salt Sensitivity analysis curves for *S. terebinthifolius*.

The higher of the two runs produced growth similar to that shown in Fig. 3-3 where growth of *S. terebinthifolius* was not affected by salinities as this run was conducted at a salinity of 35. The lower of the two produced interesting results shown in Fig. 3-13. In the first years of growth under the lower salinity curve, *S. terebinthifolius* growth was curtailed by the more salt tolerant *A. germinans* but at around year 10 the faster growing *S. terebinthifolius* appeared to be starting to be the faster grower until the change in salinity level at year 20 which again, curtailed the growth of *S. terebinthifolius*.
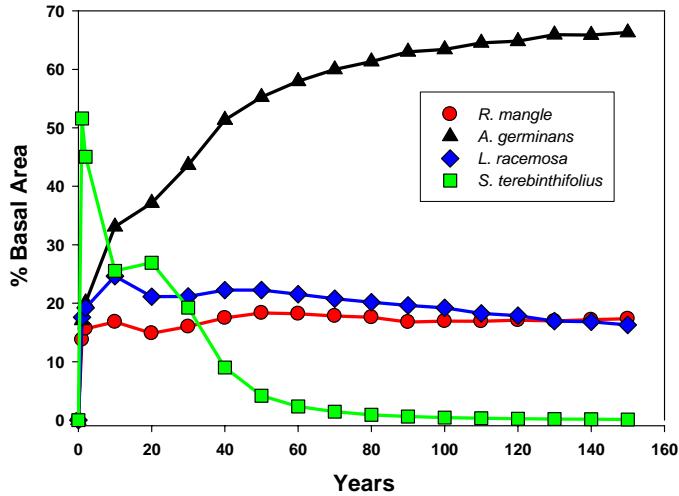
Figure 3-13. Scenario 5 with a less (or more)-salinity sensitive *S. terebinthifolius*.

The sensitivity analysis of the light curve of *S. terebinthifolius* also produced interesting results for the runs with light multiplication curves below that shown in Fig. 3-2. Two additional light curves were proposed for this analysis (Fig. 3-14). One, referred to as low, with a multiplier value of -0.1 from "normal" and the other referred to as very low with a multiplier of -0.3 away from normal.
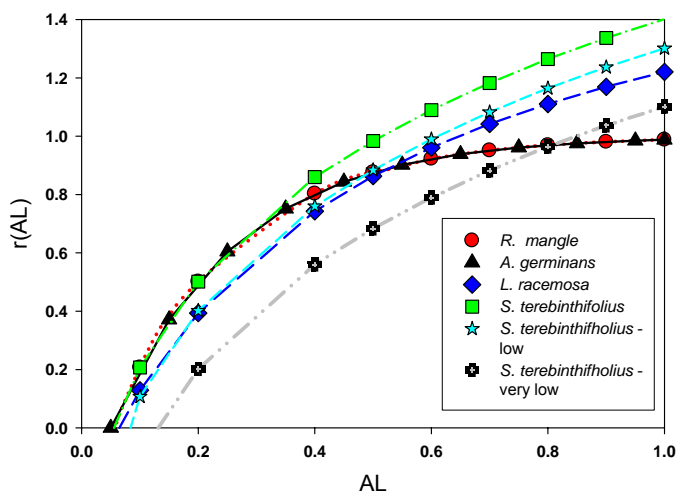
Figure 3-14. Light Sensitivity analysis curves for *S. terebinthifolius.*

To observe the effect of these lower curves, Run 2, *S. terebinthifolius* invasion scenario 1 was run under all three curves and compared in Fig. 3-15. *S. terebinthifolius* became the dominant under both the normal light curve and the low light curve. Only in the very low light curve, did *S. terebinthifolius* not become dominant over *A. germinans.* Run 3, *S. terebinthifolius* invasion scenario 2, was also run under these three light curves with similar results. It can be concluded from this analysis that unless *S. terebinthifolius* is very shade intolerant (very low curve), it will be the dominant.
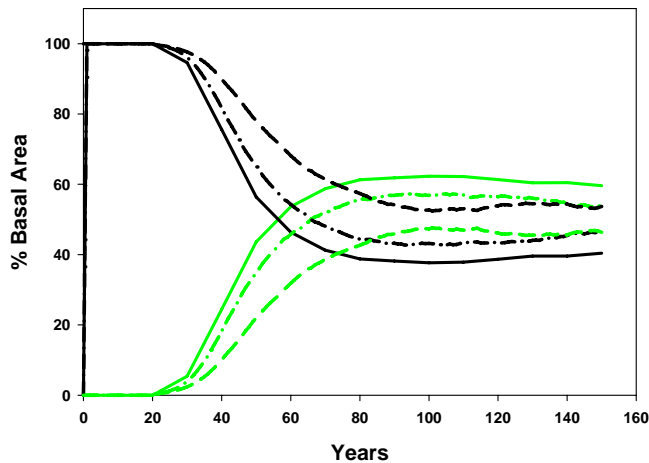
Figure 3-15. Sensitivity analysis for Run 2.

Discussion

In the MANGRO model (Fig. 3-1), FORMAN was modified to include the invasive *S. terebinthifolius*. This shading effect and the impacts from *S. terebinthifolius* increased competition for light and reduced mangrove growth in the shade intolerant plants. In the Bare Ground scenario (Fig. 3-3), *S. terebinthifolius* dominated the landscape but a decreasing percent basal area was observed at the end of the run period demonstrating possible self thinning.

However, as the long runs do not contain any additional disturbance, the long term results are unrealistic. In the absence of *S. terebinthifolius*, *L. racemosa* occupied more than 50% of the basal area in early years as it does better in light (Chen and Twilley 1998). *A. germinans* soon surpassed *L. racemosa* in coverage as its faster growth rate compensates for the competition in light levels. Even though this simulation was deemed to be run at the "high" temperature of DEGD = 9500, this was still too cold for *R. mangle* to cover more than 10-20% of basal coverage even without *S. terebinthifolius*. At the "low" temperature of DEGD = 7500 (Fig. 3-4) only *S. terebinthifolius* and *A. germinans* can survive with *S. terebinthifolius* dominating the landscape due to its higher competitive abilities in both shade and sun and faster growing rates.

The *S. terebinthifolius* Invasion 1 scenario (Fig. 3-5) was also run at this "low" temperature (DEGD = 7500) in which only *S. terebinthifolius* and *A. germinans* can grow. Regardless of which species was given the greater chance of seedling establishment, *S. terebinthifolius* dominated the basal coverage. This scenario could represent the eventual domination of the *A. germinans*-only ecosystems located in the higher study latitudes (sites ASP and GP) by *S. terebinthifolius* if the *A. germinans* ecosystem is invaded. Even though *S. terebinthifolius* has not yet been recorded in these upper latitudes, care must be taken by land managers so that it does not establish.

The *S. terebinthifolius* Invasion 2 scenario (Fig. 3-6) run at "medium" temperature (DEGD= 8500) simulated the invasion of an *A. germinans*/*L. racemosa* ecosystem which is dominated by *A. germinans*. As in the *S. terebinthifolius* Invasion 1 scenario, *S. terebinthifolius* dominated the basal area with *L. racemosa* having a very small coverage due to growth at close to its $DEGD_{min}$ of 7636. The "high" temperature (DEGD= 9500) scenario had similar results but *S. terebinthifolius* still dominated (Fig. 3-7). Changes in the chance of establishment of seeds of *S. terebinthifolius* had little impact on the basal coverage at either "medium" or "high"

temperatures. As this *A. germinans*/*L. racemosa* ecosystem is prevalent in the upper latitudes of *S. terebinthifolius'* invasion, efforts should be made to remove and contain any *S. terebinthifolius* growth before it becomes established.

In the Global Climate Change (Warming) scenario (Fig. 3-8), all three species of mangrove were able to establish in areas in which only *A. germinans* is currently found. The model showed a small presence of *R. mangle* as this warmer temperature (DEGD = 9500) is still close to its $DEGD_{min}$ of 7636. As in the above scenarios, *S. terebinthifolius* dominated the landscape with a strongly weak presence of *A. germinans*. Without *S. terebinthifolius*, *A. germinans* became the dominant vegetation with *L. racemosa* having an approximately 10% increase of basal coverage than under the influence of *S. terebinthifolius*. *R. mangle* basal coverage increased only slightly without *S. terebinthifolius*. This scenario reinforces the management conclusion stated above that efforts should be made to remove and contain any *S. terebinthifolius* growth before it becomes established even if warming under global climate change should occur.

In the Global Climate Change (Sea Level Rise) scenario (Fig. 3-9), *S. terebinthifolius* failed to grow under the increased salinity level under sea level rise. As a result, *A. germinans* became the dominant vegetation with a strong presence of *L. racemosa*. *R. mangle* continued to show a weak presence due to temperatures near its $DEGD_{min}$. This control of *S. terebinthifolius* may be the only one "positive" result of global warming other than an increase of the mangrove's range. However, Ewe and Sternberg (2007) warn that freshwater vegetation now subjected to low levels of salinity may be outcompeted by *S. terebinthifolius* which can stand low levels of salinity.

Lastly, the Freeze scenario (Fig. 2-11) showed that *S. terebinthifolius* can take full advantage over the loss of basal area due to freeze of mangroves. Under forecasted global change models, this scenario is projected to have a lower chance of occurring.

In conclusion, the containment, removal, and prevention of establishment of *S. terebinthifolius* will be crucial to the health of the current mangrove ecosystems under the current or forecasted temperature regimes.

CHAPTER 4. STUDY CONCLUSIONS

Global Climate change will lead to many changes in the landscape including alterations in the distribution of species and changes in water patterns, including sea level rise. The establishment and spread of invasive species may also lead to a change in species distribution. Along the northern edge of their range, mangroves will be affected by this change through increasing species distribution.

Currently, only *A. germinans* has been established at the northern range limit (within the GTM NERR) with a documented *R. mangle* (Zomleffer 2007) and a studied *L racemosa.* In addition, a *S. terebinthifolius* has been observed in Ft. Clinch along the Florida/Georgia border (M. Love, pers. comm.). The occurrence of these outlying mangroves is expected to change as global climate change warms the area and allows for growth of all three species with *A. germinans* being the dominant. Additionally, *L. racemosa* and *R. mangle* are expected to be present in areas that they currently do not reside. Detrimental ecological impacts may occur with replacement of salt marsh habitat by mangroves, but these effects may be compensated in part by the effects of additional mangrove detritus.

The species composition of mangroves can be expected to be greatly altered if the invasive *S. terebinthifolius* is allowed to established and spread. As up to 40% of the detrital materials in suspension in estuarine waters have been found to be of mangrove origin, a 50% reduction of mangrove leaf production may have large, possible dire, ecosystem impacts.

Sea level rise as part of global climate change may help reduce the spread of S. terebinthifolius by increasing salinities in mangrove habitat giving an advantage to the more salt tolerant mangrove. Global climate change may be more complex than just a rise in temperature

and sea levels. If precipitation rises, bay and estuaries may actually become less salty due to influxes of freshwater systems feeding the estuary.

Future changes or improvements to this study may warrant: including better parameterized constants for growth, which may be garnered by greenhouse or growth chamber studies; incorporation into the model of site specific parameters such latitude; and incorporation into the model of interaction effect such as the effects of temperature on salinity levels.

Finally, the ultimate conclusion on the fate of the northern range of the mangrove ecosystem will be dependent on a multitude of factors including the amount and rate of climate change and invasive spread. The capacity to adapt and spread due to changes in the ecosystem will be dependent on their ability to migrate without being deterred by anthropogenic sources such as development and hardened shoreline that do not allow for mangrove establishment.

APPENDIX A. SITE LATITUDE/LONGITUDE

SITE	Latitude	Longitude
SEB	27° 50' 48.46"N	80° 26' 35.08"W
ROT	28° 13' 48.58"N	80° 40' 14.88"W
KEL	28° 24' 10.33"N	80° 39' 44.86"W
CNS	28° 40' 29.72"N	80° 38' 55.23"W
TIT	28° 37' 50.20"N	80° 47' 06.51"W
LP	29° 04' 40.22"N	80° 55' 35.75"W
CP	29° 08' 50.85"N	80° 58' 37.53"W
GTM	29° 39' 47.95"N	81° 13' 00.67"W
ASP	29° 52' 22.97"N	81° 16' 32.62"W
GP	30° 01' 18.60"N	81° 20' 35.95"W

APPENDIX B. TEMPERATURE DATA

Logger	Inspection	dates	avg. (C)	DEGD (C)	Logger	Inspection	dates	avg. (C)	DEGD (C)
SEB1	1	2/17-4/9	19.75	588.064	SEB2	1	2/17-4/9	19.63	587.674
	2	4/10-5/4	21.64	344.049		2	4/10-5/4	21.72	333.559
	3	5/5-6/2	25.20	497.706		3	5/5-6/2	25.11	506.877
	4					4	6/3-7/7	26.89	673.207
	5					5	7/8-8/7	28.18	618.194
	6	8/8-9/4	29.39	610.112		6	8/8-9/4	28.88	586.892
	7	9/5-10/14	27.59	782.878		7	9/5-10/14	26.56	741.468
	8	10/15-11/17	23.77	541.359		8	10/15-11/17	23.72	555.573
	9	11/18-1/12	18.65	584.656		9	11/18-1/12	18.09	584.970
	10	1/13-2/11	17.49	292.153		10	1/13-2/11	17.58	299.820
	11	2/12-4/8	19.71	655.412		11	2/12-4/8	20.23	781.588
						12	4/9-5/20	24.10	728.438
ROT1	1	2/11-4/8	20.16	423.655		13	5/21-6/19	24.68	546.609
	2	4/9-5/20	23.41	632.620		14	6/20-7/29	26.73	762.401
	3	5/21-6/19	26.31	530.390		15	7/30-9/10	27.33	876.627
	4	6/20-7/29	27.03	742.478		16	9/11-11/5	25.50	1006.021
	5	7/30-9/10	27.33	826.659					
	6	9/11-11/5	24.92	919.377					
	7	11/6-12/17	18.87	435.853					
	8	12/18-1/21	20.43	410.570					
	9	1/22-3/11	16.46	404.646					
	10	3/12-6/22	22.02	972.957					
KEL1	1	7/19-8/7	28.68	375.694	KEL2	1	7/19-8/7	28.30	362.397
	2	8/8-9/4	29.03	580.552		2	8/8-9/4	28.74	557.083
	3	9/5-10/12	27.35	746.370		3	9/5-10/12	26.95	694.873
	4	10/13-11/21	22.88	603.707		4	10/13-11/21	22.46	557.604
	5	11/22-1/20	17.09	567.976		5	11/22-1/20	16.50	511.816
	6	1/20-2/17	16.61	249.898		6	1/20-2/17	15.95	217.309
	7	2/18-4/18	20.49	743.445		7	2/18-4/18	20.04	687.209
	8	4/19-5/21	24.15	515.408		8	4/19-5/21	23.91	507.076
	9	5/21-6/28	26.69	694.213		9	5/22-6/28	26.48	674.699
	10	6/29-7/30	27.50	606.196		10	6/29-7/30	27.35	590.724
	11	7/31-9/17	27.69	919.176		11	7/31-9/17	27.39	972.126
	12	9/18-11/13	24.38	1000.116		12	9/18-11/13	23.88	872.667
	13	11/14-12/28	19.25	530.004		13	11/14-12/28	19.07	482.220
	14	12/29-3/4	18.02	692.074		14	12/29-3/4	17.73	613.968
	15	3/5-5/29	22.72	1155.689		15	3/5-5/29	21.95	1307.633

Appendix B continued

Logger	Inspection	dates	avg. (C)	DEGD (C)	Logger	Inspection	dates	avg. (C)	DEGD (C)
CNS1	1	2/26-4/3	18.63	390.059	CNS2	1	2/26-4/3	18.13	355.879
	2	4/4-5/7	21.24	460.138		2	4/4-5/7	20.75	433.906
	3	5/8-6/7	24.56	505.881		3	5/8-6/7	24.39	511.745
	4	6/8-7/6	26.78	537.601		4	6/8-7/6	26.58	536.813
	5	7/7-8/22	27.45	1248.962		5	7/7-8/22	28.34	1193.694
	6	8/23-10/12	26.31	691.508		6	8/23-10/12	27.65	734.749
	7	10/13-11/21	23.16	624.852		7	10/13-11/21	21.72	591.851
	8	11/22-1/20	17.30	638.565		8	11/22-1/20	15.47	538.079
	9	1/21-2/17	16.71	284.032		9	1/21-2/17	14.96	236.852
	10	2/18-4/22	20.85	871.885		10	2/18-4/22	18.97	732.345
	11	4/23/5/21	24.20	475.918		11	4/23-5/21	22.38	408.201
	12	5/22-7/11	26.71	970.113		12	5/22-7/11	24.96	863.388
	13	7/12-7/30	27.46	368.112		13	7/12-7/30	25.83	342.714
	14	7/31-9/17	27.08	959.701		14	7/31-9/17	25.36	891.942
	15	9/18-11/13	24.34	984.217		15	9/18-11/13	22.80	949.638
	16	11/14-12/28	19.40	563.675		16	11/14-12/28	17.72	469.965
	17	12/29-3/4	18.01	676.108					
	18	3/5-5/29	22.32	1290.016					
LP1	1	2/24-4/12	17.88	474.244	LP2	1	2/24-4/12	18.07	483.501
	2	4/13-5/9	19.97	324.438		2	4/13-5/9	20.24	328.105
	3	5/10-6/14	24.79	605.480		3	5/10-6/14	25.16	631.447
	4	6/15-7/21	27.16	534.454		4	6/15-7/21	27.28	551.415
	5	7/22-8/8	27.78	540.398		5	7/22-8/8	28.08	557.684
	6	8/9-9/10	28.31	675.995		6	8/9-9/10	28.25	675.381
	7	9/11-11/3	25.25	991.318		7	9/11-11/3	24.95	946.622
	8	11/4-12/1	20.31	370.258		8	11/4-12/1	20.14	356.943
	9	12/2-1/4	15.42	281.252		9	12/2-1/4	15.41	268.649
	10	1/5-2/23	15.04	389.526		10	1/5-2-23	15.12	429.067
	11	2/24-4/25	19.77	770.064		11	2/24-4/25	20.10	845.602
	12	4/26-5/31	24.04	576.326		12	4/26-5/31	24.51	663.011
	13	6/1-7/10	26.21	721.783		13	6/1-7/10	27.02	844.263
	14	7/11-8/22	27.38	864.476		14	7/11-8/22	27.88	884.401
	15	8/23-10/30	25.19	1258.087		15	8/23-10/30	25.53	1350.780
	16	10/31-12/18	18.50	521.953		16	10/31-12/18	18.48	548.718
	17	12/19-2/6	17.55	488.477		17	12/19-2/6	19.28	530.807
	18	2/7-3/25	13.80	464.552		18	2/7-3/25	16.96	460.537
	19	3/26-6/4	20.16	1026.444		19	3/26/6/4	22.69	1147.695
CP1	1	2/24-4/12	17.80	448.853	CP2	1	2/24-4/12	18.60	504.426
	2	4/13-5/9	19.74	298.998		2	4/13-5/9	20.82	348.703
	3	5/10-6/14	24.61	588.314		3	5/10-6/14	25.48	650.399
	4	6/15-7/21	27.05	517.790		4	6/15-7/21	27.50	554.711
	5	7/22-8/8	27.24	516.510		5	7/22-8/8	27.74	559.242
	6	8/9-9/10	27.51	626.064		6	8/9-9/10	27.68	653.799
	7	9/11-11/3	24.01	859.208		7	9/11-11/3	24.41	915.735
	8	11/4-12/1	19.33	312.694		8	11/4-12/1	19.64	337.855
	9	12/2-1/4	14.44	222.299		9	12/2-1/4	14.66	239.493
	10	1/5-2/23	14.41	346.963		10	1/5-2-23	14.81	386.086
	11	2/24-4/25	18.60	640.015		11	2/24-4/25	19.57	746.175
	12	4/26-5/31	23.10	532.533		12	4/26-5/31	24.11	603.931
	13	6/1-7/10	25.41	684.465		13	6/01-7/10	26.28	745.602
	14	7/11-8/22	26.64	796.746		14	7/11-8/22	27.30	864.476
	15	8/22-10/30	24.06	1140.496		15	8/23-10/30	24.97	1229.103
	16	10/31-12/18	17.72	520.566		16	10/31-12/18	X	X
	17	12/19-2/6	16.48	427.696		17	12/19-2/6	X	X
	18	2/7-3/25	20.59	408.327		18	2/7-3/25	16.20	408.327
	19	3/26-6/4	21.30	957.040		19	3/26-6/4	21.72	1025.073

Appendix B continued

Logger	Inspection	dates	avg. (C)	DEGD (C)
GTM1	1	3/14-4/26	18.44	471.082
	2	4/27-5/25	22.18	435.465
	3	5/26-6/21	25.72	470.623
	4	6/22-7/22	27.75	625.556
	5	7/23-8/17	28.12	538.429
	6	8/18-9/23	28.18	765.812
	7	9/24-11/11	23.47	813.114
	8	11/12-1/6	16.07	549.569
	9	1/7-2/1	15.03	238.700
	10	2/2-3/14	15.52	375.846
	11	3/15-3/30	17.15	153.077
	12	3/31-5/1	22.32	876.261
	13	5/2-6/5	24.75	607.275
	14	6/6-8/11	27.54	1359.482
	15	8/12-10/16	26.39	1298.836
	16	10/17-12/4	19.13	600.070
	17	12/5-1/15	17.69	441.287
	18	1/16-2/20	13.00	255.749
	19	2/24-4/25	18.79	641.458
ASP1	1	3/14-4/27	17.90	411.525
	2	4/28-5/25	21.89	376.799
	3	2/26-6/21	25.51	470.545
	4	6/22-7/22	27.58	606.831
	5	7/23-8/16	27.82	489.439
	6	8/17-9/23	27.64	736.799
	7	9/24-11/11	22.47	697.782
	8	11/12-12/28	15.13	351.398
	9	12/29-2/1	14.37	482.685
	10	2/2-3/14		
	11	3/15-3/30	16.56	141.044
	12	3/31-5/1	21.61	440.072
	13	5/2-6/5	24.36	581.686
	14	6/6-8/11	27.23	1281.882
	15	8/12-10/16	25.57	1149.206
	16	10/17-12/3	18.17	486.573
	17	12/4-1/15	16.80	368.813
	18	1/16-2/20	12.02	186.523
	19	2/20-4/25	17.94	754.096
GP1	1			
	2	5/25-621	25.32	463.243
	3	6/22-7/22	27.00	581.094
	4	7/23-8/16	27.35	475.942
	5	8/17-9/23	27.11	717.538
	6	9/24-11/11	22.22	704.708
	7	11/12-12/28	15.00	359.516
	8	12/29-2/1	14.64	272.708
	9	2/2-3/14	14.61	298.706
	10	3/15-3/30	15.87	121.699
	11	3/31-5/1	21.38	430.649
	12	5/2-6/5	23.98	562.536
	13	6/6-8/10	26.77	1248.614
	14	8/11-10/7	26.04	1054.590
	15	10/8-12/3	18.60	610.281
	16	12/4-1/15	16.87	392.431
	17	1/16-2/20	12.09	191.441
	18	2/21-4/25	17.90	652.314

Logger	Inspection	dates	avg. (C)	DEGD (C)
GTM2	1	3/14-4/26	18.60	462.047
	2	4/27-5/25	22.27	426.492
	3	5/26-6/21	25.57	453.369
	4	6/22-7/22	27.50	596.709
	5	7/23-8/17	27.97	526.095
	6	8/18-9/23	27.73	719.995
	7	9/24-11/11	23.35	771.053
	8	11/12-1/6	16.15	487.507
	9	1/7-2/1	15.24	218.291
	10	2/2-3/14	15.53	332.566
	11	3/15-3/30	17.22	139.874
	12	3/31-5/1	22.20	456.754
	13	5/2-6/5	24.73	592.912
	14	6/6-8/11	27.32	1313.638
	15	8/12-10/16	26.13	1215.154
	16	10/17-12/4	19.10	561.236
	17	12/5-1/15	17.73	423.457
	18	1/16-2/20	13.15	221.898
	19	2/20-4/25	18.88	622.896
ASP2	1	3/14-4/27	17.93	414.427
	2	4/28-5/25	21.80	375.624
	3	2/26-6/21	25.34	456.788
	4	6/22-7/22	27.25	581.778
	5	7/23-8/16	27.65	480.390
	6	8/17-9/23	27.67	730.883
	7	9/24-11/11	22.74	723.474
	8	11/12-12/28	15.23	369.809
	9	12/29-2/1	14.59	284.905
	10	2/2-3/14	14.68	311.022
	11	3/15-3/30	16.15	119.839
	12	3/31-5/1	21.40	422.798
	13	5/2/5-6/5	23.96	555.508
	14	6/6-8/11	26.88	1250.511
	15	8/12-10/16	25.53	1156.888
	16	10/17-12/3	18.35	511.551
	17	12/4-1/15	16.96	390.695
	18	1/16-2/20	12.21	203.037
	19	2/20-4/25	17.88	713.724
GP2	1	4/20-5/25	21.59	478.928
	2	5/25-6/21	25.58	475.403
	3	6/22-7/22	27.33	597.232
	4	7/23-8/16	27.71	485.194
	5	8/17-9/23	27.40	721.451
	6	9/24-11/11	22.31	697.025
	7	11/12-12/28	15.00	340.191
	8	12/29-2/1	14.60	256.274
	9	2/2-3/14	14.66	289.276
	10	3/15-3/30	15.86	117.120
	11	3/31-5/1	21.53	431.000
	12	5/2-6/5	24.27	578.072
	13	6/6-8/10	27.06	1272.897
	14	8/10-10/7	26.23	1054.841
	15	10/8-12/3	18.62	601.472
	16	12/4-1/15	16.85	380.518
	17	1/16-2/20	11.95	175.128
	18	2/21-4/25	17.94	633.130

APPENDIX C. NUMBER OF LEAVES

Site	Date	Inspection	Total number of leaves			
			R. mangle	*A. germinans*	*L. racemosa*	*Schinus*
SEB	02/17/05	1	173	180	85	
	04/09/05	2	191	189	70	
	05/04/05	3	200	217	71	
	06/02/05	4	213	239	78	
	07/07/05	5	219	197	110	
	08/07/05	6	249	202	96	
	09/04/05	7	258	204	104	
	10/14/05	8	289	276	108	
	11/17/05	9	260	307	171	
	01/12/06	10	258	327	178	
	02/11/06	11	301	313	153	
	04/08/06	12	299	260	136	
	05/20/06	13	249	289	111	
	06/19/06	14	289	281	126	
	07/29/06	15	328	349	121	
	09/10/06	16	361	483	114	
	11/05/06	17	383	410	84	
ROT	02/11/06	1	197	139	164	878
	04/08/06	2	180	119	144	786
	05/20/06	3	190	155	108	744
	06/19/06	4	193	147	169	1180
	07/29/06	5	221	153	164	1610
	09/10/06	6	235	225	190	2481
	11/04/06	7	234	222	187	2737
	12/17/06	8	251	245	206	2426
	01/21/07	9	229	246	207	1886
	03/11/07	10	200	244	177	2608
	05/22/07	11	207	227	192	1187
KEL	07/19/05	1	230	63	138	
	08/07/05	2	249	61	149	519
	09/04/05	3	301	58	143	649
	10/12/05	4	306	66	149	1025
	11/21/05	5	299	58	159	760
	01/20/06	6	326	57	107	853
	02/01/06	7	332	62	141	688
	04/18/06	8	332	46	126	621
	05/21/06	9	332	55	103	794
	06/28/06	10	332	52	144	797
	07/30/06	11	312	61	141	130
	09/17/06	12	288	67	98	113
	11/16/06	13	345	64	101	50
	12/28/06	14	296	67	102	
	03/04/07	15	296	51	99	
	05/29/07	16	313	62	78	

Appendix C continued

Site	Date	Inspection	Total number of leaves			
			R. mangle	*A. germinans*	*L. racemosa*	*Schinus*
CNS	02/26/05	1		209	59	
	04/03/05	2		207	86	
	05/05/05	3		222	106	
	06/07/05	4		250	112	
	07/06/05	5		242	119	
	08/22/05	6		297	103	
	10/12/05	7		258	136	
	11/12/05	8		262	113	
	01/20/06	9		255	79	
	02/17/06	10		294	67	
	04/22/06	11		356	105	
	05/21/06	12		350	100	
	07/30/06	13		308	88	
	09/17/06	14		276	68	
	11/13/06	15		321	55	
	12/28/06	16		305	48	
	03/04/07	17		288	30	
	06/04/07	18		247	12	
LP	02/24/05	1	56	134	69	
	04/12/05	2	64	126	80	
	05/09/05	3	62	146	70	
	06/14/05	4	53	161	126	
	07/07/05	5	86	156	159	
	08/08/05	6	92	144	193	
	09/10/05	7	103	136	267	
	11/03/05	8	99	122	245	
	12/01/05	9	108	123	235	
	01/04/06	10	92	119	213	
	02/23/06	11	114	116	197	
	04/25/06	12	98	73	171	
	05/31/06	13	115	81	192	
	07/10/06	14	124	80	198	
	08/22/06	15	123	70	265	
	10/30/06	16	108	67	211	
	12/18/06	17	98	91	204	
	02/06/07	18	82	47	191	
	03/25/07	19	91	48	163	
	06/04/07	20	72	42	182	

Appendix C continued

Site	Date	Inspection	Total number of leaves			
			R. mangle	*A. germinans*	*L. racemosa*	*Schinus*
CP	02/24/05	1	74	155	72	338
	04/12/05	2	69	183	92	323
	05/09/05	3	82	206	180	342
	06/14/05	4	107	215	216	549
	07/07/05	5	119	290	213	741
	08/08/05	6	130	364	221	811
	09/10/05	7	142	334	226	376
	11/03/05	8	120	327	234	201
	12/01/05	9	129	323	224	125
	01/04/06	10	120	299	202	110
	02/23/06	11	104	308	216	404
	04/25/06	12	98	297	183	228
	05/31/06	13	112	300	181	266
	07/10/06	14	107	334	172	302
	08/22/06	15	116	363	146	422
	10/30/06	16	97	370	126	X
	12/18/06	17	99	343	105	X
	02/06/07	18	92	384	114	X
	03/25/07	19	89	365	160	X
	06/04/07	20	80	384	143	X
GTM	03/14/05	1		410	76	
	04/24/05	2		592	78	
	05/25/05	3		586	99	
	06/21/05	4		616	148	
	07/22/05	5		666	134	
	08/17/05	6		767	121	
	09/23/05	7		782	119	
	11/11/05	8		840	82	
	01/06/06	9		781	78	
	02/01/06	10		803	79	
	03/14/06	11		814	59	
	03/30/06	12		824	62	
	05/01/06	13		908	98	
	06/05/06	14		941	182	
	08/11/06	15		966	224	
	10/16/06	16		1038	259	
	12/03/06	17		1069	274	
	01/15/07	18		987	248	
	02/20/07	19		1164	264	
	04/25/07	20		1009	235	

Appendix C continued

Site	Date	Inspection	R. mangle	A. germinans	L. racemosa	Schinus
ASP	03/14/05	1		318		
	04/24/05	2		425		
	05/25/05	3		504		
	06/21/05	4		534		
	07/22/05	5		572		
	08/17/05	6		724		
	09/23/05	7		707		
	11/11/05	8		672		
	12/28/05	9		708		
	02/01/06	10		704		
	03/14/06	11		712		
	03/30/06	12		687		
	05/01/06	13		829		
	06/05/06	14		864		
	08/11/06	15		879		
	10/16/06	16		877		
	12/03/06	17		803		
	01/15/07	18		770		
	02/20/07	19		740		
	04/25/07	20		797		
GP	04/21/05	1		433		
	05/25/05	2		544		
	06/21/05	3		562		
	07/22/05	4		616		
	08/17/05	5		674		
	09/23/05	6		602		
	11/11/05	7		693		
	12/28/05	8		660		
	02/01/06	9		670		
	03/14/06	10		676		
	03/30/06	11		639		
	05/01/06	12		705		
	06/05/06	13		654		
	08/10/06	14		701		
	10/07/06	15		709		
	12/04/06	16		663		
	01/15/07	17		663		
	02/20/07	18		649		
	04/25/07	19		720		

APPENDIX D. FLOWERS, FRUITS AND BUDS

SITE	Inspection	Date	*R. mangle*			*A. germinans*			*L. racemosa*			*Schinus*		
			Fl	Fr	B	Fl	Fr	B	Fl	Fr	B			
SEB	0	02/17/05	0	0	0	0	0	0	0	0	0			
	1	04/09/05	0	0	0	0	0	0	0	0	0			
	2	05/04/05	0	0	0	0	0	0	0	0	0			
	3	06/02/05	0	0	0	0	0	3	0	0	0			
	4	07/07/05	0	0	0	0	0	0	0	0	0			
	5	08/07/05	0	0	0	0	0	0	0	0	0			
	6	09/04/05	0	0	0	0	0	0	0	0	0			
	7	10/14/05	0	0	0	0	0	0	0	0	0			
	8	11/17/05	0	0	0	0	0	0	0	0	0			
	9	01/12/06	0	0	0	0	0	0	0	0	0			
	10	02/11/06	0	0	0	0	0	0	0	0	0			
	11	04/08/06	0	0	0	0	0	0	0	0	0			
	12	05/20/06	0	0	0	0	0	0	0	0	0			
	13	06/19/06	0	0	0	0	0	0	0	0	0			
	14	07/28/06	0	0	24	0	0	0	0	0	20			
	15	09/10/06	0	0	9	0	0	0	0	0	0			
	16	11/05/06	0	0	0	0	0	0	0	0	0			
ROT	0	02/11/06	0	0	0	0	0	0	0	0	0	0	0	0
	1	04/08/06	0	0	0	0	0	0	0	0	0	0	0	0
	2	05/20/06	0	0	0	0	0	0	0	0	0	0	0	0
	3	06/19/06	0	0	4	0	0	10	0	25	0	0	0	0
	4	07/29/06	6	0	10	0	0	0	50	130	0	0	0	0
	5	09/10/06	3	1	0	0	0	0	0	37	30	0	0	0
	6	11/04/06	0	0	0	0	0	0	0	0	30	500	200	0
	7	12/17/06	0	0	0	0	0	0	0	0	0	0	500	0
	8	01/21/07	0	0	0	0	0	0	0	0	0	0	250	0
	9	03/11/07	0	0	0	0	0	0	0	0	0	0	50	0
	10	05/22/07	0	0	0	0	0	0	0	0	0	0	0	0

Fl = Flowers, Fr = Fruits, B= Buds

Appendix D continued

SITE	Inspection	Date	R. mangle			A. germinans			L. racemosa			Schinus		
			Fl	Fr	B	Fl	Fr	B	Fl	Fr	B			
KEL														
	0	07/19/05	16	4	41	0	0	3	0	0	36	0	0	8
	1	08/07/05	36	0	44	0	0	10	0	0	5	0	0	5
	2	09/04/05	20	12	36	0	5	0	0	0	2	0	0	0
	3	10/12/05	18	12	51	0	3	0	0	0	0	150	0	350
	4	11/21/05	23	13	12	0	0	3	0	0	0	0	0	25
	5	01/20/06	11	13	6	0	0	0	0	0	0	0	0	0
	6	02/01/06	6	16	0	0	0	3	0	0	0	0	0	0
	7	04/18/06	0	16	3	0	0	0	0	0	0	0	0	0
	8	05/21/06	0	18	4	0	0	0	0	0	0	0	0	0
	9	06/28/06	7	13	85	0	0	3	0	0	30	0	0	0
	10	07/30/06	66	11	35	0	0	0	0	0	105	0	0	50
	11	09/17/06	7	20	0	0	0	0	0	22	0	0	0	30
	12	11/16/06	3	19	1	0	0	0	0	0	0	0	0	0
	13	12/28/06	0	16	1	0	0	0	0	0	0	0	0	0
	14	03/04/07	0	10	0	0	0	0	0	0	0	0	0	0
	15	05/29/07	0	15	0	0	0	0	0	0	0	0	0	0
CNS		02/26/05				0	0	2	0	0	0			
	1	04/03/05				0	0	0	0	0	0			
	2	05/05/05				0	0	0	0	0	12			
	3	06/07/05				0	3	19	0	0	109			
	4	07/06/05				3	15	72	70	0	26			
	5	08/22/05				0	0	4	0	0	5			
	6	10/12/05				0	3	0	0	0	0			
	7	11/12/05				0	0	0	0	0	0			
	8	01/20/06				0	0	0	0	0	0			
	9	02/17/06				0	0	0	0	0	0			
	10	04/22/06				0	0	0	0	0	0			
	11	05/21/06				0	0	30	0	0	0			
	12/13	07/30/06				0	0	12	0	0	10			
	14	09/17/06				0	50	0	0	15	0			
	15	11/13/06				0	0	0	0	0	0			
	16	12/28/06				0	0	0	0	0	0			
	17	03/04/07				0	0	0	0	0	0			
	18/19	06/04/07				0	0	0	0	0	0			

Fl = Flowers, Fr = Fruits, B= Buds

Appendix D continued

SITE	Inspection	Date	*R. mangle*			*A. germinans*			*L. racemosa*			*Schinus*		
			Fl	Fr	B	Fl	Fr	B	Fl	Fr	B			
LP	0	02/24/05	0	0	0	0	0	0	0	0	0			
	1	04/12/05	0	0	0	0	0	0	0	0	0			
	2	05/09/05	0	0	0	0	0	0	0	0	0			
	3	06/14/05	0	0	0	0	0	0	0	0	0			
	4	07/07/05	0	20	0	0	0	0	0	0	142			
	5	08/08/05	6	0	45	0	0	0	0	0	25			
	6	09/10/05	13	5	6	0	0	0	0	0	0			
	7	11/03/05	0	7	21	0	0	0	0	0	0			
	8	12/01/05	7	11	7	0	0	0	0	0	0			
	9	01/04/06	1	8	3	0	0	0	0	0	0			
	10	02/23/06	0	9	1	0	0	0	0	0	0			
	11	04/25/06	0	8	0	0	0	0	0	0	0			
	12	05/31/06	0	7	0	0	0	6	0	0	0			
	13	07/10/06	0	8	20	6	0	12	10	0	40			
	14	08/22/06	10	7	0	0	0	0	0	0	53			
	15	10/30/06	0	0	0	0	0	0	0	0	0			
	16	12/18/06	0	0	0	0	0	0	0	0	0			
	17	02/06/07	0	0	0	0	0	0	0	0	0			
	18	03/25/07	0	0	0	0	0	0	0	0	0			
	19	06/04/07	0	0	0	0	0	0	0	0	0			
CP	0	02/24/05	0	0	4	0	0	0	0	0	0	0	0	0
	1	04/12/05	0	1	5	0	0	0	0	0	0	0	0	0
	2	05/09/05	0	4	8	0	0	0	0	0	0	0	0	0
	3	06/14/05	0	3	5	0	0	7	0	0	0	0	0	0
	4	07/21/05	0	9	19	47	0	58	0	0	30	0	0	0
	5	08/08/05	13	9	22	3	0	10	0	0	35	0	0	0
	6	09/10/05	0	1	0	0	37	0	0	31	0	0	0	0
	7	11/03/05	0	3	0	0	20	0	0	0	0	0	0	0
	8	12/01/05	0	0	0	0	1	0	0	0	0	0	0	0
	9	01/16/06	0	0	2	0	0	0	0	0	0	0	0	0
	10	02/23/06	0	0	0	0	0	0	0	0	0	0	0	0
	11	04/25/06	0	0	0	0	0	0	0	0	0	0	0	0
	12	05/31/06	0	0	0	0	0	25	0	0	30	0	0	0
	13	07/10/06	0	0	10	5	0	310	0	0	70	0	0	0
	14	08/22/06	5	13	20	4	5	12	0	0	19	0	0	0
	15	10/30/06	0	7	0	0	11	0	0	11	0	0	0	0
	16	12/18/06	0	11	0	0	2	0	0	0	0	0	0	0
	17	02/06/07	2	9	0	0	0	0	0	0	0	0	0	0
	18	03/25/07	0	11	0	0	0	0	0	0	0	0	0	0
	19	06/04/07	0	9	0	0	0	55	0	0	0	0	0	0

Fl = Flowers, Fr = Fruits, B= Buds

Appendix D Continued

SITE	Inspection	Date	R. mangle			A. germinans			L. racemosa			Schinus
			Fl	Fr	B	Fl	Fr	B	Fl	Fr	B	
	1	04/24/05				0	0	0	0	0	0	
	2	05/25/05				0	0	6	0	0	0	
	3	06/21/05				0	0	35	0	0	150	
	4	07/22/05				10	0	44	108	0	156	
	5	08/17/05				0	0	0	0	0	310	
	6	09/23/05				0	6	5	0	255	0	
	7	11/11/05				0	6	0	0	11	0	
	8	01/06/06				0	0	0	0	0	0	
	9	02/01/06				0	0	0	0	0	0	
	10	03/14/06				0	0	0	0	0	0	
	11	03/30/06				0	0	0	0	0	0	
	12	05/01/06				0	0	17	0	0	0	
	13	06/05/06				1	0	136	0	0	3	
	14	08/11/06				1	0	140	2	0	80	
	15	10/16/06				0	192	24	0	87	0	
	16	12/04/06				2	14	103	0	0	0	
	17	01/05/07				0	4	13	0	0	0	
	18	02/20/07				0	0	35	0	0	0	
	19	04/25/07				0	0	72	0	0	15	
ASP	0	03/14/05				0	0	0				
	1	04/24/05				0	0	0				
	2	05/25/05				0	0	22				
	3	06/21/05				0	5	149				
	4	07/22/05				19	0	114				
	5	08/17/05				0	0	11				
	6	09/23/05				0	12	0				
	7	11/11/05				0	6	0				
	8	12/28/05				0	0	0				
	9	02/01/06				0	0	0				
	10	03/14/06				0	0	0				
	11	03/30/06				0	0	0				
	12	05/01/06				0	0	4				
	13	06/01/06				0	0	55				
	14	08/11/06				2	0	90				
	15	10/16/06				0	82	2				
	16	12/03/06				0	16	14				
	17	01/15/07				0	2	5				
	18	02/20/07				0	2	0				
	19	04/25/07				0	0	5				

Fl = Flowers, Fr = Fruits, B= Buds

Appendix D continued

SITE	Inspection	Date	R. mangle			A. germinans			L. racemosa			Schinus		
			Fl	Fr	B	Fl	Fr	B	Fl	Fr	B	Fl	Fr	B
GP	0	04/21/05				0	0	0						
	1	05/25/05				0	0	0						
	2	06/21/05				0	0	6						
	3	07/22/05				0	0	5						
	4	08/17/05				0	0	0						
	5	09/23/05				0	0	0						
	6	11/11/05				0	0	0						
	7	12/28/05				0	0	0						
	8	02/01/06				0	0	0						
	9	03/14/06				0	0	0						
	10	03/30/06				0	0	0						
	11	05/01/06				0	0	33						
	12	06/05/06				1	0	132						
	13	08/10/06				0	0	59						
	14	10/07/06				0	14	0						
	15	12/03/06				0	2	0						
	16	01/15/07				0	3	0						
	17	02/20/07				0	0	0						
	18	04/25/07				0	0	13						
TIT	0	06/07/05										0	0	13
	1	07/06/05										0	0	13
	2	08/09/05										0	0	13
	3	10/12/05										23	0	2000
	4	11/21/05										0	750	13
	5	01/20/06										0	10	13
	6	02/27/06										0	4	13
	7	04/22/06										0	0	13

Fl = Flowers, Fr = Fruits, B= Buds

APPENDIX E. INITIAL STEM DIAMETER AND GROWTH

SITE	R. mangle		A. germinans		L. racemosa		S. terebinthifolius	
	Init. Dia.	growth	Init. Dia.	growth	Init. Dia.	growth	Init. Dia.	growth
SEB	5.62	1.00	1.40	1.01	1.59	1.02		
	1.45	1.01	0.94	1.01	2.63	1.00		
	1.03	1.01	0.39	0.99	3.30	1.00		
	1.68	1.01	2.16	1.02	2.67	1.00		
	1.38	1.02	1.74	1.00	0.66	1.01		
	0.41	1.01	1.45	1.02	1.86	1.00		
	3.07	1.01	3.50	1.00	8.21	1.01		
	1.45	1.01	6.61	1.00	1.41	1.01		
	0.89	1.00	1.32	1.00	1.09	1.00		
	2.51	1.00	7.63	1.00	5.37	1.00		
	0.59	1.01	2.69	1.00	0.70	1.01		
	0.71	1.01	2.53	1.00	0.70	1.02		
ROT	4.70	1.00	3.74	1.01	6.05	1.00	4.67	1.00
	0.93	1.00	1.18	1.00	2.58	1.00	2.42	1.00
	0.97	1.00	0.50	1.01	1.57	1.01	0.93	1.01
	3.50	1.01	5.56	1.00	4.20	1.00	3.94	1.00
	1.50	1.01	3.27	1.00	1.44	1.00	1.54	1.00
	1.73	1.03	1.66	1.00	1.05	1.00	1.43	1.01
	1.62	1.00	6.58	1.00	7.72	1.00	2.31	1.05
	0.75	1.00	1.82	1.01	1.25	1.00	0.44	1.01
	0.92	1.00	0.56	1.03	4.00	1.00	0.92	1.02
	1.20	1.01			5.54	1.02	7.93	1.00
	0.56	1.02			3.41	1.01	5.19	1.00
	0.42	1.02			1.17	1.00	0.62	1.00
KEL	4.81	1.01	3.14	1.01	7.23	1.00	3.19	1.03
	1.52	1.03	1.88	1.01	0.59	1.01	1.51	1.06
	1.22	1.04	0.35	0.98	0.83	0.99	0.71	1.01
	4.25	0.99	2.32	1.00	4.88	1.00	1.66	1.04
	1.50	1.01	0.77	1.00	0.77	1.01	0.41	1.09
	0.69	1.01	1.05	1.00	1.10	1.01	0.69	1.07
	2.68	0.97	5.54	1.01	3.72	1.00		
	0.77	0.99	1.99	1.01	1.63	1.01		
	0.93	1.00	0.72	1.00	0.69	1.00		
					4.39	1.00		
					1.05	1.02		
					1.04	1.00		
CNS			1.67	1.03	1.87	1.02		
			0.57	1.02	0.86	1.06		
			0.34	1.03	0.53	1.01		
			2.45	1.01	2.59	1.02		
			1.13	1.01	1.85	1.03		
			0.64	1.01	0.69	1.01		
			5.36	1.01	2.01	1.01		
			1.96	0.98	0.63	1.05		
			2.46	1.00	0.77	1.04		
			3.60	1.02	2.60	1.00		
			0.85	1.03	0.72	1.02		
			0.98	1.01	0.53	1.01		
			5.77	1.01	2.79	1.03		
			1.84	1.02	2.20	1.02		
			1.31	1.01	1.32	1.03		
TIT							1.06	1.05
							1.54	1.03
							0.80	1.05
							3.09	1.00
							0.89	1.02
							1.35	1.03
							2.19	1.03
							0.53	1.02
							0.73	1.04
							5.21	1.00
							1.39	1.00
							0.99	1.02

Appendix E continued

SITE	R. mangle		A. germinans		L. racemosa		S. terebinthifolius	
	Init. Dia.	growth	Init. Dia.	growth	Init. Dia.	growth	Init. Dia.	growth
LP	1.49	1.02	2.00	1.02	1.70	1.01		
	0.97	1.02	1.50	1.02	0.70	1.02		
	0.72	1.01	0.79	1.02	0.40	1.02		
	1.55	1.01	3.33	1.00	1.55	1.01		
	0.89	1.02	0.73	1.01	0.97	1.02		
	0.54	0.99	1.92	1.01	0.78	1.01		
	1.50	1.00	1.50	0.98	1.48	1.01		
	2.00	1.01	2.79	1.01	0.69	1.02		
	2.00	1.01	0.77	1.00	0.40	0.99		
	2.00	1.01	0.46	1.01	1.27	1.01		
	2.50	1.01	2.69	1.01	0.54	1.01		
	1.50	1.02	0.60	1.01	0.54	0.99		
			1.13	1.02				
CP	2.59	1.01	1.46	1.01	2.69	1.01	1.34	1.02
	0.79	1.02	0.73	1.02	1.68	1.00	3.57	1.02
	0.87	1.01	0.37	0.99	0.89	1.00	3.23	1.05
	2.58	1.03	2.55	1.02	1.70	1.02	1.82	1.01
	1.05	1.04	0.81	1.01	1.19	1.00	1.32	1.02
	0.68	1.00	0.54	1.05	0.63	1.01	1.13	1.03
	1.42	1.00	1.11	1.00	1.91	1.01	2.83	1.01
	1.37	0.99	0.74	1.01	1.68	0.99	0.91	0.99
	0.84	1.03	0.47	1.01	0.40	1.01	0.69	1.00
	1.72	1.02	3.06	1.00	2.18	1.00		
	0.69	1.02	0.76	1.00	0.65	1.02		
	1.02	1.00	0.42	1.02	0.45	1.00		
GTM			2.49	1.00	1.39	1.02		
			0.90	1.01	0.72	1.03		
			0.46	1.04	0.87	1.03		
			1.04	1.02	0.65	1.02		
			0.58	1.04	0.39	1.04		
			0.45	1.05	1.32	1.01		
			2.41	1.01	1.13	1.02		
			0.51	1.05	0.76	1.03		
			1.84	1.01	0.29	1.04		
			3.07	1.00	0.60	1.01		
			1.50	1.01	0.47	0.99		
			0.86	1.01	0.52	1.00		
			4.67	1.00				
			0.93	1.01				
			0.97	1.02				
			1.45	1.02				
			0.97	1.01				
			0.35	1.02				
			2.04	1.00				
			0.61	1.01				
			0.79	1.01				
			4.13	1.00				
			0.74	1.01				
			2.41	1.00				
			2.36	0.99				
			0.85	1.00				
			0.45	1.02				

Appendix E continued

SITE	R. mangle		A. germinans		L. racemosa		S. terebinthifolius	
	Init. Dia.	growth	Init. Dia.	growth	Init. Dia.	growth	Init. Dia.	growth
ASP			1.44	1.02				
			0.36	1.07				
			0.61	0.99				
			3.86	1.00				
			0.72	1.03				
			1.72	1.02				
			2.12	1.03				
			0.57	1.03				
			0.78	1.02				
			1.73	1.02				
			0.53	1.05				
			0.59	1.02				
			1.19	1.02				
			0.45	1.02				
			1.39	1.00				
			1.32	1.02				
			0.79	1.02				
			0.53	1.02				
			0.83	1.03				
			0.42	1.06				
			0.45	0.97				
			1.78	1.02				
			0.31	1.05				
			0.29	1.04				
			1.19	1.02				
			0.91	1.02				
			0.43	1.03				
GP			4.25	1.01				
			1.27	1.02				
			2.16	1.02				
			1.89	1.01				
			0.93	1.00				
			1.22	1.00				
			2.62	1.01				
			0.95	1.01				
			1.95	1.01				
			2.63	1.01				
			0.84	1.01				
			0.53	1.01				
			3.18	1.01				
			0.90	1.01				
			0.83	1.00				
			2.98	1.00				
			0.75	1.01				
			0.48	1.00				

APPENDIX F. SITE CALENDAR
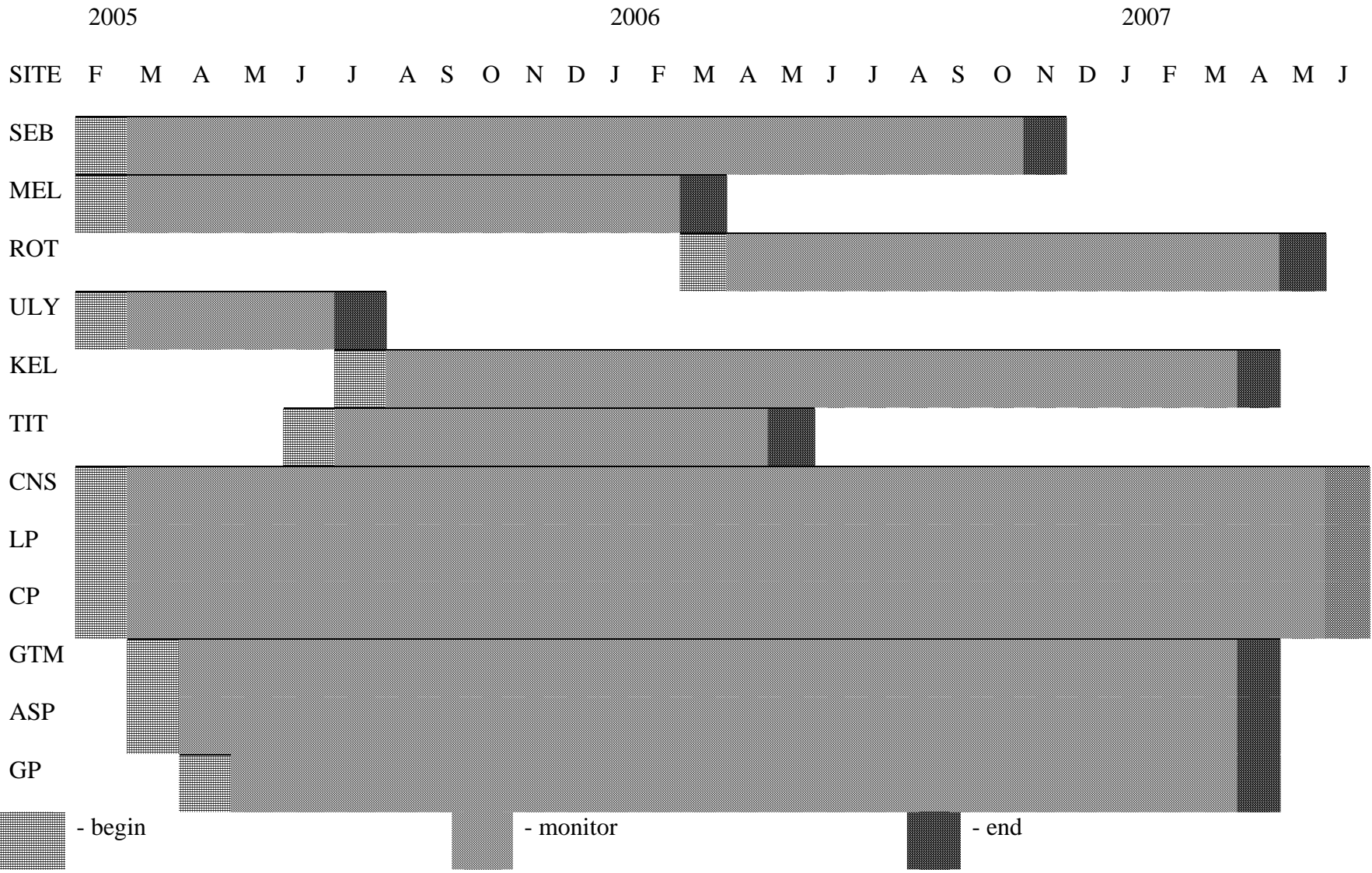
APPENDIX G. MANGRO CODE

AvD[tree](t) = AvD[tree](t - dt) + (Avgrowth[tree] - AvMortality[tree]) * dt
INIT AvD[tree] = 0
INFLOWS:
Avgrowth[tree] = (((AVG*Av_gap[tree]*(1-
(Av_Gap[tree]*AvH[tree])/(AvDmax*AvHmax)))/(274+3*Avb2*Av_gap[tree]-
4*Avb3*Av_Gap[tree]^2))*AvTDEGD*AvrAL[tree]*AvSSALT)*AvDeath[tree]*Av_Failure_t
o_Grow[tree]
OUTFLOWS:
AvMortality[tree] = if(AvDeath[tree]=0 or Av_Failure_to_Grow[tree]=0) then AvD[tree] else 0
LaD[tree](t) = LaD[tree](t - dt) + (Lagrowth[tree] - LaMortality[tree]) * dt
INIT LaD[tree] = 0
INFLOWS:
Lagrowth[tree] = ((LaG*La_Gap[tree]*(1-
(La_Gap[tree]*LaH[tree])/(LaDmax*LaHmax)))/(274+3*Lab2*La_Gap[tree]-
4*Lab3*La_Gap[tree]^2))*LarAL[tree]*LaSSALT*LaTDEGD*LaDeath[tree]*
La_Failure_to_Grow[tree]
OUTFLOWS:
LaMortality[tree] = if (LaDeath[tree]=0 or La_Failure_to_Grow[tree]=0) then LaD[tree] else 0
RhD[tree](t) = RhD[tree](t - dt) + (Rhgrowth[tree] - Rhmortality[tree]) * dt
INIT RhD[tree] = 0
INFLOWS:
Rhgrowth[tree] = ((RhG*Rh_Gap[tree]*(1-
(Rh_Gap[tree]*RhH[tree])/(RhDmax*RhHmax)))/(274+3*Rhb2*Rh_gap[tree]-
4*Rhb3*Rh_Gap[tree]^2))*rAL[tree]*RhSSALT*RhTDEGD*Rhdeath[tree]*Rh_Failure_to_Gr
ow[tree]
OUTFLOWS:
Rhmortality[tree] = if (RhDeath[tree]=0 or Rh_Failure_to_Grow[tree]=0) then RhD[tree] else 0
SD[tree](t) = SD[tree](t - dt) + (Sgrowth[tree] - SMortality[tree]) * dt
INIT SD[tree] = 0
INFLOWS:
Sgrowth[tree] = ((SG*S_Gap[tree]*(1-
(S_Gap[tree]*SH[tree])/(SDmax*SHmax)))/(274+3*SLab2*S_Gap[tree]-
4*SLab3*S_Gap[tree]^2))*SrAL[tree]*SSSALT*STDEGD*SDeath[tree]*
S_Failure_to_Grow[tree]
OUTFLOWS:
SMortality[tree] = if (SDeath[tree]=0 or S_Failure_to_Grow[tree]=0) then SD[tree] else 0
Av_Area_Array[tree] = Pi*(AvD[tree]/2)^2
Av_Basal_Area = ARRAYSUM(Av_Area_Array[*])
Av_Count = ARRAYSUM(Av_Count_Arrary[*])
Av_Count_Arrary[tree] = if AvD[tree]>0 then 1 else 0
Av_Failure_to_Grow[tree] = if (time >0 AND (AvD[tree]>0 or AvD[tree]<0) AND AvD[tree]-
HISTORY(AvD[tree],time-1)<.01) then 0 else 1
Av_Gap[tree] = if (AvD[tree]=0) then (if (Random_Seedling[tree]<=.30) then 1.25 else 0) else
AvD[tree]
AvAGEmax = 300
AvAL[tree] = exp(-(AvTOTAL_LAI_above_tree[tree])*Avk)
Avb2 = 48.04
Avb3 = .172

Appendix G continued

AvDeath[tree] = if(Avrandomd[tree]<4.605/AvAGEmax) then 0 else 1
AvDiamSort[tree] = int((AvD[tree])/10)
AvDmax = 140
AVG = 162
AvH[tree] = (137+Avb2*Av_Gap[tree]-Avb3*Av_Gap[tree]^2)
AvHmax = 3500
Avk = .525
Avrandomd[tree] = RANDOM(0,1)
AvTOTAL_LAI_above_tree[tree] = if (AvDiamSort[tree]=14) then 0 else if
(AvDiamSort[tree]=13) then LAI_greater_13 else
if (AvDiamSort[tree]=12) then LAI_greater_12 else if (AvDiamSort[tree]=11) then
LAI_greater_11 else
if (AvDiamSort[tree]=10) then LAI_greater_10 else if (AvDiamSort[tree]=9) then
LAI_greater_9 else
if (AvDiamSort[tree]=8) then LAI_greater_8 else if (AvDiamSort[tree]=7) then LAI_greater_7
else
if (AvDiamSort[tree]=6) then LAI_greater_6 else if (AvDiamSort[tree]=5) then LAI_greater_5
else
if (AvDiamSort[tree]=4) then LAI_greater_4 else if (AvDiamSort[tree]=3) then LAI_greater_3
else
if (AvDiamSort[tree]=2) then LAI_greater_2 else if (AvDiamSort[tree]=1) then LAI_greater_1
else
if (AvDiamSort[tree]=0) then LAI_greater__0 else 1
c = .00019283295
D0[tree] = (if (AvDiamSort[tree]=0) then 1 else 0) + (if (RhDiamSort[tree]=0) then 1 else 0) +
(if (LaDiamSort[tree]=0) then 1 else 0) +(if (SDiamSort[tree]=0) then 1 else 0)
D1[tree] = (if (AvDiamSort[tree]=1) then 1 else 0) + (if (RhDiamSort[tree]=1) then 1 else 0) +
(if (LaDiamSort[tree]=1) then 1 else 0) + (if (SDiamSort[tree]=1) then 1 else 0)
D10[tree] = (if (AvDiamSort[tree]=10) then 1 else 0) + (if (RhDiamSort[tree]=10) then 1 else 0)
+ (if (LaDiamSort[tree]=10) then 1 else 0) + (if (SDiamSort[tree]=10) then 1 else 0)
D11[tree] = (if (AvDiamSort[tree]=11) then 1 else 0) + (if (RhDiamSort[tree]=11) then 1 else 0)
+ (if (LaDiamSort[tree]=11) then 1 else 0) + (if (SDiamSort[tree]=11) then 1 else 0)
D12[tree] = (if (AvDiamSort[tree]=12) then 1 else 0) + (if (RhDiamSort[tree]=12) then 1 else 0)
+ (if (LaDiamSort[tree]=12) then 1 else 0) + (if (SDiamSort[tree]=12) then 1 else 0)
D13[tree] = (if (AvDiamSort[tree]=13) then 1 else 0) + (if (RhDiamSort[tree]=13) then 1 else 0)
+ (if (LaDiamSort[tree]=13) then 1 else 0) + (if (SDiamSort[tree]=13) then 1 else 0)
D14[tree] = (if (AvDiamSort[tree]=14) then 1 else 0) + (if (RhDiamSort[tree]=14) then 1 else 0)
+ (if (LaDiamSort[tree]=14) then 1 else 0) + (if (SDiamSort[tree]=14) then 1 else 0)
D2[tree] = (if (AvDiamSort[tree]=2) then 1 else 0) + (if (RhDiamSort[tree]=2) then 1 else 0) +
(if (LaDiamSort[tree]=2) then 1 else 0) + (if (SDiamSort[tree]=2) then 1 else 0)
D3[tree] = (if (AvDiamSort[tree]=3) then 1 else 0) + (if (RhDiamSort[tree]=3) then 1 else 0) +
(if (LaDiamSort[tree]=3) then 1 else 0) + (if (SDiamSort[tree]=3) then 1 else 0)
D4[tree] = (if (AvDiamSort[tree]=4) then 1 else 0) + (if (RhDiamSort[tree]=4) then 1 else 0) +
(if (LaDiamSort[tree]=4) then 1 else 0) + (if (SDiamSort[tree]=4) then 1 else 0)
D5[tree] = (if (AvDiamSort[tree]=5) then 1 else 0) + (if (RhDiamSort[tree]=5) then 1 else 0) +
(if (LaDiamSort[tree]=5) then 1 else 0) + (if (SDiamSort[tree]=5) then 1 else 0)

D6[tree] = (if (AvDiamSort[tree]=6) then 1 else 0) + (if (RhDiamSort[tree]=6) then 1 else 0) + (if (LaDiamSort[tree]=0) then 1 else 0) + (if (SDiamSort[tree]=6) then 1 else 0)

D7[tree] = (if (AvDiamSort[tree]=7) then 1 else 0) + (if (RhDiamSort[tree]=7) then 1 else 0) + (if (LaDiamSort[tree]=7) then 1 else 0) + (if (SDiamSort[tree]=3) then 1 else 0)

D8[tree] = (if (AvDiamSort[tree]=8) then 1 else 0) + (if (RhDiamSort[tree]=8) then 1 else 0) + (if (LaDiamSort[tree]=8) then 1 else 0) + (if (SDiamSort[tree]=8) then 1 else 0)

D9[tree] = (if (AvDiamSort[tree]=9) then 1 else 0) + (if (RhDiamSort[tree]=9) then 1 else 0) +(if (LaDiamSort[tree]=9) then 1 else 0) + (if (SDiamSort[tree]=9) then 1 else 0)

DEGD = 9500

La_Area_Array[tree] = Pi*(LaD[tree]/2)^2

La_Basal_Area = ARRAYSUM(La_Area_Array[*])

La_Count = ARRAYSUM(La_Count_Array[*])

La_Count_Array[tree] = if LaD[tree] > 0 then 1 else 0

La_Failure_to_Grow[tree] = if (time >0 AND (LaD[tree]>0 or LaD[tree]<0) AND LaD[tree]-HISTORY(LaD[tree],time-1)<.01) then 0 else 1

La_Gap[tree] = if (LaD[tree]=0) then (if (Random_Seedling[tree]>.30 AND Random_Seedling[tree]<.45) then 1.25 else 0) else LaD[tree]

LaAGEmax = 200

LaAL[tree] = exp(-(LaTOTAL_LAI_above_tree[tree]*Lak))

Lab2 = 71.58

Lab3 = 0.447

LaDeath[tree] = if(Larandomd[tree] <4.605/LaAGEmax) then 0 else 1

LaDiamSort[tree] = int((LaD[tree])/10)

LaDmax = 80

LaG = 243

LaH[tree] = 137+Lab2*La_gap[tree]-Lab3*La_Gap[tree]^2

LaHmax = 3000

LAI_0 = (c*(0^2.129))*ARRAYSUM(D0[*])

LAI_1 = (c*(1^2.129))*ARRAYSUM(D1[*])

LAI_10 = (c*(10^2.129))*ARRAYSUM(D10[*])

LAI_11 = (c*(11^2.129))*ARRAYSUM(D11[*])

LAI_12 = (c*(12^2.129))*ARRAYSUM(D12[*])

LAI_13 = (c*(13^2.129))*ARRAYSUM(D13[*])

LAI_14 = (c*(14^2.129))*ARRAYSUM(D14[*])

LAI_2 = (c*(2^2.129))*ARRAYSUM(D2[*])

LAI_3 = (c*(3^2.129))*ARRAYSUM(D3[*])

LAI_4 = (c*(4^2.129))*ARRAYSUM(D4[*])

LAI_5 = (c*(5^2.129))*ARRAYSUM(D5[*])

LAI_6 = (c*(6^2.129))*ARRAYSUM(D6[*])

LAI_7 = (c*(7^2.129))*ARRAYSUM(D7[*])

LAI_8 = (c*(8^2.129))*ARRAYSUM(D8[*])

LAI_9 = (c*(9^2.129))*ARRAYSUM(D9[*])

LAI_greater__0 = LAI_1+LAI_2+LAI_3+LAI_4+LAI_5+LAI_6+LAI_7+LAI_greater_7

LAI_greater_1 = LAI_2+LAI_3+LAI_4+LAI_5+LAI_6+LAI_7+LAI_greater_7

LAI_greater_10 = LAI_11+LAI_12+LAI_13+LAI_14

LAI_greater_11 = LAI_12+LAI_13+LAI_14

LAI_greater_12 = LAI_13+LAI_14
LAI_greater_13 = LAI_14
LAI_greater_2 = LAI_3+LAI_4+LAI_5+LAI_6+LAI_7+LAI_greater_7
LAI_greater_3 = LAI_4+LAI_5+LAI_6+LAI_7+LAI_greater_7
LAI_greater_4 = LAI_5+LAI_6+LAI_7+LAI_greater_7
LAI_greater_5 = LAI_6+LAI_7+LAI_greater_7
LAI_greater_6 = LAI_7+LAI_greater_7
LAI_greater_7 = LAI_8+LAI_9+LAI_10+LAI_11+LAI_12+LAI_13+LAI_14
LAI_greater_8 = LAI_9+LAI_10+LAI_11+LAI_12+LAI_13+LAI_14
LAI_greater_9 = LAI_10+LAI_11+LAI_12+LAI_13+LAI_14
Lak = .525
Larandomd[tree] = RANDOM(0,1)
LaTOTAL_LAI_above_tree[tree] = if (LaDiamSort[tree]=14) then 0 else if
(LaDiamSort[tree]=13) then LAI_greater_13 else
if (LaDiamSort[tree]=12) then LAI_greater_12 else if (LaDiamSort[tree]=11) then
LAI_greater_11 else
if (LaDiamSort[tree]=10) then LAI_greater_10 else if (LaDiamSort[tree]=9) then LAI_greater_9
else
if (LaDiamSort[tree]=8) then LAI_greater_8 else if (LaDiamSort[tree]=7) then LAI_greater_7
else
if (LaDiamSort[tree]=6) then LAI_greater_6 else if (LaDiamSort[tree]=5) then LAI_greater_5
else
if (LaDiamSort[tree]=4) then LAI_greater_4 else if (LaDiamSort[tree]=3) then LAI_greater_3
else
if (LaDiamSort[tree]=2) then LAI_greater_2 else if (LaDiamSort[tree]=1) then LAI_greater_1
else
if (LaDiamSort[tree]=0) then LAI_greater__0 else 1
Random_Seedling[tree] = Random(0,1)
Rh_Area_Array[tree] = Pi*(RhD[tree]/2)^2
Rh_Basal_Area = ARRAYSUM(Rh_Area_Array[*])
Rh_Count = ARRAYSUM(Rh_Count_Array[*])
Rh_Count_Array[tree] = if RhD[tree]>0 then 1 else 0
Rh_Failure_to_Grow[tree] = if (time >0 AND (RhD[tree]>0 or RhD[tree]<0) AND RhD[tree]-
HISTORY(RhD[tree],time-1)<.01) then 0 else 1
Rh_Gap[tree] = if (RhD[tree]=0) then (if (Random_Seedling[tree]>.15 AND
Random_Seedling[tree]<.30) then 1.25 else 0) else RhD[tree]
RhAGEmax = 250
RhAL[tree] = exp(-RhTOTAL_LAI_above_tree[tree]*Rhk)
Rhb2 = 77.26
Rhb3 = 0.386
Rhdeath[tree] = if(Rhrandomd[tree] <4.605/RhAGEmax) then 0 else 1
RhDiamSort[tree] = int((RhD[tree])/10)
RhDmax = 100
RhG = 267
RhH[tree] = 137+Rhb2*Rh_Gap[tree]-Rhb3*Rh_Gap[tree]^2
RhHmax = 4000

Rhk = .525
Rhrandomd[tree] = random(0,1)
RhTOTAL_LAI_above_tree[tree] = if (RhDiamSort[tree]=14) then 0 else if
(RhDiamSort[tree]=13) then LAI_greater_13 else
if (RhDiamSort[tree]=12) then LAI_greater_12 else if (RhDiamSort[tree]=11) then
LAI_greater_11 else
if (RhDiamSort[tree]=10) then LAI_greater_10 else if (RhDiamSort[tree]=9) then
LAI_greater_9 else
if (RhDiamSort[tree]=8) then LAI_greater_8 else if (RhDiamSort[tree]=7) then LAI_greater_7
else
if (RhDiamSort[tree]=6) then LAI_greater_6 else if (RhDiamSort[tree]=5) then LAI_greater_5
else
if (RhDiamSort[tree]=4) then LAI_greater_4 else if (RhDiamSort[tree]=3) then LAI_greater_3
else
if (RhDiamSort[tree]=2) then LAI_greater_2 else if (RhDiamSort[tree]=1) then LAI_greater_1
else
if (RhDiamSort[tree]=0) then LAI_greater__0 else 1
S_AL[tree] = exp(-(STOTAL_LAI_above_tree[tree]*Sk))
S_Area_Array_S[tree] = Pi*(SD[tree]/2)^2
S_Basal_Area = ARRAYSUM(S_Area_Array_S[*])
S_Count = ARRAYSUM(S_Count_Array[*])
S_Count_Array[tree] = if SD[tree] > 0 then 1 else 0
S_Failure_to_Grow[tree] = if (time >0 AND (SD[tree]>0 or SD[tree]<0) AND SD[tree]-
HISTORY(SD[tree],time-1)<.01) then 0 else 1
S_Gap[tree] = if (SD[tree]=0) then (if (Random_Seedling[tree]>.30 AND
Random_Seedling[tree]<=.60) then 1.25 else 0) else SD[tree]
SAGEmax = 200
Salinity = 20
SDeath[tree] = if(Srandomd[tree] <4.605/SAGEmax) then 0 else 1
SDiamSort[tree] = int((SD[tree])/10)
SDmax = 100
SG = 150
SH[tree] = 137+SLab2*S_Gap[tree]-SLab3*S_Gap[tree]^2
SHmax = 1500
Sk = .525
SLab2 = 27.26
SLab3 = 0.136
Srandomd[tree] = RANDOM(0,1)
STOTAL_LAI_above_tree[tree] = if (SDiamSort[tree]=14) then 0 else if (SDiamSort[tree]=13)
then LAI_greater_13 else
if (SDiamSort[tree]=12) then LAI_greater_12 else if (SDiamSort[tree]=11) then LAI_greater_11
else
if (SDiamSort[tree]=10) then LAI_greater_10 else if (SDiamSort[tree]=9) then LAI_greater_9
else
if (SDiamSort[tree]=8) then LAI_greater_8 else if (SDiamSort[tree]=7) then LAI_greater_7 else
if (SDiamSort[tree]=6) then LAI_greater_6 else if (SDiamSort[tree]=5) then LAI_greater_5 else

if (SDiamSort[tree]=4) then LAI_greater_4 else if (SDiamSort[tree]=3) then LAI_greater_3 else
if (SDiamSort[tree]=2) then LAI_greater_2 else if (SDiamSort[tree]=1) then LAI_greater_1 else
if (SDiamSort[tree]=0) then LAI_greater__0 else 1

AvrAL[tree] = GRAPH(AvAL[tree])
(0.00, -0.023), (0.05, 0.188), (0.1, 0.356), (0.15, 0.49), (0.2, 0.595), (0.25, 0.679), (0.3, 0.746),
(0.35, 0.798), (0.4, 0.84), (0.45, 0.873), (0.5, 0.899), (0.55, 0.92), (0.6, 0.937), (0.65, 0.95), (0.7,
0.96), (0.75, 0.968), (0.8, 0.975), (0.85, 0.98), (0.9, 0.984), (0.95, 0.988), (1.00, 0.99)

AvSSALT = GRAPH(Salinity)
(0.00, 1.00), (5.00, 1.00), (10.0, 1.00), (15.0, 1.00), (20.0, 1.00), (25.0, 1.00), (30.0, 0.999), (35.0,
0.999), (40.0, 0.997), (45.0, 0.992), (50.0, 0.981), (55.0, 0.955), (60.0, 0.897), (65.0, 0.779),
(70.0, 0.589), (75.0, 0.368), (80.0, 0.192), (85.0, 0.088), (90.0, 0.038), (95.0, 0.016), (100, 0.006)

AvTDEGD = GRAPH(DEGD)
(0.00, 0.00), (2500, 0.00), (5000, 0.00), (7500, 0.406), (10000, 0.666), (12500, 0.786), (15000,
0.851), (17500, 0.891), (20000, 0.916), (22500, 0.934), (25000, 0.947), (27500, 0.956), (30000,
0.963), (32500, 0.968), (35000, 0.973), (37500, 0.976), (40000, 0.979), (42500, 0.981), (45000,
0.983), (47500, 0.985), (50000, 0.987)

LarAL[tree] = GRAPH(LaAL[tree])
(0.00, 0.00), (0.05, 0.055), (0.1, 0.203), (0.15, 0.33), (0.2, 0.44), (0.25, 0.536), (0.3, 0.62), (0.35,
0.695), (0.4, 0.761), (0.45, 0.821), (0.5, 0.875), (0.55, 0.923), (0.6, 0.968), (0.65, 1.01), (0.7,
1.05), (0.75, 1.08), (0.8, 1.11), (0.85, 1.14), (0.9, 1.17), (0.95, 1.20), (1.00, 1.22)

LaSSALT = GRAPH(Salinity)
(0.00, 1.00), (5.00, 1.00), (10.0, 1.00), (15.0, 1.00), (20.0, 1.00), (25.0, 1.00), (30.0, 0.999), (35.0,
0.998), (40.0, 0.993), (45.0, 0.982), (50.0, 0.953), (55.0, 0.881), (60.0, 0.731), (65.0, 0.5), (70.0,
0.269), (75.0, 0.119), (80.0, 0.047), (85.0, 0.018), (90.0, 0.007), (95.0, 0.002), (100, 0.001)

LaTDEGD = GRAPH(DEGD)
(0.00, 0.00), (2500, 0.00), (5000, 0.00), (7500, 0.00), (10000, 0.417), (12500, 0.627), (15000,
0.741), (17500, 0.81), (20000, 0.854), (22500, 0.885), (25000, 0.907), (27500, 0.923), (30000,
0.935), (32500, 0.945), (35000, 0.952), (37500, 0.959), (40000, 0.964), (42500, 0.968), (45000,
0.971), (47500, 0.974), (50000, 0.977)

rAL[tree] = GRAPH(RhAL[tree])
(0.00, -0.023), (0.05, 0.188), (0.1, 0.356), (0.15, 0.49), (0.2, 0.595), (0.25, 0.679), (0.3, 0.746),
(0.35, 0.798), (0.4, 0.84), (0.45, 0.873), (0.5, 0.899), (0.55, 0.92), (0.6, 0.937), (0.65, 0.95), (0.7,
0.96), (0.75, 0.968), (0.8, 0.975), (0.85, 0.98), (0.9, 0.984), (0.95, 0.988), (1.00, 0.99)

RhSSALT = GRAPH(Salinity)
(0.00, 1.00), (5.00, 1.00), (10.0, 1.00), (15.0, 1.00), (20.0, 1.00), (25.0, 1.00), (30.0, 0.999), (35.0,
0.997), (40.0, 0.989), (45.0, 0.963), (50.0, 0.881), (55.0, 0.679), (60.0, 0.378), (65.0, 0.148),
(70.0, 0.047), (75.0, 0.014), (80.0, 0.004), (85.0, 0.001), (90.0, 0.00), (95.0, 0.00), (100, 0.00)

RhTDEGD = GRAPH(DEGD)
(0.00, 0.00), (2500, 0.00), (5000, 0.00), (7500, 0.00), (10000, 0.417), (12500, 0.627), (15000,
0.741), (17500, 0.81), (20000, 0.854), (22500, 0.885), (25000, 0.907), (27500, 0.923), (30000,
0.935), (32500, 0.945), (35000, 0.952), (37500, 0.959), (40000, 0.964), (42500, 0.968), (45000,
0.971), (47500, 0.974), (50000, 0.977)

SrAL[tree] = GRAPH(S_AL[tree])
(0.00, -0.023), (0.05, 0.188), (0.1, 0.356), (0.15, 0.49), (0.2, 0.595), (0.25, 0.679), (0.3, 0.746),
(0.35, 0.81), (0.4, 0.87), (0.45, 0.925), (0.5, 0.984), (0.55, 1.04), (0.6, 1.09), (0.65, 1.14), (0.7,
1.18), (0.75, 1.23), (0.8, 1.26), (0.85, 1.30), (0.9, 1.34), (0.95, 1.37), (1.00, 1.40)

Appendix G continued

SSSALT = GRAPH(Salinity)
(0.00, 1.00), (5.00, 1.00), (10.0, 1.00), (15.0, 0.99), (20.0, 0.9), (25.0, 0.8), (30.0, 0.7), (35.0, 0.00), (40.0, 0.00), (45.0, 0.00), (50.0, 0.00), (55.0, 0.00), (60.0, 0.00), (65.0, 0.00), (70.0, 0.00), (75.0, 0.00), (80.0, 0.00), (85.0, 0.00), (90.0, 0.00), (95.0, 0.00), (100, 0.00)
STDEGD = GRAPH(DEGD)
(0.00, 0.00), (2500, 0.00), (5000, 0.00), (7500, 0.406), (10000, 0.666), (12500, 0.786), (15000, 0.851), (17500, 0.891), (20000, 0.916), (22500, 0.934), (25000, 0.947), (27500, 0.956), (30000, 0.963), (32500, 0.968), (35000, 0.973), (37500, 0.976), (40000, 0.979), (42500, 0.981), (45000, 0.983), (47500, 0.985), (50000, 0.987)

APPENDIX H. MANGRO RUN PARAMETERS

Name	Run	DEGD start	DEGD end	Salinity start	Salinity end	*A. germinans*	*R. mangle*	*L. racemosa*	*S. terebinthifolius*
Bare Ground	1a	9500	9500	20	20	15	15	15	15
	1b	9500	9500	20	20	20	20	20	
	1c	7500	7500	20	20	15	15	15	15
	1d	7500	7500	20	20	20	20	20	
S. terebinthifolius invasion 1	2a	7500	7500	20	20	30			30
	2b	7500	7500	20	20	50			10
	2c	7500	7500	20	20	10			50
S. terebinthifolius invasion 2	3a	8500	8500	20	20	20		20	20
	3b	8500	8500	20	20	10		10	40
	3c	9500	9500	20	20	20		20	20
	3d	9500	9500	20	20	10		10	40
Global Climate Change (Warming)	4a	7500	9500	20	20	15	15	15	15
	4b	7500	9500	20	20	20	20	20	
Global Climate Change (Sea Level Rise)	5a	9500	9500	20	35	15	15	15	15
	5b	9500	9500	20	35	20	20	20	
	5c	7500	7500	20	35	15	15	15	15
	5d	7500	7500	20	35	20	20	20	
Global Climate Change Combo	6a	7500	9500	20	35	15	15	15	15
	6b	7500	9500	20	35	20	20	20	
Freeze	7a	9500	9500	20	20	15	15	15	15
	7b	9500	9500	20	20	20	20	20	

The DEGD and Salinity columns each have "start" and "end" sub-columns; the "Chance of seedling establishment" columns are *A. germinans*, *R. mangle*, *L. racemosa*, and *S. terebinthifolius*.

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