

**CARBON POOLS AND FLUXES AS AN
INDICATOR OF RIPARIAN RESTORATION**

by

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(ABSTRACT)

Riparian forests are integral components of the landscape. The inherent biogeochemical processes that occur in such forests provide numerous benefits to wildlife and society. Maintaining good water quality is a major benefit from riparian forests and therefore, the maintenance, creation, or restoration of riparian forests is indispensable. This study was designed to broaden current knowledge of the complex, interrelated biogeochemical processes and determine indices for riparian forest restoration based on the various carbon pools/fluxes that may represent restoration success.

This study was implemented on the Savannah River Site, an Environmental Research Park, where several riparian forests are recovering from thermal disturbances. The streams in these forests were subjected to thermal discharges that increased flows and resulted in removal of soil and a decline in the amount of woody vegetation. Two of these riparian forests are at different ages post-disturbance and represent different stages of recovery, which provides an exceptional opportunity to study successional processes in riparian forests and enhance restoration efforts.

Linear transects perpendicular to the main stream channels were established in 2 recovering riparian forests of different ages (two areas in Pen Branch ~ 8 years post-disturbance; Fourmile Branch ~ 12 years post disturbance) and an undisturbed (thermally) more mature riparian forest (Meyer's Branch ~ 60 years). Along these transects quantitative data were obtained on above and belowground carbon pools and fluxes.

Carbon pools exhibited a close correlation with riparian forest development. Biomass and carbon pools increased with increasing riparian forest stand age. The importance of the herbaceous carbon pool declined relative to the total above ground biomass, and the root carbon pool increased with forest age/succession. In general, net primary production (NPP) in young riparian forests (~8-10 years) rapidly approached and even exceeded NPP of more mature riparian forests. Once the herbaceous stage of succession was surpassed, the litterfall component of NPP plays a greater role in riparian forests. As a woody overstory became established (after ~ 8-10 years), annual litterfall rates as a function of NPP were independent of forest age.

Establishment of woody species occurred ~8 to 10 years after thermal disturbance and litterfall amount in young riparian forests rapidly became comparable to mature riparian forests. Lateral litter movement from the riparian forest toward the stream was less than the amount of litter (carbon pool) deposited from upstream into the riparian forest during a flood event. Overall lateral litter movement supplied less energy to the stream system than vertical inputs. A decline in riparian forest floor biomass was observed with increasing riparian forest development. However, a difference in foliar forest floor percent carbon lent itself to a minimal increase in the forest floor carbon pool with increasing riparian forest age. Woody debris in riparian forests comprised a relatively small carbon pool compared to tree and soil carbon pools.

The species composition of litter appeared to be more of an overriding factor influencing decomposition rates than forest age. The influence of litter quality was evident in the decomposition rates of the different litter composites used in this study. In all 4 sites the litter composite from the mature riparian forest decomposed significantly more than the litter composites from the younger riparian forests. The fairly rapid decomposition of red maple (*Acer rubrum* L.), which was one of the main components in the mature riparian forest litter composite, influenced the greater decomposition rate. The litter composites from the younger riparian forests were similar and both included more decomposition resistant litter types, specifically waxmyrtle (*Myrica cerifera* L.) and alder (*Alnus serrulata* (Ait.) Willd.). Decomposition rates did not differ between the individual successional stages.

Riparian forests are intimately associated with their hydroperiod. During flood events the riparian forest receives inputs of organic matter and sediment, and the amount of deposition may decrease along a distance gradient from the main stream channel. The differential amount of inputs could affect forest productivity. However, in these riparian forests, a distance gradient effect was not observed. Trends in herbaceous biomass were evident along a microtopographic moisture gradient. The ridge and swale microtopography prevalent in the younger riparian forests counteracted a distance from the stream channel gradient effect across the riparian forest.

This study provided knowledge of how carbon pools and fluxes change with riparian forest recovery from disturbance as well as through different seral stages. Implementing the findings of this study will enhance restoration evaluation efforts to ensure that these areas continue to provide the numerous benefits gleaned from them.

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*“Chaos is just an appearance,
a mask,
and with a different eye
it metamorphoses into pure order.”*

**Deepak Chopra
Quantum Healing**

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Chapter I. Introduction

Study Rationale

Riparian ecosystems are unique because of their linear position along rivers and streams. These ecosystems include a mosaic of topography, floral and faunal communities, and environments that serve as an interface between terrestrial and aquatic ecosystems. Riparian ecosystems are considered to be more vegetatively productive and have higher species diversity and density than adjacent uplands because of the periodic influx of water and nutrients, especially when flooding is seasonal rather than continuous (Wharton et al. 1982). The hydroperiod of a riparian forest greatly influences the dynamic nature of the processes dictating forest productivity. Flood events may provide or remove nutrients available for vegetative growth. Depending of the extent and duration of a flood event, anaerobic conditions will retard root growth, thereby limiting nutrient uptake critical for forest productivity. Also, anaerobic conditions will affect decomposition rates of organic matter and incorporation of the nutrients.

The most extensive riparian systems in the United States are the mesic bottomland hardwood forest ecosystems of the Southeast (Mitsch and Gosselink 1993). Riparian ecosystems provide numerous goods and services (values) to society because of the processes (functions) that occur within them (Walbridge 1993). Three main categories describe the functions and values of riparian forests: 1) water quality and hydrology, 2) wildlife and fish, and 3) aesthetics and outdoor recreation (Palone and Todd 1997). Anthropocentric values of riparian forests include flood mitigation, stormwater control, improved water quality, removal of nonpoint source pollutants, structure and habitat for fish and wildlife, travel corridors for wildlife, recreational hunting and fishing, timber, and aesthetics. Maintaining healthy aquatic environments will subsequently enhance water quality and the establishment, or restoration, of riparian forests is a vehicle to achieve this objective. Streamside vegetation is very

important for certain insect instars (life stages). Knowledge of the natural processes involved in riparian forests, particularly the carbon/energy dynamics will facilitate success of restoration projects.

Disturbance interferes with the variety of riparian forest functions and subsequently the values these riparian areas provide. Riparian ecosystems recover more slowly with increased disturbance severity and some types of perturbations have longer lasting effects (Scott et al. 1985). A disturbance may cause a forest to revert to an earlier seral stage. Therefore, understanding successional processes will enhance restoration activities. For example, knowledge of how above and belowground biomass and carbon pools change at successive seral stages will provide a reference to determine whether restoration efforts have been successful.

An understanding of the structure and function of undisturbed systems is an underlying assumption of restoration research, yet this understanding is often lacking in current restoration efforts (Cairns 1987). The perpetuation of ecosystem quality requires baseline studies of biogeochemical conditions (Cairns et al. 1978). Maintenance of natural energy inflows must be a high priority in wetland management/restoration to sustain the integrity of riparian ecosystems and prevent the immigration of invasive and exotic floral and faunal species. Changes in site productivity occur through changes in nutrient supply and cycling patterns, water availability and flux rates, and in root and aboveground plant processes. An evaluation of impacts on ecosystem processes or the determination of future productivity depends on the quantification of changes in these processes or their controlling factors.

Riparian issues are in the forefront of current research. Research is occurring on restoring riparian areas in the Pacific Northwest to revive salmon populations. A large scale effort in the East, referred to as the Chesapeake Bay Initiative (2010 miles of riparian buffer by 2010) is currently being implemented. In pastures across the country, programs are being implemented to prevent range

animals from destroying stream banks and therefore water quality. In forestry, the creation of streamside management zones as a best management practice are employed to protect water quality.

Carbon continues to be a hot topic, specifically in reference to its role in global warming. An international treaty, the Kyoto Protocol, which has been signed, but not yet ratified, addresses crediting forested areas as carbon sinks to offset CO₂ emissions, given their ability to sequester carbon. Aggrading forests are considered to be net carbon sinks whereas mature forests are generally in equilibrium (Trettin et al. 1999). A better understanding of carbon pools and dynamics within riparian ecosystems may provide insight to applying the appropriate credits.

Human influence on forests, particularly changes in landuse and harvesting, have resulted in regional differences in carbon storage (Murray et al. 2000). Knowledge of litter and soil carbon pools and dynamics is limited and the effects of management activities on soil and litter carbon are not well understood (Hoover et al. 2000). Knowing how carbon pools change through forest development is important to understanding natural forest recovery processes and will aid restoration efforts.

This study was implemented on the Savannah River Site, Environmental Research Park, where several riparian forests are recovering from thermal disturbance. The streams in these forests were subjected to elevated, thermal discharges that removed soil and caused a decline in woody vegetation. In 1981, environmental cleanup began due to the Resource Conservation and Recovery Act. In 1985 and 1989, reactors that discharged into the streams were shut down. The final impact statement and subsequent record of decision directed that the riparian areas associated with these streams should be restored to “functional forested wetland status to the extent possible.” Several of these riparian forests are at different ages post-disturbance and represent different stages of recovery which provides an exceptional opportunity to study successional processes in riparian forests and enhance restoration efforts.

Current measures of restoration success are based on plant/tree survival and density at relatively young ages. Mitsch et al. (1998) suggest that ‘the introduction of plant species, although necessary to meet legal requirements of early plant cover in created wetlands, may not always be necessary to start wetlands on a trajectory toward becoming a functional ecosystem.’ The complexity/specialization of interactions between abiotic and biotic factors involved in a functioning riparian ecosystem make it difficult to consider only one index as a measure of success. However, quantifying individual factors may reveal those components that play a greater role in riparian processes. Development of more accurate and efficient indices, and their interactions, is needed to determine riparian restoration success. Carbon is an underlying component linking the cyclic processes responsible for succession and restoration. Carbon serves as an energy source for detritivores in the decomposition of organic matter, specifically litterfall, and this process returns nutrients to the system where they are available for reuse. Carbon is also an important structural component of woody vegetation. Therefore, carbon pools may represent an accurate and efficient index of riparian restoration.

Objectives

The overall objective of this research project was to quantify and compare environmental factors and their influence on restored and non-disturbed riparian sites to develop more accurate and efficient indices of riparian restoration success. The following general and specific null hypothesis were tested to achieve these objectives.

Carbon pools in a riparian ecosystem are not affected by successional state.

- Riparian forest productivity (aboveground) and biomass (above and belowground, and litterfall) are independent of successional stage.

- Litter decomposition rate is not affected by seral stage. Rates of litter decomposition are independent of vegetation type.
- Woody debris in low order streams and associated riparian areas do not significantly contribute to the total organic matter content across successional stages.
- Soil organic matter quantity is consistent throughout each riparian area regardless of the successional stage.
- The successional stage of a riparian area does not affect litter movement into the stream (vertical and lateral), and instream litter.
- The successional stage of a riparian area does not affect submerged aquatic vegetation biomass.

Carbon pool magnitude in a riparian ecosystem is not affected by microtopography or the gradient from stream channel to upland.

- Riparian forest biomass (above and belowground) is not affected by microtopography.
- There is no linear relationship correlating riparian forest biomass with a distance gradient from stream channel to upland.
- Soil organic matter quantity is not affected by microtopography within a riparian forest.

Chapter II. Methods

Study Site Description

The study sites are located in riparian forests adjacent to three braided, blackwater streams on the Savannah River Site (SRS), a National Environmental Research Park in South Carolina (latitude 33° N, longitude 82° W) (Fig. II-1). The climate is temperate with warm, humid summers and cool winters. The mean annual temperature and precipitation are 18 °C and 124 cm, respectively. Surrounding land use is generally forested. Watershed sizes are Pen Branch, 55 km²; Fourmile Branch, 57 km²; and Meyer's Branch, 51 km².

The Savannah River Site was designated by the federal government for nuclear fuel production in the early 1950's. Ecological studies also commenced on site at this time. Four reactors were built in the years 1952 to 1956 and two were shut down in 1964-1971. In 1981 environmental cleanup began due to the Resource Conservation and Recovery Act. In 1985 and 1989 the reactors affecting the streams of Fourmile Branch and Pen Branch were shut down, respectively. The final impact statement and subsequent record of decision directed that the riparian areas associated with Fourmile Branch and Pen Branch be restored to "functional forested wetland status to the extent possible" (Nelson 1996). In Pen Branch the objective was to accelerate the establishment of a bottomland-hardwood ecosystem in 223 acres of disturbed forest.

Pen Branch and Fourmile Branch streams are third order tributaries of the Savannah River and these tributaries received thermal, elevated discharge from nuclear production processes between 1954 to 1989, and 1955 to 1985, respectively (Fig. II-2). The stream corridors experienced elevated temperatures (up to 70 °C) and increased discharge (1 to 2 orders of magnitude greater than base flow). The thermal discharge killed the bottomland hardwood vegetation and altered sediment erosion and deposition patterns. The third stream in this study, Meyer's Branch, represents a minimally

disturbed, third order reference site (Fig. II-2). Only minor disturbances such as selective logging in the 1940's occurred in Meyer's Branch, but it never received thermal effluent.

The age of the riparian forests adjacent to Pen Branch, Fourmile Branch, and Meyer's Branch at the time this study began were 8 years, 12 years, and approximately 60 years, respectively. There are 2 treatment areas within the Pen Branch corridor. One area has been allowed to regenerate naturally. Following a site preparation of herbicides to remove black willow (*Salix nigra* Marsh.) and wax myrtle (*Myrica cerifera* L.) seedlings, and prescribed burning in November 1993, an adjacent area was artificially regenerated by planting bottomland hardwoods in January 1994. In January and February 1995, the corridor was replanted to replace seedlings lost to herbivory. Species planted included cherrybark oak (*Quercus falcata* var. *pagodifolia* Ell.), water oak (*Q. nigra* L.), water hickory (*Carya aquatica* (Michx. f.) Nutt.), swamp tupelo (*Nyssa sylvatica* var. *biflora* (Walt.) Sarg.), Shumard oak (*Q. shumardii* Buckl.), swamp chestnut oak (*Q. michauxii* Nutt.), persimmon (*Diospyros virginiana* L.), green ash (*Fraxinus pennsylvanica* Marsh.), bald cypress (*Taxodium distichum* L.), sycamore (*Platanus occidentalis* L.), water tupelo (*N. aquatica* L.), and pignut hickory (*C. glabra* (Mill.) Sweet). For the remainder of this document natural regeneration and artificial regeneration areas of Pen Branch will be referred to as Pen Branch (NR) and Pen Branch (AR), respectively.

Early successional species such as willow (*Salix* spp. L.), waxmyrtle, smooth alder (*Alnus serrulata* (Ait.) Willd.), and buttonbush (*Cephalanthus occidentalis* L.) dominated Pen Branch (NR). The planted section (artificial regeneration) of Pen Branch was dominated by herbaceous vegetation and blackberry (*Rubus* spp.), with some buttonbush and alder. The woody component of the Fourmile Branch riparian forest was also dominated by willow, with the addition of red maple (*Acer rubrum* L.), alder, waxmyrtle, and loblolly pine (*Pinus taeda* L.). Meyer's Branch represents a mature bottomland forest with a mixed species composition including bald cypress, swamp and water tupelo, red maple, Virginia willow (*Itea virginica* L.), arrowwood (*Viburnum dentatum* L.), and dog-hobble

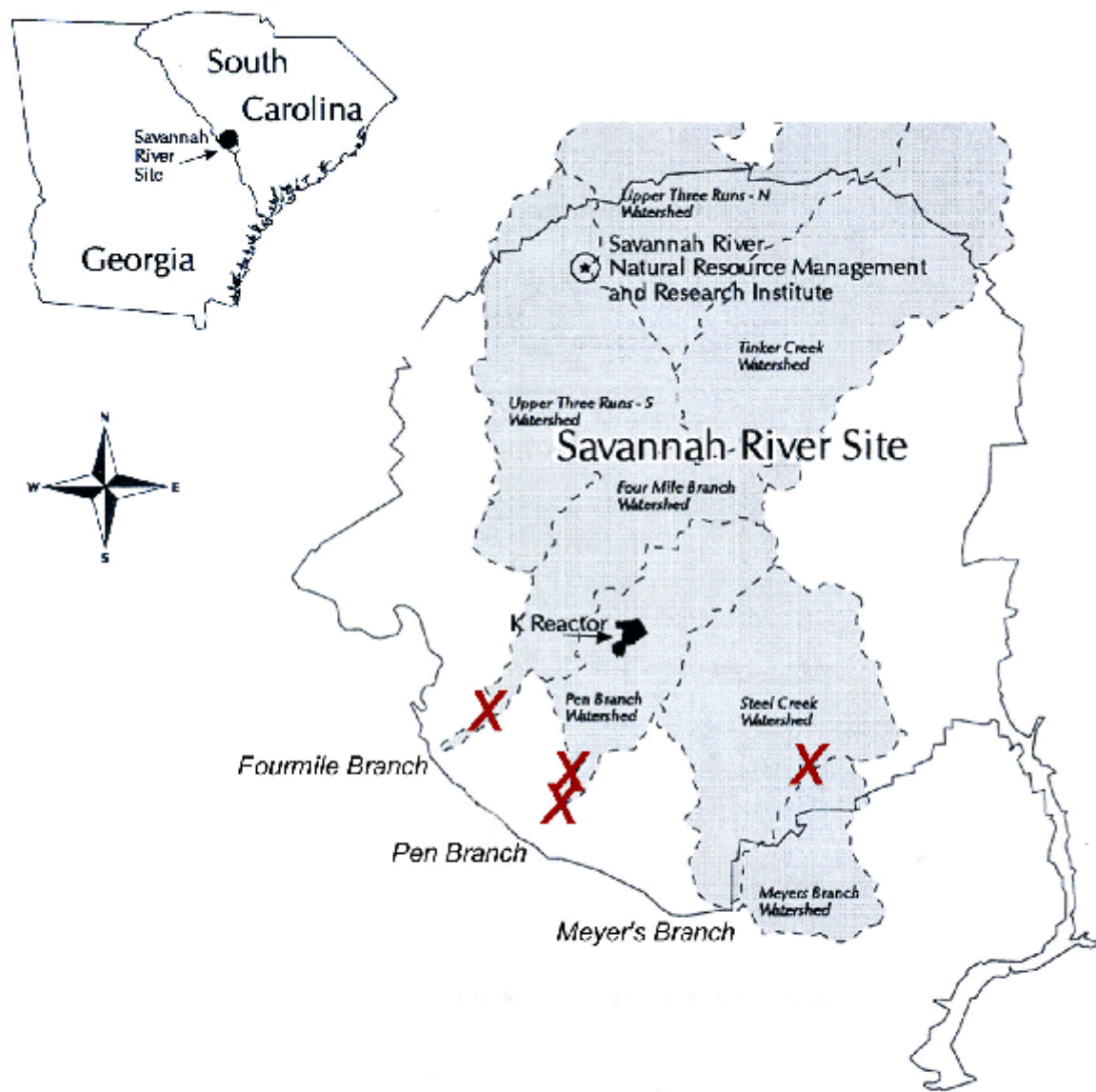


Figure II-1. Site map with location of the four study sites (X).

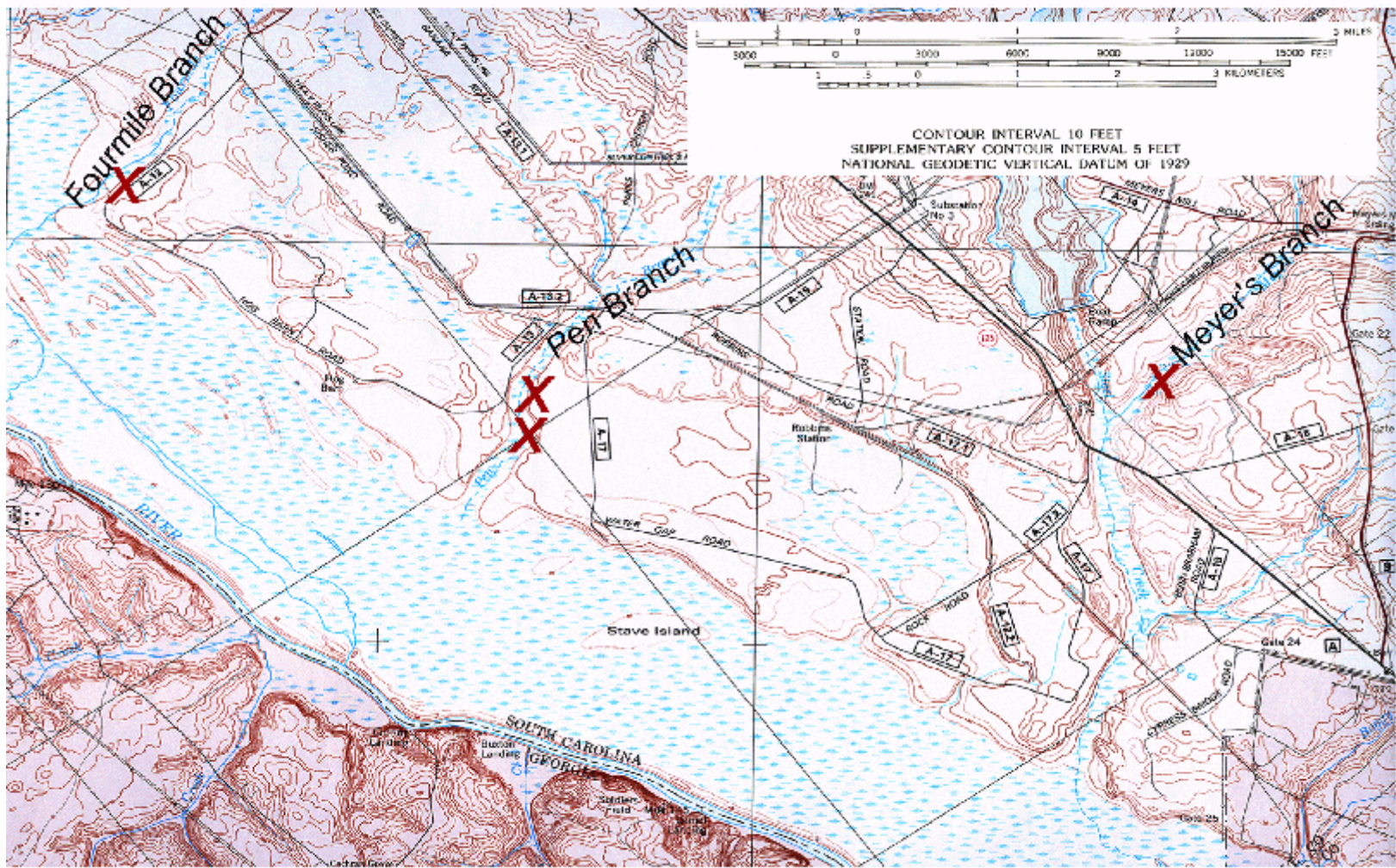


Figure II-2. Location of the four study sites (X) within the Savannah River Site, South Carolina.

(*Leucothoe axillaris* (Lam.) D. Don.) as the dominant species. A complete species list may be found in Appendix Table 1.

Soil Descriptions

Soil descriptions were determined via an intensive examination of over 25 soil auger derived soil profiles for each site (Azola 1997). Soil profiles were described using standard Natural Resources Conservation Service techniques as described by the Keys to Soil Taxonomy (NRCS 1998). The soils in the riparian forest of Pen Branch include Typic Endoaquepts, Typic Fluvaquents, and Thapto-Histic Fluvaquents indicating the alluvial nature of the sites. In Pen Branch microtopography has influenced soil development resulting in different soil characteristics on the ridge and swales. Adjacent upland soils were characterized as Entisols and Ultisols.

In the Fourmile Branch riparian forest soils are generally Thapto-Histic Fluvaquents, which have a buried A or histic horizon. Characterization of soil profiles was not significantly influenced by microtopography, so ridges and swales were mapped as one unit. Adjacent upland soils are ultisols on the west side of the main channel (Typic Endoaquults, Aquic Hapludults) and entisols on the east side of the main channel (Typic and Aquic Quartzipsamments).

Much of the soils in the Meyer's Branch riparian forest have an organic layer ≥ 18 cm deep and the Typic Medisaprists had several organic layers extending to an average depth of 102 cm. Other riparian soil types include Humaqueptic Endoaquepts and Fluvaquents. Microtopography effects on the morphology of the soils were minimal. The upland soils are very sandy (Grossarenic Hapludults and Arenic Endoaquults).

Currently the two thermally disturbed areas are dominated by aquents and aquepts whereas Meyer's Branch is dominated by organic soils (histosols). The use of Meyer's Branch as a control is

reasonable because the Thapto-Histic nature of the soils in the disturbed areas indicates that these areas were histic in nature prior to the human induced changes to hydroperiod.

General Experimental Design

Gradients (e.g., elevation, moisture) perpendicular to stream channels have been studied by numerous researchers (Bell and Sipp 1975; Johnson and Bell 1976; Hauer et al. 1986; Brinson 1993; Reese and Moorhead 1996; Burke et al. 1999, Bledsoe and Shear 2000). In 1997, 17 transects were established perpendicular to the main stream channels and in most cases spanned the width of the riparian area extending into the upland. Placement of the transects was predetermined based on a previously installed hydrology study (Kolka et al. 2000). Transect length ranged from 3 to 94 m (Fig. II-3) originating from the main stream channel. Three transects were established within Pen Branch (NR), 3 within Pen Branch (AR), 6 within the Fourmile Branch riparian forest, and 5 within the Meyer's Branch riparian forest (Appendix Fig. 1).

Tree and shrub plots were used to measure tree and shrub biomass (Fig. II-4). Smaller and more numerous subplots were used to measure herbaceous biomass and species richness, root biomass, and soil chemical and physical properties (Fig. II-4). The number of tree and shrub plots and subplots (for herb, root, and soil sampling) established along the transects for the riparian areas within each study site are provided in Table II-1.

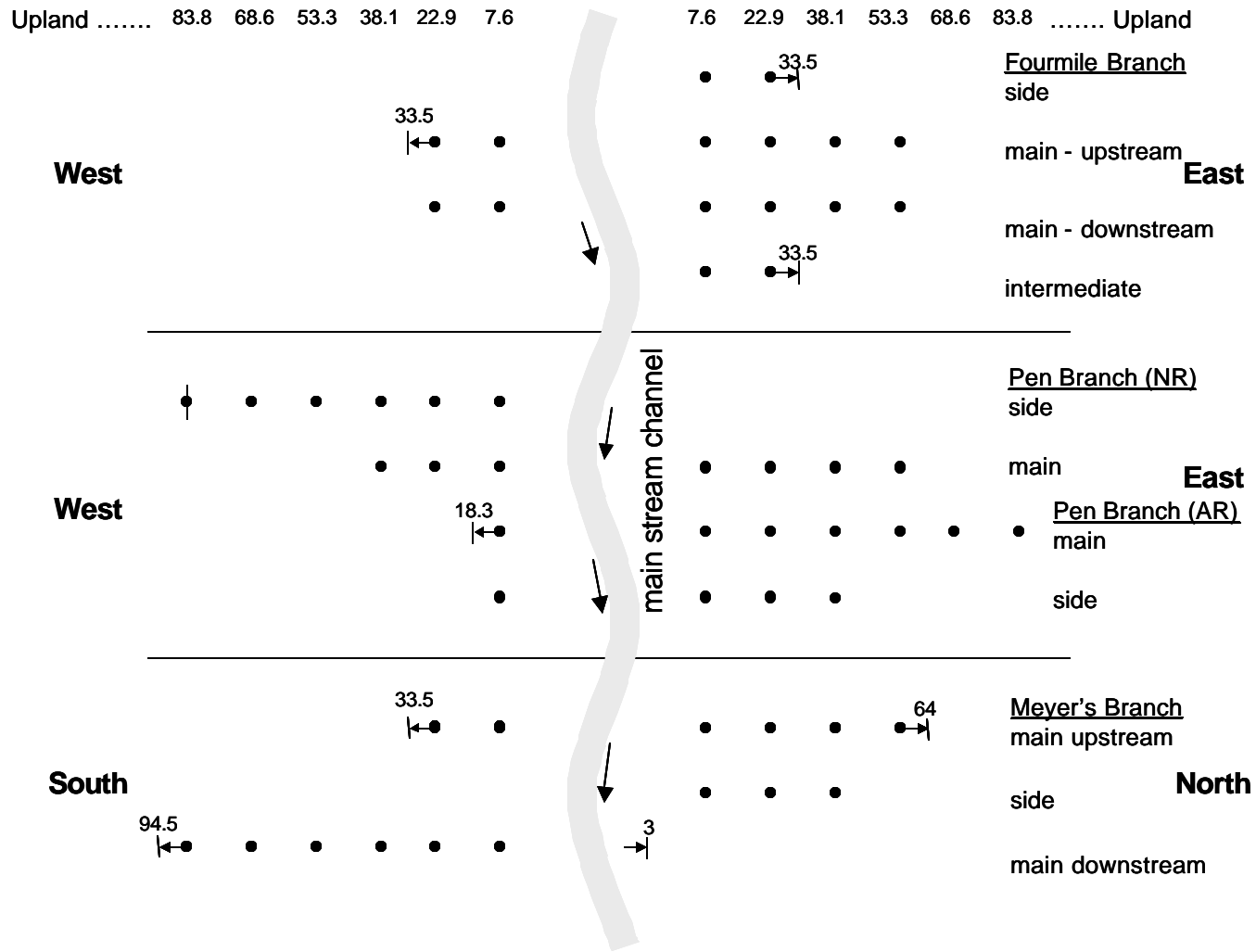


Figure II-3. Conceptual layout of riparian transects with plot location based on distance (meters) from main stream channel. Each (●) is a plot center. Distance from last riparian plot to upland is not to scale

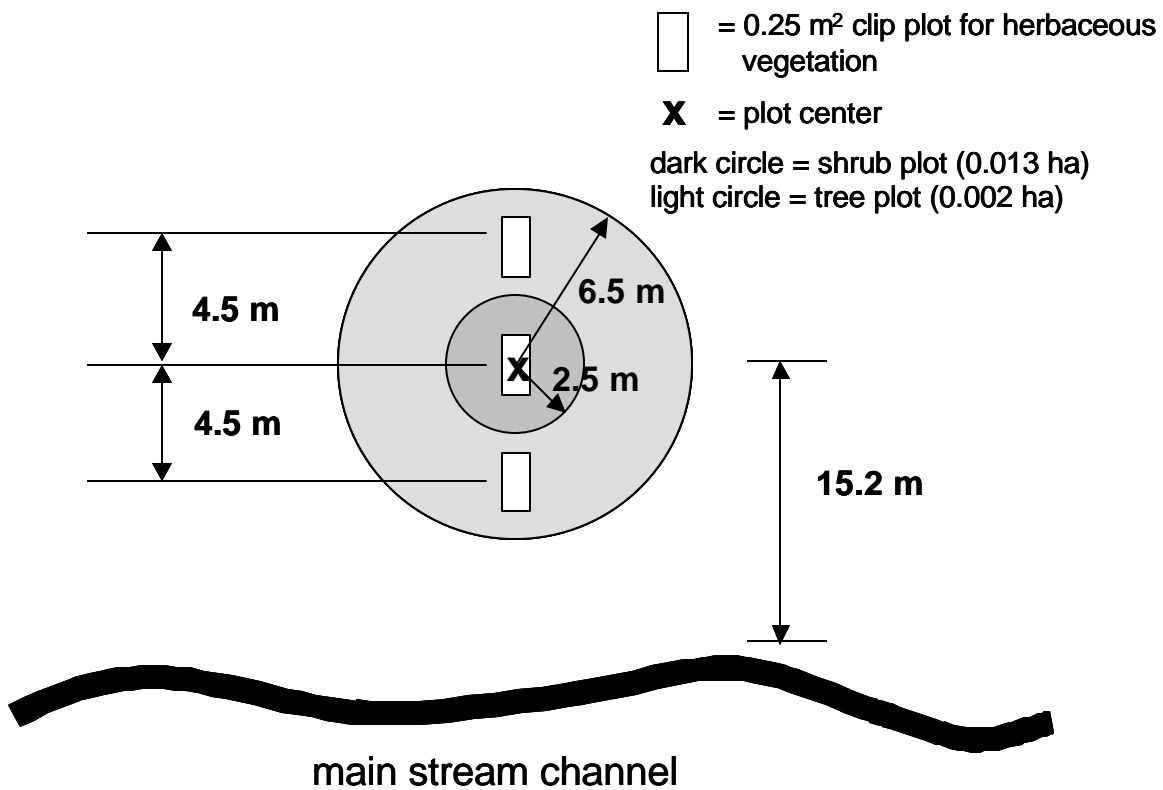
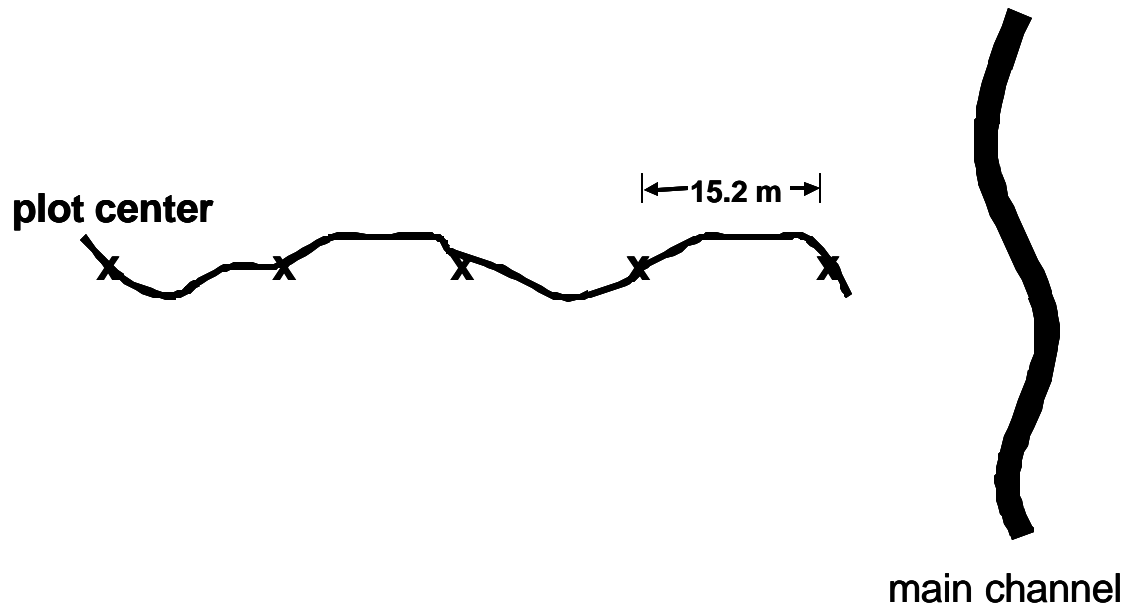


Figure II-4. Conceptual design of herbaceous, shrub, and tree plot layout.

Table II-1. Number of tree and shrub plots and subplots within the riparian and upland forests.

Study Area	Riparian		Upland	
	Tree/Shrub Plots	Subplots	Tree/Shrub Plots	Subplots
Pen Branch (AR)	11	34	3	9
Pen Branch (NR)	12	37	3	9
Fourmile Branch	16	51	6	18
Meyer's Branch	15	49	5	15

Field and Laboratory Methods and Analysis

Identification and quantification of carbon pools and fluxes were central themes of this research (Table II-2) and a wide variety of techniques were used to acquire this data. Table II-2 lists the overall pools and fluxes that were identified and measured, and the chapter where the results are discussed. The following methods describe the techniques used to acquire the field and laboratory samples necessary to estimate carbon quantities for each of the identified pools.

Table II-2. The pools and fluxes in a riparian forest. X denotes the pools and fluxes examined in this study and the chapter(s) where they can be found.

Pools		Chapter	Fluxes		Chapter
Trees	X	III	Litterfall	X	III, IV
Shrubs	X	III	Lateral Litter Movement	X	IV
Herbs	X	III, VI	Decomposition	X	V
Fine Roots	X	III, VI	Respiration		
Litterfall	X	III, IV	Leaching		
Forest Floor	X	III, IV	Sediment (attached carbon)	X	III
Woody Debris	X	III	Instream Litter	X	IV, V
Soil	X	III, VI			
Stream Vegetation	X	III			

Standing Biomass

Trees and shrub layers comprise 1/4 to 3/4 of the biomass on a forested site (Kimmins 1987). Along each riparian forest transect, tree and shrub plots (Wenger 1984) were spaced at 15.2 m intervals originating at the main stream channel. Within each tree and shrub plot, the diameter at breast height (dbh @ 1.4m), height, and species of all trees (dbh > 4.0 cm) within a 0.013 ha circular plot were recorded. Diameter (measured just above the root collar), height, and species were recorded for all shrubs (dbh < 4.0 cm and height > 0.5 m) within a 0.002 ha plot. Field sampling was conducted in June, 1997 and November 1999. Aboveground biomass values for trees and shrubs were estimated using existing dbh:biomass regressions (Clark and Taras 1976; Peet and Council 1980; Clark et al. 1985; Muzika et al. 1987; Mader 1990; Hauser 1992; Gholz et al. in press). The dbh:biomass regression equations may be found in Appendix Table 4.

Herbaceous Biomass/Species Richness

Depending on the seral stage of a riparian area, herbaceous biomass may comprise a substantial amount (Kimmins 1987). Along each transect, clip plots (Hall et al. 1993) were spaced at 4.5 m intervals. All vegetation in the herbaceous layer (< 0.5 m in height, regardless of growth form) was clipped from each 0.25 m² area. The number of species observed in each clip plot was recorded to determine species richness (# of species per 0.25 m²). Microtopography was subjectively rated at each clip plot as wet, intermediate, or dry based on position in the landscape (ridge or swale). Clip plots were also established in the adjacent uplands. Sampling was conducted four times: June & August 1997, and June & August 1998. Consecutive clip plots were taken from the same general area and microtopography with no overlap of clip plot area to avoid influence from previous sampling. All clipped vegetation was dried to a constant temperature (60 °C) and weighed.

Net Primary Productivity

Aboveground biomass increments are a well recognized pool of carbon. Estimation of total net annual primary productivity was determined by the mean annual increment method (Art and Marks 1971) in which the woody biomass is divided by the age of the forest stand. The mean annual increment method generally underestimates current woody production, but allows interpretations of chronosequence type data. Trees and shrubs were divided by the respective riparian forest age (8 & 10.5, 8 & 10.5, 12 & 14.5 and 60 & 62 years for the 2 areas in Pen Branch, the riparian forest along Fourmile Branch, and the Meyer's Branch riparian forest, respectively). Sixty years was used for Meyer's Branch although some older residual trees remained following the selective harvest. A 60-year age was also used for upland forests. The herbaceous strata was considered to be an annual increment. Shrub biomass was divided by forest stand age and this will underestimate shrub NPP in the Meyer's Branch riparian forest and the four upland forests.

Litterfall

Deciduous hardwood forests typically have nutrient cycles involving large litterfall inputs. Therefore, measurement of annual litterfall (vertical) provides information pertaining to the carbon inputs (flux) to the forest floor and subsequent incorporation into the soil organic matter component. Sources of water to streams within bottomland riparian forests can have complex origins, each of which contributes to a variety of instream organic particles. Water and associated detritus may come from upstream sources, overbank flooding, or overland flow from adjacent sources (lateral litter movement). A multi-directional approach to quantify lateral litter transport and deposition, and subsequent determination of the direction of the transport may be novel.

Riparian Litter

Vertical: Eight litter traps (0.187 m² each) per site were randomly placed within the riparian area (Conner and Day 1992). Collectors were elevated approximately 0.6 m to prevent inundation during flood events. Litter was collected biweekly (September - November) followed by approximately every 2 months for one year (9/97-8/98) for a total of 10 collection periods. Litterfall was also collected four times during peak litterfall of the following year (9/98-2/99). Litter was separated by component (leaves, stems, miscellaneous [e.g., fruits, flowers, insects]). Vertical litter samples were dried to a constant temperature (60 °C) and weighed by component (leaves, twigs, and miscellaneous). For all four sites, only tree and shrub litterfall components were included. In Pen Branch (AR), herbaceous vegetation tended to engulf the litter traps, but was not included in the sample.

Lateral Litter Movement: A multi-directional lateral litter (+-shaped) collector (Mudll) was constructed with a one-quarter to one-half mesh size to catch litter, but not impede flow or trap sediment. Screening was placed on top to prevent the addition of vertical litterfall. A collector was placed on each side of the stream channels (main, intermediate, and side) and prominent swales encountered crossing the riparian area (approximately 5-10 collectors per transect) (Fig. II-5). Two sets of collectors were placed (one upstream transect and a second downstream transect) in each riparian forest. The four Mudll compartments were labeled based on orientation (upstream, overbank, toward stream [i.e., from the riparian forest], and downstream [i.e., backwards flow] to the stream or swale). The Mudlls are approximately one meter tall and the compartments range in size from 0.32 - 0.38 m³. Sampling was done following significant hydrologic events. Lateral litter samples were dried to a constant temperature (60 °C), weighed and subsequently dry ashed to correct for sediment deposition.

Upland Litter

Litterfall dynamics in upland forests may differ from riparian forests due to species composition. Three to 4 litter traps (0.187 m² each) were placed in the adjacent upland of each riparian forest. Collectors were elevated approximately 0.6 m above ground surface for consistency with the riparian litter traps and to be prepared for the possibility of inundation during unusually high flood events. Upland litter was collected at the same times as the riparian litterfall collection. Litter samples were dried to a constant temperature (60 °C) and weighed according to component (leaves, twigs, and miscellaneous).

Stream Litter

In bottomland hardwoods, small streams are often shaded by overarching branches of trees and shrubs and litter components may fall directly into the stream. Litter that falls into the stream is important to the aquatic food web, but also may become deposited into the riparian forest during a flood event. Litterfall collectors were individually constructed to span the width of the main stream channel to collect vertical inputs from riparian zone. Three litter collectors each were placed in Fourmile Branch and Meyers Branch. Two litter collectors each were placed in Pen Branch (AR) and Pen Branch (NR). Litter was collected at the same times as the riparian litterfall collection. Litter samples were dried to a constant temperature (60 °C) and weighed according to component (leaves, twigs, and miscellaneous).

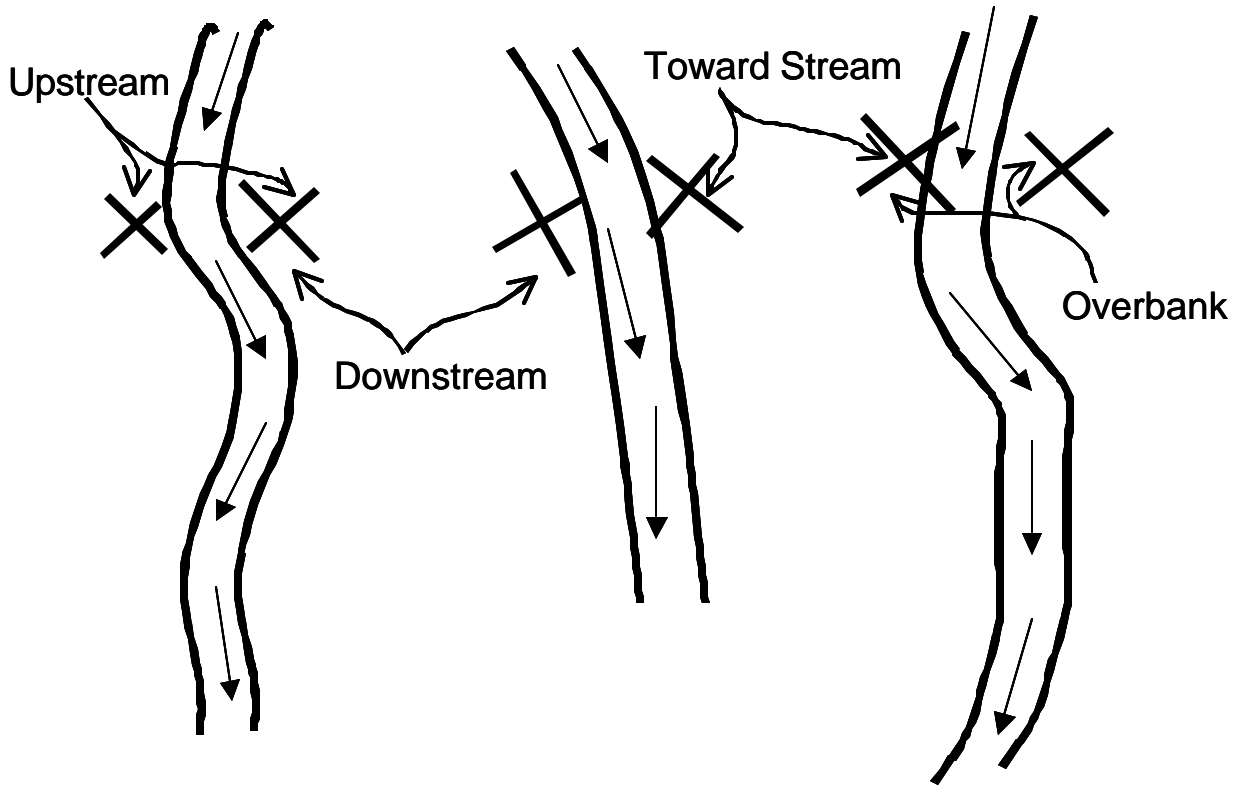


Figure II-5. Conceptual diagram of Mudfl transect illustrating the four directions for lateral litter movement (quadrants -- upstream, downstream, toward stream, and overbank).

Instream Litter

It is commonly recognized that bottomland hardwoods serve as an important source of detritus (carbon) for aquatic food chains, but the quantity of litter transport is not well understood. Three drift nets (0.135 m² each) with a fine mesh were placed in the main stream channels for approximately one hour to collect litter flowing in the stream. The drift nets were spaced at one-third, one-half, and two-thirds intervals based on stream width. Samples were only collected during baseflow conditions. Ideally the entire net was submerged, but that was not always possible due to low water depths. The fine mesh size of the drift net appeared to alter stream flow near the collector. However, a coarser mesh would have allowed fine litter particles to escape. Stream discharge was also determined at the time of sampling by obtaining several stream measurements (width, depth, velocity [Swoffer current velocity meter, model 2100 (pigmy)]). Sampling was conducted 6 times during the fall, winter, and spring months. Litter samples were dried to a constant temperature (60 °C), weighed, and subsequently dry ashed to correct for sediment deposition.

Forest Floor

The depth and quantity of the forest floor is controlled by litter inputs, exports, and on-site decomposition rates. Measurement of the forest floor may provide information on these fluxes. Forest floor samples consisting of the Oi (leaves, twigs) and Oe (fragmented leaves and twigs) layers combined were collected from approximately fifteen 0.25 m² areas within each riparian forest except Pen Branch (AR) due to the density of herbaceous vegetation, and approximately six to eight 0.25 m² areas in the adjacent upland forest (Elliott et al. 1993). Samples were separated into two categories; leaves, and twigs& miscellaneous. Litter samples were dried to a constant temperature (60 °C) and weighed. Forest floor samples were collected early May 1998 to emulate what would be remaining of the previous season's litterfall.

Woody Debris

Larger woody debris is an important carbon pool that is sometimes overlooked because it is not sampled as living biomass or included within forest floor litter samples. The abundance of woody debris may significantly contribute to the overall riparian forest carbon pool. Woody debris was inventoried using the line-intersect method. From randomly selected azimuths, ten 20-meter transects originated from the subplot centers in each riparian area. Where riparian transects cross the main stream channel, one 25-meter transect was established upstream and another 25-meter transect established downstream. Woody debris was tallied along these transects. In the riparian area woody debris was recorded as fine (1-2.5 cm), medium (2.5-10 cm) and large (> 10 cm) diameter. The median diameter of the fine and medium size class, the actual diameter of the large size class, and average relative density for mixed hardwoods (Harmon et al. 1980; Phillips 1981) were used to convert woody debris to biomass. Penetrometer readings were taken on the medium and large pieces to determine their soundness (Scheungrab, personal communication). A sound/rotten designation was subjectively given to the fine woody debris.

Fine Roots

Root biomass may account for one-quarter to three-quarter of the total living biomass in a forest, but it is seldom measured due to the difficulties associated with sampling, particularly in bottomland areas. It is important to recognize that the belowground biomass associated with larger roots has not been included in the samples. Two 5-cm diameter by 20-cm length metal cores were inserted into the soil near, but not within, each clip plot (Hall et al. 1993). Depth of core insertion was measured when obstructions (large roots or rock) prevented insertion of the total length of the core. Samples (soil and roots) were refrigerated until fine roots could be washed/separated from the soil with a jet of water on a sieve (pore openings ≤ 2 mm). Only roots ≤ 5 mm were retained. Roots were rated subjectively as live or dead. Live roots are considered resilient, flexible and fleshy. Roots were

classified dead if they were limp and crumbled easily. Fine roots were dried to a constant temperature (60 °C) and each sample weighed.

Stream Vegetation - submerged aquatic vegetation (SAV)/macrophyte

Submerged aquatic vegetation is a pool of carbon that is often overlooked in bottomland hardwood areas. This vegetation may significantly influence stream hydrodynamics and, in turn, may affect riparian forest productivity by altering the hydroperiod. Stream plots were an extension of the terrestrial transect. The number of sample points for estimating submerged aquatic vegetation biomass was based on stream width (<500 cm - three 'clip plots'; > 500 cm - five 'clip plots'). Each sample size was 177 cm² (15 cm diameter). Canopy cover was determined subjectively as no canopy (open), partial, or full canopy. Other stream measurements included: water depth at each point, percent macrophyte cover at each point, percent macrophyte cover across stream reach, and bank to bank stream width. Sampling occurred four times: August and December 1997, and May and August 1998. Samples were dried to a constant temperature (60 °C) and weighed. One species (*Egeria densa*) dominated streams in both Pen Branch sites. No SAV was observed in Meyer's Branch during the sampling times. An unidentified species was observed sparsely growing in the Fourmile Branch main stream channel, but it never occurred within the sampling transects.

Soils

Soils, particularly wetter soils, may store large quantities of carbon (Mohanty and Dash 1982; Kozlowski 1985; James and Wells 1990; Collins and Wein 1998; Bledsoe and Shear 2000). Soil samples and bulk density samples were collected so that this pool could be quantified. Bulk soil samples from the O/A horizons were randomly collected from the different microtopography areas in each riparian forest. Samples were taken corresponding to fixed distances from the main channel (0-15.2 m, 15.2-30.3 m, 30.3-45.4, and 60.6 m). The A-horizon is approximately 7.5-13 cm in depth in

the Fourmile Branch riparian forest and 7.5-15 cm in depth in the two areas of Pen Branch (Azola 1997). The histic O-horizon in the Meyer's Branch riparian forest ranges from 20-76+ cm. Bulk density was determined with the core method (Blake and Hartage 1986) from the O/A horizon. Organic matter was determined by loss on ignition (LOI) (Nelson and Sommers 1982) (380 °C for 24 hrs). Porosity (total/micro) of the O/A horizons was determined with the a modified water desorption method (Danielson and Sutherland 1986).

Sediment / Reduction-Oxidation Potential

Significant volumes of sediment including attached organic matter, have been deposited in bottomlands (Mitsch et al. [1979]; Kleiss [1996]; Kelley and Nater [2000]). A 4-foot piece of rust-free rebar with a washer placed halfway along the bar length was placed one meter from monitoring wells located along each transects. The rebar was stuck in the ground until the washer was flush with the ground and served as a sedimentation rod (NCASI 1986). Eleven, 7, 15, and 13 rods were placed in Pen Branch (AR), Pen Branch (NR), Fourmile Branch and Meyer's Branch, respectively, on August 8, 1997. Measurements of sediment change were taken after approximately 66 weeks. These rods were also used to evaluate site hydrology by determining the depth of iron reduction (McKee 1978). After 66 weeks rods were visually inspected (subjectively) for depth to initial rust and permanent gray coloration to assess redox potential by observing changes in rod color as well as water table fluctuations (McKee 1978).

Carbon Laboratory Analyses

The vegetation of the herbaceous layer, soil, litterfall, fine roots, and forest floor samples collected were dried, stored and analyzed for carbon content, which was determined via infrared analysis (LECO Total Carbon Analyzer, CR12, LECO Corp., Saint Joseph, MI). The extremely high

temperatures rapidly ignite the sample and cause a release of an infrared signature specific to carbon. Three replicates of the respective sample were analyzed for carbon content.

Statistical Analysis Procedures

The main analysis tool was analysis of variance (ANOVA) for a completely randomized design (SAS Institute 1996) (Table II-3). The four sites (Pen Branch (AR), Pen Branch (NR), Fourmile Branch and Meyer's Branch) representing different seral stages comprised treatments. Differences in various biomass and carbon pool components among the four sites were analyzed. The Tukey multiple range test was used to test treatment mean differences. A significance level (α) of 0.05 was used for all tests. Means were calculated for the 3 carbon replicates for herbaceous vegetation, roots, and soil for use in statistical analyses.

Table II-3. The general ANOVA for the completely randomized design used to test differences in above and belowground biomass and carbon pools in several riparian forests representing different seral stages.

Source	Degrees of Freedom	Mean Square Error	F test
Site (trt)	$t - 1 = 3$	$MST = SST / 3$	MST / MSE
Biomass variable	$n_t - t$ (n is variable)	$MSE = SSE / n_t - t$	
Total	$n_t - 1$		

Regression techniques were used to determine whether there was a linear relationship between distance from the main stream channel and the following vegetation variables: tree biomass (1997 and 1999); shrub biomass (1997 and 1999); total aboveground biomass (1997); net primary productivity; herbaceous biomass, percent carbon, and carbon pool; herbaceous species richness; and root biomass and carbon pool. Linear regression was also used to determine whether there was a linear relationship between distance from the main stream channel and the following soil properties: percent organic

matter; percent carbon; bulk density; total and non-capillary porosity. A liberal significance level ($\alpha = 0.1$) was used for all linear regression tests.

Tests for a correlation between several vegetation and soil variables, and elevation were performed. The following vegetation variables were tested: herbaceous biomass, percent carbon, and carbon pool; herbaceous species richness; and root biomass and carbon pool. The following soil properties were tested: percent organic matter; percent carbon; bulk density; total and non-capillary porosity.

CARBON

Collective cosmic consciousness
Assumption underlying productivity
Research global warming
Bonds dictating structure
Objective invisible element
Nature's energy cycle

Chapter III. Successional Patterns Influence Riparian Forest Biomass and Carbon Pools

Abstract

Knowledge of the changes in carbon pools with forest development/succession will facilitate riparian restoration success and increase awareness of the potential for forests to sequester global carbon. Riparian forest biomass and carbon pools were quantified for four riparian forests representing different seral stages in the South Carolina Upper Coastal Plain. Three of the riparian forests are recovering from thermal pollution whereas the fourth represents a more mature bottomland hardwood forest that has not been disturbed by thermal pollution. Above and belowground carbon pools were determined from linear transects established perpendicular to the main stream channel and generally spanning the width of the riparian area. The main objective of this study was to determine how carbon pools in a riparian ecosystem are affected by disturbance and/or successional state.

Riparian forest biomass and carbon pools are affected by disturbance and succession. The severity of the disturbance will dictate the degree to which forward successional processes are interrupted or set backwards. In these South Carolina Coastal Plain riparian forests, biomass increased with forest stand age. With increasing forest age and development, the importance of the herbaceous biomass and carbon pool declined relative to the total above ground biomass. As stands grew older fine root biomass increased, indicating an inverse relationship between percentage of fine root biomass to total biomass with increasing riparian forest age. A combination of greater fine root biomass and higher root percent carbon in the more mature riparian forest contributed to a greater root carbon pool than found in the younger riparian forests. Overall the root carbon pool increased with forest age/succession.

In general net primary production (NPP) in young riparian forests (~8-10 years) rapidly approached and exceeded NPP of the more mature riparian forest. Once the herbaceous stage of succession was surpassed, the litterfall component of NPP changed the schema between riparian forests. As a woody overstory becomes established (after ~ 8-10 years) after thermal disturbance, annual litterfall rates as a function of NPP were relatively independent of forest age. The litterfall amount associated with the woody component in young riparian forests was comparable to mature riparian forests. A decline in riparian forest floor biomass was observed with increasing riparian forest development. However, in contrast the forest floor carbon pool increased with increasing riparian forest development. Woody debris in riparian forests and associated streams was a function of forest development. However, woody debris in these riparian forests comprised a relatively small carbon pool.

Soil physical and chemical properties were tied closely to successional stage and the processes involved in plant community change. An inverse relationship between total porosity and bulk density was observed with increasing forest age. Forest development and differential stratification of vegetation influenced the movement of sediment to, from, and within a riparian forest. The type or severity of disturbance may affect submerged aquatic vegetation (SAV) establishment, but successional stage did not appear to be a sole decisive factor. Neither canopy coverage or water depth independently affected SAV biomass.

Introduction and Literature Review

Plant succession in riparian forests is particularly complex due to the connection between terrestrial and stream biotic processes, and the effects the local hydroperiod has on moisture availability, and redistribution of organic matter (nutrients) and soil particles. Succession in forest ecosystems is not necessarily an unidirectional process (Hodges 1997). Disturbance in any forest

community provides an opportunity for change in the carbon pools and fluxes. The severity of the disturbance may alter successional patterns (Loucks 1970). Riparian forests associated with third order braided stream systems in the Coastal Plain consistently undergo perturbation during seasonal flood events. The successional stage/forest development of a riparian forest may buffer the effects of hydrology. For example, greater forest structure, specifically within the herbaceous layer, will impede inputs (and outputs) of sediment and organic matter from the stream (Zaebst 1997). Because riparian forests are subject to flooding events, successional processes (from an herb dominated community to a tree dominated one) may be delayed. Biomass and primary production closely are associated with how individual species respond to their environment, especially the hydroperiod (Johnson et al. 1985).

Riparian forest succession is tied closely to the hydroperiod. Changes in the timing and duration of flooding affect productivity and may alter the course of succession (Monk 1968; Conner 1994; Hodges 1997). The depth and duration of inundation during flood events could produce anaerobic conditions that will alter nutrient cycling processes and possibly slow productivity. However, nutrient subsidies brought in during flood events may enhance productivity. The species currently established in a riparian area are adapted to the current hydroperiod. Changes to the moisture regime will alter growth of existing species and patterns of establishment or succession. As species composition and growth form change with time, above- and below-ground biomass, net primary production, litterfall and forest floor dynamics, and woody debris may be affected. These in turn may influence the soil carbon pool, growth of aquatic vegetation in the streams, and sediment deposition to and from the stream. These relationships will be discussed in the following paragraphs.

Above-ground Vegetative Biomass

Biomass data are essential for quantitative evaluation of successional patterns. They can be utilized to compare riparian forest communities and study the biological and physical processes that affect productivity. Hitchcock and McDonnell (1979) synthesized the literature on biomass

measurement and found considerable variability in methodology and information collected on biomass. However, their review includes little reference to forested wetland species.

There are several theories on how biomass changes with succession (Peet 1981). The simplest is that biomass increases in a smooth, logistic fashion toward an upper limit fixed by site conditions (Fig. III-1A). Loblolly pine stands (*Pinus taeda*) appear to add biomass in a logistic manner (Kinnerson et al. 1977). A second hypothesis states that biomass increases to a maximum in late successional stages, only to drop with development of the ‘climax’ community (Fig. III-1B). The “shifting mosaic” model proposed by Bormann and Likens (1979) supports this concept. A third hypothesis predicts biomass to have an initial increase followed by a drop and then subsequent recovery (Fig. III-1C). A forest stand subject to periodic disturbance (flooding, fire, hurricane) may drop in biomass and revert to an earlier stage of succession followed by recovery. A fourth hypothesis of forest biomass predicts that after the initial peak, the quantity of living biomass that can be supported steadily decreases as available nutrients are tied up in dead organic matter (Fig. III-1D). Boreal sites with organic soils generally support this hypothesis (Peet 1981).

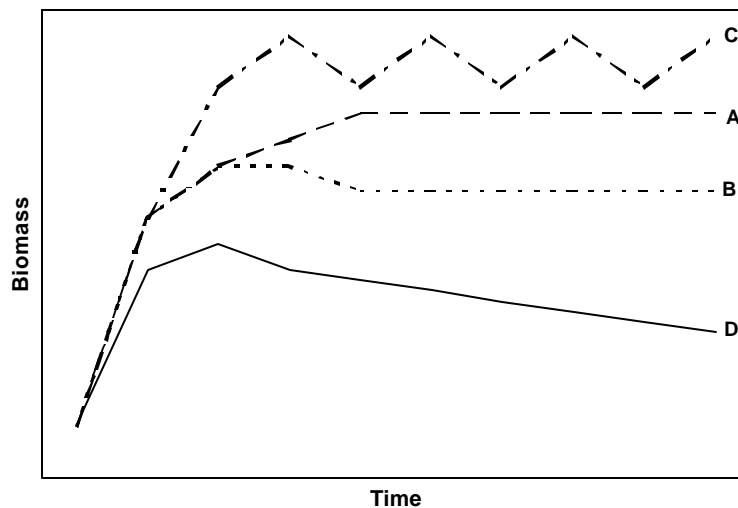


Figure III-1. Conceptual diagram of several theories on how biomass changes with succession. A = logistic manner, B = shifting mosaic, C = periodic disturbance, D = organic accumulation.

Generally, the above mentioned hypotheses pertain to upland communities. Succession in forested wetlands, and specifically riparian areas, may not follow the same patterns due to close association with hydrologic effects. For example, Kirkman et al. (1996) speculate that herb-dominated bays in South Carolina do not appear to be on a successional continuum toward a hardwood forest. In early oldfield seral stages, succession generally proceeds rapidly with a uniformity of species composition (Hopkins and Wilson 1974). Riparian forests subject to frequent flooding may remain at an early seral stage for a longer period of time.

Net Primary Productivity

Art and Marks (1971) compiled a comprehensive summary table of biomass and net primary productivity (NPP). However, there are few references to forested wetlands or riparian forests, probably because of the volume of literature concerning uplands relative to wetlands. Wetlands since have become a forefront issue and more research related to wetlands has been conducted since their review. Still a majority of the literature refers only to aboveground NPP. Belowground production generally is ignored although ratios of belowground biomass to aboveground biomass may be a more valid index for comparison of NPP among forests (Brown et al. 1978). Hydrology also influences the above to belowground productivity ratio (Meronigal and Day 1988).

Successional patterns of NPP have been established for upland forest ecosystems (Odum 1960). A similar pattern of productivity increasing in a stepwise fashion with time can be found in riparian forests as succession proceeds to dominance by tree forms. Net primary production in early successional forests quickly can reach the level of production in a mature forest (Peet 1981). Net primary productivity can vary depending principally on availability of site resources, species composition, and health of the floral community. The shift in dominance from herbs to woody species produces a rapid increase in annual productivity with canopy closure followed by stabilization (Peet 1981). The drop in production during later stages of succession can be attributed to developing forest

structure, changing species composition, and changing nutrient availability (Margalef 1963; Odum 1969; Peet 1981) or failure to recognize belowground biomass accumulation patterns in older stands. There is little evidence that the addition of a new species in later successional stages results in higher productivity (Mooney and Gulmon 1983). In riparian forests, net primary production is not correlated absolutely with biomass (Johnson and Bell 1976).

The hydroperiod of a riparian forest will affect primary productivity (Conner and Day 1976; Mitsch 1978; Conner 1994). Low NPP may occur when periodic flooding causes soil chemistry to fluctuate, resulting in disequilibrium between the plant community and environmental conditions (Burke et al. 1999). Wharton et al. (1982) found that a wet-dry cycle in riparian forests contributes to high productivity because it provides water necessary for growth while maintaining optimum conditions for aerobic driven processes. Mitsch et al. (1991) observed that no single abiotic variable could predict site productivity. However, the biotic variable, average tree diameter, inversely was related to productivity. Productivity in one year may integrate the history of hydrologic conditions (Mitsch et al. 1991).

Litterfall

Litterfall in riparian forests is an integral factor in a multitude of functions. It supplies energy to the aquatic food web, provides habitat for small fauna and insects, and contributes to the formation of soil. Litterfall plays a key role in the recycling of nutrients critical for forest productivity. Changes in species composition or disturbance to the litterfall process could alter these important ecosystem functions.

Litterfall is a critical parameter of energy flow influencing the proportion of the NPP that is stored as woody biomass. The greatest loss of aboveground forest NPP is by litterfall: the annual transfer of living organic material to organic matter pools of the forest floor and mineral soil (Kimmins

1987) where it supplies energy to the detritus food web. Litterfall accounts for approximately 50 % of the aboveground NPP in forested wetlands and about 70 to 80 % is comprised of leaves (Brown et al. 1978; Conner 1994). Non-woody litter, including flowers, fruits, and seeds, typically accounts for less than 10 % of litterfall total (Magonigal and Day 1988). Factors influencing aboveground litterfall include climate, soil moisture and fertility, and altitude. Foliage retention can vary latitudinally as well as with elevation. Climatic factors highly influence the seasonal and annual variation in litterfall, and rates vary depending on forested wetland type (species composition) and geographic location. Trends of leaf biomass change with succession. Foliar biomass peaks at early seral stages followed by a decline to a more constant level at later stages of forest development (Kira and Shidei 1967). Delong and Brusven (1994) demonstrated that litterfall in a riparian area widely varies, yet generally decreases with forward succession from herbaceous to herbaceous-shrub to shrub, and to tree dominated areas.

Forest Floor

The forest floor of a riparian forest could be considered the stage where annual litterfall inputs are transformed and redistributed. It's biomass is a function of the litterfall inputs, detrital community, decomposition rates, and litter redistribution and outputs during flood events. Natural (undisturbed) functioning of all of these components is important in nutrient cycling and maintaining the health of a riparian forest. Elliott et al. (1993) suggests that forest floor biomass is more a function of decay rate than the rate at which litter reaches the forest floor. Because riparian areas are subject to periodic flooding, portions of the forest floor may be transported to the stream as well as receive organic matter inputs from the stream. Hydroperiod (Bell and Sipp 1975) and microtopography or elevation (Bell et al. 1978) influence litter depth and coverage. The influx of detritivores during flood events may stimulate decomposition and increase decay rates (Wharton et al. 1982).

Fine Roots

Trees in the saturated riparian zone often have shallow root systems that enable them to take advantage of the nutrients imported via sediments and organic matter/litter, and survive in the poorly aerated soils. Fine root biomass distribution changes seasonally in Coastal Plain riparian forests; minimum values are attained in August, January and May, maximum values in December, March and June (Baker 1998). Root growth and development are affected by several chemical (e.g., pH, Al toxicity, mineral nutrient deficiency) and physical (e.g., soil moisture, temperature, aeration) factors. Roots typically constitute 15 to 25% of the total biomass in forests (Harris et al. 1977) and 4 to 16% of the aboveground biomass (Montague and Day 1980). Raich and Nadelhoffer (1989) found the ratio of belowground carbon allocation to litterfall decreases as litterfall carbon increases. Fine roots can comprise a large portion of forest NPP (50%+), yet typically comprise < 10% of forest biomass (Santantonio et al. 1977). A decrease in root biomass relative to shoot biomass is a common response to flooding (Kozlowski 1985). In forested wetlands, the combination of less extensive flooding and greater amount of shrubs and herbs contributes to greater root biomass (Montague and Day 1980). Fine root quality differs among successional species and the roots of early seral species generally have faster decomposition rates (Cromack 1981).

Woody Debris

Woody debris, coarse and fine, is gaining recognition as an important component of forested ecosystems. Many of the functions in forested wetlands are related to the quantity and dynamics of downed woody debris. It provides energy, nutrients, and habitat for plants, animals, fish, birds, amphibians, reptiles, invertebrates, and especially microbes (Angermeier and Karr 1984; Benke et al. 1985; Harmon et al. 1986). Woody debris is important in nutrient dynamics due to its relative permanence compared to other more mobile and labile litter components. Further, woody debris can act as a terrestrial dam that retains fine woody debris and other litter components as well as retards

sediment movement. Coarse woody debris (CWD) not only directly sequesters nutrients, but also indirectly enhances microbial habitat. Additionally, the availability of carbon and nutrients enhance the woody substrate for microbial and macro-detritivore habitat during the summer (Polit and Brown 1996).

In forest ecosystems, input rates of coarse woody debris range from 0.12 to 30 Mg ha⁻¹ year⁻¹ (Harmon et al. 1986). In a central Illinois floodplain forest, Polit and Brown (1996) found 6.6 Mg ha⁻¹ of downed woody debris. Causes of tree mortality such as windthrow, insects, and disease, generally occur locally within a forest and thus create an irregular and patchy spatial input of woody debris. Snags that stand for ≤ 10 years are more frequent in lowlands and riparian areas than on upland sites (Van Lear 1996). Temporal variation in CWD input are associated with seasonal, annual, and successional time scales. Successional stage affects the size, species, amount, decay class, and distribution of CWD. Disturbance affects biomass by adding or removing CWD. Severe disturbance retards forest reestablishment, delaying the addition of new CWD and reducing current CWD biomass below predicted steady-state values (Harmon et al. 1986).

In forests where the CWD input is high, a large amount of nutrient transfer to the forest floor will be overlooked if CWD is not measured. Although woody debris generally is low in nutrient concentration and is resistant to mineralization, it can be a substantial source of mineral nutrients. Small diameter woody debris may have limited quantities of nutrients and a long residence time. Therefore, its role in a mature forest may not be as a nutrient reservoir, but as a long-term organic matter storage pool (Chueng and Brown 1995). Polit and Brown (1996) found N, P, and biomass pools in dead wood tissues in a floodplain forest to be more nutrient rich than their upland counterparts.

The variable rate of woody debris decomposition is due to species, size, location, climate, and presence and availability of decomposer organisms (Harmon et al. 1986). Abiotic and biotic factors that can control CWD decomposition include temperature, moisture, oxygen, substrate quality, and the

organisms involved. Most wood-decaying organisms need an optimum temperature of 25° - 30 °C. Both extremely low and high moisture content can limit organism activity. Decomposition rates of CWD generally are higher in the Southeast presumably because of favorable temperature and moisture conditions for the microbes and invertebrates involved in the decay process (Van Lear 1996). Coniferous woody debris generally decomposes more slowly than hardwood debris due to greater lignin, resin, and polyphenolic compound content (Harmon et al. 1986). Day (1982) found a half-life of 2.2 to 8.5 years for small diameter (1.2 - 3.0 cm) willow (*Salix* spp.) and red maple (*Acer rubrum* L.) woody debris in wetland forests.

Soil Carbon Pool

The soil carbon pool is derived from vegetative inputs (e.g., litterfall, woody debris, roots) and micro-organisms, and depends greatly on land-use history (Hoover et al. 2000). Wetland organic soils have been estimated to sequester 1.3×10^8 t C yr⁻¹ under undisturbed conditions (Vymazal 1995). Approximately 66% of terrestrial carbon is belowground and typically has a longer turnover time than aboveground carbon (Garten and Wullschlegel 2000). Roots contribute approximately 60%, leaf litter 6-28% and wood debris 5-15% of the annual soil organic matter inputs (Megonigal and Day 1988). Decomposition rates of inputs and subsequent incorporation will determine the magnitude of the soil carbon pool. Riparian forest succession and species composition may influence the decomposition rates. In several forest ecosystems, root senescence can exceed above-ground litterfall in contributing a major input to soil organic matter (Harris et al. 1980). Johnson (1992) concluded that rooting patterns of different species can either have no effect or a large effect on soil carbon.

Soil heterogeneity may affect the rate or direction of succession (Collins and Wein 1998). Available soil resources may cause spatial and temporal differences in vegetation. Increased growth of early successional species will retard the establishment of later successional species. Soil carbon pools not only fluctuate in early seral stages as greater amounts of organic matter become incorporated and

decomposition rates change, but also soil carbon pools have been shown to increase and decrease over time in undisturbed forests (Trettin et al. 1999). However, after disturbance (i.e., forest harvesting), soil carbon rapidly recovers to pre-disturbance (pre-harvest) levels (Johnson 1992) and, therefore, organic matter content can be a useful indicator of ecosystem recovery (Aust and Lea 1991).

Sediment

The displacement/transport/deposition of soil particles (sediment) in riparian forests is a function of soil texture, vegetation, microtopography, and hydroperiod. Changes in surrounding landuse will affect sedimentation rates (Kelley and Nater 2000). Sediment deposition appears to be seasonal, dictated by local hydrologic events (Mitsch 1978). Mitsch et al. (1979) found the highest rates of sediment deposition occur during the time of maximum litterfall. The proportion of organic/inorganic components that comprise sediment varies throughout the year (Mitsch et al. 1979). The capacity for an area to buffer sediment movement is affected by species composition, where a combination of herbaceous and woody species trap the greatest amount (Lee et al. 2000). Differential buffering occurs with dense herbaceous vegetation trapping coarse sediment and associated nutrients, and deep rooted woody species effectively trapping clay and soluble nutrients (Lee et al. 2000). In contrast with classical fluvial geomorphology, Kleiss (1996) found maximum sedimentation rates occur in the “first bottom” instead of on the natural levee. She attributed this to the small particle size of the suspended material that is transported during normal flooding. However, natural levees trap more sediment during 50 to 100 year flood events that carry coarser material. Kleiss also found that variation in sedimentation rates is a function of distance from the river, flood duration, and tree basal area. Hupp and Bazemore (1993) found deposition rates to be correlated inversely with elevation and degree of ponding or hydroperiod.

Sediment transport, specifically of its carbon content, to the streams will affect the aquatic ecosystem, in stream processes (Hill and Sanmugadas 1985), and submerged aquatic vegetation

(Barko and Smart 1983). Sediment characteristics can influence water flow path direction and ground-surface-water interactions (Mann and Wetzel 2000).

Reduction-Oxidation Potential

Riparian forests are subject to a variety of hydrologic conditions and soil reduction-oxidation potential is considered to be a good index of long term hydrologic status. Spring floods that inundate the riparian forest for an extended period of time (2 days or longer) will affect the reduction-oxidation (redox) potential in the soil environment. In inundated soils, the oxygen is rapidly consumed and Eh falls as microorganisms use alternative electron acceptors during anaerobic respiration. Extensive periods of inundation allow Fe oxides to be reduced, producing the characteristic gray color in soils. Soil mottling occurs with alternating oxidation and reduction periods. In bottomland hardwood forests, there is a wide range in water fluctuations that create a variety of reducing conditions (Faulkner and Patrick 1992).

The redox potential will alter nutrient availability for vegetation, and saturated soils will adversely affect root processes. In seasonally flooded forested wetlands, vegetation directly influences the redox state of the rhizosphere (Havens 1997) similar to submerged aquatic vegetation (Barko and Smart 1981). There is a greater potential for decline in redox potential in soils with greater amounts of organic matter and iron (Mohanty and Dash 1982). The species adaptability to hydroperiod will influence the redox potential. Dissolved organic carbon (DOC) mobility into the soil is related to the redox environment (Hagedorn et al. 2000) where low retention of DOC under reducing conditions will reduce the soil carbon pool.

Submerged Aquatic Vegetation

Submerged aquatic vegetation (SAV) in stream ecosystems affects stream productivity (floral and faunal) and biogeochemical cycles (Carpenter and Lodge 1986). SAV affects the physical environment (i.e., light extinction, temperature, hydrodynamics, substrate), chemical environment (oxygen, inorganic and organic carbon, nutrients) and the biota (i.e., epiphytes, grazers, detritivores, fishes) in streams (Carpenter and Lodge 1986). SAV beds retard stream flow and enhance deposition of fine sediments. Terrestrial allochthonous material is retained in SAV beds and decomposed to a greater extent than in unvegetated stream reaches (Dawson 1980). However, SAV growth can be inhibited by organic matter additions (Barko and Smart 1983). Biomass of SAV decreased with increasing quantity of organic matter added, especially oak (*Quercus* spp.). Successional stage and associated species composition of the adjacent terrestrial ecosystem may influence the amount of allochthonous material entering the stream. The decline in herbaceous vegetation with increasing forest age may influence lateral litter inputs.

In shallow streams and lakes, biomass production and carbon metabolism of SAV is influenced more by temperature than light (Barko and Smart 1981). Barko and Smart (1983) found growth of SAV was correlated negatively with mean dissolved carbon concentration in the interstitial water of sediments. SAV growth may be influenced strongly by variations in stream bottom sediment composition. The physical texture of sediment rather, than its chemical composition, appears to be the principle influence on the distribution of SAV (Barko and Smart 1980). Barko and Smart (1986) suggest that growth of some aquatic plants may be retarded significantly on very organic sediments.

Water becomes more oxygenated by SAV than by floating-leaved macrophytes (Pokorný and Rejmanková 1983). In a river, Kelly et al. (1983) found that diel and annual oxygen dynamics strongly were dependent on macrophyte biomass. SAV oxidizes the rhizosphere, which causes the precipitation of iron and manganese that diffuse upward from deep reduced sediments. Actively

growing SAV release 1-10 % of their photosynthetically-fixed carbon to the water as dissolved organic compounds (Hough and Wetzel 1975). In streams, SAV stands act as sinks for particulate organic matter during the growing season, but export organic matter upon senescence (Dawson 1980).

Objectives

The main objective of this study was to determine how carbon pools in a riparian ecosystem are affected by successional state. To achieve this objective, the following hypotheses were addressed: 1) riparian forest productivity, biomass and carbon pool (above and belowground, and litterfall) are independent of successional stage; 2) woody debris in low order streams and associated riparian areas contributes significantly to the total carbon pool; 3) soil physical and chemical properties are not influenced by the successional stage of riparian area; and 4) successional stage of a riparian area does not affect submerged aquatic vegetation biomass.

Methods

Site Description

Study sites are located in riparian forests adjacent to three braided, blackwater streams on the Savannah River Site (SRS), National Environmental Research Park, in South Carolina (latitude 33 ° N, longitude 82 ° W). Pen Branch and Fourmile Branch streams, third order tributaries of the Savannah River, received thermal, elevated discharge from nuclear production processes between 1954 to 1989, and 1955 to 1985, respectively. These stream corridors experienced elevated temperatures (up to 70 °C) and increased discharge (1 to 2 orders of magnitude greater than base flow). The thermal discharge killed the bottomland hardwood vegetation and disrupted sediment erosion and deposition patterns. The third stream in this study, Meyer's Branch, represents a minimally disturbed, third order

reference site. Only minor disturbances, such as selective logging in the 1940s occurred in Meyer's Branch, but it never received thermal effluent.

The age of the riparian forests adjacent to Pen Branch, Fourmile Branch, and Meyer's Branch at the time this study began were 8 years, 12 years, and approximately 60 years, respectively. There are 2 treatment areas along Pen Branch: one area has been allowed to regenerate naturally (Pen Branch NR) whereas an adjacent area was regenerated artificially with bottomland hardwood plantings following site preparation with herbicides and prescribed burning (Pen Branch AR).

Field and Laboratory Techniques

Quantification of above and belowground biomass and carbon pools will reveal whether riparian forests are affected by disturbance or seral stage. A wide variety of field techniques were used to acquire these data. The following methods describe the techniques used to acquire field and laboratory samples necessary to estimate carbon quantities for each of the identified pools.

Standing Biomass

In 1997 transects were established perpendicular to the main stream channel and generally spanned the width of the riparian area extending into the upland. Placement of the transects was predetermined based on a previously installed hydrology study (Kolka et al. 2000). Transect length ranged from 3 to 94 m originating from the main stream channel. Three transects were established within the natural regeneration area of Pen Branch (NR), 3 within the artificial regeneration area of Pen Branch (AR), 6 within the Fourmile Branch riparian forest, and 5 within the Meyer's Branch riparian forest. Along each riparian forest transect, tree and shrub plots (Wenger 1984) were spaced at 15.2 m intervals originating at the main stream channel. Within each tree plot, the diameter at breast height (dbh @ 1.4 m), height, and species of all trees (dbh > 4.0 cm) within a 0.013 ha circular plot were

recorded. Diameter, height, and species were recorded for all shrubs (dbh < 4.0 cm and height > 0.5 m) within a smaller 0.002 ha shrub plot. Field sampling was conducted in June, 1997, and November, 1999. Aboveground biomass values for the trees and shrubs were estimated using existing dbh:biomass regressions (Table III-1) (Clark and Taras 1976; Peet and Council 1980; Clark et al. 1985; Muzika et al. 1987; Mader 1990; Hauser 1992; Gholz et al. in press).

Herbaceous Biomass

Along each transect, clip plots were spaced at 4.5 m intervals. All herbaceous vegetation < 0.5 m in height (regardless of growth form) was collected and removed from each 0.25 m² area (Hall et al. 1993). Sampling was conducted four times: June & August 1997, and June & August 1998 (same general area with no overlap of clip plot area to avoid influence from previous sampling). Each sample of clipped vegetation was dried to a constant temperature (60 °C) and weighed.

Net Primary Productivity

Total net annual primary productivity was estimated by the mean annual increment method (Art and Marks 1971) in which woody biomass is divided by age of the forest stand. The mean annual increment method generally underestimates current woody production, but allows interpretation of chronosequence type data. Trees and shrubs were divided by the respective riparian forest age (8 & 10.5, 8 & 10.5, 12 & 14.5 and 60 & 62 years for the two areas in Pen Branch, the riparian forest along Fourmile Branch, and the Meyer's Branch riparian forest, respectively). Sixty years was used for Meyer's Branch although some older residual trees remained following selective harvesting in the 1940s. A sixty-year age also was used for the upland forests. The herbaceous strata was considered to be an annual increment. Shrub biomass was divided by forest stand age, but this will underestimate shrub NPP in the Meyer's Branch riparian forest and the four upland forests.

Table III-1. Regression equations for determining aboveground tree and shrub biomass. Within reference, 4-letter species code (App. Tbl 1) in parentheses refer to the species for which the equation was developed and inferred for riparian species.

Shrub Species	Equation	DBH	Reference
<i>Acer rubrum</i> , <i>A. bacata</i> <i>Aronia arbutifolia</i>	$380.508 + 31.52 * (DBH_{cm}^2 * Ht_m)$	$r^2=0.9562$	Hauser ¹
<i>Alnus serrulata</i> , <i>Callicarpa americana</i> , <i>Forestiera acuminata</i> , <i>Itea virginiana</i> ,	EXP (3.124 + (2.7354 * Ln (DBH _{cm}))) <i>Myrica cerifera</i> , <i>Sambucus canadensis</i> , <i>Vaccinium</i> , <i>Viburnum dentatum</i>		Mader ²
<i>Carpinus Caroliniana</i>	$108.511 + 30.207 * (DBH_{cm}^2 * Ht_m)$ $((3.29895 * (DBH_{in}^2))^{\wedge} 1.19583) * 450$	$r^2=0.9554$	Hauser (OXAR) Clark ³ (Carya)
<i>Carya glabra</i>	$((3.299 * (DBH_{in}^2))^{\wedge} 1.196) * 450$		Clark
<i>Cephalanthus occidentalis</i>	$(10^{(-0.712 + 1.744 * \log (DBH_{cm}))} * 1000)$		Muzika ⁴
<i>Cornus foemina</i>	$10^{(2.54 + (1.928 * \log (DBH_{cm})))}$		P&C ⁵ (COFL)
<i>Diospyros virginiana</i>	$((1.822 * (DBH_{in}^2))^{\wedge} 1.264) * 450$		Clark
<i>Fraxinus pennsylvanica</i> , <i>Aesculus pavia</i>	EXP(4.149 + (2.203*Ln (DBH _{cm})))	2-48 mm	Mader (FRCA)
<i>Ilex opaca</i> , <i>I. glabra</i> , <i>I. decidua</i> , <i>Persea borbonia</i>	$337.443 + 42.665 * (DBH_{cm}^2 * Ht_m)$	$r^2=0.9947$	Hauser
<i>Liquidambar styraciflua</i>	$80.364 + 22.603 * (DBH_{cm}^2 * Ht_m)$	$r^2=0.9868$	Hauser
<i>Liriodendron tulipifera</i>	$10^{(2.165 + (2.363 * \log (DBH_{cm})))}$		P&C
<i>Magnolia Virginiana</i>	$-122.84 + 29 * (DBH_{cm}^2 * Ht_m)$	$r^2=0.8840$	Hauser
<i>Nyssa sylvatica</i>	$((0.175 * (DBH_{in}^2 * Ht_{ft}))^{\wedge} 0.91) * 450$ $565.7 + 26.653 * (DBH_{cm}^2 * Ht_m)$	$r^2=0.9510$	Hauser (soft Hdwd)
<i>Ostrya virginiana</i>	$755.121 + 42.751 * (DBH_{cm}^2 * Ht_m)$		Hauser
<i>Pinus taeda</i>	$(10^{(-1.029 + 0.988 * \log((DBH_{in}^2 * Ht_{ft})))} * 450$	$r^2=0.9056$	Hauser
<i>Quercus velutina</i> , <i>Q. laurifolia</i> , <i>Q. nigra</i> , <i>Q. lyrata</i>	$108.511 + 30.207 * (DBH_{cm}^2 * Ht_m)$ $1280.568 + 39.4 (DBH_{cm}^2 * Ht_m)$	$r^2=0.9376$	Hauser
<i>Sabal minor</i>	Rachis EXP (-10.38 + (2.72*Ln(Rachis _{cm}))) Frond -13.31 + (0.85*Frond _{cm})		Ghoetz ⁶
<i>Salix nigra</i> , <i>Betula nigra</i>	$(10^{(-1.017 + 2.07 * \log (DBH_{cm}))} * 1000)$		Muzika
<i>Taxodium distichum</i>	EXP (4.247 + (2.144 * Ln (DBH _{cm})))		Mader
<i>Ulmus americana</i>	$10^{(2.22 + (2.391 * \log (DBH_{cm})))}$		P&C (ULRU)

Table III-1 continued.

Tree Species	Equation	DBH Range/r ²	Reference
<i>Acer rubrum</i> , <i>Fraxinus pennsylvanica</i> , <i>Platanus occidentalis</i> , <i>Sambucus canadensis</i>	$((0.149 * (DBH_{in}^2 * Ht_{ft})) ^ 0.94)*450$ $8.299 + 0.3714*DBH_{cm}$ $9.76 + 3.9*DBH_{in}$	r ² =0.99 r ² =0.3172	Hauser Clark
<i>Alnus serrulata</i> , <i>Myrica cerifera</i>	EXP (3.124 + (2.7354 * Ln (DBH _{cm})))		Mader
<i>Carpinus caroliniana</i> , <i>Ilex opaca</i> , <i>Ostrya virginiana</i>	$((0.2251 * (DBH_{in}^2 * Ht_{ft})) ^ 0.924)*450$	r ² =0.99	Hauser (Hd Hdwd); Clark
<i>Carya glabra</i>	$((3.299 * (DBH_{in}^2)) ^ 1.196)* 450$ $((1.613 * (DBH_{in}^2)) ^ 1.334)* 450$		Clark P&C > 11"
<i>Cephalanthus occidentalis</i>	$(10^{(-0.712 + 1.744 * \log (DBH_{cm}))} * 1000)$		Muzika
<i>Cornus florida</i>	$10 ^ (2.54 + (1.928 * \log (DBH_{cm})))$		P&C
<i>Diospyros virginiana</i>	$((1.822 * (DBH_{in}^2)) ^ 1.264)* 450$		Clark
<i>Liquidambar styraciflua</i> , <i>Tilia americana</i>	$((0.132 * (DBH_{in}^2 * Ht_{ft})) ^ 0.9416)*450$	r ² =0.99	Hauser Clark
<i>Nyssa sylvatica</i> , MAAN	$((0.175 * (DBH_{in}^2 * Ht_{ft})) ^ 0.91)*450$	r ² =0.99	Hauser (soft Hdwd); Clark
<i>Pinus taeda</i>	$(10 ^ (-1.029 + 0.988 * \log((DBH_{in}^2 * Ht_{ft}))) * 450$	r ² =0.99	Hauser; Clark&Taras ⁷
<i>Quercus alba</i>	$((0.2 * (DBH_{in}^2 * Ht_{ft})) ^ 0.939)*450$	r ² =0.99	Hauser; Clark
<i>Quercus nigra</i>	$((0.237 * (DBH_{in}^2 * Ht_{ft})) ^ 0.923)*450$	r ² =0.99	Hauser; Clark
<i>Salix nigra</i> , <i>Betula nigra</i>	$(10 ^ (-1.017 + 2.07 * \log (DBH_{cm})) * 1000)$		Muzika
<i>Taxodium distichum</i>	$((0.1066 * (DBH_{in}^2 * Ht_{ft})) ^ 0.935)*450$		Mader
<i>Ulmus americana</i> , <i>U. alata</i>	$10 ^ (2.22 + (2.391 * \log (DBH_{cm})))$		P&C (ULRU)

1) Hauser 1992

2) Mader 1990

3) Clark et al. 1985

4) Muzika et al. 1987

5) P&C refers to Peet and Council 1980

6) Gholz et al. in press

7) Clark and Taras 1976

Litterfall

Eight litter traps (0.187 m² each) per site were placed randomly in each riparian area (Conner and Day 1992) and 3 to 4 litter traps (0.187 m² each) were randomly placed in the adjacent upland of each riparian forest. Collectors were elevated approximately 0.6 m to prevent inundation during flood events. Litter was collected biweekly from September to November and approximately every two months for one year (9/97-8/98) thereafter for a total of 10 collection periods. Litterfall also was collected four times during peak litterfall of the following year (9/98-2/99). Litter was separated by component (leaves, stems, miscellaneous [e.g., seeds, flowers, and insects]). Vertical litter samples were dried to a constant temperature (60 °C) and each sample weighed by component (leaves, twigs, and miscellaneous). For all four sites, only tree & shrub litterfall components were included. In Pen Branch (AR), herbaceous vegetation tended to engulf the litter traps, but was not included in the sample.

Forest Floor

Forest floor samples consisting of the Oi (leaves, twigs) and Oe (fragmented leaves and twigs) layers combined were collected from fifteen 0.25 m² areas placed randomly within each riparian forest except Pen Branch (AR), due to the density of herbaceous vegetation, and 6 to 8 0.25 m² areas in the adjacent upland forest (Elliott et al. 1993). Samples were separated into two categories; leaves, and twigs & miscellaneous. Litter samples were dried to a constant temperature (60 °C) and each sample weighed. Forest floor samples were collected in early May 1998 to emulate what would be remaining of the previous season's litterfall.

Woody Debris

Woody debris was inventoried using a line-intersect method (Wenger 1984). From randomly selected azimuths, 10 20-meter transects originated from vegetation plot centers in each riparian area. Where riparian transects cross the main stream channel, 1 25-meter transect was established upstream and another 25-meter transect established downstream. Woody debris was tallied along these transects. In the riparian area, woody debris was recorded as fine (1-2.5 cm), medium (2.5-10 cm), and large (> 10 cm) diameter. The median diameters of the fine and medium size classes, the actual diameter of the large size class, and average relative density for mixed hardwoods (Harmon et al. 1980; Phillips 1981) were used to convert woody debris to biomass. Penetrometer readings were taken on medium and large pieces to determine their soundness (Scheungrab, personal communication). A sound/rotten designation was given subjectively to fine woody debris.

Fine Roots

It is important to recognize that the belowground biomass associated with larger roots has not been included in the samples collected from each riparian forest. Sampling was conducted in June 1999. Two 5-cm diameter by 20-cm length metal cores were inserted into the soil near, but not within, each clip plot (Hall et al. 1993). Depth of core insertion was measured when obstructions (large roots or rock) prevented insertion of the total length of the core. Samples (soil and roots) were refrigerated until fine roots could be washed/separated from the soil with a jet of water on a sieve (pore openings ≤ 2 mm). Only roots ≤ 5 mm were retained. Roots were rated subjectively as live or dead. Live roots are considered resilient, flexible and fleshy. Roots were classified dead if they were limp and crumbled easily. Fine roots were dried to a constant temperature (60 °C) and each sample weighed.

Soil Carbon

Bulk soil samples were randomly collected from the O/A horizons in each riparian area and adjacent upland (James and Wells 1990). The A-horizon was approximately 7.5-13 cm in depth in the Fourmile Branch riparian forest and 7.5-15 cm in depth in the 2 areas of Pen Branch (Azola 1997). The histic O-horizon in the Meyer's Branch riparian forest ranged from 20-76+ cm. Carbon content of the soil samples were determined via infrared analysis (LECO Total Carbon Analyzer, CR12, LECO Corp., Saint Joseph, MI).

Sediment / Reduction Oxidation Potential

A 4-foot piece of rust-free rebar with a washer placed halfway along the bar length was placed 1 meter from a monitoring well that was located along the transects. For placement of monitoring wells see Kolka et al. (2000). The rebar was stuck in the ground until the washer was flush with the ground and served as a sedimentation rod (NCASI 1986). Eleven, 7, 15, and 13 rods were placed in Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively. These rods also were used to evaluate the site hydrology by determining the depth of iron reduction (McKee 1978). Rods were placed in Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively, on August 8, 1997. Measurements of sediment change were taken after approximately 66 weeks. After 66 weeks rods were inspected visually (subjectively) for depth to initial rust (iron oxidation) and permanent gray coloration (iron reduction) to assess relative redox potential by observing changes in rod color as well as water table fluctuations (McKee 1978).

Stream Vegetation - submerged aquatic vegetation (SAV)/macrophyte

Stream plots were an extension of the terrestrial transect. Submerged aquatic vegetation biomass was sampled based on stream width (<500 cm - 3 points; > 500 cm - 5 points). Each sample

size is 177 cm² (15-cm diameter). Canopy coverage over the stream was determined subjectively as no canopy (open), partial, or full canopy. Other stream measurements included: water depth at each point, percent macrophyte cover at each point, percent macrophyte cover across stream reach, and bank to bank stream width. Sampling occurred four times: August and December 1997, and May and August 1998. Samples were dried to a constant temperature (60 °C) and each sample weighed. One species (*Egeria densa*) dominated the streams at both Pen Branch sites. No SAV was observed in Meyer's Branch during the sampling times. An unidentified species was observed growing sparsely in the Fourmile Branch main stream channel, but it never occurred within the sampling transects.

Carbon Laboratory Analyses

All vegetation, roots, soil, litterfall, and forest floor samples collected were dried, stored, and analyzed for carbon content. Carbon content was determined via infrared analysis (LECO Total Carbon Analyzer, CR12, LECO Corp., Saint Joseph, MI). Three replicates of the respective sample were analyzed for carbon content. Means were calculated for the three carbon replicates for herbaceous vegetation, roots, litterfall, forest floor, and soil for use in statistical analyses.

Statistical Analysis Procedures

The main analysis tool was analysis of variance (ANOVA) for a completely randomized design (SAS Institute 1996). The four sites (Pen Branch (AR), Pen Branch (NR), Fourmile Branch and Meyer's Branch) representing different seral stages comprised the treatments. Differences in various biomass and carbon pool components among the four sites were analyzed. Aboveground biomass variables included tree biomass, shrub biomass analyzed individually for both 1997 and 1999, and herbaceous biomass for all 4 sampling dates. Belowground biomass variables included fine root biomass and soil organic matter. Additional soil properties tested included percent carbon, bulk density, and total and non-capillary porosity. Differences in annual litterfall, forest floor, woody debris,

sediment, and submerged aquatic vegetation each were compared among the four sites. The Tukey multiple range test was used to test treatment mean differences. A significance level (α) of 0.05 was used for all tests.

Results and Discussion

Standing Biomass

Riparian

Site preparation measures used in the artificial regeneration section of Pen Branch have slowed succession of the woody component, maintaining a thick herbaceous cover. Specifically, because fire is an infrequent natural occurrence in these riparian forests, burning as a site preparation method retarded establishment of woody species (other than *Rubus*). Therefore, Pen Branch (AR) was considered a younger seral stage than Pen Branch (NR). The Pen Branch (NR) and Fourmile Branch riparian forests were relatively similar in successional development, as displayed by an increase in shrub and tree species and coverage, a nearly closed canopy, and a decline in herbaceous cover. Although Meyer's Branch was a relatively mature riparian forest with a closed canopy, it still exhibited an increase in biomass over 2 ½ years and may be considered a later seral stage, but not a temporal 'endpoint'. Aboveground biomass in all four riparian forests increased over a 2 ½ year period (Fig. III-2). The slight discrepancy in Fourmile Branch possibly was the result of hydroperiod differences that could affect forest productivity.

Herbaceous vegetation rapidly becomes established after a disturbance (Dunn and Sharitz 1987). With increasing forests development, the herbaceous biomass declined and became a very small portion of the total above ground biomass (Fig. III-3 and III-4). Herbaceous biomass in the younger seral stage in Pen Branch (AR) significantly was greater than that of the other three riparian

forests. Herbaceous biomass data obtained for several riparian forests recovering from thermal disturbance as well as an undisturbed riparian forest illustrates a general decline in herbaceous biomass with increasing forest age/succession (Table III-2).

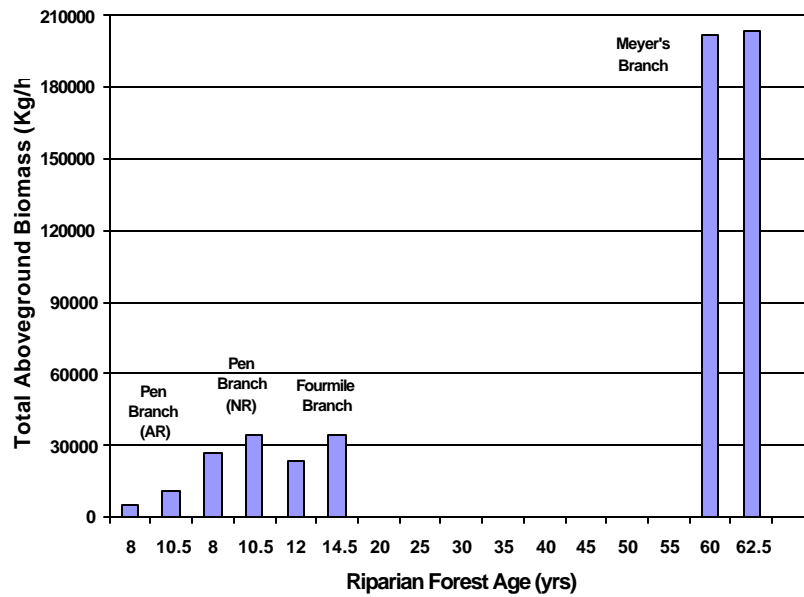


Figure III-2. Total aboveground biomass (tree, shrub and herb) for several South Carolina Coastal Plain riparian forests of differing ages. X-axis is not linear. Pen Branch (AR) is considered to represent a riparian forest younger than 8 and 10.5 years of age.

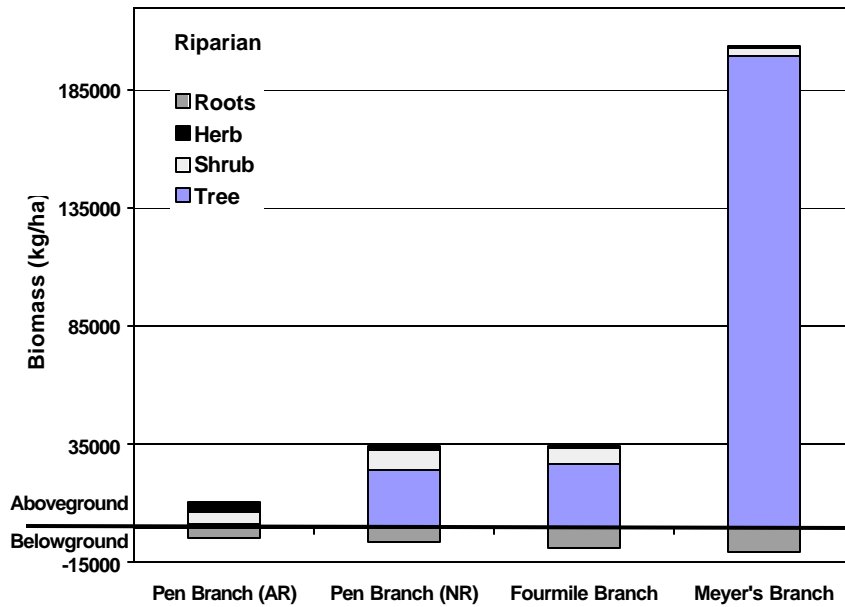


Figure III-3. Tree, shrub, herb, and fine root biomass for four riparian forests of differing stand age in the South Carolina Coastal Plain. Tree and shrub calculations are from the 11/99 data, herb values are the mean of the 4 sample dates (June&Aug. 1997 and June&Aug 1998), and root values are from the 6/99 data.

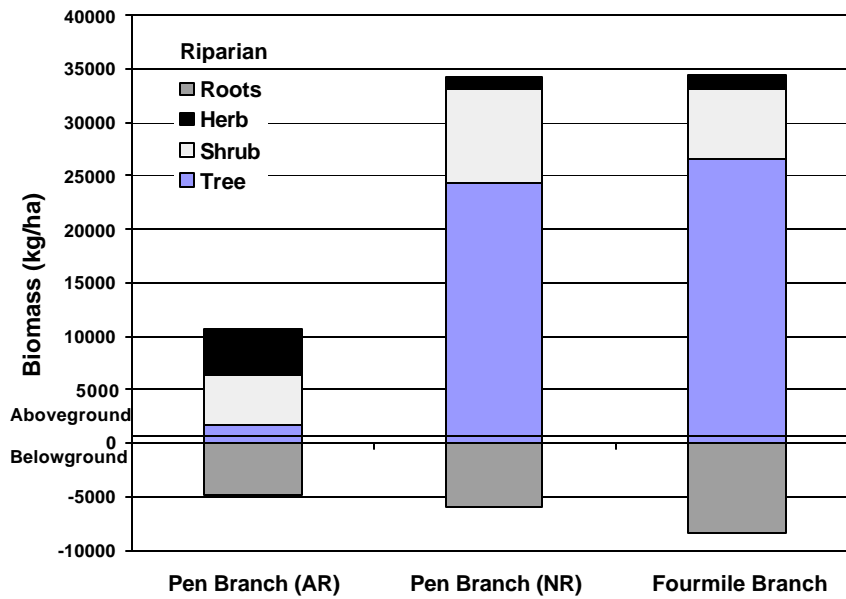


Figure III-4. Tree, shrub, herb, and fine root biomass for the three younger riparian forests in the South Carolina Coastal Plain. Tree and shrub calculations are from the 11/99 data, herb values are the mean of the 4 sample dates (June&Aug. 1997 and June&Aug 1998), and root values are from the 6/99 data.

Herbaceous species composition changed with seral stage and differences in percent carbon may influence carbon pool magnitude. The abundance of *Rubus*, which was included in the herbaceous component, generated a significantly greater percent carbon in herbaceous vegetation of Pen Branch (AR) than the percent carbon in herbaceous vegetation of Pen Branch (NR) and Fourmile Branch (Table III-3). The percent carbon in herbaceous vegetation in Meyer's Branch significantly was greater than the percent carbon in herbaceous vegetation in Fourmile Branch. A predominant herb (*Commelina virginica* L.) in Fourmile Branch has a rhizomatous growth form that may require less structural carbon and therefore possesses a lower percent carbon. Whether differences in percent carbon are ecologically significant depends on scale of interest. The subtle differences in percent carbon may play a role in plant evolutionary strategy yet to be determined. The combined greater herbaceous biomass and higher percent carbon result in Pen Branch (AR) having a significantly greater herbaceous carbon pool compared to the other three riparian forests (Table III-3). Both Pen Branch (NR) and Fourmile Branch riparian forests have significantly greater herbaceous carbon pools than the Meyer's Branch riparian forest. This implies that despite apparent statistical differences in the percent carbon of herbaceous species, the herbaceous carbon pool decreases with forest age/succession in riparian forests.

The tree and shrub biomass increased in each site over a 2 ½ year period, except for a decrease in shrub biomass in Meyer's Branch (Table III-4). Both tree and shrub biomass increased significantly in Pen Branch (AR) over the 2 ½ years suggesting that this site is following successional patterns toward a forest community. The towering tree and shrub biomass of the Meyer's Branch riparian forest is the result of the broad age difference between it and the other three riparian forests (Fig. III-3). Aboveground biomass in Meyer's Branch is comparable to values reported for other forested wetlands (Table III-5). Both Pen Branch riparian forests and the Fourmile Branch riparian forest had lower aboveground biomass compared to more mature forested wetlands (Table III-6).

Table III-2. Herbaceous biomass at several undisturbed and thermally recovering riparian forests on the Savannah River Site in the Coastal Plain of South Carolina.

Study Area	Stand Age	Herbaceous Biomass	Reference
		kg ha⁻¹	
Pen Branch	Thermal 20 yrs	2230	Sharitz et al. 1974
Steel Creek Natural Regeneration	5 yrs Post Thermal	3400	Sharitz et al. 1974
Pen Branch (AR)	8 yrs Post Thermal	4468	This Study
Pen Branch (NR)	8 yrs Post Thermal	1295	This Study
Pen Branch (AR)	9 yrs Post Thermal	3800	This Study
Pen Branch (NR)	9 yrs Post Thermal	945	This Study
Fourmile Branch	12 yrs Post Thermal	1462	This Study
Fourmile Branch	13 yrs Post Thermal	735	This Study
Steel Creek	15 yrs Post Thermal	900	Muzika et al. 1987
Meyer's Branch	Mature Undisturbed (~1983)	150	Muzika et al. 1987
Meyer's Branch	Mature Undisturbed (1997) 60+ yrs	520	This Study
Meyer's Branch	Mature Undisturbed (1998) 60+ yrs	370	This Study
Upper Three Runs Creek	Mature Undisturbed ~75 yrs	1340	Sharitz et al. 1974

Table III-3. Percent carbon and carbon pools for the herb and root components of 4 riparian forests and adjacent upland forests in the South Carolina Coastal Plain. Within a column and ecosystem (riparian or upland), letters different from each other are significantly different ($\alpha = 0.05$). Standard deviations are in parentheses (). Sample size (N) for Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch respectively are 53, 40, 60, 40 and 54, 40, 86, 44 for riparian herbs and roots, respectively and 6, 5, 11, 10 and 9, 9, 15, 15 for upland herbs and roots.

	Herbs		Roots	
	% Carbon	Carbon Pool (g C m ⁻²)	% Carbon	Carbon Pool (g C m ⁻²)
Riparian				
Pen Branch (AR)	46 (2) a	213 (97) a	41 (5) b	185 (105) c
Pen Branch (NR)	44 (3) bc	62 (43) b	46 (3) a	277 (182) bc
Fourmile Branch	43 (4) c	62 (53) b	44 (6) ab	304 (211) b
Meyer's Branch	45 (2) ab	16 (15) c	46 (5) a	436 (242) a
Upland				
Pen Branch (AR)	48 (4) a	13 (6) ab	44 (5) a	588 (205) a
Pen Branch (NR)	47 (2) a	6 (2) b	49 (1) a	537 (169) a
Fourmile Branch	46 (1) a	12 (16) ab	45 (5) a	426 (178) a
Meyer's Branch	48 (2) a	34 (28) a	48 (3) a	498 (196) a

There was an increase in fine root biomass with increasing forest age (Fig. III-3 and III-4), however, an inverse relationship was observed between percentage of fine root biomass to total biomass and riparian forest age. Fine root biomass comprised 31%, 15%, 20% and 5% of the total biomass for Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively, all of which were in the range found by Harris et al. (1977) and Montague and Day (1980). Fine root biomass in Meyer's Branch significantly was greater than that in the other three riparian forests, and fine root biomass in Fourmile Branch significantly was greater than that in both Pen Branch riparian forests. Fine root biomass found in the three younger riparian forests was one-fourth to one-half that found in other mature forested wetlands, however, fine root biomass in Meyer's Branch was only slightly less than the other mature forested wetlands (Montague and Day 1980). Either forest age or hydroperiod

could account for the differences in fine root biomass between this study and others. Also, differences in root biomass may not be apparent if all roots are included.

The number of roots from woody species increases with forest development/succession and roots from woody species generally have a greater percent carbon than roots of herbaceous species. The percent carbon in fine roots at Pen Branch (NR) and Meyer's Branch significantly was greater than the percent carbon in those at Pen Branch (AR) (Table III-3). The percent carbon of the fine roots in Fourmile Branch also was greater than the Pen Branch (AR) fine root percent carbon which implies that the predominance of roots associated with trees and shrubs have higher percent carbon than herbaceous roots. Greater fine root biomass combined with a higher percent carbon in the fine roots result in Meyer's Branch having a significantly greater root carbon pool than the other three riparian forests (Table III-3). The fine root carbon pool in Fourmile Branch significantly was greater than the Pen Branch (AR) fine root carbon pool. The 4 fine root carbon pools in this study were comparable to a mature mesophytic deciduous forest (Edwards and Harris 1977). Based on these data, the fine root carbon pool increases with forest age/succession.

The ratio of aboveground biomass to belowground biomass appears to decrease with increasing forest development/succession (Table III-4) in the riparian forests. The upland forests have comparable above/belowground ratios (except for Pen Branch (AR)) and was comparable to the mature riparian forest. Therefore, this biomass ratio may be representative of forest age.

Table III-4. The above and belowground biomass (kg ha^{-1}), above/belowground biomass ratio, and net primary productivity (NPP) ($\text{kg ha}^{-1} \text{ yr}^{-1}$) with and without litterfall for 4 riparian and upland forests in the South Carolina Coastal Plain.

	Pen Branch (AR)	Pen Branch (NR)	Fourmile Branch	Meyer's Branch
Riparian				
Trees ¹ (kg ha^{-1})	313 1731	19,487 24,414	17,510 26,516	196,558 199,847
Shrubs ¹ (kg ha^{-1})	833 4702	6303 8629	4609 6713	4694 3378
Herbs ² (kg ha^{-1})	4290	1160	1130	430
Fine Roots (kg ha^{-1})	4770	6010	8460	10,590
Above/below ground ratio ³	0.44	0.18	0.25	0.05
NPP ⁴ w/o litterfall ($\text{kg ha}^{-1} \text{ yr}^{-1}$)	4903	4307	3422	3682
NPP w/ litterfall ⁵ ($\text{kg ha}^{-1} \text{ yr}^{-1}$)	5187	10,319	7649	8947
Upland				
Trees (kg ha^{-1})	123,093	285,981	312,041	245,579
Shrubs (kg ha^{-1})	4598	9238	6534	6670
Herbs (kg ha^{-1})	270	100	260	650
Fine Roots (kg ha^{-1})	14,100	11,430	9860	10,800
Above/below ground ratio	0.11	0.04	0.03	0.04
NPP w/o litterfall ($\text{kg ha}^{-1} \text{ yr}^{-1}$)	2330	4862	5398	4719
NPP w/ litterfall ($\text{kg ha}^{-1} \text{ yr}^{-1}$)	7750	10,302	12,998	11,769

- 1) In each riparian forest, mean biomass was for 1997 and 1999, respectively.
- 2) Herbaceous biomass was the mean for all four sampling dates (June&Aug. 1997 and June&Aug 1998).
- 3) Above/Belowground biomass ratio: root/(tree+shrub+herb). 1999 tree and shrub data.
- 4) NPP includes trees (1999), shrubs (1999), and herbs.
- 5) Annual litterfall was collected 9/97-8/98.

Table III-5. Aboveground biomass and production of Coastal Plain riparian forests and similar forested wetlands (adapted from Conner, 1994 and modified from Zaebst, 1997).

Forest Type / Location	Aboveground Biomass ¹ (Mg ha ⁻¹)	Annual Productivity (Stem growth only) ² (Mg ha ⁻¹ yr ⁻¹)	Reference
Cypress-water tupelo / LA	375	5.0	Conner & Day 1976
Cypress-water tupelo / FL	190	2.89	Mitsch & Ewel 1979
Cypress-tupelo / IL	--	3.30	Mitsch 1978
Bottomland hardwood / IL floodplain / transition	289 / 141	11.5 / 7.1	Johnson and Bell 1976
Bottomland hardwood / IL stillwater / flowing	--	4.24 / 1.77	Brown and Peterson 1983
Forested wetlands/ KY various hydroperiods	94, 102, 184, 303, 312	1.42, 2.71, 4.98, 8.12, 9.14	Mitsch et al. 1991
Floodplain swamp / NC	267	5.85	Mullholland 1979
Floodplain swamp / FL	284	10.86	Brown 1981
Bottomland hardwood / LA	165	8.0	Conner & Day 1976
Dismal swamp-BLH ³ / VA	189	--	Day & Dabel 1978
Dismal swamp-maple/gum / VA	190	--	Day & Dabel 1978
Cypress swamp / LA	278	--	Conner & Day 1982
Cypress-hardwood / FL	154	3.36	Mitsch & Ewel 1979
Dismal swamp-cypress / VA	339	--	Day & Dabel 1978
Okefenokee swamp /GA	307	3.53	Schlesinger 1976
Cypress-hardwood / SC	348	13.4	Muzika et al. 1987
Bottomland hardwood / SC mesic / dry transition wet transition / flooded	--	5.86 / 4.62 5.09 / 8.81	Burke et al. 1999
Cypress-tupelo / SC low / high disturbance	--	3.73 / 4.13	Scott et al. 1985
Naturally Recovering BLH / SC 15 yrs post disturbance	26	2.85	Muzika et al. 1987
Riparian BLH 7-8 yrs post harvest	0.06	9.09	Bates 1989

- 1) Trees and Shrubs, no herbs,
- 2) Trees and Shrubs, Leaf litterfall was not included.
- 3) BLH - bottomland hardwood.

Table III-6. Aboveground biomass and annual productivity for the four South Carolina Coastal Plain riparian forests in this study (1997-1999).

Forest Type / Location	Aboveground Biomass ¹ (Mg ha ⁻¹)	Annual Productivity (Stem growth only) ² (Mg ha ⁻¹ yr ⁻¹)
Cypress-hardwood / SC Meyer's Branch (1997)	201	3.35
Cypress-hardwood / SC Meyer's Branch (1999)	203	3.25
Naturally Recovering BLH ³ / SC 12 yrs post disturbance Fourmile Branch	22.1	1.89
Naturally Recovering BLH/ SC 14.5 yrs post disturbance Fourmile Branch	33.2	2.29
Naturally Recovering BLH/ SC 8 yrs post disturbance Pen Branch (NR)	25.8	3.24
Naturally Recovering BLH/ SC 10.5 yrs post disturbance Pen Branch (NR)	33.0	3.15
Restored BLH/ SC 8 yrs post disturbance Pen Branch (AR)	1.1	0.16
Restored BLH/ SC 10.5 yrs post disturbance Pen Branch (AR)	6.4	0.61

- 1) Trees and shrubs, no herbs,
- 2) Trees and shrubs, leaf litterfall was not included.
- 3) BLH - bottomland hardwood.

Upland

The aboveground biomass of the mature upland forests adjacent to each of the riparian forests generally was greater than the aboveground biomass in the Meyer's Branch riparian forest except for the upland forest in Pen Branch (AR) (Table III-4). The differences in upland aboveground biomass demonstrates the variability within mature forests (Fig. III-5).

The herbaceous biomass in the Meyer's Branch upland forest significantly was greater than the herbaceous biomass in the other three upland forests. However, similar to mature riparian forests, the herbaceous biomass component in upland stands is inconsequential compared to the woody biomass component (Fig. III-5). There was no significant difference in the percent carbon of the herbs in the four upland forests (Table III-3). There was no significant difference in fine root biomass, percent carbon in the roots, or fine root carbon pool among the four upland forests (Table III-3).

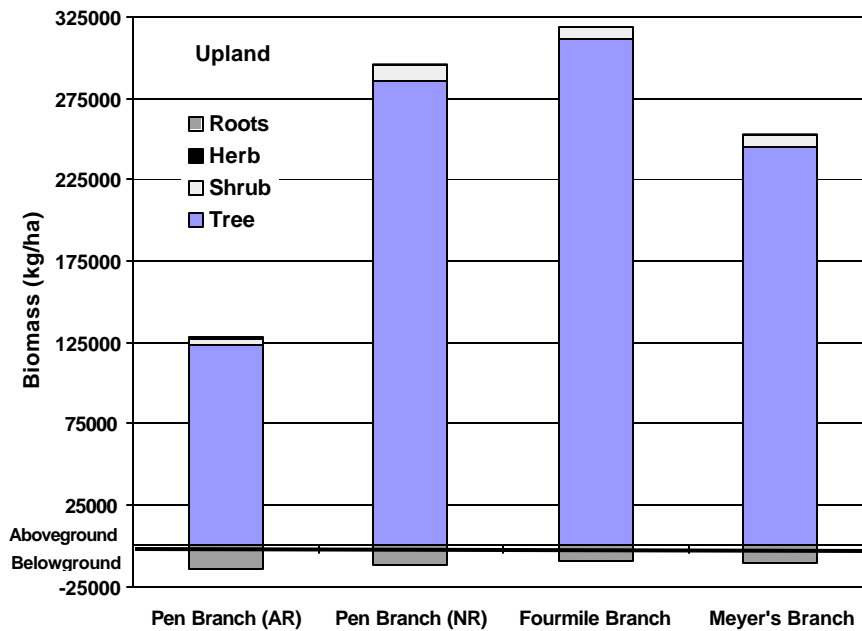


Figure III-5. Tree, shrub, herb and root biomass for the adjacent upland forests in the South Carolina Coastal Plain. Tree and shrub calculations are from 11/99 data, herb values are the mean of the 4 sample dates (June&Aug. 1997 and June&Aug. 1998), and root values are from the 6/99 data.

Riparian vs Upland

Herbaceous biomass significantly was greater in the riparian forests of both Pen Branch sites and Fourmile Branch than their adjacent upland forests due to differences in forest stage of

development (stand age). In contrast, the herbaceous biomass in the Meyer's Branch riparian forest was less than the herbaceous biomass in the adjacent upland forest, but the difference was not significant ($p=0.1086$). The saturated riparian environment and shadier closed canopy in Meyer's Branch may create conditions unsuitable for the continued existence of certain herbaceous species or preclude the establishment of herbaceous species. The percent carbon of the herbaceous vegetation was significantly less in the riparian forests of all four sites compared to their adjacent upland forests because woody seedlings (which were greater in number in the uplands compared to the riparian areas) were included in the herbaceous component. The differences in percent carbon did not override herbaceous biomass in determining the herbaceous carbon pool. The herbaceous vegetation carbon pool significantly was higher in the three younger riparian forests compared to their adjacent upland forests. In contrast, the herbaceous vegetation carbon pool in the mature riparian forest significantly was less than that of the adjacent upland forest.

Less woody biomass in the riparian forests of both Pen Branch sites and Fourmile Branch resulted in significantly less root biomass than in the upland forests. There was no significant difference in percent carbon of the upland fine roots and riparian fine roots, however, the percent carbon of the upland fine roots was greater than the percent carbon of the riparian roots in each site respectively. The difference in upland versus riparian fine root biomass translates into significantly lower fine root carbon pools in the riparian forests of both Pen Branch sites and Fourmile Branch than their respective upland forests. The maturity of the Meyer's Branch riparian forest registers root carbon pools comparable to upland forest root carbon pools.

Net Primary Productivity

Forest development/succession patterns influenced net primary production in these riparian forests. A drop in production during later stages of succession can be attributed to developing forest structure. In general, NPP in young riparian forests (~8-10 years) rapidly approached and exceeded

NPP of more mature riparian forests. Marks (1974) observed production to reach steady-state levels after 4-5 years in *Prunus* dominated communities. NPP of trees, shrubs, and herbs combined was greater in both Pen Branch riparian forests than either Fourmile Branch or Meyer's Branch riparian forest (Fig III-6a). Similar to findings by Mitsch (1978) and Johnson and Bell (1976), herbaceous vegetation in this study comprised a very small portion of the NPP. Including litterfall as a component of NPP changed the balance between the four riparian forests (Fig. III-6b). NPP in the Pen Branch (NR) riparian forest exceeded NPP in the other three riparian forests. The drier hydroperiod (personal observation) in Pen Branch (NR) appeared to promote forest productivity, especially leaf production. This supports the theory that hydrology greatly effects nutrient dynamics and therefore, forest productivity. Comparing NPP (with litterfall) in Pen Branch (AR) to the other riparian forests may be inappropriate because it is dominated by herbaceous vegetation. The flashy hydroperiod in the Fourmile Branch riparian forest and saturated conditions in the Meyer's Branch riparian forest certainly impact the productivity of these sites. Except for Pen Branch (AR), NPP for each riparian forest was comparable to other forested wetlands (Tables III-5 and III-6).

NPP varied in the upland forests adjacent to the riparian forests, but generally increased over a 2 ½ year period, demonstrating that these forests still are growing (Fig. III-7a). Including litterfall in NPP did not change the schema among the four upland forests (Fig. III-7b). Except for the upland Pen Branch (AR) forest, upland forest NPP (without litterfall) was equivalent to NPP in both Pen Branch riparian forests and greater than NPP in the riparian forests of Fourmile Branch and Meyer's Branch.

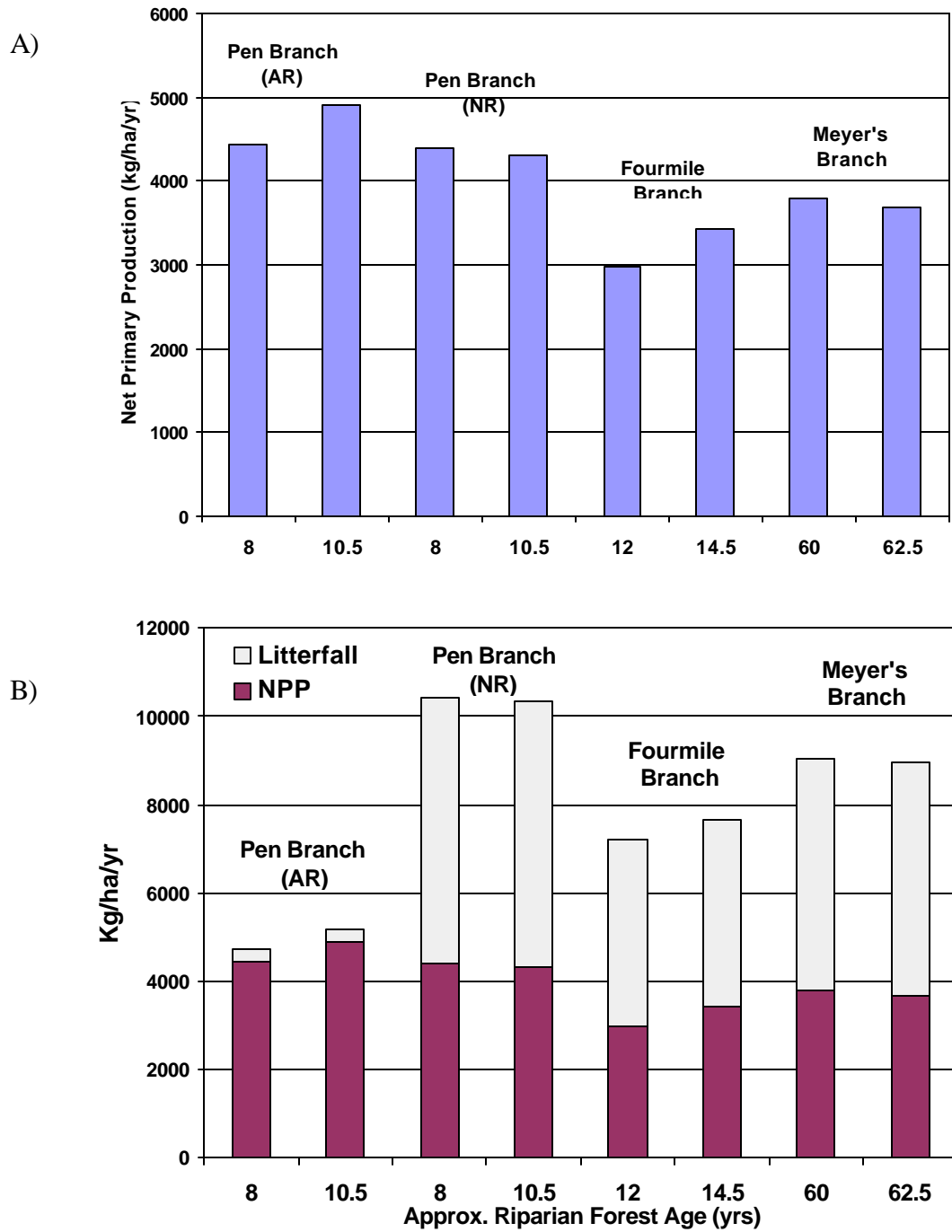


Figure III-6. A) Net primary productivity for the riparian forests at age x and $x+2\frac{1}{2}$ for each site. The mean herb biomass for the four samples was included as annual productivity; tree and shrub biomass values were divided by the respective stand age. B) Same NPP as in A with the addition of annual litterfall.

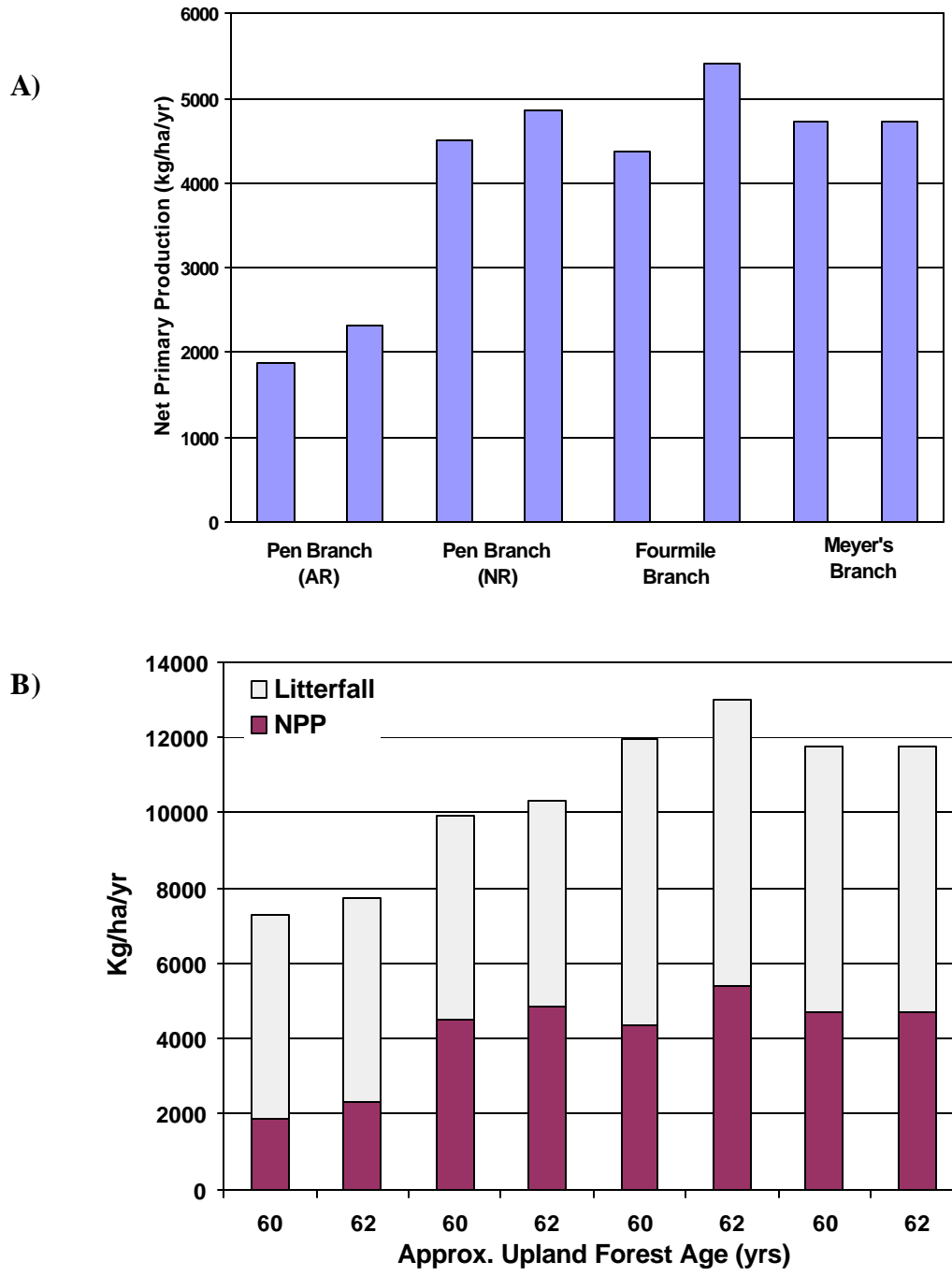


Figure III-7. A) Net primary productivity for the upland forests at age x and x +2 1/2 for each site. The mean herb biomass for the four samples was included as annual productivity; tree and shrub biomass values were divided by their respective age (assumed 60 and 60 1/2). B) Net primary productivity for the upland forests at age x and x +2 1/2 for each site with the addition of annual litterfall.

Litterfall and Forest Floor

Establishment of woody species occurred within 8-10 years, and possibly sooner, after thermal disturbance and litterfall amount in young riparian forests became comparable to mature riparian forests. Annual litterfall was significantly less in Pen Branch (AR) than the other three riparian forests due to the lack of woody species in the overstory. Annual litterfall comprised approximately 55-59% of the NPP in the riparian forests and 53-70% in the upland forests. In the herbaceous dominated riparian forest of Pen Branch (AR), annual litterfall only comprises approximately 5% of total NPP (Fig. III-6B). Once the herbaceous stage of succession is surpassed and a woody overstory becomes established (after ~ 8-10 years), annual litterfall rates as a function of NPP are independent of forest age. Differences in forest floor biomass were observed with increasing riparian forest development. The forest floor biomass in the Meyer's Branch riparian forest was less (although not significantly) than the forest floor biomass in Pen Branch (NR) and Fourmile Branch riparian forests (Table III-7). The forest floor biomass was slightly lower, however, the forest floor carbon pool was equivalent to findings by Trettin et al. (1999).

Table III-7. Mean riparian forest floor biomass, foliar % carbon and forest floor carbon pool for 3 riparian forests in the South Carolina Coastal Plain. Standard deviations are in parentheses (). Sample sizes are in brackets []. Within a column, means with different letters are significantly different.

Site	Biomass		Carbon	
	(g m ⁻²)	(%)	(g C m ⁻²)	
Pen Branch (NR)	99 (79) [15] a	25 (5) [14] a	33 (13) [14] a	
Fourmile Branch	88 (101) [15] a	32 (8)[9] a	42 (25) [9] a	
Meyer's Branch	65 (118) [15] a	45 (4) [8] a	43 (47) [8] a	

Woody Debris

Woody debris comprised a relatively small part of the total carbon pool. Mean woody debris biomass was 0.26 g m^{-2} , 0.23 g m^{-2} , 0.18 g m^{-2} , and 0.28 g m^{-2} for Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively. High annual litterfall input of twigs in Pen Branch (NR) (Chapter IV) accounted for the greater woody debris biomass in Pen Branch (NR) compared to Fourmile Branch. In each riparian forest the amount of fine woody debris (1-2.5 cm) was significantly greater than medium sized woody debris (2.5-10 cm). No large woody debris ($> 10 \text{ cm}$) was found in Pen Branch (NR), however, several large pieces intersected the transect in Pen Branch (AR), probably remnants from the original forest. Meyer's Branch logically had the greatest number of large woody debris pieces due to its more mature forest composition, closely followed by Fourmile Branch. There was no significant difference in the biomass contribution between the fine and medium sized woody debris for all sites. The majority of the woody debris was considered sound and had undergone little decay.

The amount of woody debris in the streams accumulates as a function of forest development. The main stream channel within the mature riparian forest had considerably more woody debris in all three size classes than the main stream channels within the three younger riparian forests. Several large wood pieces, possibly remnants of pre-disturbance forest conditions, were found in the streams associated with the younger riparian forests.

Soil Physical and Chemical Properties

Riparian

Forest maturity and intrinsic stability or equilibrium (resistant and resilient to change) of nutrient cycling processes appear to affect soil organic matter and carbon percentages and quantities. The mature riparian forest had significantly greater percent carbon and organic matter than the three younger riparian forests (Table III-8) due to the high litterfall inputs (leaves and roots) in Meyer's Branch. The organic matter (%) in these riparian forests are comparable to other Coastal Plain forested wetlands (Wharton et al. 1982; Axt and Walbridge 1999).

An inverse relationship between total porosity and bulk density was observed with increasing forest age. As forest development progresses, the total porosity increases and bulk density decreases. Total porosity was significantly greater in Meyer's Branch due to the elevated accumulation of organic matter, however, the lower macro-porosity was due to differences in soil structure and a low sand component. The amount of organic matter also contributed to the significantly lower bulk density in Meyer's Branch. The significantly higher macro-porosity in Fourmile Branch potentially is linked to the higher percentage of sand in the soil. Bulk density was slightly lower in these four riparian forests compared to other Coastal Plain forested wetlands (Axt and Walbridge 1999).

There is a web of interrelationships between hydroperiod, species composition and chemical and physical soil properties in a riparian forest. Species litterfall dynamics (leaves, twigs, fruits and flowers) affect organic matter and carbon incorporation into the soil, and these factors in conjunction with root dynamics affect porosity and bulk density. The same processes occur in an upland forest, however, for uplands the driving forces of hydrology are not apparent. Mann and Wetzel (2000) found higher organic matter and lower bulk density in vegetated areas compared to areas subject to intermittent stream flow.

Upland

There was no significant difference in percent organic matter and carbon, total and non-capillary porosity, and bulk density between the four upland forests (Table III-8). The percent organic matter and carbon, and total porosity was lower in the uplands forests than the riparian forests. The higher sand component in the upland forests results in higher macro-porosity than the riparian forests. The low organic matter content and soil structure contribute to the higher bulk densities in the upland forests. A comparison of the soil carbon values of the upland and wetland forest reveals why wetland soils are considered to be more important as carbon sinks. With the exception of Pen Branch (AR), the wetland soils contained 2-4 times more carbon.

Table III-8. Soil chemical and physical properties of four riparian and upland forests in the South Carolina Coastal Plain. Values are for the A horizon in both Pen Branch sites and Fourmile Branch, and the O horizon in Meyer's Branch to a depth of 10 cm. Within a row, letters different from each other are significantly different. No statistical analysis was performed on soil carbon kg ha⁻¹ and organic matter kg ha⁻¹.

	Pen Branch (AR)	Pen Branch (NR)	Fourmile Branch	Meyer's Branch
Riparian*				
Soil Carbon				
Percent	4.2 (1.9) b	4.7 (1.3) b	4.0 (2.3) b	11.4 (4.2) a
kg ha ⁻¹	20,261	17,470	15,840	12,038
Organic Matter				
Percent	12.3(6) b	12.9 (3) b	10.7 (6) b	30.3 (10) a
kg ha ⁻¹	59,335	47,949	42,372	31,997
Soil Porosity				
Total	68 (11) b	70 (4) b	75 (12) b	85 (2) a
Non-capillary	18 (5) ab	15 (5) b	20 (4) a	15 (4) b
Bulk Density (g cm ⁻³)	0.72 (0.30) a	0.63 (0.09) a	0.55 (0.33) a	0.24 (0.06) b
Upland*				
Soil Carbon				
Percent	4.0 (2) a	1.7 (1) a	2.4 (2) a	3.3 (2) a
Organic Matter				
Percent	8.2 (4) a	4.6 (3) a	7.4 (6) a	8.6 (6) a
Soil Porosity				
Total	61 (4) a	54 (3) a	61 (8) a	65 (11) a
Non-capillary	25 (6) a	23 (5) a	27 (5) a	24 (8) a
Bulk Density (g cm ⁻³)	0.88 (0.09) a	1.05 (0.04) a	0.83 (0.20) a	0.83 (0.33) a

* Sample size (N) for % soil carbon, % organic matter, total and non-capillary porosity, and bulk density are 18, 9, 28 & 29 for riparian and 3, 3, 6, 5 for upland for Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively.

Sediment / Reduction-Oxidation

Pen Branch (AR,) which was dominated by herbaceous vegetation had the least sediment deposition. Meyer's Branch, although a mature forest, had little ground cover and the greatest amount of sediment deposition (Table III-9). Meyer's Branch also had very subtle microtopography within the riparian forest and no distinct natural levee next to the stream, both points would promote movement of sediment. Loss of sediment occurred in the Fourmile Branch riparian forest which may have been more a function of its hydroperiod than vegetation. This lack of sediment input into the Fourmile Branch riparian forest may also partially account for the lower productivity compared to the Pen Branch riparian forest. The sediment deposition in Meyer's Branch was comparable to a Mississippi backwater lake (1.7 cm yr⁻¹; Eckblad et al. 1977), cypress-tupelo bottomland hardwood (> 1 cm yr⁻¹; Kleiss 1996), and higher than an inundated cypress swamp (0.8 cm yr⁻¹; Mitsch et al. 1979) and several Tennessee forested wetlands (0.24 cm yr⁻¹ and 0.28 cm yr⁻¹; Hupp and Bazemore 1993). Cooper et al. (1987) reported 25-yr sediment depths to range between 0-5 cm in floodplain swamps along a Coastal Plain watershed.

Table III-9. Sediment depth in each riparian forest after 66 weeks converted to annual sediment depth in parentheses. Within a column, letters different from each other are significantly different. Sample sizes (N) are 11, 7, 15 & 13 for Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively.

Site	Sediment Depth	Depth to Obvious Oxidation	Depth to Obvious Reduction
	------(cm)-----		
Pen Branch (AR)	0.08 (0.06) ab	5.59 a	9.14 ab
Pen Branch (NR)	0.15 (0.12) ab	2.54 a	10.16 ab
Fourmile Branch	-0.53 (-0.42) b	3.05 a	10.92 a
Meyer's Branch	2.39 (1.88) a	2.54 a	4.06 b

Reduction-Oxidation potential is a function of water table fluctuations and influences nutrient availability for plant uptake. In all four riparian forests, the water table rises to approach the ground surface during the year and subsequently recedes. Evapotranspiration probably was very high due to abundant herbaceous vegetation and no canopy in Pen Branch (AR) resulting in the lowest water table rise (Fig. III-9). The depth at which the water table typically resides (depth to iron reduction) was significantly lower in the Fourmile Branch riparian forest than Meyer's Branch (Table III-9). The sandier soils in Fourmile Branch probably have a higher hydraulic conductivity allowing water to move more freely. The difference between the depth to initial rust and a permanent gray color was less in the Meyer's Branch riparian forest compared to both Pen Branch sites and Fourmile Branch (Fig. III-8), which supports the saturated soil conditions observed in Meyer's Branch. The distance between water table rise and water table residency may be a function of vegetative characteristics associated with forest development/succession. Plant growth form and amount will influence transpiration rates which will affect water use and subsequently the water table depth.

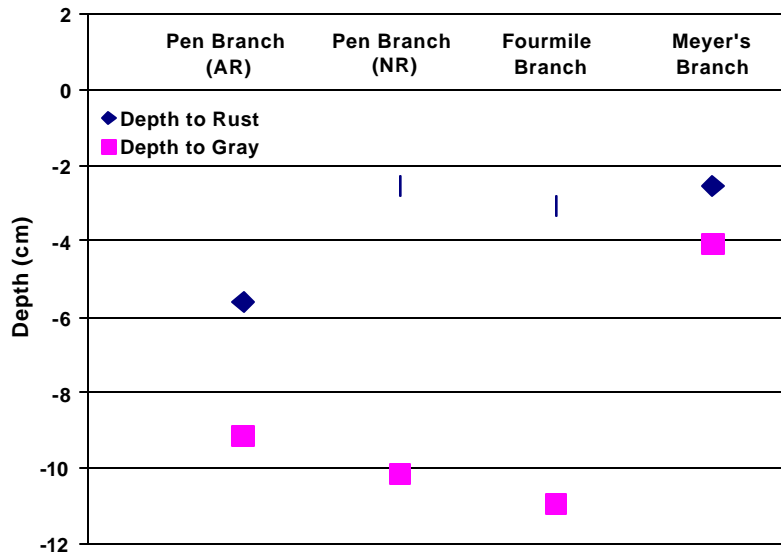


Figure III-8. Reduction oxidation patterns for iron rebar in four South Carolina Coastal Plain riparian forests. Subjectively measured from rebar installed in each site for approximately one year.

Submerged Aquatic Vegetation

The main stream channels of each site were similar. All of the streams had sandy substrates, base flow rates of 12 to 38 cm s⁻¹, and widths ranged from 550 to 920 cm. With the exception of water chemistry in each stream, the only major difference between the stream was the age of the adjacent riparian forest. Submerged aquatic vegetation was abundant in the two younger riparian forests (Pen Branch AR & NR). The closed canopy and subsequent shaded stream of Meyer's Branch may have prevented the establishment of macrophytes. A canopy effect on SAV biomass was examined in the Pen Branch sites and found not to be significant (Fig III-9).

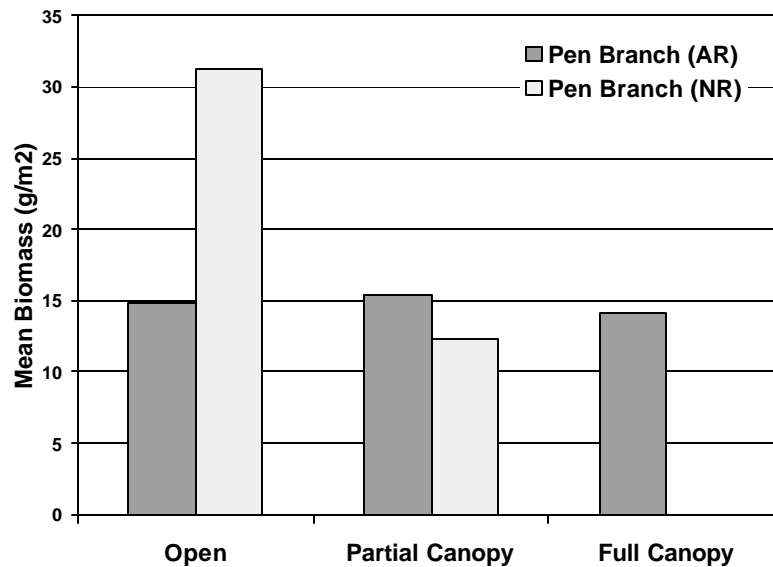


Figure III-9. Mean submerged aquatic vegetation biomass as a function of canopy coverage over the main stream channel associated with the two youngest riparian forests. No full canopy data were available for Pen Branch (NR).

Barko and Smart (1986) found a decline in SAV growth with increasing sediment organic matter and/or high sand fraction. Therefore, the highly organic soils in the mature riparian forest that may be deposited in the stream during hydrologic events may have affected SAV establishment and/or growth.

Water depth, clarity, and the amount of suspended particulates are several factors that could influence light penetration and affect the proliferation of macrophytes. However, a correlation between biomass and water depth was not found ($R = 0.129$ for both sites combined) (Table III-10). The amount of macrophyte biomass in Pen Branch (AR) was approximately 2.5 times greater than the macrophyte biomass in Pen Branch (NR) and the difference was significant ($P=0.0180$). This could be an anomaly since the two sites are adjacent to each other with Pen Branch (NR) immediately upstream from Pen Branch (AR) or there are factors (not analyzed), such as water chemistry, associated with each site that may account for the presence of macrophytes. Macrophyte mats in the uncanopied areas of the large Orinoco floodplain can reach densities of 4000 g C m^{-2} (Lewis et al. 2000) which is substantially greater than the SAV carbon pool in these third order streams.

Table III-10. High and low water depths (cm) and mean macrophyte biomass (g m^{-2}) for each sampling time. Biomass sample sizes (N) for each date are 12, 8, 13, & 10 for Pen Branch (AR) and 13, 13, 13, & 10 for Pen Branch (NR).

Date	Pen Branch (AR)			Pen Branch (NR)		
	Water Depth		Mean Biomass	Water Depth		Mean Biomass
	Low	High		Low	High	
August 1997	8.9	94.6	78.9	12.7	47.6	30.0
December 1997	39.4	69.8	10.1	8.9	45.5	23.4
May 1998	9.4	95.2	44.0	23.4	59.9	2.2
August 1998	0	50.8	41.6	4.4	22.9	11.8

Carbon Pools

The total carbon pool in the mature riparian forest (Meyer's Branch) was conspicuously greater than the three younger riparian forests (Table III-11) primarily due to greater tree and soil carbon pools. Riparian forest total carbon pools appear to increase with forest development/succession (Table III-11). The herbaceous carbon pool decreased with increasing forest age. Fine root biomass increased with forest development, which supports the proposition by Nadelhoffer et al. (1985) that fine root production increases in direct proportion to aboveground production. In the herb dominated community the above to belowground ratio was very small. As woody species initially become established, the ratio approached 1, implying a balance between above and belowground carbon pools. With riparian forest maturity the aboveground carbon pool increased substantially resulting in an above to belowground ratio > 1 .

The litterfall carbon pools in the young riparian forests was comparable to those in the mature riparian forest. However, the litterfall carbon pools for all of the sites contributed a small percentage of the total riparian forest carbon pool. The forest floor carbon pool increased with forest age, but again constituted a very small percentage of the total carbon pool. The woody debris carbon pool was comparable between the four riparian forests, however its percentage was negligible.

Table III-11. Carbon pools by component (kg ha⁻¹) for four S.C. Coastal Plain riparian forests. The percentage of each component is in parentheses. Assume 50% Carbon for trees, shrubs, and SAV (Turner 1995; Meyer 1986).

Component	Pen Branch (AR)	Pen Branch (NR)	Fourmile Branch	Meyer's Branch
-----kg ha ⁻¹ -----				
Aboveground				
Trees 1997	156 (0.6)	9744 (27)	8755 (27)	98,279 (82)
1999	866 (3.0)	12,207 (31)	13,258 (35)	99,924 (83)
Shrubs 1997	416 (1.6)	3152 (9)	2304 (7)	2347 (2)
1999	2351(8.5)	4314 (11)	3356 (9)	1689 (1)
Herbs	2134 (8.5) (8.0)	615 (2) (2)	616 (2) (2)	159 (0.0) (0.0)
Woody debris	2.6 (0.0) (0.0)	2.3 (0.0) (0.0)	1.8 (0.0) (0.0)	2.8 (0.0) (0.0)
Litterfall	40 (0.1) (0.1)	2180 (6) (5)	1580 (5) (4)	2280 (2) (2)
Forest Floor	ŠŠ	330 (0.4) (0.3)	418 (0.9) (0.8)	430 (0.4) (0.4)
Belowground				
Carbon Š	20,261 (81) (73)	17,470 (48) (44)	15,840 (49) (42)	12,038 (10) (10)
Fine Roots	1850 (7.4) (6.7)	2770 (8) (7)	3040 (9) (8)	4360 (4) (4)
Above/Below 1997	0.12	0.78	0.72	6.3
Ground Ratio 1999	0.24	0.96	1.01	6.3
Instream				
Submerged Aquatic Vegetation (SAV)	212 (0.8) (0.7)	93 (0.2) (0.2)	0	0
-----Mg ha ⁻¹ -----				
Total				
1997	25.1 (100)	36.3 (100)	32.5 (100)	120.0 (100)
1999	27.7 (100)	39.9 (100)	38.1 (100)	120.0 (100)

Š Soil carbon was calculated for the top 10 cm.

ŠŠ No forest floor was sampled in Pen Branch (AR) because it was negligible.

Conclusion

Riparian forest biomass and carbon pools are affected by disturbance and successional state. The severity of the disturbance will dictate the degree to which forward successional processes are interrupted or set backwards. Aboveground biomass in all 4 riparian forests increased over a 2 ½ year period. The total carbon pool in riparian forests increases with forest development/succession due to the greater tree and soil carbon pools. The mature riparian forest stored approximately 4 times more carbon than the younger (8-14 year old) stands. The ratio of above to belowground carbon pools is small in herb dominated communities, approaches 1 with the onset of a woody component, and continues to increase with riparian forest maturity.

Riparian forest productivity was independent of seral stage particularly with the inclusion of woody species providing substantial amounts of litterfall. In general NPP in young riparian forests (~8-10 years) rapidly approached and exceeded NPP of more mature riparian forests. Including litterfall as a component of NPP changed the balance between riparian forests.

Total riparian forest biomass was a function of forest succession with the individual components following distinct patterns. With forest development, the herbaceous biomass and herbaceous carbon pool comprised a very small portion of the total above ground biomass and generally declined with increasing forest age/succession. An increase in fine root biomass occurred with increasing forest age, however, an inverse relationship between percentage of fine root biomass to total biomass with riparian forest age was observed. The combination of greater fine root biomass and higher root percent carbon in a relatively mature riparian forest contributed to a greater root carbon pool than younger riparian forests. Overall the root carbon pool was increased with forest age/succession. This finding is important because it supports the premise that carbon storage by forests can be significantly increased by management practices that favor below ground carbon storage.

Once the herbaceous stage of succession was surpassed and a woody overstory becomes established (after ~ 8-10 years), annual litterfall rates as a function of NPP are independent of forest age. Establishment of woody species occurred within 8-10 years after thermal disturbance and litterfall amount in young riparian forests rapidly becomes comparable to mature riparian forests. With the rapid recovery of litterfall, incorporation and recycling of nutrients to the riparian ecosystem will provide the resources necessary for maintaining a healthy forest. Since litterfall recovers at a young age it may be used as an index for riparian restoration demonstrating that a riparian forest is on a trajectory toward a functioning mature riparian forest.

A decline in riparian forest floor biomass was observed with increasing riparian forest development. However, an increase in the forest floor carbon pool was observed with increasing forest age. Overall, the forest floor appears to stabilize after 10-12 years demonstrating an equilibrium between the inputs and outputs to the forest floor, suggesting that nutrient cycling processes within each site are functioning.

Woody debris in riparian forests and associated streams was a function of forest development, however, it does not significantly contribute to the total riparian forest carbon pool. Theoretically mature riparian forests should have a greater amount of terrestrial and stream woody debris than younger riparian forests. However, this was not observed in these riparian forests. The more mature riparian forest did have a greater amount of larger pieces of woody debris, but overall, all four sites had comparable estimates of woody debris biomass. Although woody debris in these riparian forests comprised a relatively small carbon pool, that may not be reflective of its importance in furnishing critical forest functions. At what stage of forest development woody debris becomes a significant carbon component remains unknown.

Soil physical and chemical properties were closely tied to successional stage and the processes involved in plant community change. An inverse relationship between total porosity and bulk density

with increasing forest age was observed. As forest development progressed, the total porosity increased and bulk density decreased. Forest development and differential stratification of vegetation influences the movement of sediment to, from, and within a riparian forest. However, it was not conclusive that soil physical and chemical properties are a function of forest age and not hydroperiod, but, if forest development dictates hydrologic processes then the effects can not be separated.

Several integrated factors such as light, water chemistry, and substrate control the establishment of submerged aquatic vegetation. The type or severity of disturbance may affect SAV establishment, but successional stage does not appear to be a decisive factor. Neither canopy coverage or water depth independently affect SAV biomass. Therefore, canopy closure associated with mature riparian forests may not be the only factor that influences the growth of macrophytes. Although the submerged aquatic vegetation constituted a small percentage of the total riparian forest carbon pool, it should not be overlooked for it plays an important role in the proper functioning of other riparian forest processes, particularly because it may influence stream hydrology.

LITTERFALL

Chicken Little said “the sky is falling!”

Fisheries Biologist believed it to be energy for the aquatic ecosystem.

Wildlife Biologist exclaimed “oh good, habitat for small critters.”

Soil Scientist thought it was organic matter for soil formation.

Hydrologist pondered, it will get washed away in the next flood.

Biologist calculated victuals for soil fauna/flora.

Statistician estimated X% probability that next year there will be more
or less - that’s mean (or mode, or median).

Project Leader responded “Aha! A significant carbon component
for forest productivity”

“All are correct.” It is litterfall, dependent on species composition
as a function of forest succession and can be used as an index of
riparian restoration.

Chapter IV. Riparian Forest Litter Dynamics

Abstract

Litterfall has been extensively studied because it is a component/measure of productivity and plays a key role in the cycling of nutrients. Litter dynamics within three Southeastern Coastal Plain riparian forests representing successional stages of 9, 13, and 60+ years were studied. The litter components measured included vertical inputs, lateral movement, forest floor, and instream particulate organic matter. Riparian litter dynamics were also compared to those in adjacent upland forests and litter falling into the stream channel. For vertical litter, traps were placed in the riparian forests and upland forests and collected biweekly (September - November) followed by approximately every 2 months for one year (9/97-8/98) for a total of 10 collection periods. Forest floor was measured near the end of the vertical litter sampling. Lateral litter movement was measured after a flood event and instream litter was measured at least once in the spring, summer and fall.

Aboveground litterfall inputs to riparian forests and their associated streams were influenced by forest productivity and species composition, both which are linked to seral stage. As a woody overstory becomes established (after ~ 8-10 years) annual litterfall rates were relatively independent of forest age. The litterfall amount associated with the woody component in young riparian forests was comparable to mature riparian forests. The mature, closed canopy riparian forest indicative of a later successional stage contributed 2-3 times more annual litterfall biomass and carbon to the streams than the younger riparian forests. However, the younger riparian forest contributed more woody material to the stream.

The percent carbon of individual litterfall components (leaf, twig, miscellaneous) differed according to species. However, regardless of the differences in percent carbon of the litterfall components for several of the riparian forests, the litterfall carbon pools (total, leaves, twigs, and

miscellaneous) reflected biomass differences between the sites. Therefore, the difference in percent carbon was not great enough to overcome the amount of biomass in each litterfall component. The same biomass effect was observed for the upland forests. The species composition in the younger riparian forests generally had greater percent carbon in their leaves throughout the year than the mature riparian forest. Leaf percent carbon was similar between stream and riparian inputs in the younger riparian forests; however, this close association was not observed in the mature riparian forest.

There was a slight decrease in total forest floor biomass with increasing riparian forest age. The percent carbon in the riparian forest floor leaves was greatly reduced compared to the percent carbon of leaf litter inputs to the riparian forests. This relationship was not observed in the uplands suggesting that decomposition rates are greater in the riparian forests than the upland forests. The amount of lateral litter biomass transported from the riparian forest toward the stream was 283 and 347 g m⁻². Although not significantly different, the amount of litter (carbon pool) deposited from upstream was greater than adjacent overbank deposits. Less understory vegetation and little elevation difference next to the stream bank may influence lateral litter toward and from the stream. Overall lateral litter supplied less energy to the stream system than vertical inputs, pointing out the importance of overhanging trees and shrubs for providing detritus for small streams.

Introduction

Litterfall has been extensively studied for a variety of ecosystems (temperate, tropical, terrestrial - upland & wetland) (Bray and Gorham 1964) because it is a component/measure of productivity and plays a key role in the cycling of nutrients. The information on litterfall within forested wetland ecosystems is appreciable (Table IV-1). Litter dynamics in riparian forests are controlled by more than just localized vertical inputs. Forest age (Oelbermann & Gordon 2000), species composition (riparian and adjacent upland) (Bell and Sipp 1975), plant community structure (stratification) (Bell and Sipp

Table IV-1. Annual litterfall rates (g dry wt m⁻² yr⁻¹) for several forested wetlands.

Type	Location	Litterfall	Reference
Cypress-tupelo swamp	Illinois	348	Mitsch 1978
Cypress-tupelo swamp	Louisiana	620	Conner and Day 1976
Cypress-tupelo swamp	Louisiana	405	Conner and Day 1992
Cypress-tupelo swamp	Louisiana	316-767	Megonigal et al. 1997
Cypress-tupelo swamp	North Carolina	643	Brinson et al. 1981
Cypress-tupelo swamp	South Carolina	314-837	Megonigal et al. 1997
Cypress-tupelo swamp thermal	South Carolina (SRS) ¹	151-415	Scott et al. 1985
Cypress	Florida	224-941	Brown 1981
Okefenokee swamp	Georgia	310	Schlesinger 1976
Great Dismal Swamp	Virginia/N. Carolina	652-758	Gomez and Day 1982
Bottomland hardwood	Louisiana	293-579	Conner and Day 1992
Bottomland hardwood	Illinois	521	Bell et al. 1978
Bottomland hardwood	Illinois	797	Peterson and Rolfe 1982
Bottomland hardwood still water / flowing water	Illinois	645-655 / 524-998	Brown and Peterson 1983
Bottomland hardwood	Louisiana	574	Conner and Day 1976
Bottomland hardwood	Louisiana	328-549	Conner et al. 1981
Bottomland hardwood	Louisiana	376-845	Conner et al. 1993
Bottomland hardwood	Louisiana	551-855	Megonigal et al. 1997
Pine/Bottomland hdwd ²	Mississippi	386	Post & De La Cruz 1977
Bottomland hardwood	South Carolina	581-832	Megonigal et al. 1997
Bottomland hardwood	South Carolina	300-634	Burke et al. 1999
Bottomland hardwood	South Carolina (SRS)	439-614 / 552-595	Muzika et al. 1987
Bottomland hdwd - 8 yrs	South Carolina	500	Bates 1989
Bottomland hdwd - 9 yrs	South Carolina (SRS)	601	This Study
Bottomland hdwd - 13 yrs	South Carolina (SRS)	423	This Study
Bottomland hdwd - 60 yrs	South Carolina (SRS)	526	This Study

1) SRS - Savannah River Site; 2) hdwd - hardwood

1975; Delong and Brusven 1994; Oelbermann & Gordon 2000), tree density and riparian buffer width (Oelbermann & Gordon 2000), predominant wind direction (Welbourn et al. 1981; Oelbermann and Gordon 2000), slope/elevation (France 1995; Bell and Sipp 1975), hydroperiod (Burke et al. 1999), and time of year influence the litter dynamics of riparian forests. Litter quality (physical and chemical characteristics) determines durability to withstand alterations by its biological and physical environment. Furthermore, upstream species may influence nutrient dynamics as their litter is deposited to downstream riparian areas during flood events. Lateral litter movement in low gradient regions (e.g., the Atlantic Coastal Plain), is controlled more by stream width than slope (Connors and Naiman 1984). Litter dynamics in braided stream systems can be even more complex.

Most forested wetland studies focus on aboveground terrestrial, vertical litterfall and do not investigate litter movement within an ecosystem. Therefore, the movement of litter within a riparian forest is not well studied. Until litterfall components become somewhat permanently situated, specifically leaves and lighter miscellaneous components, they are subject to displacement by wind, and in riparian forests, by water. The litter dynamics in a forested riparian ecosystem are more complex than generic terrestrial or upland forests. Besides the standard litterfall from the canopy, movement/inputs of litter (both towards the stream and from the stream into the riparian area) during flood events must be considered. Stream width strongly influences the role of lateral litter as the major component of allochthonous inputs (Connors and Naiman 1984). Hill and Brooks (1996) found lateral bank transfer and swamp surface runoff contributed 14-16% and 20-25%, respectively, of annual litter inputs to a headwater stream. Pozo et al. (1997) reported 8 to 20% lateral input depending on riparian forest species composition. France (1995) found lateral inputs of 6% of the total allochthonous input to northern lakes from the riparian litter pool, with deciduous leaves traveling slightly farther than coniferous needles. McDowell and Fisher (1976) found 21% of the total litter input to a stream (for 77 days) occurred as lateral transport (blown in). Connors and Naiman (1984) observed that there is less lateral movement of catkins and needles than vertical inputs.

The seasonal or annual pattern of a regions hydroperiod will impact the movement of litter (Wallace et al. 1982). Surface runoff litter is generally greatest during periods of rapid overland flow associated with thunderstorms (Hill and Brooks 1996). Leaf litter undergoes comminution in the riparian area prior to lateral transport during periods of inundation (Smock 1990) and therefore, any disruption of riparian forest processes could alter leaf litter movement and inputs to the stream. Transport of litter, specifically particulate organic matter, off the floodplain, instead of onto it, may be favored in the riparian forests in this study because southeastern Coastal Plain blackwater streams normally do not carry large suspended sediment loads (Cuffney 1988). Tate and Meyer (1983) observed a decrease in dissolved organic carbon concentration and export over the first two decades of secondary succession. However, they found that periodic variations in hydrology were more significant than successional changes.

Litterfall entering the stream is very important to the nutrient/energy cycling of the aquatic ecosystem and stream order dictates the magnitude and path of litterfall inputs. Headwater streams in forested watersheds primarily receive allochthonous organic matter inputs (Mulholland 1981). Vertical litterfall inputs to a stream can comprise approximately 60% of annual litter inputs (Hill and Brooks 1996) and up to 80-90% of the total input (Pozo et al, 1997). Organic matter inputs to forested headwaters range between 45-90% for leaves and 5-33% for wood (Connors and Naiman 1984). Annual litterfall per unit area of stream surface declined exponentially with increasing stream order. 1st & 2nd order streams had 81-95% allochthonous and 5th & 6th order streams had 85-95% autochthonous organic carbon (Connors and Naiman 1984). Meyer and Edwards (1990) found less efficient organic carbon processing (i.e. longer turnover lengths) in higher order streams.

Litter within the stream (coarse or fine particulate organic matter) should also be addressed because it is an important energy source for the aquatic food web. Riparian areas with different plant species composition will influence particulate organic matter inputs to streams (Hope et al. 1997; Pozo et al. 1997). Particulate organic matter exports can comprise 10 to 25% of the total organic carbon

flux in rivers and typically vary between 10 and 100 kg ha⁻¹ yr⁻¹ in temperate river systems (Hope et al. 1997). Disturbance to a riparian forest that decreases the density of woody species will affect the export of particulate organic matter, especially during storms (Leff and McArthur 1988; Webster et al. 1990).

Hydroperiod exerts a strong influence on nutrient availability, vegetation composition, and net primary productivity (Burke et al. 1999) and adds important mitigating factors by removing, concentrating, or burying litter. Storms (especially during the spring) appear to enhance litterfall inputs. Gosz et al. (1972) observed that storms influence the amount of litterfall, and Gomez and Day (1982) concluded that periodic flooding promotes litter production which could result in higher litterfall inputs. The timing of flood events, in conjunction with litterfall peaks or lulls, will influence the amount of organic matter redistributed within a riparian forest and play a role in determining the composition, structure, distribution, and energy content of the litter layer (forest floor) in riparian forests. The proportion of carbon forms (cellulose, lignin) within each litter component (leaf, twig, flower, fruit) will influence resistance to decomposition and may result in greater forest floor biomass. Surface slope, exposure to precipitation and absence of ground vegetation increases lateral transport of riparian leaf litter (France 1995). Lateral movement of riparian litter is often impeded by stream bank vegetation (Dawson 1976) and vegetation-waterflow interactions (Hardin and Wistendahl 1983). Although leaf litter is generally rapidly processed in the stream, a storm occurring right after peak litter fall may significantly redistribute litter components to and within the riparian area, especially contributing more woody material.

Successional stage and species composition (Gomez and Day 1982) influence litter dynamics in riparian forests. Differences in plant communities associated with successional stage would seem to dictate differences in amounts of litter and litter quality. Litterfall is usually assessed in mature forests, therefore less information has been obtained on litterfall for younger successional stages. Because litter is an intricate component of cycling nutrients, it is important to know at what stage of succession litter

cycling processes in younger forest stands reflect mature forest stands. Based on extensive data compiled by Bray and Gorham (1964), there appears to be no obvious litterfall trends with increasing forest age once canopy closure has occurred.

The amount of litter that accumulates on the forest floor is a function of litterfall quality and quantity as well as lateral movement due to wind or flood events. Litter quality has a strong influence on decomposition rates and, therefore, forest floor biomass, which according to Elliott et al. (1993), is more a function of the decay rate than the rate at which the litter reaches the forest floor.

Successional stage or watershed disturbance can change organic matter inputs subsequently significantly effecting stream communities. Delong and Brusven (1994) observed an increase in allochthonous input of organic matter when dominant vegetation type changed from herbaceous to deciduous trees. As the forest regenerates and provides allochthonous organic matter, the qualitative composition of this material will not recover as quickly. The quantitative input of litter to the stream may rapidly recover to pre-disturbance levels or be unrelated to forest age, however, species composition may be significantly different (Webster and Waide 1982). Plant species that become established after disturbance generally have a relatively fast processing rate (Golladay et al. 1983; Griffith and Perry 1991). Composition of litterfall entering the stream varies according to density of understory vegetation and physical structure of the riparian zone (Campbell et al. 1992). Litterfall dynamics within the riparian areas may not exactly reflect those along the streambank due to differing landscape surrounding the streambank or species composition on the streambank.

Riparian litterfall dynamics change after a disturbance and the magnitude of the change depends on the severity of the successional regression. The time it takes to recover and restore the litterfall functions indicative of a mature riparian forest are unknown. Riparian restoration may occur naturally or through the actions of humans. Using litterfall as an index of riparian restoration may provide insight to which method provides rapid trajectory toward a mature riparian forest.

The objectives of this study were to: 1) quantify vertical litterfall inputs to the riparian forest, upland forest, and main stream channels of four sites representing different successional stages, 2) quantify lateral litter movement within four sites representing different successional stages, 3) measure and compare instream particulate organic matter in the braided stream systems of each site, 4) compare litterfall inputs between ecosystem (riparian, upland and stream) within each site, 5) quantify the forest floor of four riparian sites representing different successional stages, and 6) quantify the percent carbon or carbon pool (g C m^{-2}) for the litterfall inputs.

This project was specifically designed to address the following null hypotheses: 1) the amount of litterfall is independent of seral stage, 2) lateral litter flow dynamics and inputs do not comprise a substantial carbon pool, 3) instream litter is not a function of riparian forest seral stage, and 4) the carbon content of all litter components is not a function of seral stage.

Methods

Site Description

The study sites are located in riparian forests adjacent to three braided, blackwater streams on the Savannah River Site (SRS), a National Environmental Research Park, in South Carolina (latitude 33° N, longitude 82° W). Pen Branch and Fourmile Branch streams, third order tributaries of the Savannah River, received thermal, elevated discharge from nuclear production processes between 1954 to 1989, and 1955 to 1985, respectively. These stream corridors experienced elevated temperatures (up to 70°C) and increased discharge (1 to 2 orders of magnitude greater than base flow). The thermal discharge killed the bottomland hardwood vegetation and altered sediment erosion and deposition patterns. The third stream in this study, Meyer's Branch, represents a minimally

disturbed, third order reference site. Only minor disturbances, such as selective logging in the 1940s occurred in Meyer's Branch, but it never received thermal effluent.

The age of the riparian forests adjacent to Pen Branch, Fourmile Branch, and Meyer's Branch at the time this study began were 8 years, 12 years, and approximately 60 years, respectively. There are two treatment areas along Pen Branch. One area has been allowed to regenerate naturally. An adjacent area was artificially regenerated with planted bottomland hardwoods following a site preparation using herbicides and prescribed burning.

Litterfall

Hardwood forests typically have nutrient cycles involving large litterfall inputs. Therefore, measurement of annual litterfall (vertical) provides information pertaining to the carbon inputs (flux) to the forest floor and subsequent incorporation into the soil organic matter component. The sources of water to streams within bottomland riparian forests can have complex origins and contribute to a variety of instream organic particles. Water and associated detritus may come from upstream sources, overbank flooding or overland flow from adjacent sources (lateral litter movement). A multi-directional approach to quantify lateral litter transport and deposition, and subsequent determination of the direction of the transport may be novel.

Riparian

Vertical: Eight litter traps (0.187 m² each) per site were randomly placed in the riparian forest (Conner and Day 1992). Collectors were elevated approximately 0.6 m to prevent inundation during flood events. Litter was collected biweekly from September to November, than approximately every 2 months for one year (9/97-8/98) for a total of 10 collection periods. Litterfall was also collected four times during peak litterfall the following year (9/98-2/99). Litter was separated by component (leaves,

stems, miscellaneous [e.g., seeds, flowers, insects]). Vertical litter samples were dried to a constant temperature (60 °C) and weighed according to individual component (leaves, twigs, and miscellaneous). For all four sites, only tree & shrub litterfall components were included. In Pen Branch (AR), herbaceous vegetation tended to engulf the litter traps, but was not included in the sample.

Lateral: A multi-directional lateral litter (+-shape) collector (Mudll, Fig. IV-1) was constructed with a one-fourth to one-half inch mesh size to catch litter, but not impede water flow or trap sediment. Screening was placed on top to prevent the addition of vertical litterfall. A collector was placed on each bank of the stream channels (main, intermediate, and side) and prominent swales encountered crossing the riparian area (approximately 5-10 collectors per transect). Two sets of collectors were placed (one upstream transect and a second downstream transect) in each riparian forest. The four Mudll compartments were labeled based on orientation (upstream, overbank, toward stream [from the riparian forest], and downstream [i.e., backwards flow] to the stream or swale). The Mudlls are approximately one meter tall and the compartments range in size from 0.32 - 0.38 m³. Sampling was done following significant hydrologic events. Lateral litter samples were dried to a constant temperature (60 °C) and weighed. Each quadrant sample was subsequently dry ashed to correct for sediment deposition.

Upland

Three to 4 litter traps (0.187 m² each) were randomly placed in the adjacent upland of each riparian forest. Collectors were elevated approximately 0.6 m above ground surface for consistency with the riparian litter traps and to be prepared for the possibility of inundation during flood events. Litter was collected along the same time intervals as the riparian litterfall collection. Individual litter samples were dried to a constant temperature (60 °C) and weighed according to component (leaves, twigs, and miscellaneous).

A)



B)



Figure IV-1. Multi-directional lateral litter collector (Mudll) before (A) and after (B) a significant flood event in riparian forests of South Carolina.

Stream

Litterfall collectors (Fig. IV-2) were constructed to span the width of the main stream channel to collect vertical inputs from the riparian zone. Three litter collectors each were placed in Fourmile Branch and Meyers Branch. Two litter collectors each were placed in Pen Branch (AR) and Pen Branch (NR). Litter was collected during the same time intervals as the riparian litterfall collection. Individual litter samples were dried to a constant temperature (60 °C) and weighed according to component (leaves, twigs, and miscellaneous).

Forest Floor

Forest floor samples consisting of the Oi (leaves, twigs) and Oe (fragmented leaves and twigs) layers combined were randomly collected from approximately 15 0.25 m² areas within each riparian forest except Pen Branch (AR), where herbaceous vegetation was too dense, and approximately 6 to 8 0.25 m² areas in the adjacent upland forest (Elliott et al. 1993). Samples were separated into two categories; leaves, and twigs& miscellaneous. Litter samples were dried to a constant temperature (60 °C) and weighed. Forest floor samples were collected early May 1998 to emulate what would be remaining of the previous season's litterfall.

Instream Litter

Three drift nets (0.135 m² each) with a fine mesh were placed in the main stream channels for approximately one hour to collect litter flowing in the stream. Drift nets were spaced at one-third, one-half, and two-thirds intervals based on stream width. Samples were only collected during baseflow conditions. Ideally the entire net was submerged, but that was not always possible due to low water depths. The fine mesh size of the drift net appeared to alter stream flow near the collector. However, a coarser mesh would have allowed fine litter particles to escape. Stream discharge was also determined

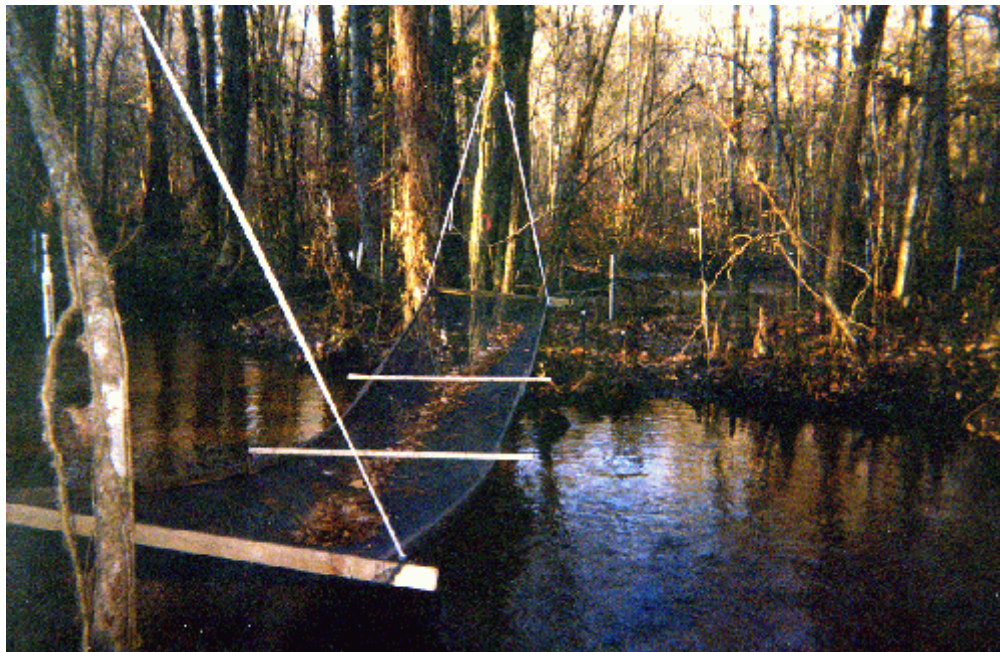


Figure IV-2. Litter traps spanning the main stream channel of a mature riparian forest in SC.

at the time of sampling by obtaining several stream measurements (width, depth, velocity [Swoffer current velocity meter, model 2100 (pigmy)]. Sampling was conducted 6 times during the fall, winter, and spring months. Litter samples were dried to a constant temperature (60 °C), weighed, and subsequently dry ashed to correct for sediment deposition.

Carbon

Carbon content was determined with a LECO gas analyzer (LECO 1987) on a subsample of the leaf, twig, and miscellaneous component of each vertical litterfall collection period (riparian and upland). Only the foliar component of the stream litterfall and forest floor was analyzed for carbon content. The entire lateral litter sample was analyzed for carbon content. Three replicates were analyzed for each sample, unless the sample volume was too small. Percent carbon was multiplied by biomass (g m^{-2}) to obtain g C m^{-2} for each component. Percent organic matter in the lateral litter samples was determined by loss on ignition (LOI) (Nelson and Sommers 1982) (380 °C for 24 hrs).

Statistical Analysis Procedures

Data were analyzed using analysis of variance (ANOVA) procedures for a completely randomized design (SAS Institute 1996). The four sites (Pen Branch (AR), Pen Branch (NR), Fourmile Branch and Meyer's Branch) representing different seral stages comprised the treatments. Differences in various litterfall and carbon pool components between the four sites were analyzed. Riparian/Upland/Stream litterfall totals and by component were compared between the four sites. Lateral litter movement by quadrant and stream type were compared between the four sites. Forest floor and instream particulate organic matter were compared between the four sites. The Tukey multiple range test was used to distinguish treatment mean differences. A significance level (") of 0.05 was used for all tests. Means were calculated for the three carbon replicates for each litterfall component, forest floor, and Mudll samples for use in statistical analyses.

Results and Discussion

Litterfall (Between Sites)

Riparian

Annual litterfall in Pen Branch (NR), Fourmile Branch, and Meyer's Branch were comparable to other forested wetlands (Table IV-1). Total annual litterfall biomass in Pen Branch (NR), Fourmile Branch, and Meyer's Branch was 8 to 12 times greater than Pen Branch (AR) (Fig. IV-3) due to the young seral stage Pen Branch (AR) represents. Meyer's Branch had a closed canopy, but Pen Branch (NR) and Fourmile Branch were estimated to have 75% canopy closure, which influenced annual litterfall.

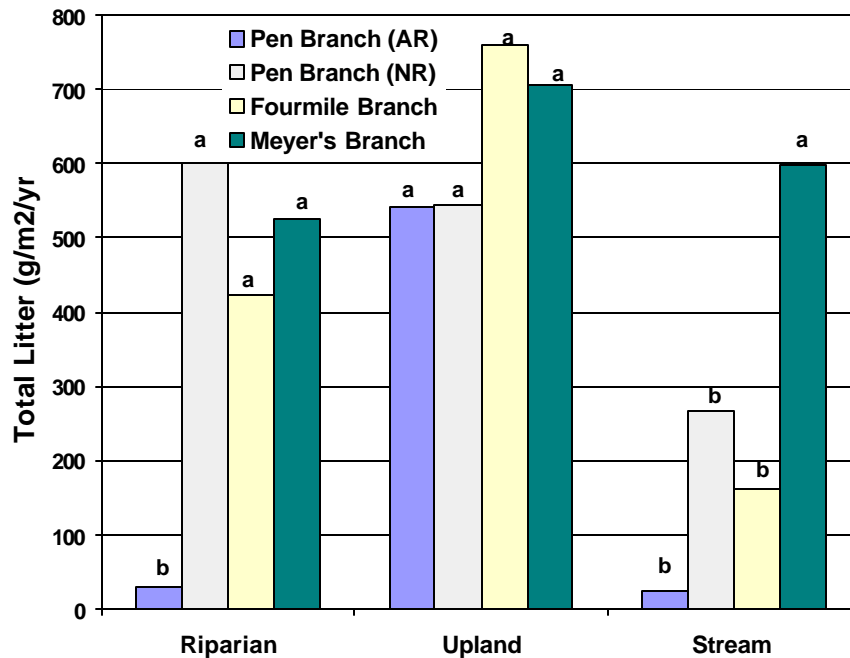


Figure IV-3. Total annual riparian, upland and stream litterfall (leaves, twigs and miscellaneous) for four South Carolina Coastal Plain forests. Means with different letters are significantly different ($\alpha = 0.05$) from each other within each ecosystem type.

Annual leaf biomass was significantly less in Pen Branch (AR) than the other three sites (Figure IV-4) and follows the same pattern as annual litterfall biomass suggesting that in these riparian forests leaf litter is the most important litterfall component (Figure IV-3). Lower leaf biomass has been attributed to stress (Brown 1981), however, the two formerly thermally polluted sites no longer appear to be under unusual stress as indicated by leaf biomass comparable with the mature stand and that of other studies (Table IV-2). The breakdown of annual litterfall into each component (leaf, twig/woody, and miscellaneous) for Pen Branch (NR), Fourmile Branch, and Meyer's Branch were comparable to other forested wetlands (Table IV-2). The litter components in Pen Branch (AR) were considerably lower than other studies due to its lack of woody species. The natural regeneration area of Pen Branch provided significantly greater annual twig biomass than the artificial regeneration area of Pen Branch (Figure IV-4). Although not significantly different, annual twig biomass decreased with increasing riparian forest age. Forest age also affected annual miscellaneous litter biomass with Meyer's Branch having significantly greater miscellaneous litter biomass than Pen Branch (AR) (Figure IV-4).

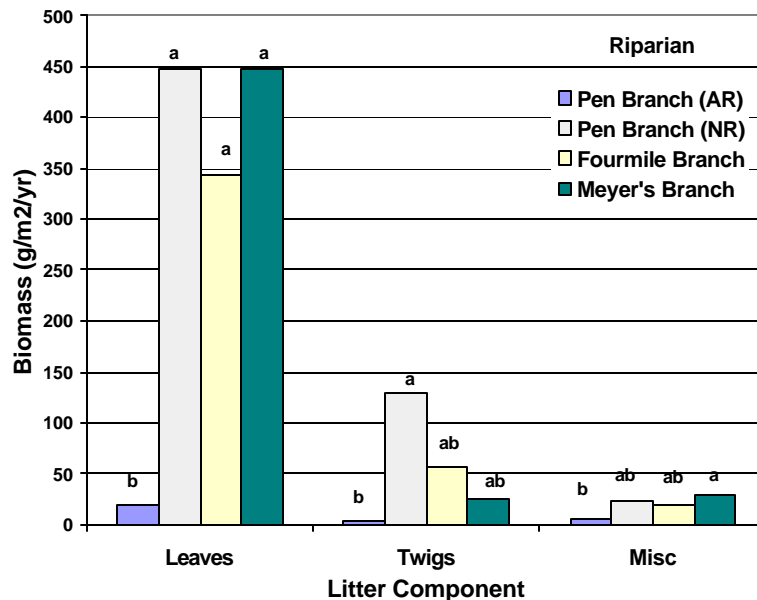


Figure IV-4. Annual litterfall by component for four South Carolina Coastal Plain riparian forests. Means with different letters are significantly different ($\alpha = 0.05$) from each other.

Table IV-2. Leaf, twig, and miscellaneous litterfall biomass (g m^{-2}) for several forested wetlands.

Site		Leaves	Twigs	Miscellaneous	Reference
-----(g m^{-2})-----					
Bottomland Hdwd ¹	Ridge	484-584	112-261	--	Conner et al. 1993
	Transition	442-496	43-102	--	
	Flooded	344-357	32-97	--	
Great Dismal Swamp	Atlantic White Cedar	506	189	62	Gomez & Day 1982
	Cypress	528	110	40	
	Mixed Hdwd	456	108	88	
	Maple-Gum	536	88	34	
Bottomland Hdwd	Still Water	376-449	88-141	84-128	Brown & Peterson 1983
	Flowing Water	350-430	105-469	4-179	
Bottomland Hdwd	Post Thermal Recovering	354-449	75-138	11	Muzika et al. 1987
	Undisturbed	270-521	70-86	23-196 (128 Spanish moss)	
Bottomland Hdwd	Floodplain	385	306	106	Peterson & Rolfe 1982
Bottomland Hdwd	Floodplain	415	47	62	Bell et al. 1978
	Transition	496	156	90	
Bottomland Hdwd		404-731	16-104	13-104	Brown 1981
Bottomland Hdwd		442	91	130	Brinson et al. 1980
Bottomland Hdwd	2 nd Order	416	73	118	Cillero et al. 1999
	3 rd Order	351	22	146	
Bottomland Hdwd	Various Hydroperiods	300-634		14-70 (seedfall)	Burke et al. 1999
Pen Branch (AR)	Riparian	19	3	6	This Study
Pen Branch (NR)	Riparian	448	129	24	
Fourmile Branch	Riparian	344	56	19	
Meyer's Branch	Riparian	448	26	28	

1) Hdwd - Hardwood

In a relatively short time span (~10 years) after a disturbance the annual litterfall amounts in the young (10 yrs, 14 yrs) riparian forests were not significantly different than the mature riparian forest. At this time, the site preparatory measures in the artificial regeneration section of Pen Branch have detained succession to a woody component by maintaining a thick herbaceous cover. Therefore, in this study Pen Branch (AR) was considered at a younger seral stage than Pen Branch (NR) and the herbaceous dominated Pen Branch (AR) resulted in significantly lower annual litterfall. Most of the litter collected in the Pen Branch (AR) traps probably blew in from the surrounding upland forest.

Although percentages of litterfall components vary annually (Brown and Peterson 1983) due to the inherent variability in nature, the annual values still represent valid information for comparison between sites. Annual leaf litter comprised 74%, 81%, and 85% of the total annual litter for Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively. After 24 weeks of a consecutive year total litterfall biomass was 25%, 71%, 71%, and 86% of annual litterfall biomass in the riparian forests of Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively. Therefore, if interested in the leaf component only, obtaining quantitative data would require little time allocation. Although not significantly different, the annual twig component decreased with increasing forest age. The predominance of *Salix* species in Pen Branch (NR) contributed to higher twig biomass (personal field observation). Also, it was believed that Pen Branch (NR) was at a transitional stage with *Salix* declining and species composition starting to change. Gomez and Day (1982) found the miscellaneous component comprised 5.2 to 13.5% of total litterfall. However, in these riparian forests the miscellaneous component comprised a very small amount of the total annual biomass.

Differences in percent carbon of the litter components resulted from the quality and structural makeup of an individual species. The percent carbon in the leaf, twig, and miscellaneous components generally varied between sites (Figs. IV-5 and IV-6) and this supports the assertion that the quantitative input of litter to the stream (and riparian forest) may rapidly recover (Webster and Waide 1982), however, the species composition may be significantly different. The difference in percent carbon

(specifically in the leaves) was reflected in species composition differences. Percent carbon in the leaves for all four sites was higher than that reported by Oelbermann and Gordon (2000) and the deciduous leaves reported by Post and De La Cruz (1977), but was within the range reported by Dawson (1976) and the pine needles reported by Post and De La Cruz (1977). The lower percent carbon in the twigs in Meyer's Branch may be attributable to stand age (Fig. IV-6a). Generally, as forest stands age, there is more woody decay, therefore, the twigs that become part of the litterfall may have already undergone some proportion of decay thereby losing some of their carbon content. The percent carbon in the twigs of both Pen Branch sites and Fourmile Branch was slightly higher than values reported by Post and De La Cruz (1977), but the percent carbon in the twigs in Meyer's Branch was comparable to their values for the woody component. The percent carbon of the miscellaneous litter component was not significantly different between the four riparian forests (Figure IV-6b).

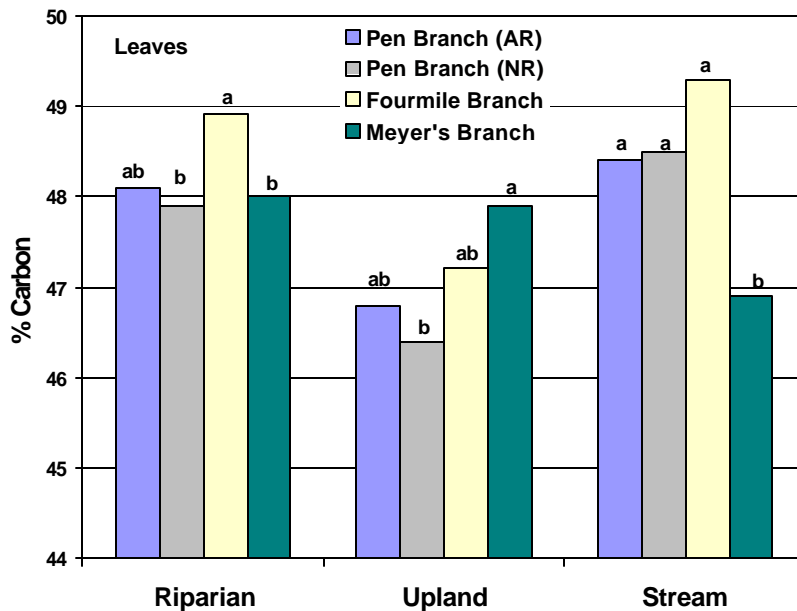


Figure IV-5. Mean foliar percent carbon for the annual litterfall for four South Carolina Coastal Plain riparian, and upland forests and the litter falling into the stream. Within an ecosystem type, means with different letters are significantly different from each other.

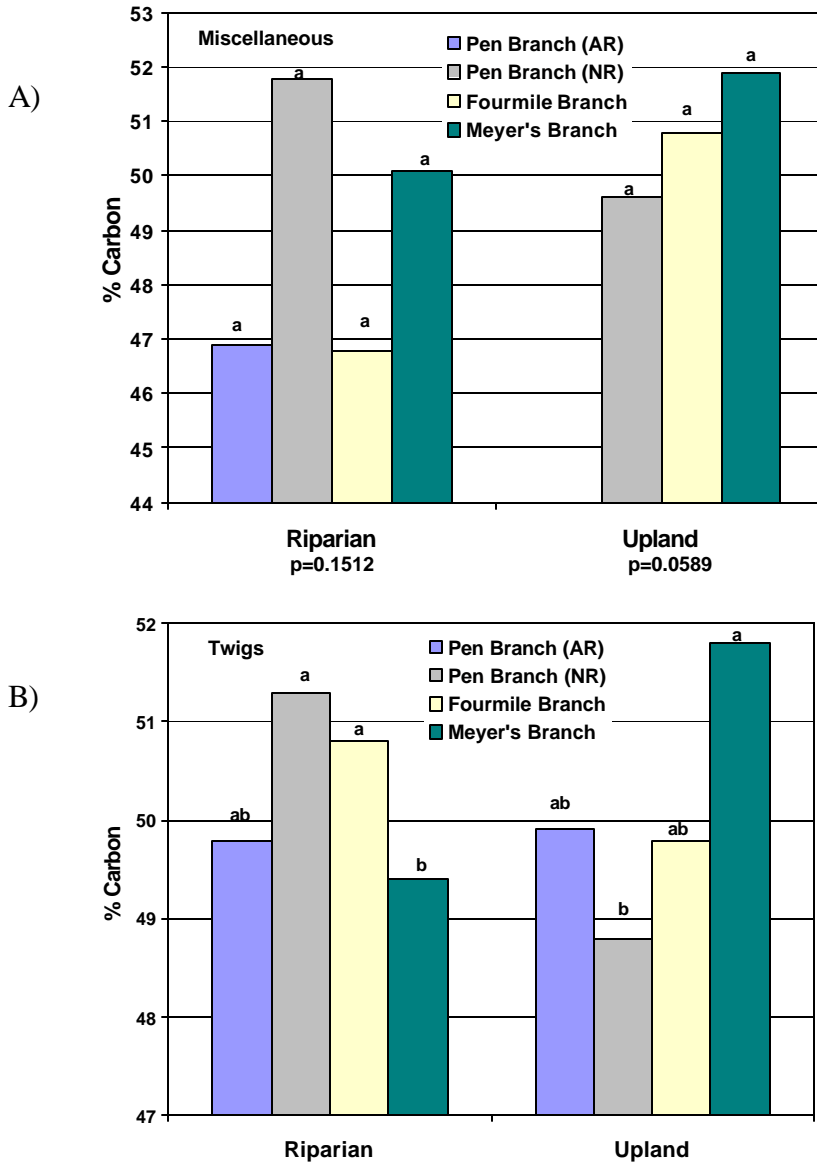


Figure IV-6. Mean percent carbon for the annual twig (A) and miscellaneous (B) litterfall component for four South Carolina Coastal Plain riparian, and upland forests. Within an ecosystem type, means with different letters are significantly different ($\alpha = 0.05$) from each other. There was insufficient sample amount to obtain the % carbon for the Pen Branch (AR) miscellaneous upland litterfall component.

The total litterfall carbon pool (Table IV-3) was similar to that found by Brinson et al. (1980) and Burke et al. (1999). The leaf litter carbon pool (Table IV-3) was slightly higher than that found by Brinson et al. (1980) due to annual variability in leaf litterfall. The twig carbon pool (Table IV-3) was higher for Pen Branch (NR) and lower for Fourmile Branch and Meyer's Branch than that found by Brinson et al. (1980). The differences in twig carbon pools was a result of species differences due to forest age as reflected by successional stage. The miscellaneous litterfall carbon pool recorded by Brinson et al (1980) was higher than that observed in this study and may be attributed to differences in species composition. Regardless of the differences in percent carbon of the litterfall components for several of the riparian forests, the litterfall carbon pools (total, leaves, twigs, and miscellaneous) reflect biomass differences between the four sites. Therefore, in this study, the difference in percent carbon was not sufficient to override the amount of biomass in each litterfall component and litterfall carbon pools follow a pattern similar to their respective biomass.

Upland

The uplands adjacent to the riparian forests are relatively mature mixed hardwood forests with scattered pine. It was correctly assumed that litterfall processes would be similar for all four upland sites because there was no significant difference in total litterfall between the four upland forests (Fig. IV-3). The total litterfall biomass in all four upland sites was slightly less than that recorded by Bell et al. (1978) and Peterson and Rolfe (1982) for upland forests adjacent to forested wetlands. Peterson and Rolfe (1982) assert that floodplain and upland forests produce contrasting patterns of nutrient transfer (i.e., litterfall dynamics) due to species characteristics and variability of the physical environment. In the Peterson and Rolfe (1982) study, there appeared to be more annual variability in floodplain litterfall than the upland litterfall.

Table IV-3. Carbon Pools (g m^{-2}) for total litterfall, and by individual component for four riparian and upland forests, and litterfall inputs to the main stream channel within each riparian forest in the S. C. Coastal Plain. By ecosystem within a row, means with different letters are significantly different from one another. Standard deviations are in parentheses. Sample sizes are the same for each litter component within a site, Pen Branch (AR), Pen Branch (NR), Fourmile Branch, and Meyer's Branch, respectively: riparian 8, 8, 8, 8; upland 3, 3, 4, 4; stream 2, 2, 3, 3.

	Pen Branch (AR)	Pen Branch (NR)	Fourmile Branch	Meyer's Branch
Riparian				
-----g C m ⁻² -----				
Leaf Litter	9 (10) b	215 (50) a	168 (55) a	215 (31) a
Twig Litter	1 (2) b	66 (76) a	29 (26) ab	13 (6) ab
Miscellaneous Litter	3 (4) b	12 (6) ab	9 (11) ab	14 (7) a
Total Litterfall	13 (13) b	293 (106) a	206 (81) a	242 (28) a
Upland				
-----g C m ⁻² -----				
Leaf Litter	213 (82) a	222 (30) a	281 (76) a	231 (52) a
Twig Litter	28 (26) a	12 (7) a	15 (4) a	26 (14) a
Miscellaneous Litter	17 (3) a	18 (10) a	68 (37) a	65 (44) a
Total Litterfall	258 (93) a	252 (25) a	364 (113) a	322 (95) a
Stream				
-----g C m ⁻² -----				
Leaf Litter	7 (7) c	92 (14) b	55 (33) bc	205 (23) a

There was no significant biomass difference in leaf, twig, or miscellaneous litterfall components between the four upland sites (Fig. IV-7). Leaf and miscellaneous litterfall biomass were similar to values found by Bell et al. (1978) and Peterson and Rolfe (1982), but the upland twig litterfall biomass was much less than both of their findings.

Interestingly the percent carbon of the leaf, twig, and miscellaneous litter components was slightly lower in Pen Branch (NR) than Fourmile Branch to Meyer's Branch. The differences were probably due to the lower pine component in Pen Branch (NR) compared to the other three upland sites because pine needles generally have more percent carbon than deciduous leaves (Post and De La Cruz 1977). Pen Branch (AR) leaf and twig components had percent carbon values similar to Fourmile Branch leaf and twig components.

Regardless of differences in percent carbon of the litterfall components for several of the upland forests, litterfall carbon pools (total, leaves, twigs, and miscellaneous) reflect biomass differences between the four sites. Therefore, the difference in percent carbon was not large enough to counterbalance the amount of biomass in each litterfall component and carbon pools followed a pattern similar to their respective upland biomass.

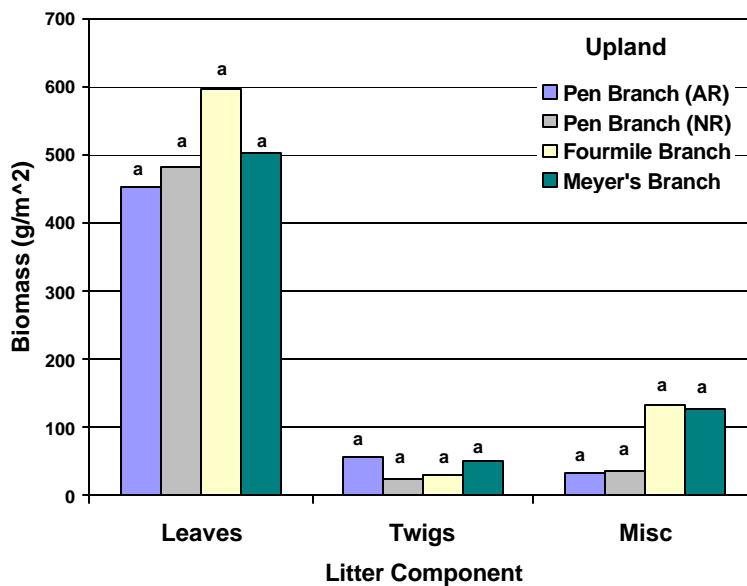


Figure IV-7. Annual litterfall by component for four South Carolina Coastal Plain upland forests. Within a litterfall component, means with different letters are significantly different ($\alpha = 0.05$) from each other.

Stream

The annual litterfall biomass contributed to the main channel within Meyer's Branch was significantly higher than the other three sites (Fig. IV-3) and this reflected the influence of a mature, closed canopy forest of a later successional stage. Litterfall inputs to the Meyer's Branch stream were much greater than the litterfall inputs recorded by Hill and Brooks (1996), however; the litterfall inputs to Pen Branch and Fourmile Branch were comparable to their observations. The mature riparian forest also significantly provided more leaf and twig litterfall biomass than the younger riparian forests (Fig. IV-8). The miscellaneous litterfall component within Meyer's Branch had significantly more biomass than both Pen Branch sites (Fig. IV-8) and increased with increasing forest age. Leaf litter biomass entering the main channel in Pen Branch (NR) was significantly greater than leaf litter biomass entering the main channel in Pen Branch (AR) implying that site preparatory measures applied to Pen Branch (AR) have delayed the incorporation of litterfall (nutrients/energy) to the aquatic ecosystem. Meyer's Branch had more leaf and twig biomass, and the other three sites had less leaf and twig biomass compared to values reported by Cillero et al. (1999). The miscellaneous litterfall component was much less in all four sites than values reported by Cillero et al. (1999).

Percent carbon in the leaves entering the main channel of Meyer's Branch was significantly less than the percent carbon in leaf litterfall entering the main channels of the other three sites, probably due to species differences associated with successional stage. Although the leaf percent carbon in Meyer's Branch was much lower than the other sites, the magnitude of leaf biomass compensated for this difference and similar to riparian and upland litterfall trends, the leaf litterfall carbon pools for each site mirror the leaf litterfall biomass of each site respectively.

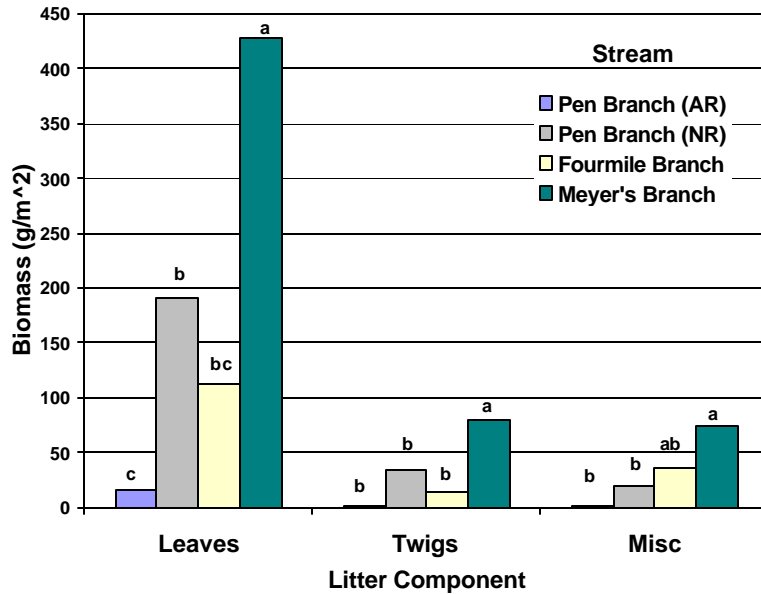


Figure IV-8. Annual litterfall by component entering the main stream channel within four South Carolina Coastal Plain riparian forests. Within a litterfall component, means with different letters are significantly different from one another ($\alpha = 0.05$).

Litterfall (within Sites)

Theoretically, if litterfall dynamics were independent of forest age, all four of the sites would demonstrate similar total litterfall for each ecosystem (riparian, and stream total litterfall would be similar to total upland litterfall). However, litterfall was not independent of forest age regardless of the ecosystem (riparian, upland, and stream inputs) as shown in this study (Fig. IV-9). Riparian forest litterfall has been estimated to be approximately 10% lower than litterfall into the stream (Cillero et al. 1999) and the Meyer's Branch riparian forest exhibits this difference. The litterfall in the younger riparian forests does not reflect the 10% decline. Annual litterfall into the stream of Meyer's Branch was comparable to other 3rd order streams (Cillero et al. 1999).

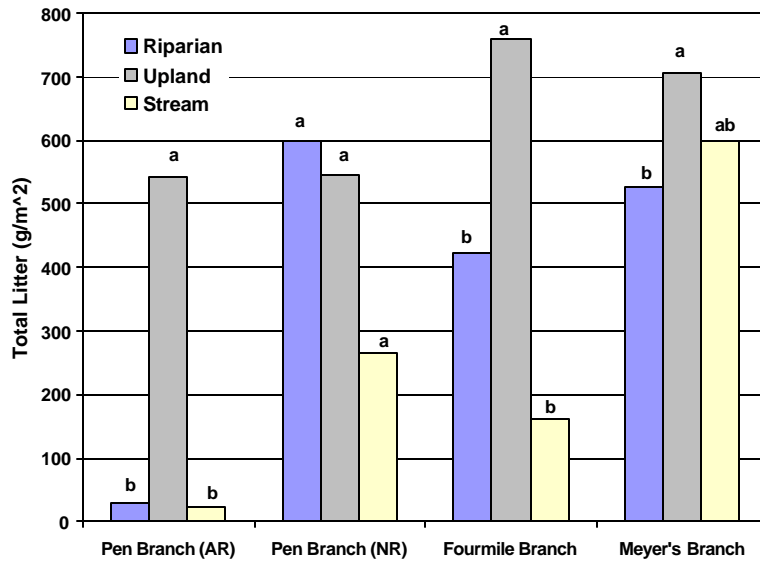


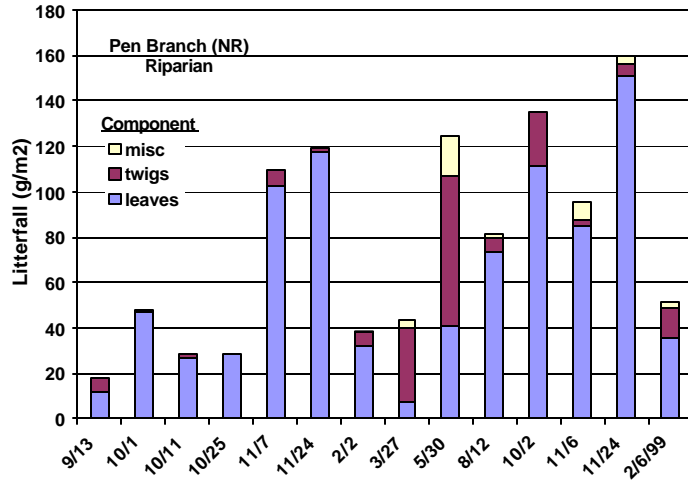
Figure IV-9. Comparison of riparian, upland and stream total annual litterfall within each South Carolina Coastal Plain site. Within a site, means with different letters are significantly different from one another ($\alpha = 0.05$).

Seasonal Litterfall Trends

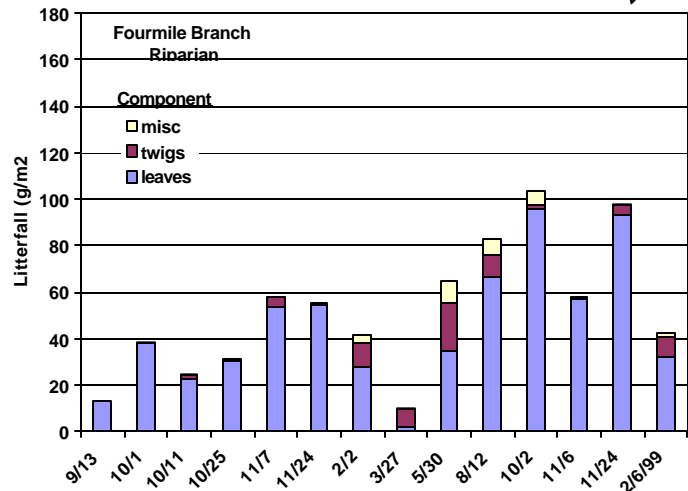
In the riparian and upland forests of Pen Branch (NR), Fourmile Branch, and Meyer's Branch, litterfall inputs peaked in the fall (Figs. IV-10 and IV-11). In spring and late summer, litterfall inputs comprised more twig and miscellaneous biomass in the riparian and upland forests of Pen Branch (NR), Fourmile Branch, and Meyer's Branch (Figs. IV-10 and IV-11).

Vertical litterfall inputs to the stream peaked in late fall (Fig. IV-12). Unfortunately, due to spring storms, stream litterfall data for the remainder of the year, past the February collection, were lost. The litterfall inputs to the stream in Meyer's Branch increased uniformly through the year whereas, at Pen Branch (NR) and Fourmile Branch litterfall inputs were more erratic. The greater canopy coverage of a mature riparian forest provides a more uniform input of litter to the stream as observed in Meyer's Branch.

A)



B)



C)

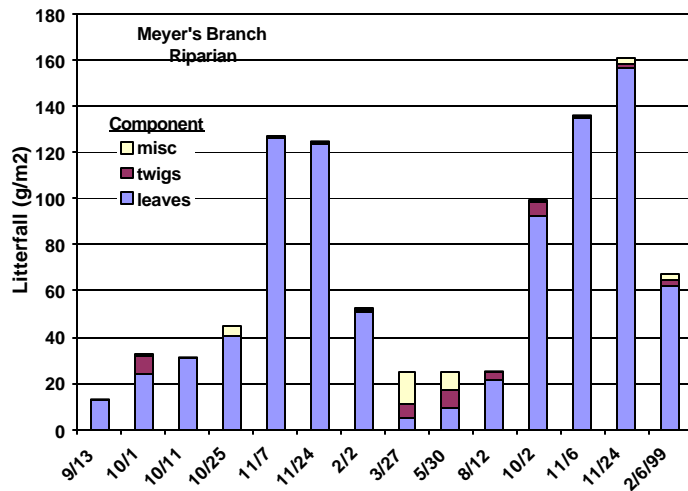
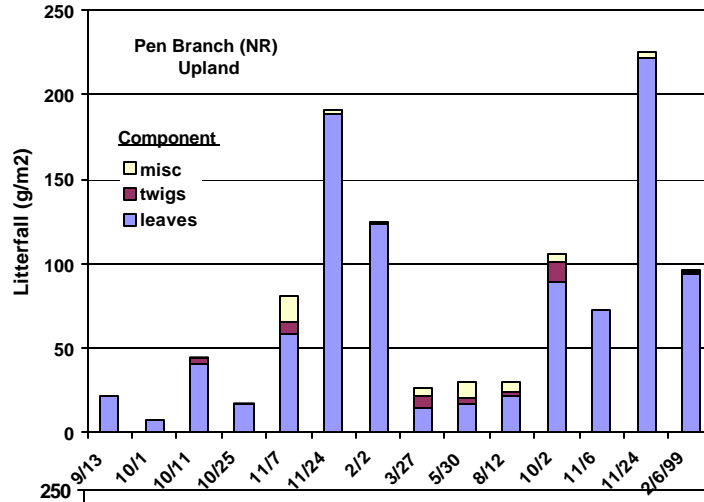
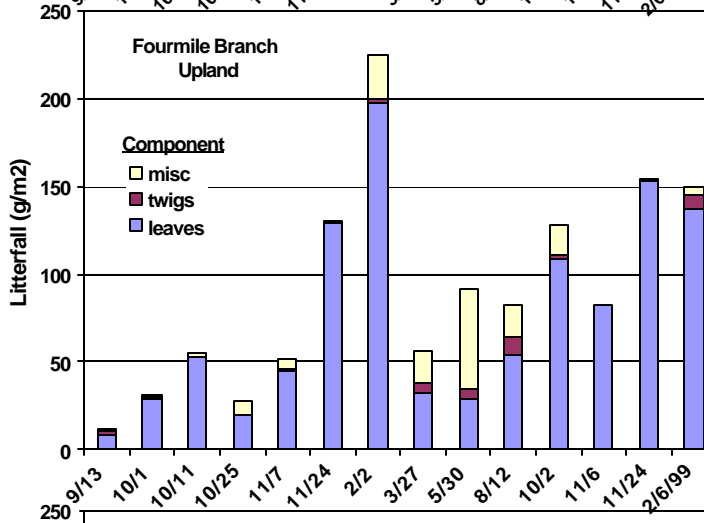


Figure IV-10. Leaf, twig, and miscellaneous litterfall component for the riparian forests of Pen Branch (NR) (A), Fourmile Branch (B), and Meyer's Branch (C) by sampling date.

A)



B)



C)

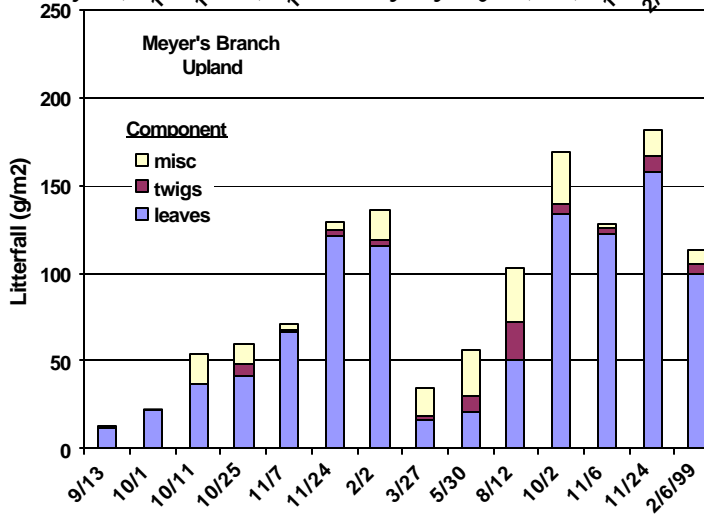
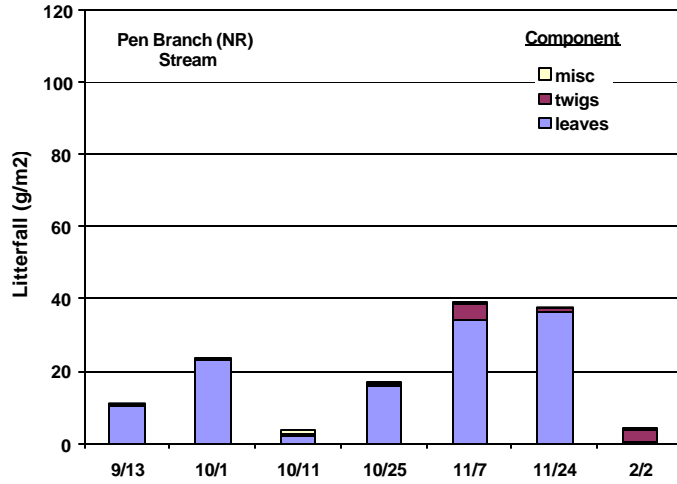
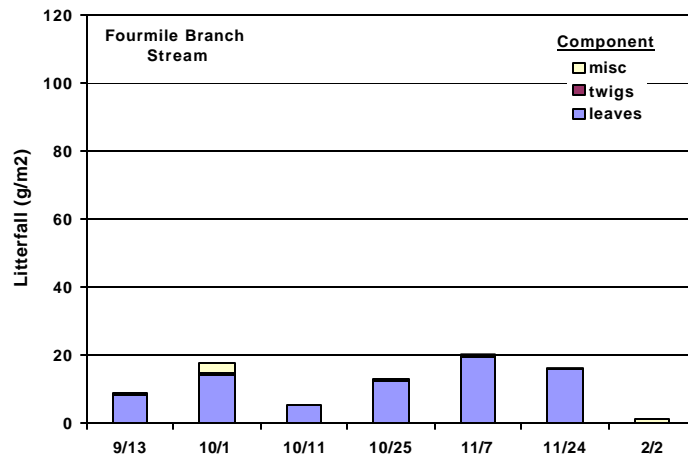


Figure IV-11. Leaf, twig, and miscellaneous litterfall component for the upland forests of Pen Branch (NR) (A), Fourmile Branch (B), and Meyer's Branch (C) by sampling date.

A)



B)



C)

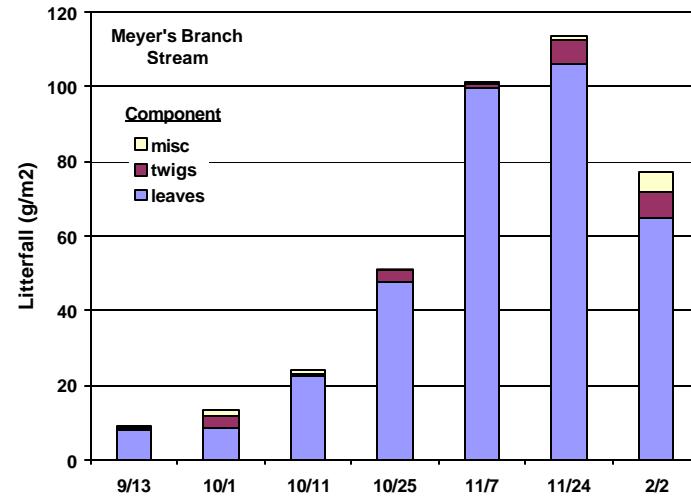


Figure IV-12. Leaf, twig, and miscellaneous litterfall component for the main stream channels of Pen Branch (NR) (A), Fourmile Branch (B), and Meyer's Branch by sampling date.

Species respond differently to environmental changes leading to dormancy and therefore, litterfall inputs may differ due to species composition (Cillero et al. 1999). For example, Bell et al. (1978) found oak peak litterfall to be slightly later than maple peak litterfall. Litter composition changed through the annual cycle, independent of forest age, as was observed in the annual litterfall of the riparian and upland forests of Pen Branch (NR), Fourmile Branch and Meyer's Branch. The vegetative-seasonal cycle of different species influences litterfall seasonal pattern of leaves and fruit (Cillero et al. 1999) and this was apparent in these riparian forests. More reproductive parts comprise litterfall components in spring (Bell et al. 1978; Peterson and Rolfe 1982). Burke et al. (1999) found the timing of seedfall was different for communities with dissimilar hydroperiods. Spring (and winter) storms often produce more twig/woody litterfall inputs (Post and De La Cruz 1977; Bell et al. 1978; Gomez and Day 1982). Summer litterfall is generally comprised of frass and small leaf fragments (Bell et al. 1978).

Species composition is an integral part of forest succession and the chemical constituents and structure of a species different litterfall components (leaf, twig, fruit, flower) is reflected in the percent carbon. The percent carbon in the leaf, twig, and miscellaneous litterfall components in each of the four riparian forests was generally higher the following year after 24 weeks compared to total values of the previous year, with a greater discrepancy observed in the leaf percent carbon (Table IV-4).

Higher leaf percent carbon the subsequent year could be attributed to annual variability due to biotic / abiotic factors, (i.e., leaching during precipitation events, differential litter composition). The percent carbon in riparian leaf litter appears to exhibit seasonal changes (Fig. IV-13). The species composition in the younger riparian forests generally had greater percent carbon in their leaves throughout the year than the mature riparian forest. In Pen Branch (NR) and Fourmile Branch the percent carbon of leaf litter inputs to the stream were similar to riparian leaf litter percent carbon and

this close association was not observed in Meyer’s Branch. However, independent of forest age, leaf litter percent carbon followed seasonal trends within riparian and upland forests. Moorhead and McArthur (1996) observed a decrease in foliage carbon as growing season progressed. More carbon was allocated to foliage in April than August and October. Post and De La Cruz (1977) found the percent carbon of deciduous leaves to be higher in the fall compared to spring, summer and winter. Pine needles had lower percent carbon in the fall compared to the other seasons.

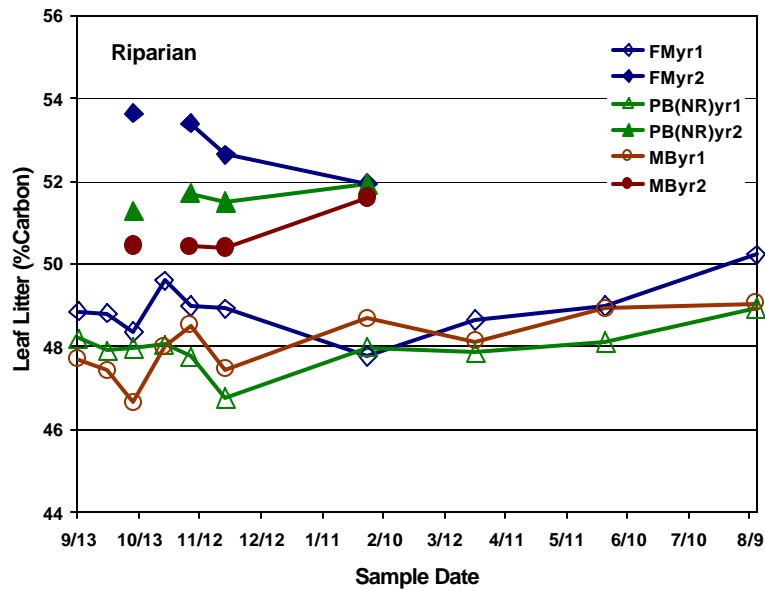


Figure IV-13. Leaf litter % carbon for four South Carolina Coastal Plain riparian forests. Open symbols are for year 1 data, closed symbols are for year 2 data. Sites are Pen Branch natural regeneration PB(NR); Fourmile Branch - FM, and Meyer’s Branch - MB.

Almost identical seasonal patterns were found in the upland leaf litter percent carbon (Fig. IV-14). The leaf litter percent carbon fluctuated among the four upland forests throughout the year. Seasonal patterns also appeared in the leaf litter percent carbon entering the streams, however, there appears to be lag responses of litter fall inputs among the four sites in the fall (Fig. IV-15). The stream leaf litter percent carbon in Fourmile Branch was consistently higher and Meyer’s Branch was consistently lower among the four sites (Fig. IV-15).

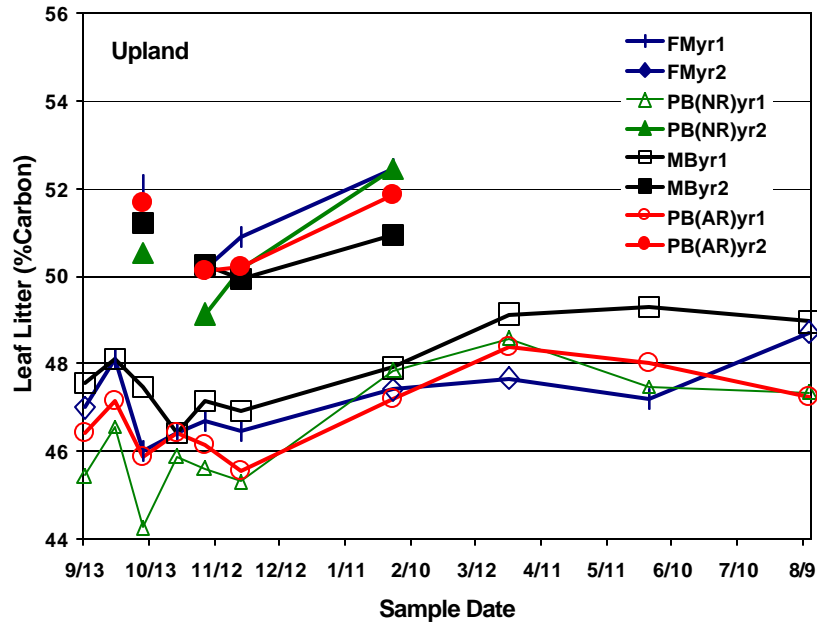


Figure IV-14. Leaf litter % carbon for four South Carolina Coastal Plain upland forests. Open symbols are for year 1 data and closed symbols are for year 2 data. Sites are Pen Branch artificial regeneration - PB(AR); Pen Branch natural regeneration PB(NR); Fourmile Branch - FM, and Meyer's Branch - MB.

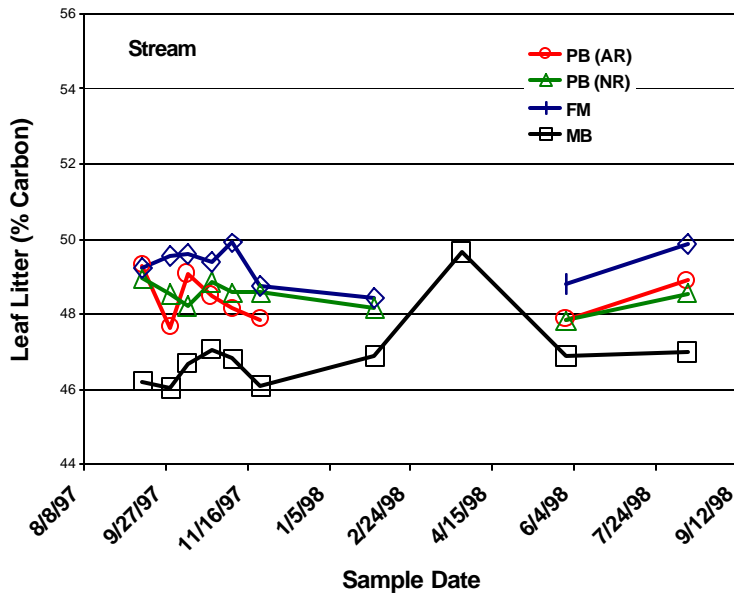


Figure IV-15. Leaf litter % carbon for the litter falling into the main stream channels of four South Carolina Coastal Plain riparian forests. Data are for year 1 only. Sites are Pen Branch (AR) - PB(AR); Pen Branch (NR) PB(NR); Fourmile Branch - FM, and Meyer's Branch - MB.

Forest Floor

Riparian

Total forest floor biomass was not significantly different ($p = 0.6418$) between the three riparian forests. However, there was a decrease in total forest floor biomass with an increase in riparian forest age (Fig. IV-16). The forest floor in the riparian forests was comprised of approximately two-thirds leaf material and the remainder a combination of twig and miscellaneous litter components (Fig IV-16). Intuitively, there would be more forest floor biomass in the mature riparian forest since it receives greater litterfall inputs. Either higher decomposition rates, greater flushing of material or blanketing by sediment deposition could explain the less forest floor biomass in the mature riparian forest. Differences in elevation (microtopography) could alter water flow patterns and influence litter and sediment deposition.

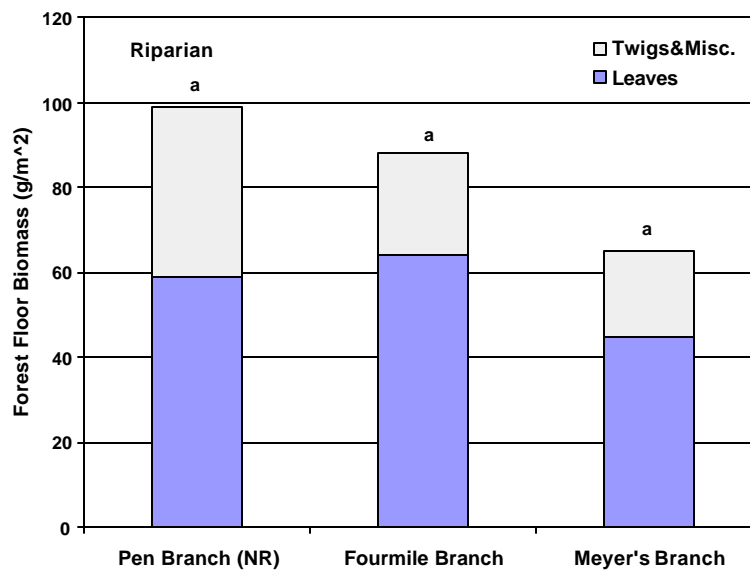


Figure IV-16. Forest floor biomass for three riparian forests in the South Carolina Coastal Plain. Means with different letters are significantly different from one another ($\alpha = 0.05$).

There was a significant increase in the percent carbon of the forest floor leaf component with increasing riparian forest age (Fig. IV-17). Differences in riparian forest floor foliar percent carbon may be reflective of differing decomposition rates or species composition. Percent carbon in riparian forest floor leaves was greatly reduced compared to percent carbon of leaf litter inputs to the riparian forests suggesting decomposers have been at work. The difference in percent carbon lends itself to a slight increase in the forest floor leaf carbon pool with increasing riparian forest age (Fig. IV-18). The forest floor carbon pools in this study were approximately 3 times greater than the forest floor carbon pool in a mesic mixed deciduous forest (Edwards and Harris 1977).

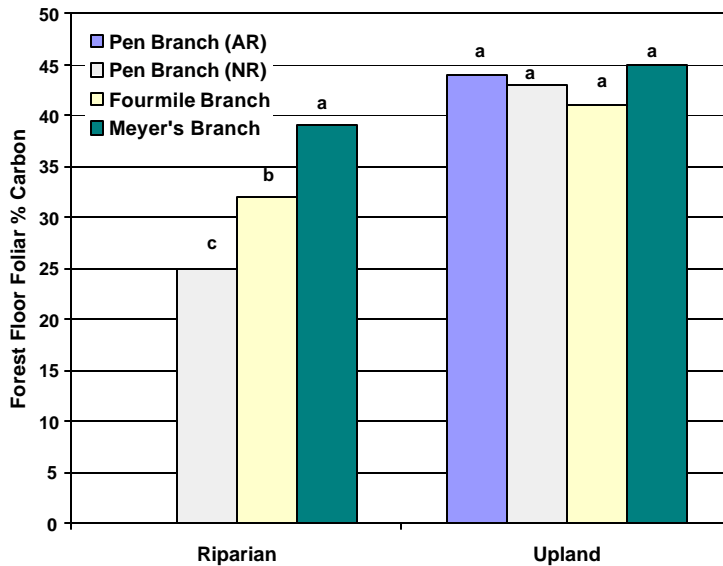


Figure IV-17. Percent carbon for the forest floor leaf component of three riparian and four upland forests in the South Carolina Coastal Plain. Within an ecosystem type, means with different letters are significantly different from each other (alpha = 0.05). Pen Branch (AR) riparian forest floor foliar component was not sampled.

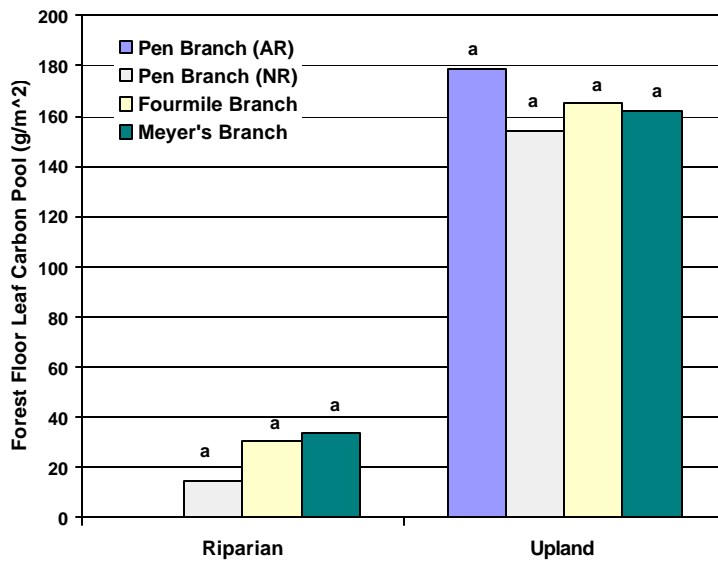


Figure IV-18. Foliar forest floor carbon pool for three riparian and four upland forests in the South Carolina Coastal Plain. Within an ecosystem type, means with different letters are significantly different from each other (alpha = 0.05). Pen Branch (AR) riparian forest floor foliar component was not sampled.

Upland

The forest floor biomass in the uplands adjacent to the riparian areas was primarily comprised of leaf material (Fig. IV-19). Total upland forest floor biomass was approximately 5 times greater than riparian forest floor biomass, but similar to values reported by Peterson and Rolfe (1982). Greater upland forest floor biomass may be due to greater litterfall inputs, differences in species composition, forest age, or decomposition rates. The lack of significant difference in forest floor leaf percent carbon (Fig. IV-17) between the four upland forests may be indicative of the stability, and proportion/distribution of species, in more mature forests, and this results in similar forest floor leaf carbon pools for each upland site (Fig IV-18). The percent carbon in the upland forest floor leaves was slightly less than the percent carbon of leaf litterfall inputs to the upland.

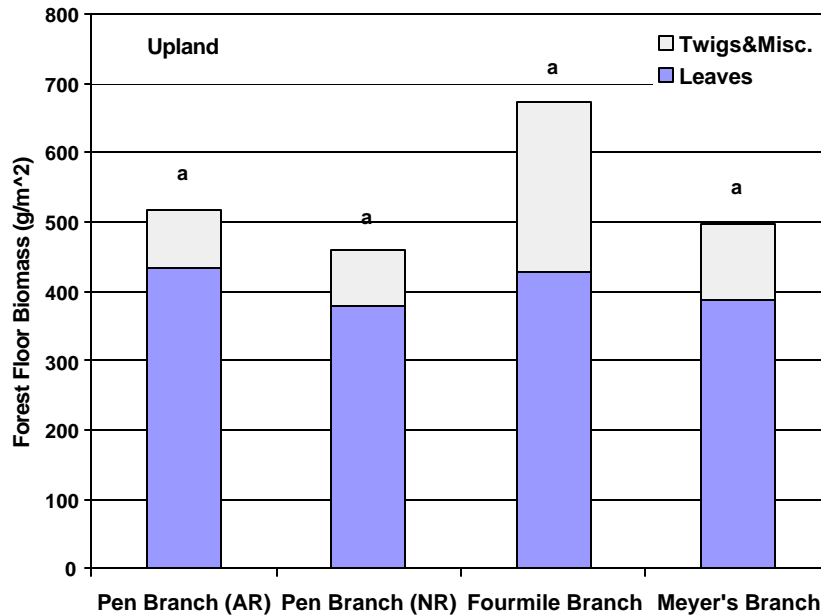


Figure IV-19. Forest floor biomass for four upland forests in the South Carolina Coastal Plain. Means with different letters are significantly different from one another ($\alpha = 0.05$).

The percent carbon in the upland forest floor leaves was significantly greater than the riparian forest floor leaf percent carbon. The difference between the riparian and upland forest floor foliar percent carbon could be indicative of decomposition rates or species composition. Factors influencing forest floor dynamics vary based on landscape position with an outcome of much smaller forest floor carbon pools in riparian forests regardless of forest age as compared to upland forest floor carbon pools.

Lateral Litter

During the period of study there was one flood event which resulted in movement of lateral litter within Fourmile Branch and Meyer's Branch. The hydrologic event occurred between November 26, 1998 and February 7, 1999. In Pen Branch substantial stream flow was not detectable during the

event timeframe, possibly due to beaver (*Castor canadensis*) influence upstream. During the hydrologic event, average lateral litter biomass in Fourmile Branch and Meyer's Branch was 404 g m⁻² and 469 g m⁻², respectively which was not significantly different. Percent carbon of the lateral litter was 40.5 and 39.5, and carbon pools were 158 and 179 g C m⁻² for Fourmile Branch and Meyer's Branch, respectively. Percent organic matter was 77 and 74, and the amount of sediment was 142 and 163 g m⁻², for Fourmile Branch and Meyer's Branch, respectively.

Lateral litter biomass was not significantly different between each quadrant in Fourmile Branch or Meyer's Branch (Fig. IV-20). Although not significantly different, the amount of litter deposited into the upstream quadrant of the Mudll was greater than the overbank quadrant. This implies that most of the litter deposited during a flood event is from the upstream direction. Meyer's Branch has less understory vegetation and little elevation difference (no distinct ridge) next to the stream bank which allowed for more overbank quadrant lateral litter than Fourmile Branch. The same physical characteristics allow more lateral movement towards the stream in Meyer's Branch than Fourmile Branch.

Lateral litter movement toward the stream for Fourmile Branch and Meyer's Branch, was 283 and 347 g m⁻², respectively. McDowell and Fisher (1976) reported similar amounts of litter that blew into a stream, however, Connors and Naiman (1984) found much less lateral litter movement toward the stream. Hill and Brooks (1996) reported an annual stream bank transport of 50-60 g m⁻¹ coarse particulate organic matter (CPOM). Surprisingly litter was collected in the downstream quadrant. Either this was litter that blew in over time or during flood events water flow patterns are not unidirectional. The high amount of lateral litter in the downstream quadrant in Fourmile Branch was probably an anomaly.

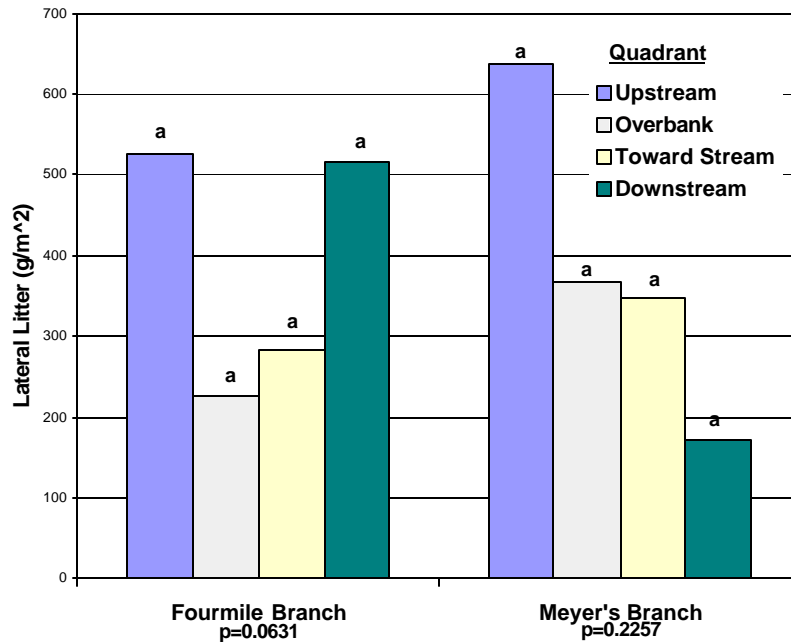


Figure IV-20. Lateral litter biomass by Mudll quadrant for two riparian forests in the South Carolina Coastal Plain. Means within a site with different letters are significantly different from each other (alpha = 0.05).

Lateral litter contained approximately 80 percent organic matter and was comparable between upstream, overbank, and toward stream quadrants in Fourmile Branch (Fig. IV-21). All four quadrants had comparable percent organic matter in Meyer's Branch (Fig. IV-21). The addition of organic matter to the stream via the riparian area and vice versa can alter the physical and chemical characteristics of stream and riparian forest. The amount of sediment in the downstream quadrant of Fourmile Branch was probably an overestimate because it represents only one sample (Fig. IV-22). Excluding the outlier, there was a decrease in the amount of sediment from upstream to overbank to toward stream (Fig. IV-22). In Meyer's Branch and slightly in Fourmile Branch, the predominant path for sediment deposition was from upstream followed by overbank. During this flood event a lesser amount of sediment moved from the riparian area to the stream.

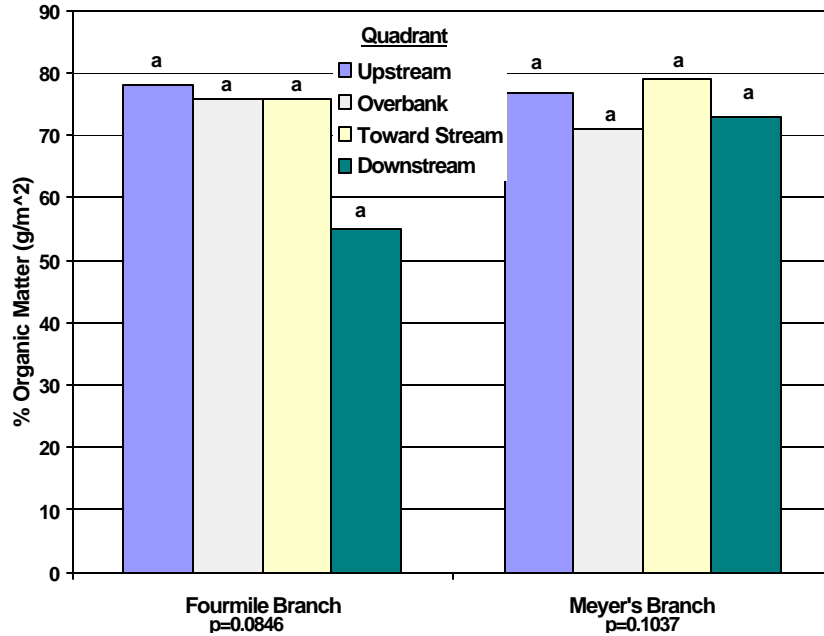


Figure IV-21. Lateral litter % organic matter by Mudll quadrant for two riparian forests in the South Carolina Coastal Plain. Within a site, means with different letters are significantly different from each other (alpha = 0.05).

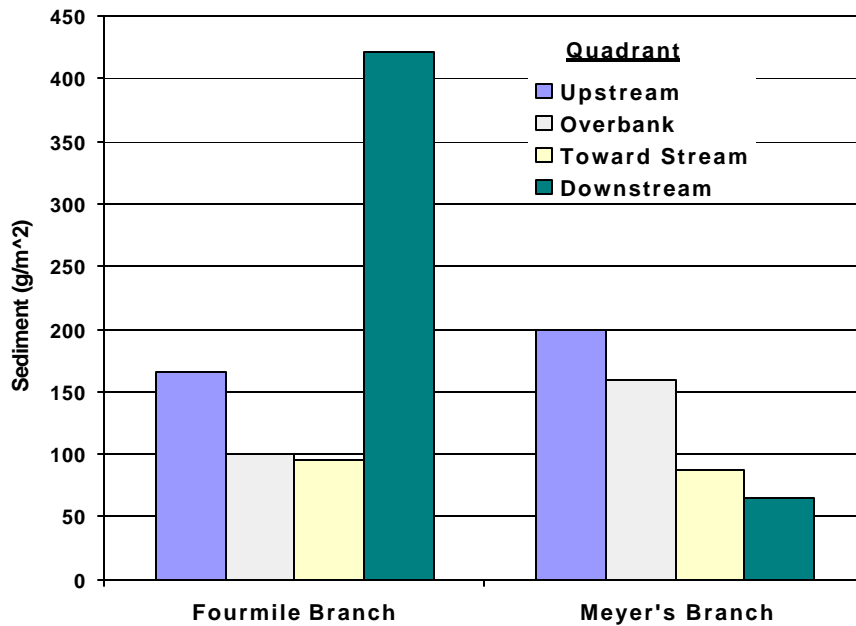


Figure IV-22. The amount of sediment collected by Mudll quadrant for two riparian forests in the South Carolina Coastal Plain.

Percent carbon of the lateral litter in each of the quadrants for both sites was less than the percent carbon of litterfall components entering the respective sites which implies that litter captured via lateral movement has undergone some decay. Also, the lateral litter collected may have included some herbaceous vegetation which could affect and possibly lower percent carbon values. In Fourmile Branch, percent carbon of lateral litter in the downstream quadrant was significantly less than the other three quadrants (Fig. IV-23). The downstream quadrant of Fourmile Branch had the greatest amount of sediment which explains the lower percent carbon, and percent organic matter values. There was no significant difference in percent carbon of lateral litter between quadrants in Meyer's Branch.

In Fourmile Branch the lateral litter carbon pool was significantly greater in the upstream quadrant than the overbank quadrant (Fig. IV-24). In general the lateral litter carbon pool had a quadrant pattern similar to lateral litter biomass for each quadrant and site respectively (Fig. IV-20), except for the toward stream quadrant in Meyer's Branch. Nevertheless, lateral litter supplied less energy to the stream system than vertical inputs. The litter components subject to lateral movement have either undergone decay to the point where all species converge to a similar percent carbon or only certain species (and associated %C) are more subject to lateral movement than others. Also, litter deposited from the stream to the riparian area during the flood event supplied less nutrients/energy. The upstream quadrant supplied the riparian forest with the greatest amount of carbon for each site during this flood event.

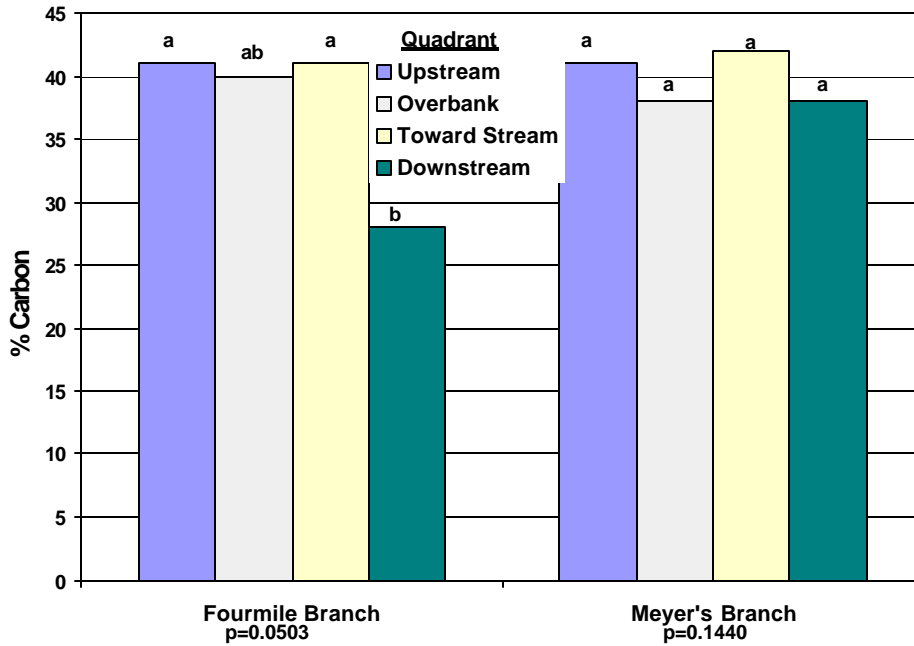


Figure IV-23. Lateral litter percent carbon by Mudtll quadrant for two riparian forests in the South Carolina Coastal Plain. Within a site, means with different letters are significantly different from each other (alpha = 0.05).

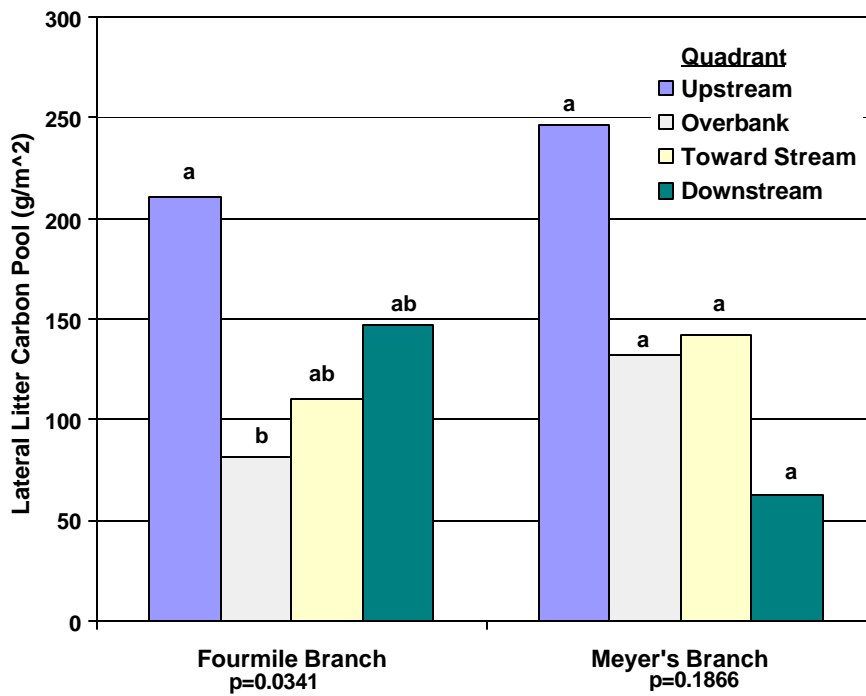


Figure IV-24. Lateral litter carbon pool by Mudtll quadrant for two riparian forests in the South Carolina Coastal Plain. Within a site, means with different letters are significantly different (alpha = 0.05).

Supporting the findings of Connors and Naiman (1984) channel type/size within a braided stream system does not significantly affect lateral litter movement. There was no significant difference in lateral litter biomass based on stream type in either Fourmile Branch or Meyer's Branch (Fig. IV-25). However, the larger (relatively) stream types moved more lateral litter in the mature riparian forest and the smaller (relatively) stream types played a greater role in the younger riparian forests in the movement of lateral litter. Also, there was no significant difference in percent carbon and percent organic matter in the lateral litter, and amount of sediment, based on stream type in either site (data not shown). The lateral litter carbon pool pattern based on stream type (Fig. IV-26) had a pattern similar to lateral litter biomass based on stream type.

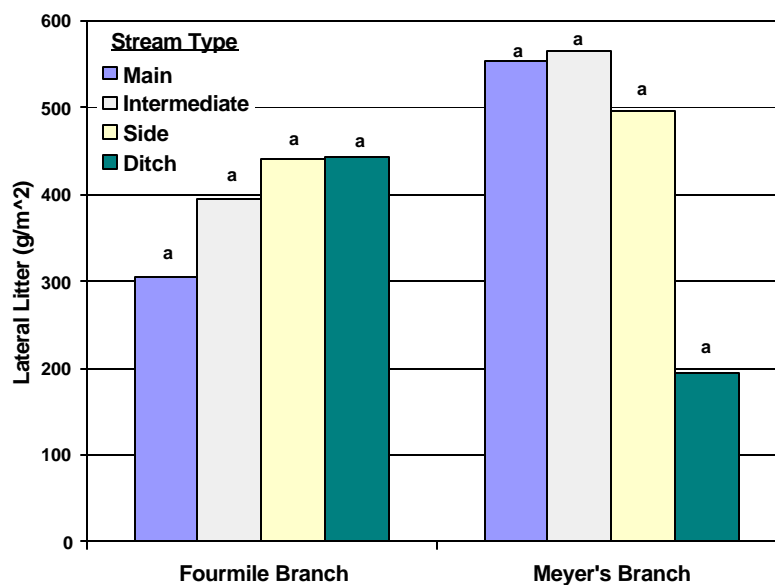


Figure IV-25. Lateral litter biomass by stream type for two riparian forests in the South Carolina Coastal Plain. Within a site, means with different letters are significantly different from each other ($\alpha = 0.05$).

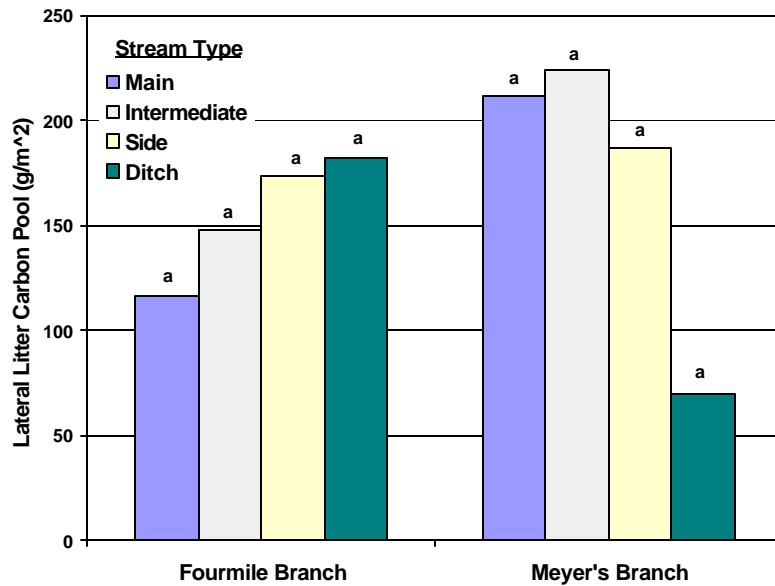


Figure IV-26. Lateral litter carbon pool by stream type for two riparian forests in the South Carolina Coastal Plain. Within a site, means with different letters are significantly different from each other (alpha = 0.05).

Instream Litter

The amount of instream litter is a product of inputs from the surrounding watershed and greatly susceptible to storm intensity. Land use and watershed area (Pen Branch, 55 km²; Fourmile Branch, 57 km²; Meyer's Branch, 51 km²) was comparable for all four sites and therefore, should not be a factor in the amount of instream litter observed in the main channels associated with each riparian forest. The similarity in litter pattern over the sampling period implies that each stream system was subject to the same influential factors (Fig IV-27).

Instream litter ranged from 0.0013 to 0.028 g s⁻¹ (0.11 to 2.42 kg day⁻¹ per stream length) for each site (Table IV-5) which was comparable to undisturbed stream values reported by Webster et al.

(1990). Sampling was generally conducted during base flow rates of 12 to 38 cm s⁻¹. Stream velocity in the main channel in Meyer's Branch had slightly higher baseflow rates than the other three sites. Stream channels in Pen Branch (AR) had a significant amount of submerged aquatic vegetation which affected stream flow and possibly instream litter dynamics.

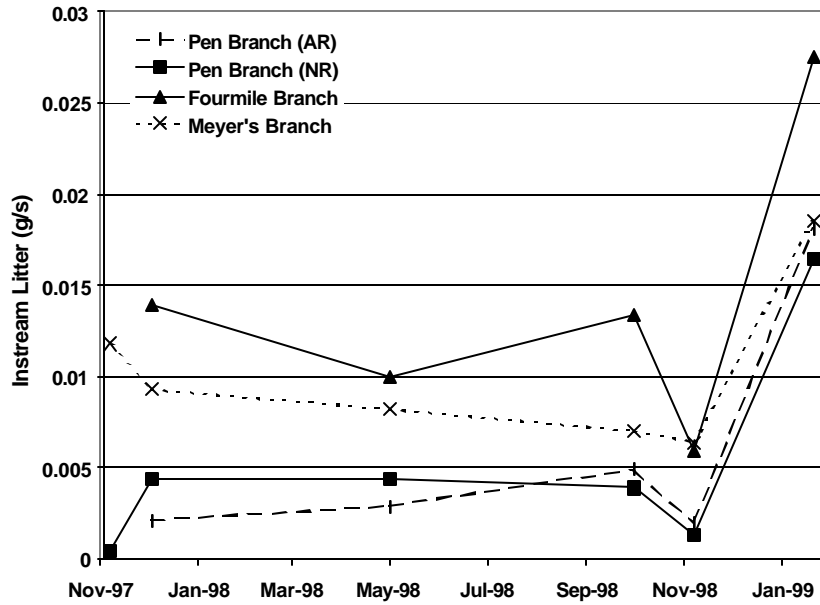


Figure IV-27. Instream litter of the main stream channel (3rd order) associated with four riparian forests representing different stages of succession located in the South Carolina Coastal Plain.

Table IV-5. Instream litter (g s^{-1}) for three 3rd order streams (main channel) associated with riparian forests representing differing successional stages in the Coastal Plain of South Carolina. Within a row, means with different letters are significantly different from each other.

Date	Pen Branch (AR)	Pen Branch (NR)	Fourmile Branch	Meyer's Branch	p-value
	----- g s^{-1} -----				
November 11, 1997	--	0.0004	0.0013	0.0118	--
December 19, 1997	0.002 b	0.004 b	0.014 a	0.009 b	<0.0001
May 17, 1998	0.003 a	0.004 a	0.010 a	0.008 a	0.1508
October 17, 1998	0.005 a	0.004 a	0.013 a	0.007 a	0.0862
November 23, 1998	0.002 a	0.001 a	0.006 a	0.006 a	0.3637
February 6, 1999	0.018 a	0.016 a	0.028 a	0.018 a	0.7848

At the alpha level of 0.05 there was no significant difference in instream litter (g s^{-1}) between the four sites. However, at an alpha level of 0.10, instream litter in Fourmile Branch was significantly greater than instream litter in Pen Branch (AR). All four sites showed a similar pattern in instream litter with sampling date (Fig. IV-27). Hill and Brooks (1996) also observed seasonal variation in CPOM flux with greatest amounts being transported between May and October. Significant site differences in instream litter only occurred during the second sampling date (Table IV-5). In Pen Branch (AR) and Meyer's Branch the February 6, 1999 sampling date was significantly greater than the other sampling dates.

Interestingly there was more instream litter with increasing forest age or succession except for Meyer's Branch which had less instream litter than Fourmile Branch. Differences in instream litter amounts may be attributed to riparian forest age and inherent species composition because leaf processing rates in streams differ by species (Petersen and Cummins 1974; Suberkropp et al. 1976; Benfield 1996). This discrepancy may be more a function of hydroperiod than forest age or species composition supplying more allochthonous material to the stream in Fourmile Branch. The amount of

instream litter in each of the four sites was much less than reported by Post and De La Cruz (1977) possibly due to the smaller stream sizes in this study.

Conclusion

Litter dynamics within riparian forests are very complex. It is often assumed on balance that litter nutrients are returned in the same area from which they were absorbed. However, in riparian forests many avenues exist for litter distribution. Besides annual vertical litterfall inputs, the movement of litter toward and from the associated stream during flood events must be incorporated into the equation. The hydroperiod of a riparian forest also influences decomposition rates and therefore, forest floor biomass. Forest age and stage of succession has quantitative and qualitative impacts on all of the factors affiliated with riparian forest litter dynamics. Litterfall biomass in riparian forests rapidly approached quantities indicative of mature forest stands after a relatively short time span (~8 -10 years). However, litter quality, primarily the percent carbon of the various litterfall components differed with forest age. Higher percent carbon in litter of the younger riparian forests combined with nitrogen fixing abilities of alder (pioneer species common to riparian forests) could enhance nutrient incorporation and availability for productivity.

Litterfall collection is a relatively inexpensive, easy, and unobtrusive method compared to some alternative methods of assessing restoration. Even though there was annual variation, and differences in percent carbon of various litterfall components between forest age, (with the amount of biomass generally overriding these differences), the overall litterfall measurements still reflect forest stand differences. Therefore, litterfall can be used as an index for riparian restoration when the objective is to ensure that woody vegetation has recovered to the extent that litterfall amount reflects a mature riparian forest. Use of this technique could provide significant savings of time and funds for agencies currently involved in restoration monitoring.

Lateral litter movement within a riparian forest is controlled by microtopography, hydroperiod, species composition (erect vegetation and litterfall composition), and density (vegetation and forest floor). More litter was deposited into the riparian area during a flood event than moved toward the stream from adjacent riparian and upland areas. This implies that headwater management may be more influential to stream litter than litter provided by wider adjacent streamside management zones. Although the stream inputs may be small, they are no doubt critical to the aquatic ecosystem. The young Pen Branch riparian forests did not have any appreciable lateral litter movement, possibly due to steeper banks along the stream channels, denser ground cover, or a different hydroperiod. Gradual, lower banks, and more uniform landscape of Meyer's Branch allowed flood waters to penetrate the riparian forest. Also since forest age affects forest floor composition and biomass, litter subject to lateral movement was a function of forest age.

Instream litter is a function of the riparian forest and surrounding landuse in the entire watershed. The closed canopy of the mature riparian forest provided greater allochthonous input to the stream ecosystem. Forest stand composition and density associated with successional stage can differentially buffer storm impacts and alter the amount of litter falling into the stream. Also forest development and stratification can impede sediment movement toward the stream. The forests in this study exhibited more sediment deposition into the riparian area. Providing allochthonous inputs and retarding sediment to the streams confirms the critical importance of riparian buffers or streamside management zones.

The carbon content of all litter mediums (vertical litterfall inputs, forest floor, and instream litter) is a function of successional stage as dictated by species composition within the riparian forest. The energy contributed by each litter faction determines the productivity of the riparian forest and provides for a healthy aquatic ecosystem in the associated stream. Riparian restoration may be accelerated by incorporating species indicative of later successional stages at an appropriate time. For example,

planting of later successional woody riparian species should occur after competition for resources from herbaceous vegetation decreases.

Decomposition

**Whole
to a sum of the parts
to atom or quark
infinitesimal**

Chapter V. Litter Decomposition within Coastal Plain Riparian Forests Representing Different Successional Stages*

* A facsimile of this chapter has been published in the 10th Biennial Southern Silvicultural Research Conference Proceedings.

Abstract

Decomposition of foliar litter is an important process for nutrient recycling. It is not known if decomposition rates differ with riparian forest seral stage. Decomposition rates of foliar litter from two thermally disturbed young riparian forests at different stages of succession and a more mature bottomland hardwood stand were compared. Decomposition rates were determined for one year among and between the sites for each mixed-species litter characteristic to each site. Species composition of each sites' respective litter, and inherent quality, influenced decomposition rates more than forest age. The influence of litter quality was evident in the decomposition rates of the different litter composites used in this study. In all four sites the litter composite from the mature riparian forest decomposed significantly more rapidly than the litter composites from the younger riparian forests. The fairly rapid decomposition of red maple (*Acer rubrum* L.), which was one of the main components in the mature riparian forest litter composite, likely influenced the greater decomposition rate. The litter composites from the younger riparian forests were similar and both included more resistant litter types, specifically waxmyrtle (*Myrica cerifera* L.) and alder (*Alnus serrulata* (Ait.) Willd.). Litter decomposition rates did not differ between the individual successional stages. The different decomposition rates of the litter composites will influence the quantity of litter movement toward the stream and eventually affect the aquatic ecosystem.

Introduction

Decomposition of leaf litter is an essential ecosystem process whereby nutrients become available for assimilation by plants, provides an energy base for the detritus food web (Post and DeLa Cruz 1977; Brinson et al. 1981; Cornelissen 1996), and contributes to the formation of soil organic matter (Bell et al. 1978; Lockaby et al. 1996b) and related physical properties. Typically, leaf litter comprises 70 percent of the total aboveground litter contributed to the forest floor on an annual basis (Brown 1981). The riparian forests in this study contribute approximately 75 to 85 percent leaf litter annually to the forest floor (Chapter IV). Forest productivity can be reduced if decomposition is too slow because the nutrients are removed from active circulation (Brinson 1977; Peterson and Rolfe 1982; Day 1983; Shure et al. 1986). Conversely, litter decomposition and subsequent nutrient release can occur faster than plants and soil are able to retain them and the nutrients are leached out of the rooting zone (Hauer et al. 1986; Moore 1986).

Rates of litter decomposition vary with forest type and generally increase as the quantity of litterfall increases. An inverse relationship exists between litterfall biomass and nutrient content and the biomass and nutrient content of the forest floor (i.e., there will be less forest floor biomass and reduced nutrient content with increased litterfall of higher nutrient content). Physical and chemical properties of foliar litter vary by species. Often, nutrient rich litter decomposes more rapidly than nutrient poor litter in the same forest environment. The individual characteristics of the leaf litter of different species affect decay rates (Witkamp 1966; Bell et al. 1978; Day 1982; McClaugherty et al. 1985; Shure et al. 1986; Elliott et al. 1993; Adams and Angradi 1996; Belyea 1996 [peat litter]; Cornelissen 1996; Heal et al. 1997). Pine needles decay more slowly than deciduous leaves (Post and De La Cruz 1977; Cornelissen 1996). Foliar lignin concentration in temperate regions is generally below 15% (Robinson 1990) and specifically controls litter decomposition rates in later stages (Meentemeyer 1978; Robinson 1990; Heal et al. 1997). Autumn color can be a key to decomposition rates - brown leaves contain more lignin and tannins resulting in lower decomposition rates (Cornelissen 1996). Adams and Angradi

(1996) found decay rates of deciduous leaves to change among species during the second year. The chemistry of litter within individuals of the same species is a function of variations in site conditions (Heal et al. 1997). Variation in litter quality occurs when defense (herbivore and pathogen) compounds are generated (Heal et al. 1997).

Although primarily a function of litter quality, rate of decomposition is a function of the decomposer community as well as decomposer - litter type interactions. Decomposition rates are a function of the health and density/magnitude of the detritivore pool, and readily available material present (no limiting condiments). The soil microclimate and chemistry induced by litter will dictate biological activity (Wardle and Lavelle 1997). Microbial populations are positively correlated with decomposition rates and controlled by species composition of the litter (Witkamp 1966.) Homogenization of substrate and stabilization of microbial populations occur over time.

The overall rate of decomposition is largely determined by soil temperature and moisture (Bell et al. 1978; Meentemeyer 1978; Hauer et al. 1986; Moore 1986). Soil temperature is a primary component because it influences microbial activity. At higher soil temperatures and moisture contents lignin and cellulose decomposition significantly increases (Donnelly et al. 1990). Donnelly et al. (1990) found soil moisture had greater affect on microbial biomass than soil temperature with greater microbial biomass at higher soil moisture contents. The temperature and moisture regime in the forest is linked to successional stage. The combined dense herbaceous groundcover and lack of canopy in early stages of succession will produce a climate much different than a closed canopy forest with little groundcover. Within a mature forest, topographic position has less of an affect on decay rate (Adams and Angradi 1996).

In riparian forests decomposition is related to flooding frequency, depth, and duration, although consistent relationships have not been established (Brinson 1977; Peterson and Rolfe 1982; Day 1983; Duever et al. 1984; van der Valk et al. 1991; Mitsch and Gosselink 1993; Lockaby et al. 1996b).

Decomposition processes are further confounded by the addition of organic material during flood events which may alter the microbial, nutrient balance of the riparian ecosystem. Permanently anaerobic riparian forests probably have the slowest litter decomposition rates (Brinson et al. 1981), specifically because lignin decay is inhibited under anoxic conditions (Crawford 1981). Decomposition rate is generally greater with increased fluctuations in aerobic-anaerobic conditions (Reddy and Patrick 1975; Brinson et al. 1981) and single, brief flooding regimes (Lockaby et al. 1996a). Peat litter had different decay rates in hollows compared to hummocks and was affected by placement relative to water table fluctuation (Belyea 1996). Wachendorf et al. (1997) found twice the litter loss at a wet site compared to a dry site.

Several studies have interchanged litter between sites with similar environmental features (Cornelissen 1996; Baker 1998). This suggests the possibility of site-specific microbial communities (Baker 1998). Belyea (1996) exchanged peat litter among depths both within and among microsites.

The uniqueness of this study was the ability to exchange litter types from three riparian forests of different successional stages within close proximity to each other (3 to 7 miles). For example, foliar litter from one riparian forest was placed in three other riparian forests of different seral stage as well as the original riparian forest, and subsequently foliar litter from each riparian forest was distributed as such. The objective of this study was to determine whether decomposition rates differ based on successional stage of a riparian forest. To achieve this objective, the following hypotheses were addressed: 1) foliar decomposition rate is independent of riparian forest seral stage; 2) the foliar litter decomposition rate will be greatest for the indigenous foliar litter.

Methods

Site Description

The study sites are located in riparian forests adjacent to three braided, blackwater streams on the Savannah River Site (SRS), a National Environmental Research Park in South Carolina (latitude 33 ° N, longitude 82 ° W). Pen Branch and Fourmile Branch streams are third order tributaries of the Savannah River and these tributaries received thermal, elevated discharge from nuclear production processes between 1954 to 1989, and 1955 to 1985, respectively. The stream corridors experienced elevated temperatures (up to 70 °C) and increased discharge (1 to 2 orders of magnitude greater than base flow). The thermal discharge killed the bottomland hardwood vegetation and altered sediment erosion and deposition patterns. The third stream in this study, Meyer's Branch, represents a minimally disturbed, third order reference site. Only minor disturbances such as selective logging in the 1940's occurred in Meyer's Branch, but it never received thermal effluent.

The age of the riparian forests adjacent to Pen Branch, Fourmile Branch, and Meyer's Branch at the time this study began were 8 years, 12 years, and approximately 60 years, respectively. There are two treatment areas along Pen Branch. One area has been allowed to regenerate naturally. An adjacent area was artificially regenerated with planted bottomland hardwoods following a site preparation of herbicide and prescribed burning.

Decomposition (Field)

Fresh leaf litter was collected in 1996 during peak litterfall from each riparian forest community, except the planted area of Pen Branch. Approximately 5 g (dry wt.) of representative litter was placed in 2-mm mesh nylon bags with a drawstring closure. One-hundred eight (108) bags were filled with litter for each riparian forest community type and placed in the field September 13 and 14, 1997. Nine

bags of litter from each riparian forest were placed in three groupings within a site for a total of 27 bags per site for each riparian community type. A reference/control consisted of craft sticks made from Maine birch (Forster, Inc.). An empty bag was also placed within each group to determine possible weight change in the bag itself. A temperature data logger (Onset Hobo) programmed to obtain readings every four hours was placed within each grouping (3 Hobos per site). However, unanticipated flooding depths and prolonged duration, waterlogged many of the temperature data loggers resulting in the loss of data for the majority of the year. Three bags (one from each grouping within a site) were collected after 7, 13, 20, 27, 42, 72, 141, 217 and 356 days. Three bags per litter type were placed in the field and then immediately retrieved to assess transportation loss.

Decomposition (Laboratory)

All of the collected bags were dried at 60 °C for at least one week, and bag plus litter were weighed. Because of sediment deposition the litter was removed from the bags, weighed and ground to pass a 20-mesh sieve in a Wiley mill. The empty bag was also weighed to address the amount of sediment deposition. Organic matter was determined for the ground litter samples by loss on ignition (LOI) (Nelson and Sommers 1982) (380 °C for 24 hrs). For comparative analysis, organic matter was also determined by Walkley-Black (Walkley 1947) on a subsample of the ground litter samples. Soil samples were obtained adjacent to the litter bag groupings and ashed at 380 °C for 24 hours to determine the amount of organic matter in the deposited sediment. A correction factor for the organic matter within the sediment was applied to bags collected at 141, 217, & 356 days. Rate of litter decomposition was calculated with the following equation (Olson 1963): $x_t = x_0 e^{-kt}$, where x_t is the amount of substrate at time t ; x_0 is the initial amount of substrate; k is the fractional loss rate per unit time.

Statistical Analysis Procedures

Data were analyzed by means of analysis of variance (ANOVA) procedures for a completely randomized design (SAS Institute 1996). The Tukey multiple range test was used to distinguish treatment mean differences. A significance level (α) of 0.05 was used for all tests. Statistical analysis consisted of comparisons between the four riparian forests and between litter types within each riparian forest.

Results and Discussion

Comparison Between Riparian Forests

Comparison of litter decomposition between the four riparian forests demonstrates that litter decomposition rates do not appear to be influenced by forest age. Decay rates (k) of foliar litter ranged from 0.27 to 0.38, 0.21 to 0.48, and 0.62 to 0.94 for Pen Branch, Fourmile Branch, and Meyer's Branch litter, respectively (Table V-1). These decomposition rates after 51 weeks are higher than the findings reported by Lockaby et al. (1996b) after 106 weeks in southeastern floodplains. Adams and Angradi (1996) observed changes in species decay rates in subsequent years. Although representing different forest cover types, the litter of the older forest stands in the study by Elliott et al. (1993) had slightly lower decomposition rates within their respective forests compared to the litter in the younger forest stands. The litter from the younger riparian forests in this study had slightly lower k values than the mature riparian forest.

Table V-1. Decomposition rates (k) for three mixed-species foliar litter types and a control in four riparian forests located in the Coastal Plain of South Carolina.

Site	Litter Type			
	Pen Branch	Fourmile Branch	Meyer's Branch	Control ¹
Pen Branch (AR)	0.27	0.31	0.66	0.43
Pen Branch (NR)	0.29	0.21	0.66	0.53
Fourmile Branch	0.33	0.48	0.94	0.30
Meyer's Branch	0.38	0.30	0.62	0.34

1) Popsicle sticks of *Betula* were used as the control/reference.

Decomposition of Pen Branch (NR) litter was not significant between sites (Fig. V-1A), nor was the decomposition of litter from the Fourmile Branch riparian forest significantly different between the four sites (Fig. V-1B). Litter from the Meyer's Branch riparian forest decomposed significantly more in Fourmile Branch and the Pen Branch (NR) riparian forests than Pen Branch (AR) (Fig. V-1C). There was no significant difference in control decomposition rates between sites (Fig. V-1D). Foliar litter from the Fourmile Branch and Pen Branch riparian forests both decomposed approximately 25 percent after one year which was much lower than the 85 percent annual decomposition of mixed floodplain species found by Shure et al. (1986).

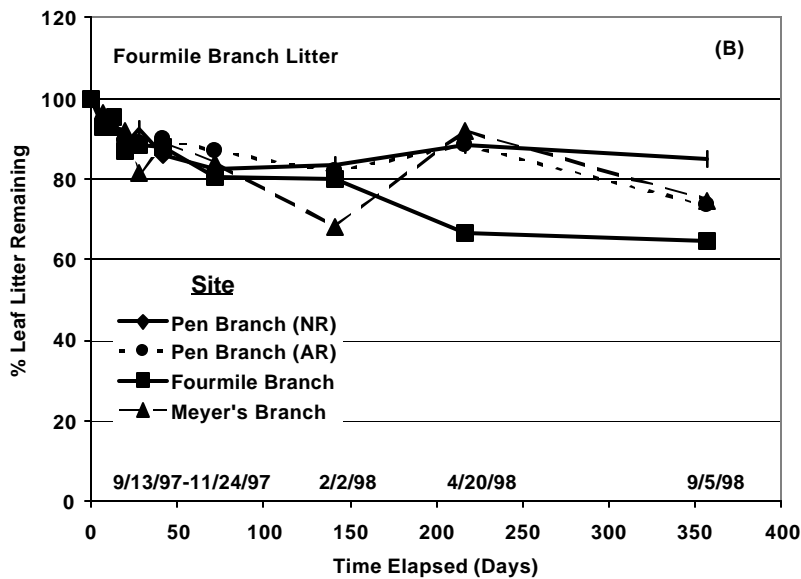
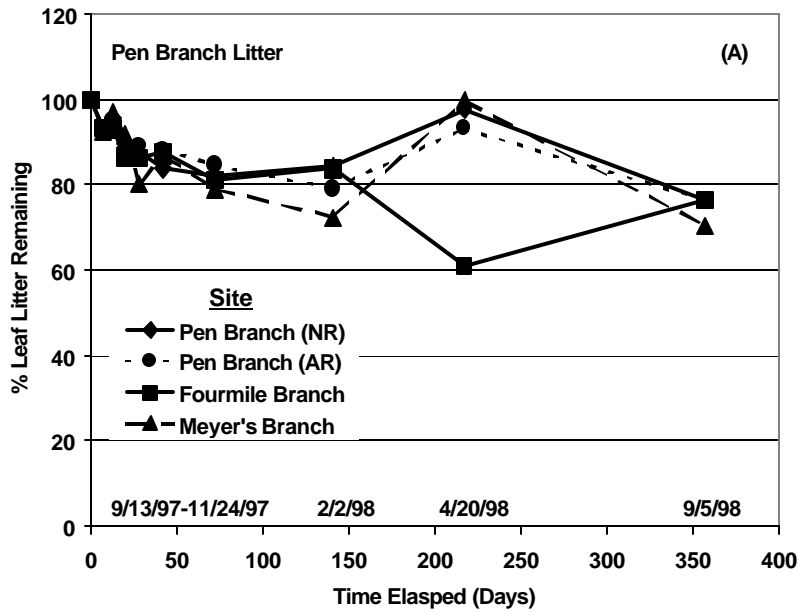


Figure V-1. Comparison of riparian forest age on litter decomposition. Mixed-species foliar litter from A) Pen Branch, B) Fourmile Branch, C) Meyer's Branch and D) a control/reference.

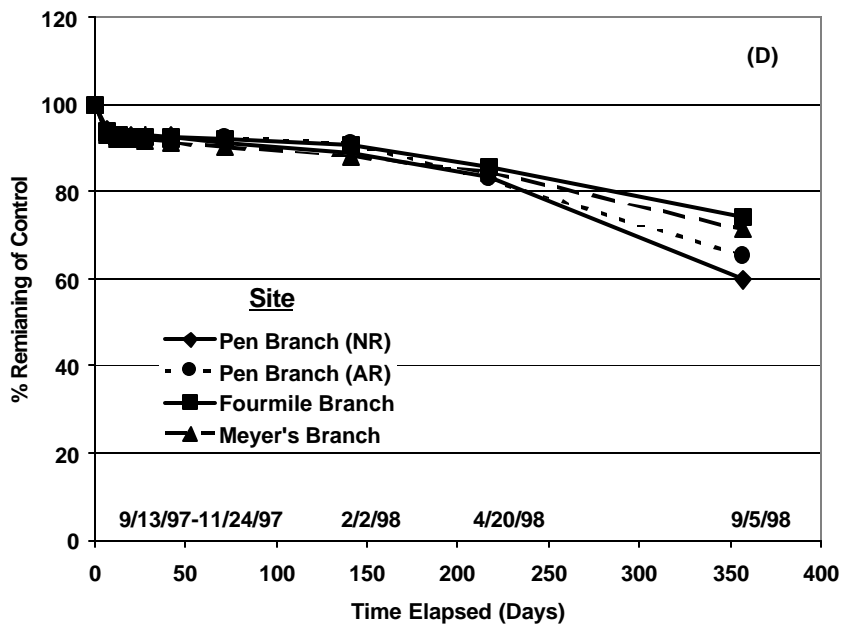
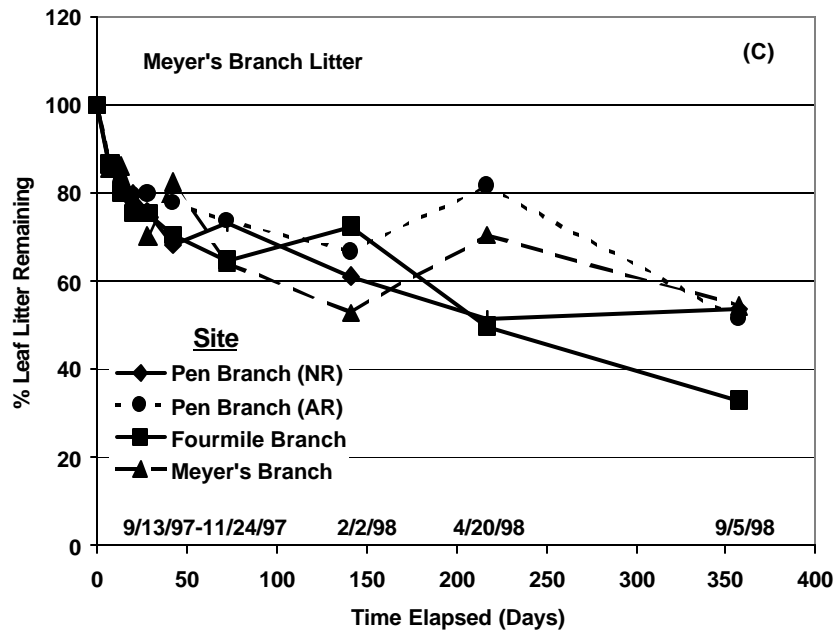


Figure V-1. Continued.

The decomposition rates in this study are for mixed-species litter representing each forest type and it has been shown that decay rates are similar for single- and mixed-species litter (Blair et al. 1990). Therefore, the decomposition rates of the mixed-species are indicative of each forest community. Hardwood litter from mixed-species forests is generally more labile when it is placed in a forest with species containing more recalcitrant litter, the decomposers and detritivores adapted to the recalcitrant litter; are able to rapidly colonize and decompose the hardwood litter. There may be a synergistic effect with mixed-species litter. Nutrient release of labile litter may stimulate decomposition of adjacent recalcitrant litter and conversely, tannins may inhibit the decomposition process. Cumulative effects of litter type and detritus community interactions may be associated with the stability that comes with forest age.

Comparison of Litter Type within each Riparian Forest

In all four sites the Meyer's Branch litter decomposed significantly more than the other litter types (Fig V-2 a-d). After one year approximately 50 percent was remaining. The fairly rapid decomposition of red maple (Shure et al. 1986) which was one of the main components in the Meyer's Branch litter likely influenced the greater decomposition of Meyer's Branch litter. Although transportation losses were accounted for and the decomposition bag mesh size was small, the small size of bald cypress needles may have influenced the decomposition rate by either falling out or succumbing to rapid decomposition. Elliott et al. (1993) found litter type to decompose most rapidly in the forest where it was generated. However, this association was only observed in the mature riparian forest. Foliar litter developed under shaded conditions generally have less carbon-based defense compounds (Heal et al. 1997) and therefore would decompose at a faster rate. Possibly with forest succession an immutable companionship develops between litter inputs and the detritivore community enriching the decomposition process.

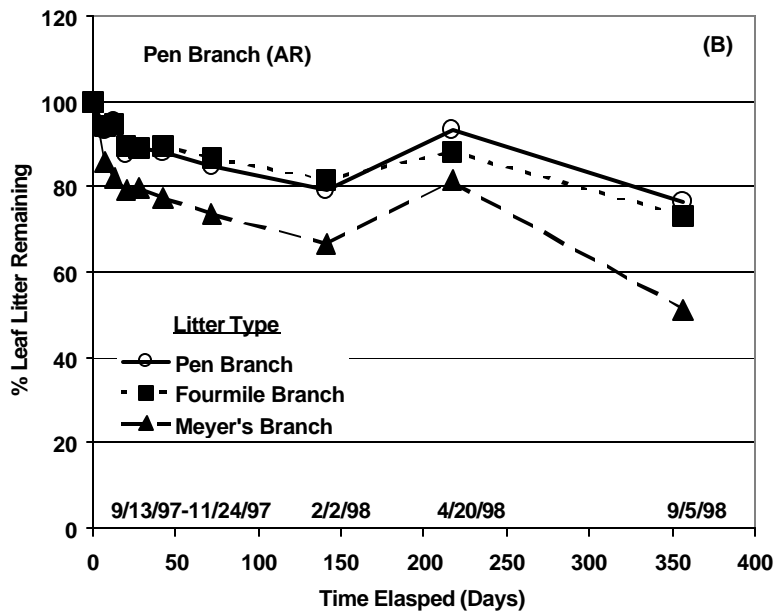
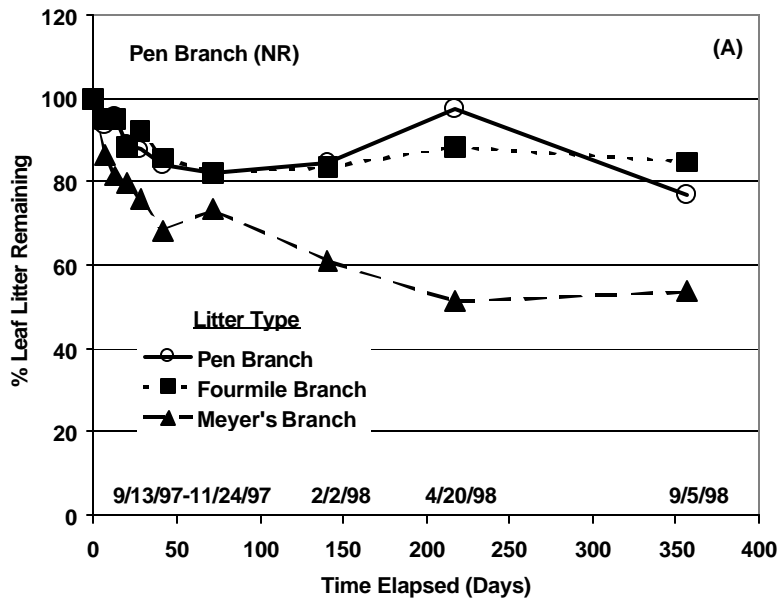


Figure V-2. Comparison between litter type within each riparian forest. A) Pen Branch (AR), B) Pen Branch (AR), C) Fourmile Branch, and D) Meyer's Branch.

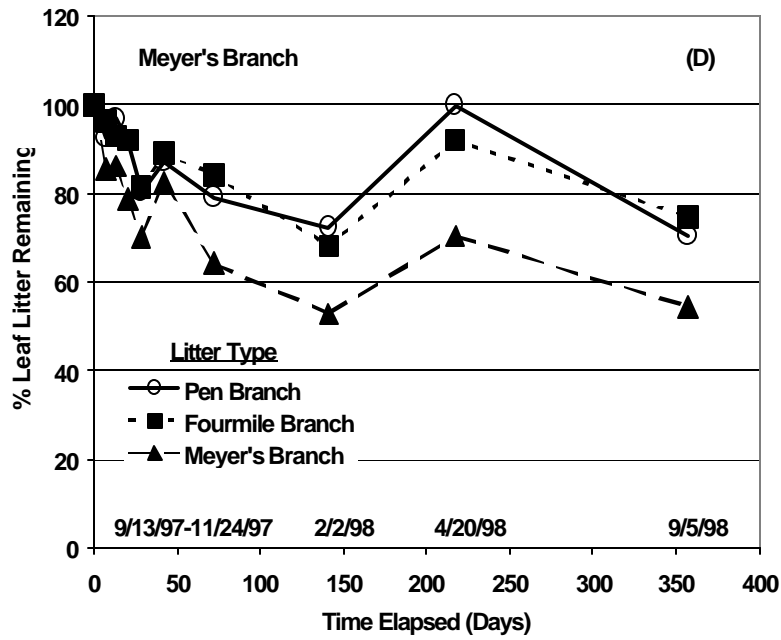
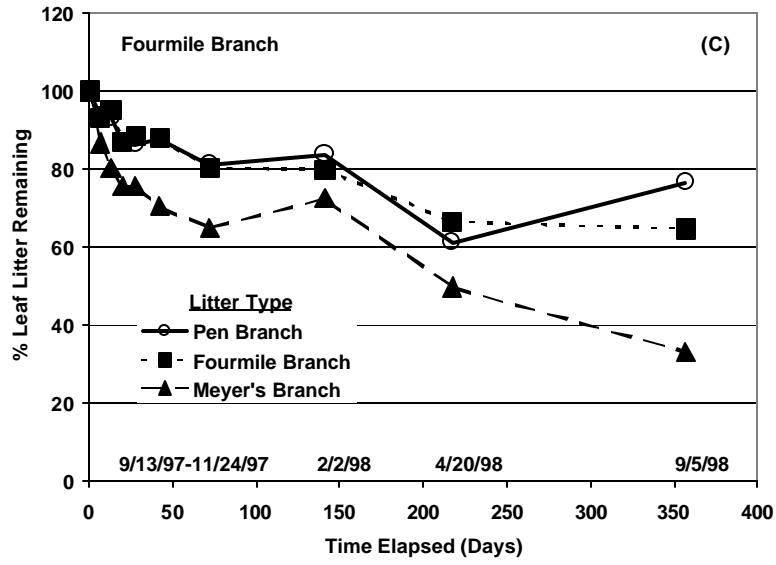


Figure V-2. Continued.

The litter composites from the younger riparian forests, Pen Branch and Fourmile Branch, were similar and both included more resistant litter types, specifically waxmyrtle and alder. Leaves with small specific area can be physically resistant to penetration due to structural chemistry. The small mesh size of the decomposition bags may have excluded the soil fauna which usually process these litter types. The control decomposed less than the leaf litter in all four sites and values were indicative of twig decomposition rates.

Temperature and Hydrologic/Sediment Deposition Effects on Litter Decomposition

The limited temperature data revealed some patterns between the four sites, however, there was no significant difference in the comparison of monthly means (Fig. V-3). Lacking a forest canopy the ambient temperature in the Pen Branch (AR) was higher than the other three sites. Temperatures at the soil surface are usually a few degrees warmer than air temperature and therefore, providing there is some form of canopy cover (herbaceous or woody), temperatures may not be significantly different at ground level. During the summer months the temperature was several °C lower in the closed canopy of the Meyer's Branch riparian forest than the other three sites. However, Meyer's Branch lacks a substantial groundcover and it is probably the closed canopy in conjunction with no groundcover resulting in the lower temperatures. Bald cypress which was a major component of the Meyer's Branch litter has a relatively slow uniform decay rate over a range of temperatures (Hauer et al. 1986).

Extremely high amounts of rainfall occurred during the winter months of 1997 and spring months of 1998. Water levels rose on the Savannah River subsequently backing up Fourmile Branch causing extensive flooding. The Fourmile Branch riparian forest remained inundated approximately from February through March potentially affecting decomposition rates. In Fourmile Branch, litter types generally had higher decomposition rates due to leaching or abrasion when the flood water receded. Wachendorf et al. (1997) attributed 30% loss due to leaching in a wet site. Pen Branch and Meyer's Branch did not receive the same intensive flooding duration, however, flooding depths were

phenomenal. The depth and duration of winter/spring flooding in the Fourmile Branch riparian forest possibly influenced the difference in litter decomposition.

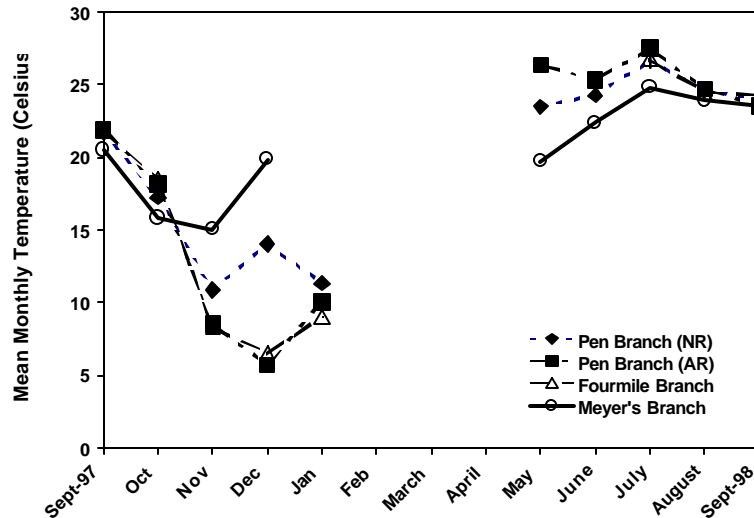


Figure V-3. The mean monthly ground temperatures in four riparian forests during the period of study (September 1997 to September 1998).

Sediment deposition was very prevalent in Meyer's Branch which receives fairly frequent, brief flood events (Fig. V-4). The riparian forest of Pen Branch (NR) was also subject to excess sediment deposition. Pen Branch (AR) and Fourmile Branch riparian forests were also affected by sediment deposition, but not to the extent of the Meyer's Branch riparian forest and Pen Branch (NR). Sediment deposition during a winter flood event in Meyer's Branch and Fourmile Branch has been documented to be approximately 350 g m^{-2} and 260 g m^{-2} , respectively (Chapter IV). The dense vegetation in Pen Branch (AR) arrested sediment deposition and the flashy hydroperiod in Fourmile Branch may have prevented or removed sediment. The sediment contributed organic matter to the decomposition bags altering the final values. Although an attempt was made to correct for the amount of organic matter in the sediment, the percent leaf litter remaining may be underestimated. Adams and Angradi (1996)

suggest that an increase after one year may be due to increased microbial/detritivore biomass in the samples.

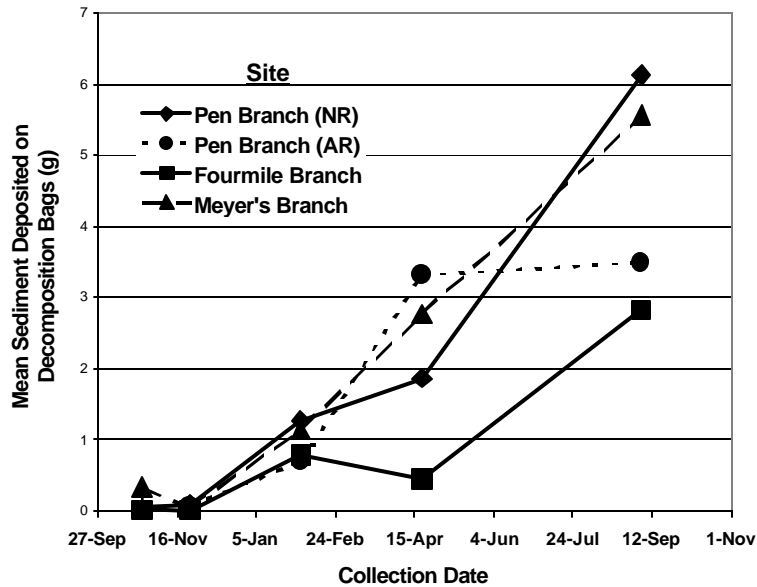


Figure V-4. Mean sediment deposited on the decomposition bags in four riparian forests in the South Carolina Coastal Plain.

The percent organic matter was determined with the LOI method with several of the samples also analyzed with the Walkley-Black method. There was high positive correlation between the two methods, specifically for dates that are associated with sediment deposition (Table V-2). The percent organic matter in the decomposition samples was approximately 2.7 times greater with the LOI method than the Walkley-Black method. The difference may be attributable to the chemical reagent's ability to digest the organic matter. The organic matter incorporated with the sediment deposited from the stream during flood events may be of different quality than the organic matter was from the original litter and influence the procedure.

Table V-2. Correlation between LOI and Walkley-Black for organic matter determination. LOI was generally 2.7 times greater than Walkley-Black.

Date	Correlation	Site	Correlation
9/5/98	0.981	Pen Branch (AR)	0.934
4/27/98	0.945	Pen Branch (NR)	0.957
2/2/98	0.839	Fourmile Branch	0.887
11/24/97	-0.217	Meyer's Branch	0.887
9/20/97	-0.619		
All Dates	0.917		

Conclusion

Woody species foliar litter and inherent quality (physical and chemical characteristics) were more important for control of decomposition rates than forest age. However, if species composition is linked to successional stage, it ensues that indirectly forest age affects foliar litter decomposition rates. The individual, mixed-species litter had similar decomposition patterns between the four riparian forests, but within each riparian forest the litter types had differing decomposition rates and the indigenous litter did not necessarily decompose to the greatest extent. The litter from the mature riparian forest decomposed at a rate greater than the litter composites from the younger riparian forests. The different decomposition rates will influence the quantity of litter movement towards the stream which in turn affects the aquatic ecosystem.

The greater decomposition rate in Meyer's Branch may accelerate incorporation into the soil and prevent litter from moving to the stream. Also the extensive sediment deposition in Meyer's Branch will blanket the litter and retard movement towards the stream. However, instream litter in Meyer's Branch was moderate compared to the other sites (Chapter IV). The magnitude of annual litterfall associated with a mature riparian forest appears to over compensate for the rapid

decomposition rate in supplying organic matter to the stream. To further support the effect of sedimentation, Fourmile Branch litter and Pen Branch litter both had similar decomposition rates, however, Fourmile Branch had the least amount of sediment and greatest quantity of instream litter, and Pen Branch had sediment amounts comparable to Meyer's Branch and very little instream litter. The combination of riparian forest age and sediment deposition (hydrologically influenced) affect transport of litter (partially decomposed or otherwise) to the stream.

This has management implications for restoring disturbed sites. Planting later successional species and providing suitable decomposition conditions could accelerate decomposition rates rendering rapid incorporation of nutrients and soil organic matter formation. Variation in site conditions and climate affect litter quality, which in turn influences decomposition rates, and this cyclic process affects nutrient release and forest productivity. The rapid incorporation of organic matter and subsequent nutrient release may affect restoration success. The concept of 'synchrony' is being studied where the release of nutrients from litterfall inputs can be coordinated with plant growth demands (Myers et al. 1997).

Factors that influence litter decomposition have profound implications for sustained productivity in forest ecosystems. Plant strategy as it relates to succession may be linked to fundamental geochemical processes, i.e. decomposition, as well as changes in the terrestrial biosphere (CO₂ levels and climate). There is a relationship between leaf life-span, photo-assimilation, and defense chemistry (Cornelissen 1996) and these attributes pertain to plant successional strategy suggesting that decomposition rates may be an evolutionary/ecological strategy. Drastic or gradual shifts in species composition may affect decomposition rates.

Micro-topography

*shades of gradient
nuances in landscape*

s

c

a

l

e

*diversity of habitat
order from chaos*

Chapter VI. Microtopography Influences Riparian Forest Processes, Functions and Structure

Abstract

Ridge and swale microtopography, depending on the magnitude of scale and distribution, has the ability to influence riparian forest processes which subsequently affect forest productivity. Also, inputs of water, organic matter and associated nutrients during flood events may have a great impact on forest productivity closer to the stream than farther inland. To address the effects of microtopography and a distance gradient, herbaceous biomass, root biomass, species richness, and several soil properties were evaluated along transects established perpendicular to each riparian forest main stream channel.

Within three Southeastern Coastal Plain riparian forests, microtopography influenced herbaceous biomass, root biomass, species richness, and soil properties. Although the riparian forests represented different successional stages, they all reflected the effects of microtopography. Percent carbon in herbaceous vegetation increased from wet to dry, however, the herbaceous carbon pool reflected herbaceous biomass patterns within each site. Root biomass generally decreased from wet to dry, except in the mature riparian forest where the reverse was observed. The riparian areas had less percent carbon in the roots than the uplands and root carbon percentages varied with the riparian microtopography. Root carbon pools generally followed a microtopography trend similar to root biomass. Species richness was generally greatest on the intermediate areas where the moisture levels/fluctuations were less extreme. Percent carbon and organic matter in the soils correlated with herbaceous and root biomass. Soil organic matter, bulk density, and porosity were interrelated and a fundamental component of microtopography.

Riparian forests are intimately associated with their hydroperiod. During flood events the riparian forest receives inputs of organic matter and sediment, and the amount of deposition may decrease along a distance gradient from the main stream channel. The differential amount of inputs could affect forest productivity. Trends in herbaceous biomass were evident along a moisture gradient. However, there was no linear relationship between biomass, carbon pools, and soil physical and chemical properties along a distance gradient from the main stream channel. The mature riparian forest exhibited more of a gradient effect than the younger riparian forests, specifically in respect to soil physical properties. Ridge and swale microtopography prevalent in the younger riparian forests counteracted a distance gradient effect across the riparian forest. Therefore, riparian restoration efforts in areas with prominent ridge and swale microtopography should address the characteristics unique to each landscape and plant appropriate species. Classic models of riparian restoration (i.e., uniform planting) do not fit for these small braided riparian ecosystems.

Introduction

The integral elements connected with riparian ecosystem processes, functions and structure are more complex than terrestrial upland ecosystems. Riparian forests are closely linked with the hydroperiod of the associated stream, which usually has created a unique landscape due to shifting of the stream channel (i.e. ridge and swale microtopography). During flood events a net increase in organic matter may be deposited into the riparian area. Theoretically, the greatest deposits would be closer to the stream channel and dissipate further inland as well as critical water supplies. Hence a distance gradient effect on riparian forest processes, functions, and structure may be observed. However, depending on the scale of ridge and swale microtopography, the distance gradient effect, and effects of seepage from adjacent uplands, may be minimal.

Microtopography

The relationship between microtopography and its inseparable companion, hydroperiod, influences plant community dynamics, soil properties and their interrelated biogeochemical cycling. Riparian forests, especially those located in the southeast United States adjacent to low- order streams exhibit slight changes in elevation gradient ranging from centimeters to meters. This type of landscape (ridge and swale) manifests nuances which control ecosystem processes at a smaller scale compared to a sizable bottomland hardwood forest or large river floodplain (Kellison et al. 1998). The microtopography within these riparian forests often resembles a braided stream system and the lower, swale areas act as small streams during certain hydrologic events and subsequently hold water during drier periods. Bledsoe & Shear (2000) found that as little as 10 cm elevation difference resulted in a 20% difference in surface flooding frequency. Hydroperiods that tend to be wetter do not make a wetland less functionally active than another, the functions are merely different (Brinson 1993).

Small scale microtopography, in conjunction with the hydroperiod, has the ability to influence herbaceous species establishment, frequency and density (Zedler and Zedler 1969). Growing season flooding frequency influences plant community composition and structure (Bledsoe and Shear 2000). Titus (1990) found species distribution of tree seedlings to be strongly correlated with gradient in a Florida hardwood floodplain swamp. Short lived herbaceous species are greatly influenced by changes in landscape and have adapted to specific substrates and moisture regimes. A more stable hydrologic regime can result in greater plant biomass, whereas low production can result from the disequilibrium between plant community composition and hydrologic regime (Burke et al. 1999). Greater biomass may also occur because of the addition of nutrients during flood events as organic matter becomes deposited in topographic lows. Biomass and carbon allocation patterns change in response to a flooding gradient (Day and Megonigal 1993). The species which become established will affect aboveground biomass because of their growth form. Herbs generally have less overall biomass

compared to shrubs and trees. An energy advantage occurs when species can maintain structure with less investment in lignin (Robinson 1990).

In forested (riparian) wetlands microtopography influences fine root dynamics (Jones et al. 1996) because of differing biogeochemical properties associated with differing hydrology. Hydroperiod and soil porosity affect root penetration, distribution, and growth (Bowden and Nambiar 1984; Kimmins 1987; Megonigal and Day 1992; Powell and Day Jr. 1991), which in turn control root biomass. Roots have difficulty penetrating compacted soils and root growth is reduced in extensively dry or moist (anoxic) soils and high root mortality can occur under anaerobic conditions (Stevenson and Day 1996).

Soil properties differ based on topographic position due to the disproportionate deposition of soil particles. Coarser soil particles fall out of solution as water velocity slows when encountering ridge areas. As the water velocity continues to slow the finer soil particles will settle in the swales. Chang (1995) found a significant correlation between elevation (microsite) and the amount of organic matter. Microsite substrate type closely correlates with woody species presence (Titus 1990) and substrate heterogeneity increases species richness (Nilsson et al. 1989).

Carbon pools within a southeastern Coastal Plain riparian forest are affected by species composition and soil physical and chemical characteristics, both of which are integrated with microtopography/hydroperiod. The carbon composition within vegetation (roots and shoots) is connected to plant structure/form. Substrate type affects plant community development, and the microtopography - hydroperiod relationship affects substrate type.

Distance Gradient

Flood waters contribute organic matter, nutrients, and soil particles to the riparian forest as well as re-arrange existing (forest floor) organic matter, nutrients, and soil particles. The extent of this form of disturbance may vary with increasing distance from the stream channel, (i.e the degree to which organic matter, etc. will be deposited inland). Riparian forest width, elevation gradient (increasing elevation) from stream to upland, and microtopography may influence the establishment and growth of vegetation, root development, and soil chemical and physical properties. Reese and Moorhead (1996) propose that vegetation patterns or hydrology caused differences in soil parameters. Microtopography, minor drainages, sloughs and depressions may have fluctuating moisture regimes independent of stream stage, especially with increasing distance from the main channel (Bledsoe and Shear 2000).

The greatest velocity of the flood forces generally occur near the berm or natural levee next to the stream channel and the energy generally dissipates as flood waters move further inland. The energy surge will shock normal operating parameters, and may disrupt and alter vegetation establishment or growth. It has been hypothesized that organic matter and nutrient inputs (subsidy) from flood events will enhance plant growth (Odum et al. 1979), especially closer to the stream. However, the stress associated with anaerobic soils during flooding may diminish the subsidy effect (Megonigal et al. 1997). Along an environmental gradient (floodplain to transition zone) differences in biomass and primary production were found to be the result of individual species responses to flooding and available water (Johnson and Bell 1976). Leaf litter production is also affected along an environmental gradient (Conner et al. 1993).

A uniform (level) landscape in a riparian forest may produce similar biomass (above and belowground) because the biotic and abiotic factors influencing growth are relatively evenly distributed. A gradual increase in elevation gradient from stream to upland may affect soil moisture due to

differences in bulk density, porosity, water availability and water table fluctuations (Stanturf and Schoenholtz 1998). Also, flooding depth and duration would be reduced farther from the stream as water retracts progressively from higher elevations, resulting in less anaerobic conditions thereby maintaining optimum growing conditions.

Elevation may be associated with differing hydrologic and edaphic gradients which will influence the distribution of plant species. Bledsoe and Shear (2000) observed that species richness of the understory species (<1 m height) was not consistent across an elevation gradient, however, species richness of the tree and shrub overstory increased with increasing elevation. Elevation can predict seedling flux and density in flooded forests (Jones et al. 1994) and influence differences in vegetation (Bledsoe and Shear 2000). Small changes in riparian forest elevation may result in distinct vegetation types. An elevation change of 15 swamp centimeters corresponds to 30 mountain meters (Conner and Day 1976).

There is a lack of quantitative data on vegetation-environment interactions occurring at the micro-topographic scale in riparian forests. Few studies exist that examine a gradient effect across riparian forests, especially in young, recovering riparian forests. The main objective of this study was to determine if biomass and/or carbon pools in a riparian ecosystem are affected by microtopography and change across a distance gradient from stream channel to upland. The objectives of this study were to quantify and analyze how microtopography influences herbaceous species biomass, carbon, and richness; root biomass and carbon; and soil properties (organic matter [%], carbon [%], bulk density, and porosity).

This project was specifically designed to address the following null hypotheses:

1) microtopography in riparian forests adjacent to low order streams does not influence herbaceous biomass, and fine root biomass: 2) microtopography does not dictate species richness and there is no pattern in the percent carbon of above and belowground components; 3) If microtopography has an

effect, it is not correlated with the associated carbon pools; 4) there is no linear relationship correlating riparian forest biomass (above and belowground) with a distance gradient from stream channel to upland, and 5) greater soil organic matter accumulation does not occur closer to the stream channel due to overbank flooding.

Methods

Site Description

The study sites are located in riparian forests adjacent to three braided, blackwater streams on the Savannah River Site (SRS), a National Environmental Research Park in South Carolina (latitude 33 ° N, longitude 82 ° W). Pen Branch and Fourmile Branch streams are third order tributaries of the Savannah River and these tributaries received thermal, elevated discharge from nuclear production processes between 1954 to 1989, and 1955 to 1985, respectively. The stream corridors experienced elevated temperatures (up to 70 °C) and increased discharge (1 to 2 orders of magnitude greater than base flow). The thermal discharge killed the bottomland hardwood vegetation and altered sediment erosion and deposition patterns. The third stream in this study, Meyer's Branch, represents a minimally disturbed, third order reference site. Only minor disturbances such as selective logging in the 1940's occurred in Meyer's Branch, but it never received thermal effluent.

The age of the riparian forests adjacent to Pen Branch, Fourmile Branch, and Meyer's Branch at the time this study began were 8 years, 12 years, and approximately 60 years, respectively. There are two treatment areas along Pen Branch. One area has been allowed to regenerate naturally. An adjacent area was artificially regenerated with planted bottomland hardwoods following a site preparation of herbicides and prescribed burning.

Herbaceous Biomass/Species Richness

Along each transect, clip plots (Hall et al. 1993) were spaced at 4.5 m intervals. Herbaceous vegetation (< 0.5 m in height, regardless of growth form) was clipped from a 0.25 m² area. The number of species observed in each clip plot were recorded to determine species richness (# of species per 0.25 m²). Microtopography was subjectively rated at each clip plot to be either wet, intermediate, or dry based on position in the landscape (ridge or swale). Clip plots were also established in the adjacent uplands. Sampling was conducted four times; June & August 1997, and June & August 1998 (same general area and microtopography with no overlap of clip plot area to avoid influence from previous sampling). All clipped vegetation was dried to a constant temperature (60 °C) and weighed.

Fine Roots

It is important to recognize that belowground biomass associated with larger roots has not been included in the sampling. Two 5 cm diameter by 20 cm length metal cores were inserted into the soil near each clip plot and subsequently extracted June 1999 (Hall et al. 1993). The depth of core insertion was measured. The samples (soil and roots) were refrigerated until the fine roots could be washed/separated from the soil with a jet of water on a sieve with pore openings of 2 mm or less. Only roots ≤ 5 mm were retained. The roots were subjectively rated as live or dead. Live roots are considered resilient, flexible and fleshy. Roots were classified dead if they were limp and crumble easily. The fine roots were dried to a constant temperature (60 °C) and weighed.

Soil

Bulk soil samples from the O/A horizons were randomly collected from the different microtopography areas in each riparian forest. Samples were taken corresponding to fixed distances

from the main channel (0-15.2 m, 15.2-30.3 m, 30.3-45.4, and 60.6 m). The A-horizon is approximately 7.5-13 cm in depth in the Fourmile Branch riparian forest and 7.5- 15 cm in depth in the two areas of Pen Branch (Azola 1997). The histic O-horizon in the Meyer's Branch riparian forest ranges from 20-76+ cm. Bulk density was determined with the core method (Blake and Hartage 1986) from the O/A horizon. Organic matter was determined by loss on ignition (LOI) (Nelson and Sommers 1982) (380 °C for 24 hrs). The porosity (total/micro) of the O/A horizons was determined with the a modified water desorption method (Danielson and Sutherland 1986).

Carbon

The carbon content (percent) of herbaceous vegetation, root, and soil samples was determined with a LECO gas analyzer (LECO 1987) on a subsample of the herbaceous vegetation, roots, and soil. Three replicates were analyzed for each sample, unless the sample volume was too small. The percent carbon was multiplied by biomass (g m^{-2}) for herbaceous vegetation and roots to obtain g C m^{-2} for each component.

Statistical Analysis Procedures

Data were analyzed by using analysis of variance (ANOVA) procedures for a completely randomized design (SAS Institute 1996). The Tukey multiple range test was used to test treatment mean differences. The treatments were microtopography categories within each site. A significance level (") of 0.05 was used for all tests. All four herbaceous vegetation sample dates were pooled and included in the herbaceous biomass analysis. The herbaceous vegetation analyzed for percent carbon was a mix of species sampled at the respective clip plot. Percent carbon was also determined for several individual herbaceous species. Only the June & August 1997 samples were used for percent carbon of herbaceous vegetation. Previous analysis demonstrated that there was no significant difference in herbaceous vegetation percent carbon between June 1997 and August 1997, therefore the

samples from both dates were pooled for analysis. It was assumed that although biomass may change annually, the percent carbon in herbaceous vegetation will not change and therefore, the 1998 data were not analyzed. Means were calculated for the three carbon replicates for herbaceous vegetation, roots, and soil for use in statistical analyses.

Regression was used to determine whether there was a linear relationship between distance from the main stream channel and the following variables analyzed individually: shrub biomass (1997 & 1999), trees (1997 & 1999), total aboveground biomass (1997 tree, shrub & herb), NPP (1997), herb percent carbon and biomass, herbaceous carbon pool, herbaceous species richness, root biomass, root carbon pool, soil percent organic matter (OM), soil percent carbon, bulk density, total porosity, and non-capillary porosity. A liberal significance level ($\alpha = 0.1$) was used for all tests.

Results and Discussion

Microtopography

Herbaceous Vegetation

When all microtopography positions were grouped, Pen Branch (AR), Pen Branch (NR), and Meyer's Branch showed no significant difference in biomass of the herbaceous layer between the four sampling dates (Fig. VI-1). The significantly less vegetation in June 1998 for Fourmile Branch was likely attributable to an extended spring flooding period. The decreasing amount of herbaceous biomass with successive samples for all sites can be reasonably associated with differences in seasonal precipitation, possibly the result of a very wet spring in 1998. Herbaceous vegetation is more dramatically affected by hydrologic events than the tree/shrub component because it often becomes inundated. The excessively wet spring of 1998 undoubtedly delayed and hampered growth of herbaceous vegetation since most sites were inundated for an extended period of time.

As discussed in Chapter III, the site preparatory measures in the artificial regeneration section of Pen Branch have slowed woody succession by maintaining a thick herbaceous cover. Therefore, Pen Branch (AR) was considered at a younger seral stage than Pen Branch (NR). In all four sites microtopography affected species establishment. Although at opposite ends of the succession scale, both Pen Branch (AR) and Meyer's Branch exhibited less herbaceous biomass in the wet areas compared to the dry areas (Fig. VI-2). This is reflective of species competition by adapting to habitat type regardless of successional stage.

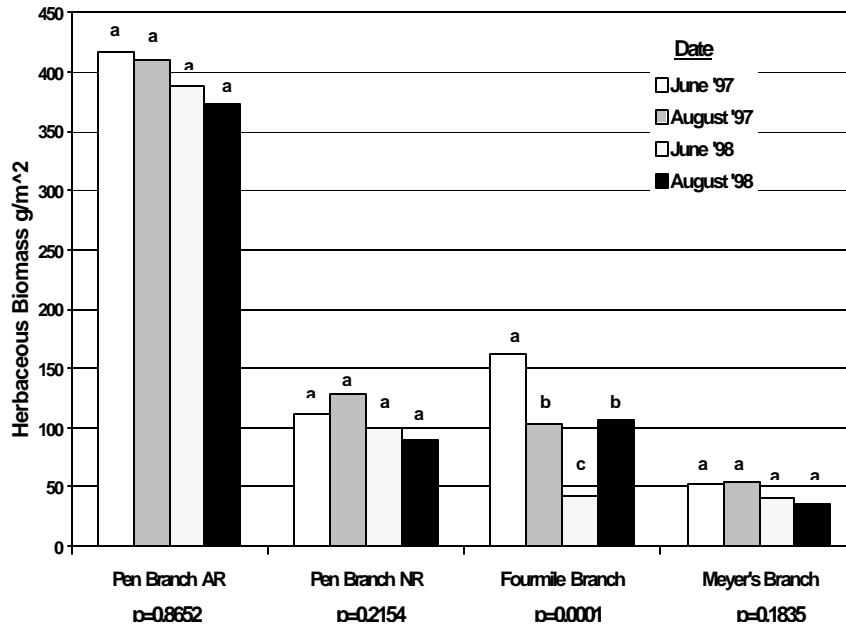


Figure VI-1. Mean herbaceous biomass for the four sampling dates within four South Carolina Coastal Plain riparian forests. Within a site, means with different letters are significantly different from one another ($\alpha = 0.05$).

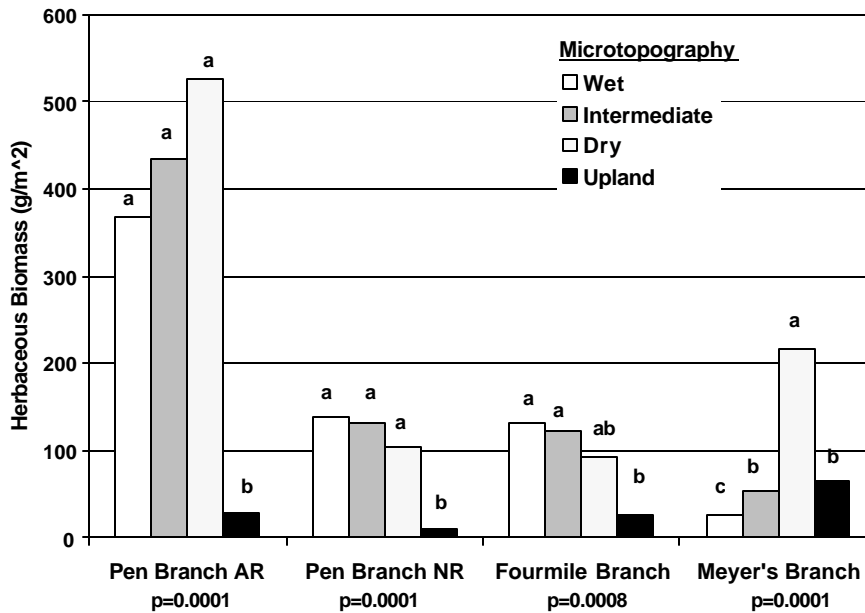


Figure VI-2. Mean herbaceous biomass for four micro-topographic positions within four South Carolina Coastal Plain riparian forests. Within a site, means with different letters are significantly different from one another ($\alpha = 0.05$).

The uplands generally had less herbaceous biomass (Fig VI-2). Even though the microtopography was subtle in Meyer's Branch, there was significantly greater herbaceous biomass in the intermediate areas than the wet areas. Although there was no significant difference in the riparian microtopography positions within Pen Branch (AR), Pen Branch (NR), and Fourmile Branch, trends were apparent. Pen Branch (AR) displayed an increasing trend in herbaceous biomass from wet to dry (Fig. VI-2), similar to Meyer's Branch. Pen Branch (NR) and Fourmile Branch which were relatively close in age/development, displayed decreasing trends in herbaceous biomass from wet to dry (Fig. VI-2). In these two sites the wet areas had greater herbaceous biomass than the dry areas. Fourmile Branch had high soil organic matter in the wet areas which reflects the strong correlation between soil organic matter and biomass in the herbaceous layer observed by Zedler and Zedler (1969). These trends may be anomalies and require further investigation or a greater number of samples may reduce the variability.

Percent carbon of vegetation is generally assumed to be approximately 50 percent. In this study the percent carbon was consistently less than 50 percent and ranged from 41 to 48 percent. Microtopography affected the percent carbon in herbaceous vegetation as it pertains to differing species that become established in respective microsites. In all of the sites the percent carbon in the herbaceous vegetation increased from wet to dry, and the upland areas had the greatest percent carbon (Fig VI-3). Herbaceous species can be genetically different due to local variation of microtopography (Zedler and Zedler 1969) and this could affect carbon allocation or plant structure. A significant difference in percent carbon of several herbaceous species was found in these riparian forests (Fig VI-4) and depending on species composition and abundance of each within a micro-topographic position, differences in percent carbon could significantly effect the carbon pools. Herbaceous species that inhabit the wetter microtopography do not have/need the same structural components [generally lignin which composes 5-45% of plant dry-weight biomass (Robinson 1990)] as those in drier areas. Also, the drier areas tended to have more *Rubus* which is woodier and therefore composed of more lignin. In the upland areas, tree seedlings in the herbaceous layer were often included in the clip plots increasing the lignin content and subsequently increasing the overall percent carbon.

The herbaceous carbon pool in all four sites followed a microtopography pattern similar to the herbaceous biomass (Fig VI-5). Upland areas generally had significantly smaller herbaceous vegetation carbon pools than the riparian areas (Fig. VI-5). Differences in herbaceous vegetation percent carbon did not offset herbaceous vegetation biomass. It is therefore possible to determine carbon pool trends associated with microtopography by examining the herbaceous biomass patterns.

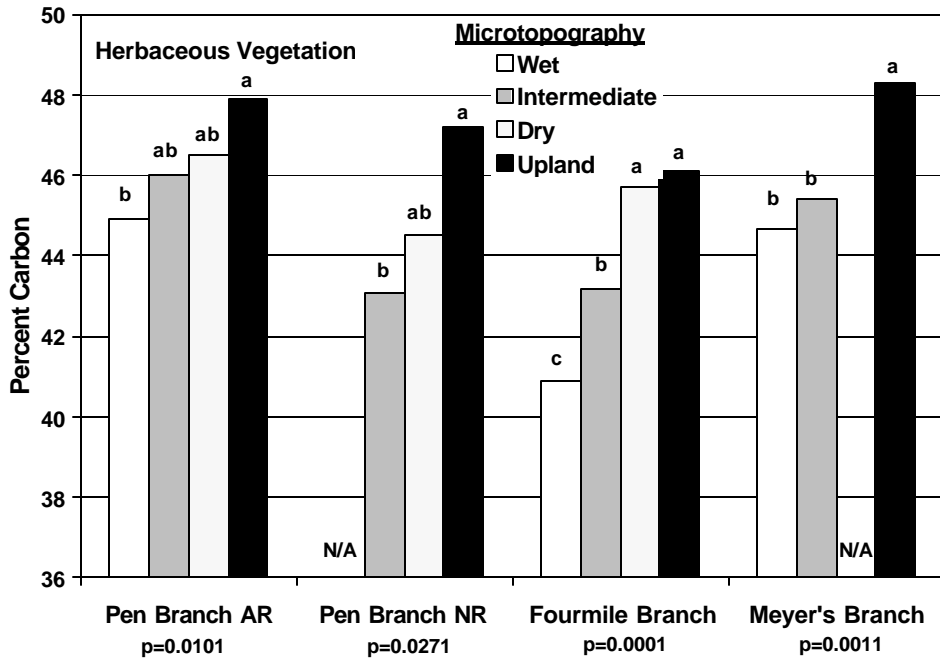


Figure VI-3. Mean percent carbon for the herbaceous vegetation associated with four microtopographic positions within four South Carolina Coastal Plain riparian forests. Within a site, means with different letters are significantly different from one another ($\alpha = 0.05$). N/A denotes that the sample size was either too small for analysis or was not available.

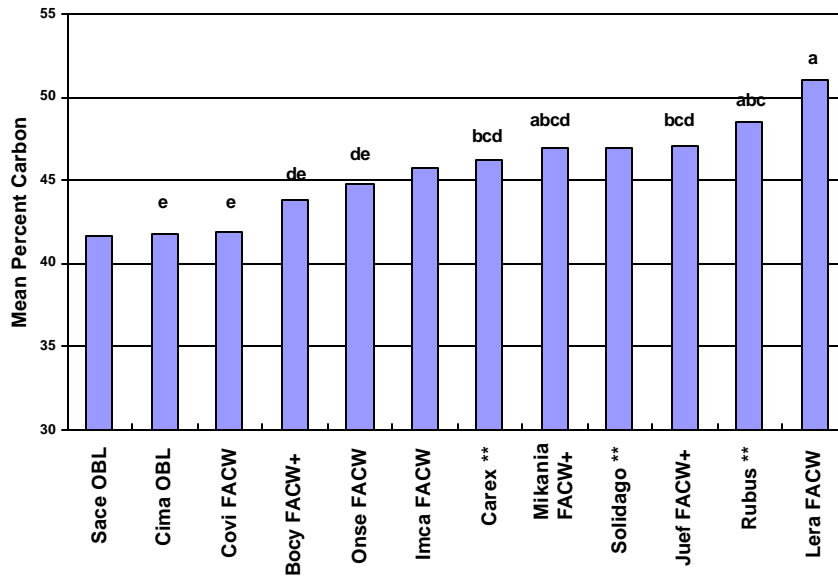


Figure VI-4. Percent carbon of select herbaceous species found in the riparian forests adjacent to third order streams in the South Carolina Coastal Plain. The following species were not included in the ANOVA due to a samples size < 3; Sace, Imca, and Solidago. Different letters signify significant difference between species percent carbon. The wetland indicator status is listed under each species; ** - unknown indicator status since the species was not determined. Species code is in Appendix Table 1.

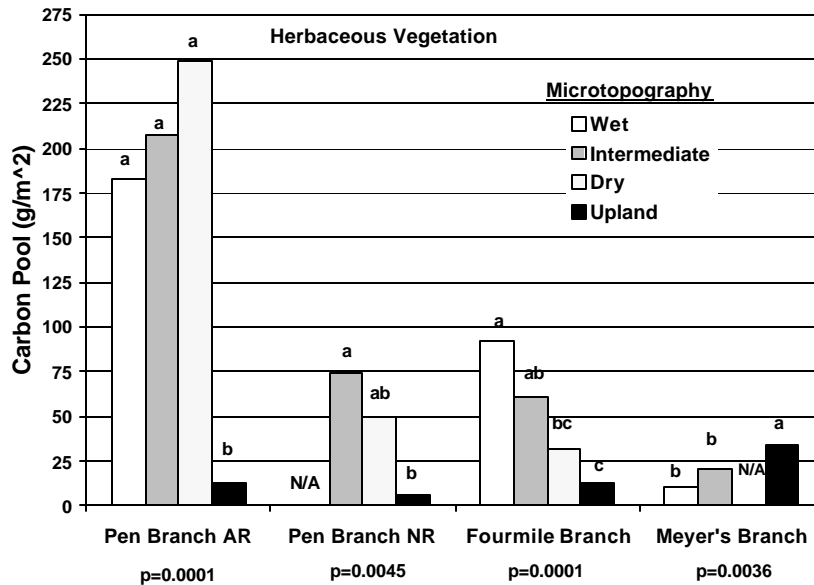


Figure VI-5. Mean carbon pools for the herbaceous vegetation associated with four micro-topographic positions within four South Carolina Coastal Plain riparian forests. Within a site, means with different letters are significantly different from one another (alpha = 0.05). N/A denotes that the sample size was either too small for analysis or was not available.

Herbaceous Species Richness

A breakdown of species in the different microtopography positions based on June versus August, and 1997 versus 1998 occurrence illustrated the richness of herbaceous species observed in these riparian forests (Table VI-1). Therefore, all four sample dates were included in the analysis of microtopography influence on herbaceous species richness to further incorporate site diversity.

Table VI-1. The percentage of herbaceous species (from riparian forest clip plots) observed either in June or August of 1997 or observed either in 1997 or 1998 in each of three microtopography areas. Ratios are in parentheses.

Site	Microtopography					
	June			August		
	Wet	Int	Dry	Wet	Int	Dry
Pen Branch (AR)	20 (6/30)	32 (9/28)	39 (7/18)	17 (5/30)	21 (6/28)	5 (1/18)
Pen Branch (NR)	27 (3/11)	17 (4/23)	17 (5/29)	27 (3/11)	13 (3/23)	3 (1/29)
Fourmile Branch	13 (3/23)	18 (4/22)	29 (10/34)	21 (5/23)	4 (1/22)	3 (1/34)
Meyer's Branch	17 (7/42)	19 (8/42)	50 (2/4)	17 (7/42)	24 (10/42)	0 (0/0)

Site	Microtopography					
	1997			1998		
	Wet	Int	Dry	Wet	Int	Dry
Pen Branch (AR)	23 (7/30)	39 (11/28)	33 (6/18)	30 (9/30)	25 (7/28)	39 (7/18)
Pen Branch (NR)	36 (4/11)	9 (2/23)	10 (3/29)	36 (4/11)	48 (11/23)	55 (16/29)
Fourmile Branch	22 (5/23)	27 (6/22)	3 (1/34)	35 (8/23)	27 (6/22)	44 (15/34)
Meyer's Branch	26 (11/42)	24 (10/42)	0 (0/0)	24 (10/42)	28 (12/42)	25 (1/4)

In both Pen Branch sites and Fourmile Branch, more species were found within each of the microtopography positions in June compared to August. This observation correlates with early successional species and their ability to capture available resources and establishment opportunities. Hence, there was less species change later in the growing season. The species occurrence in each of

the microtopography positions in Meyer’s Branch was similar for both June and August, possibly was the result of a more later successional environment. A breakdown of species by growth form revealed that more shrub, tree and vine species were present in the dry and upland micro-topographic positions (Table VI-2). The distinction was greater in the three younger riparian forests whereas the mature riparian forest had a more uniform distribution of species in the different growth forms. Huenneke and Sharitz (1986) also found differences in plant growth form based on microsite, as well as differences among species within growth form. These findings support the need for establishment of mounds or beds for enhanced establishment of tree species in disturbed or mitigation wetland sites.

Table VI-2. Number of species in each growth form class recorded from the herbaceous clip plots based on topographic position (wet, intermediate [int], and dry) in four South Carolina Coastal Plain riparian forests and adjacent uplands. An expanded version by individual species according to microtopography may be found in Appendix Table 3.

Form	Pen Branch (AR)				Pen Branch (NR)			
	Wet	Int	Dry	Upland	Wet	Int	Dry	Upland
Herb	29	26	17	10	11	22	24	8
Shrub	1	1	1	5		1	3	3
Tree		1		4			1	3
Vine				3			1	3
Total	30	28	18	22	11	23	29	17
Form	Fourmile Branch				Meyer’s Branch			
	Wet	Int	Dry	Upland	Wet	Int	Dry	Upland
Herb	22	19	23	18	29	27	1	13
Shrub	1	2	2	5	5	6	2	7
Tree			4	3	3	5		6
Vine		1	5	4	5	4	1	4
Total	23	22	34	30	42	42	4	30

Microtopography affected species richness in several of the sites (Table VI-3). The upland areas had the highest species richness due to the inclusion of woody seedlings. In the riparian areas the intermediate position generally had the highest species richness which can be attributed to intermediate areas providing enough, but not too much moisture which is similar to findings by Bledsoe and Shear (2000) in a small Coastal Plain riparian swamp.

Table VI-3. Herbaceous species richness means for three riparian micro-topographic positions and adjacent upland in four South Carolina Coastal Plain riparian forests.

Species Richness	Microtopography					
	Site	Wet	Int	Dry	Upland	p-value
Pen Branch (AR)		3.0 (1.6) bc	3.5 (1.7) b	2.3 (1.1) c	5.0 (2.5) a	0.0001
Pen Branch (NR)		2.8 (1.0) a	2.8 (1.0) a	3.5 (1.5) a	3.4 (1.8) a	0.1292
Fourmile Branch		2.1 (1.1) c	3.4 (1.6) ab	2.9 (1.8) b	4.0 (1.8) a	0.0001
Meyer's Branch		2.9 (1.7) b	3.5 (1.8) b	2.2 (1.5) b	6.8 (2.9) a	0.0001

1) Standard deviations are in parentheses ().

2) Means in rows with different letters are significantly different from one another (alpha = 0.05).

Fine Roots

Root biomass values were for total biomass which included approximately 10 percent dead roots consistently observed for each site. Fine root biomass was generally greater in the upland of Pen Branch, but not the other two sites (Fig. VI-6) due to forest development/succession. Pen Branch (AR) and Fourmile Branch demonstrated decreasing trends in fine root biomass from wet areas to dry areas (Fig. VI-6). In micro-topographic areas subject to regular inundation, less fine root biomass was observed except in the Fourmile Branch and Pen Branch (AR) riparian forests. Jones et al. (1996) also observed less root biomass in wet areas (hollows) compared to drier areas (hummocks) and Day and Megonigal (1993) found less belowground biomass in flooded sites. The significant amount of fine root biomass in the wet areas of Fourmile Branch was likely attributable to the aggressive, rhizomatous,

perennial species that inhabits the wet areas. The fine root biomass in Pen Branch (AR) was associated with the density and composition of herbaceous species. Montague and Day (1980) also attributed greater shrub and herb presence to increased root biomass.

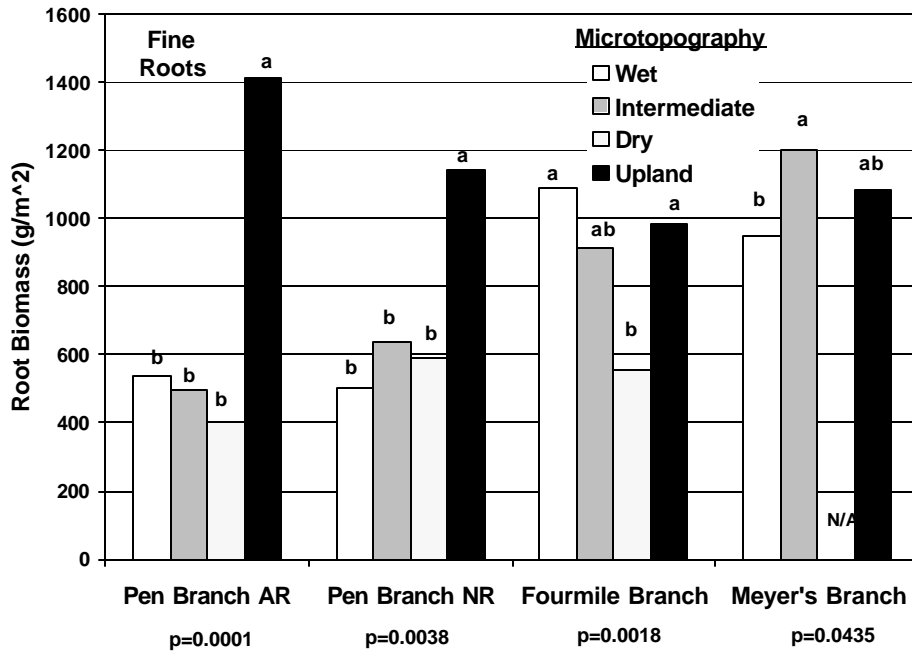


Figure VI-6. Mean fine root biomass associated with four micro-topographic positions within four South Carolina Coastal Plain riparian forests. Within a site, means with different letters are significantly different from one another ($\alpha = 0.05$). N/A denotes that the sample size was either too small for analysis or was not available.

Subtle microtopography and predominance of tree roots throughout Meyer's Branch would suggest no influence of the small scale microtopography. However, this was not the case since the intermediate areas had greater fine root biomass than the wet areas. Possibly the wet areas do not provide a suitable environment for root growth (Titus 1990; Day and Megonigal 1993).

The root biomass values in the study were much higher than values reported by Megonigal and Day (1992) probably due to the age of their saplings (3-year old) and growth environment (rhizotron). However, root biomass found by Powell and Day (1991) for several mature forested wetlands (696 to 1,887 g m⁻²) was comparable to root biomass values in this study.

In the riparian areas fine root percent carbon ranged from 41 to 47 percent (Fig. VI-7). The percent carbon of fine roots in upland areas was slightly higher and ranged from 44 to 49 percent. There was no difference in fine root percent carbon based on microtopography because most of the samples likely included a significant tree root component which could confound the results.

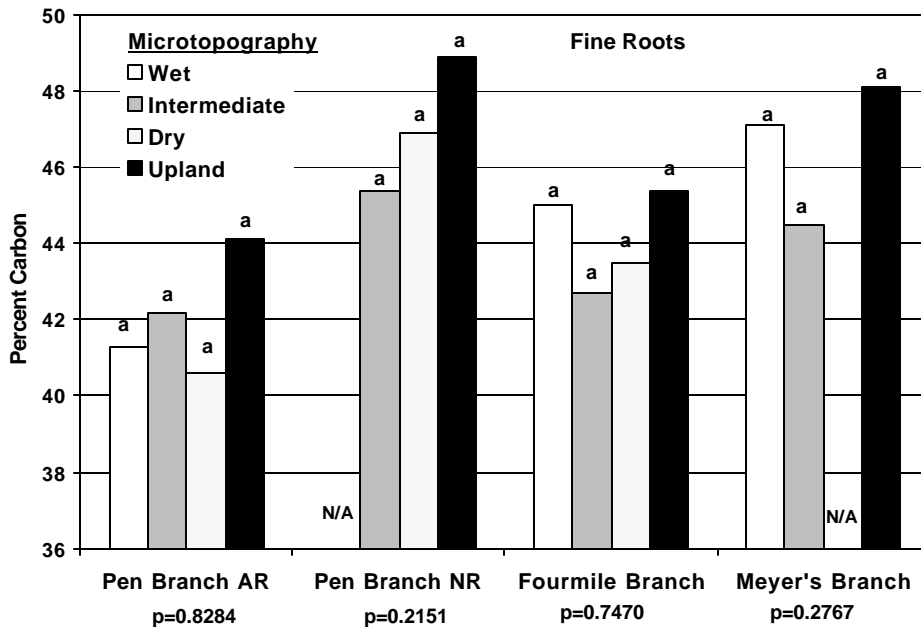


Figure VI-7. Mean percent carbon of the fine roots associated with four micro-topographic positions within four South Carolina Coastal Plain riparian forests. Within a site, means with different letters are significantly different from one another (alpha = 0.05). N/A denotes that the sample size was either too small for analysis or was not available.

Since there was no significant difference in fine root percent carbon, it is therefore possible to determine the fine root carbon pool trends associated with microtopography by examining the fine root biomass patterns. The fine root carbon pool ranged from approximately 150 to 440 g m⁻² in the riparian forests and 420 to 590 g m⁻² in the uplands (Fig VI-8). These values fall within the range of 25 to 820 g m⁻² yr⁻¹ that Nadelhoffer and Raich (1992) found for fine root carbon content in various forest ecosystems. Trends in fine root carbon pools (Fig. VI-8) were generally similar to fine root biomass trends.

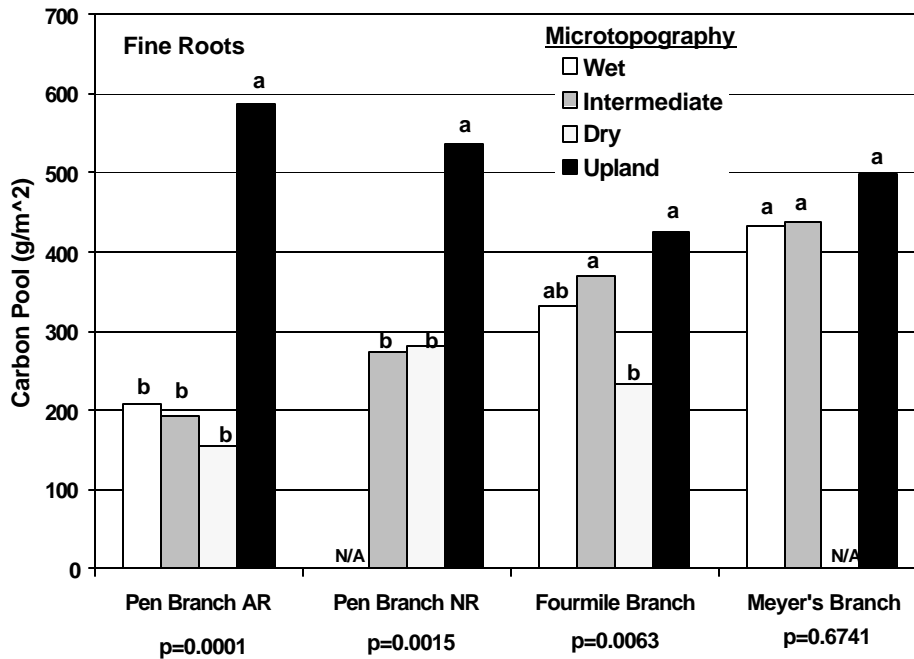


Figure VI-8. Mean carbon pool for the roots associated with four micro-topographic positions within four South Carolina Coastal Plain riparian forests. Within a site, means with different letters are significantly different from one another ($\alpha = 0.05$). N/A denotes that the sample size was either too small for analysis or was not available.

Soil Properties

Organic Matter

Wetter areas generally had greater amounts of organic matter compared to drier areas due to slower decomposition rates in an anoxic environment. However, this was not definitively observed in the microtopography of the riparian forests in this study. Overall, the riparian forests had significantly greater organic matter than their adjacent upland (Table VI-4), but the elevation difference within the riparian forests generally was not significant to allow microtopography to affect organic matter accumulation. The percent soil organic matter found in the riparian areas of all four sites was approximately twice that observed along a flooding gradient in a South Carolina Coastal Plain forest (Burke et al. 1999). The difference may be attributable to greater herbaceous biomass, slower decomposition rates, or different hydroperiods in this study's sites.

Patterns describing changes in organic matter can be correlated with herb and root biomass trends. The herbaceous component in Pen Branch (AR) increased from wet to dry whereas the root component decreased from wet to dry, therefore the higher percent organic matter in the dry areas of Pen Branch (AR) compared to the wet areas may be attributed to the extremely dense herbaceous biomass in the dry areas. In contrast both herbaceous biomass and root biomass decreased from the intermediates areas to the dry areas in Pen Branch (NR) and the organic matter increased. Since Pen Branch (NR) had a greater woody component, litterfall and root inputs may be the dominating factor for soil organic matter. Herbaceous and root biomass in Fourmile Branch decreased from wet to dry and there was an associated decrease in organic matter from wet to dry. The reverse occurred in Meyer's Branch where an increase in herbaceous and root biomass from wet to dry corresponded to an increase in organic matter from wet to dry. Like that found in Meyer's Branch, Bledsoe and Shear (2000) found an increase in percent organic matter from a wet area to a transitional area in a North Carolina Coastal Plain swamp.

Table VI-4. Soil property means (carbon (%), organic matter (%), bulk density g cm^{-3} , total porosity (%), and non-capillary porosity (%)) for four riparian forests in the Coastal Plain of South Carolina. Standard deviations are in parentheses (). Means with different letters are significantly different from one another. Means with a small sample size and therefore no standard deviation were not included in the analysis.

		Microtopography				
Site	Soil Property	Wet	Int	Dry	Upland	p-value
Pen Branch (AR)	Carbon (%)	3.0 (1.6)	4.5 (--)	5.2 (1.7)	4.0 (1.8)	0.1056
	Organic Matter (%)	8.6 b (4.6)	14.8 ab (--)	15.4 a (5.0)	8.2 b (3.9)	0.0325
	Bulk Density (g cm^{-3})	0.91 (0.44)	0.57 (--)	0.60 (0.05)	0.88 (0.09)	0.2094
	Total Porosity (%)	60.1 (15.8)	72.9 (--)	72.5 (2.7)	60.6 (4.1)	0.1355
	Non-Capillary Porosity (%)	19.9 (6.9)	17.8 (--)	17.3 (4.4)	24.7 (6.0)	0.3374
Pen Branch (NR)	Carbon (%)	N/A	3.4 ab (--)	4.8 a (1.3)	1.7 b (1.2)	0.0079
	Organic Matter (%)	N/A	10.2 ab (--)	13.2 a(3.3)	4.6 b (2.6)	0.0015
	Bulk Density (g cm^{-3})	N/A	0.57 a (--)	0.63 a (0.09)	1.05 a (0.04)	0.0001
	Total Porosity (%)	N/A	72.8 a (--)	69.5 a (4.5)	54.2 b (2.6)	0.0010
	Non-Capillary Porosity (%)	N/A	10.8 b (--)	15.3 b (5.1)	23.0 a (5.1)	0.0854
Fourmile Branch	Carbon (%)	4.7 a (2.7)	N/A	2.9 b (0.6)	2.4 b (1.8)	0.0295
	Organic Matter %	11.9 (6.9)	N/A	8.8 (2.0)	7.4 (5.6)	0.1681
	Bulk Density (g cm^{-3})	0.32 b (0.18)	N/A	0.82 a (0.27)	0.83 a (0.20)	0.0001
	Total Porosity (%)	82.4 a (6.9)	N/A	65.4 b (9.7)	60.8 b (7.8)	0.0001
	Non-Capillary Porosity (%)	20.9 b (4.1)	N/A	18.7 b (4.3)	26.8 a (4.6)	0.0035
Meyer's Branch	Carbon (%)	10.1 a (4.8)	12.7 a (2.9)	N/A	3.2 b (2.3)	0.0002
	Organic Matter (%)	28.2 a (12.0)	32.6 a (6.7)	N/A	8.6 b (5.6)	0.0001
	Bulk Density (g cm^{-3})	0.25 b (0.05)	0.23 b (0.06)	N/A	0.83 a (0.33)	0.0001
	Total Porosity (%)	84.5 a (2.2)	84.9 a (1.9)	N/A	65.3 b (11.3)	0.0001
	Non-Capillary Porosity (%)	14.6 b (3.5)	16.1 b (5.2)	N/A	24.0 a (8.4)	0.0152

The percent organic matter was generally greater in the riparian forests than the uplands (Table VI-4). The dry areas of Pen Branch (AR) had significantly greater percent soil organic matter than the wet areas.

Percent Carbon

The organic matter in the soil is comprised of a variety of decayed material (leaves, twigs, roots, macro/micro fauna) and the percent carbon in the soil is a measure of the disproportionate assortment of these components. Soil type influences chemical interactions between organic matter and soil particles, and therefore may affect the percent carbon in the soil. Although not significant, there was an increase in percent carbon in the soil from the wet areas to the dry areas, except in Fourmile Branch (Table VI-4). In the dry areas of Fourmile Branch which had a higher sand component and lower organic matter, lower percent carbon was observed. In contrast to Pen Branch and Meyer's Branch, but similar to Fourmile Branch, Reese and Moorhead (1996) found the organic carbon content to decrease from the center of a Carolina bay to the rim. Pen Branch AR & NR had a higher and more consistently distributed clay component which will retain carbon. In all four sites, the percent carbon mirrored the increases or decreases in organic matter.

Lignin degradation requires O₂ due to its molecular structure (Robinson 1990) and therefore, wet areas which have a higher woody species biomass component should exhibit a greater percentage of organic matter and/or carbon. Both the Fourmile Branch and Meyer's Branch riparian forests exhibited higher organic matter and carbon in the wet areas compared to drier or upland areas possibly as a result of the limited oxygen environment in the wet areas.

Bulk Density/Porosity

Bulk density of the soil can influence the distribution and growth of vegetation primarily by affecting rooting processes and moisture availability. A higher bulk density (> 1.4 to 1.6) will restrict root growth and reduce water infiltration and internal movement. Since microtopography dictates soil particle deposition and hydrology, it can also indirectly affect bulk density. The incorporation/presence of organic matter due to higher inputs or slow decomposition rates will also contribute to a lower bulk density. The lower bulk density on the wet areas of Fourmile Branch can be attributed to the greater organic matter in the wet areas and may be associated with the higher root biomass observed in the wet areas (Table VI-4). The bulk density in Pen Branch (AR) was associated with the amount of organic matter in each area. Lower organic matter in the wet areas had a higher bulk density compared to higher organic matter in the dry areas and a lower bulk density.

Soil porosity will affect plant growth and stability. Higher macro (non-capillary) porosity will enhance the movement of roots as well as water and nutrients to the plants. Soil texture will influence total porosity, and soil compaction (higher bulk density) will generally be reflected in lower macro-porosity. In Pen Branch (AR), the wet areas had fairly low total porosity which was related to the higher bulk density in the wet areas (Table VI-4). Greater total porosity and lower bulk density was found in the intermediate and dry areas of Pen Branch (AR). Total porosity was similar for the intermediate and dry areas of Pen Branch (NR). In Fourmile Branch the connection between total porosity and bulk density was observed; lower bulk density in the wet areas and higher total porosity; bulk density increased in the dry areas and the total porosity decreased. The uniform nature of the soils in the mature riparian forest (Meyer's Branch) was reflected in the similar values for total porosity and non-capillary porosity.

In all the adjacent uplands the total porosity was lower than the riparian areas. Non-capillary porosity comprised approximately 40 percent of total porosity in the uplands compared to approximately 17- 30 percent non-capillary porosity in riparian areas (Table VI-4). Sandier soils, that are comprised of larger soil particles and less compact packing, in the uplands accounts for the greater macro porosity.

Distance Gradient / Elevation

The presence of microtopography may confound a relationship between abiotic/biotic factors affecting productivity in a riparian forest as well as a distance gradient from the stream channel. Since microtopography is associated with differences in elevation, a connection between elevation and the same factors may be evident. Very few of the parameters exhibited a linear relationship with distance from the main stream channel (Table VI-5) because in these sites, there was a gradual increase in elevation from the main stream channel, but it was complicated by a complex mosaic of ridge and swale microtopography comprised of old stream channels, especially in the younger riparian forests. A low correlation coefficient was associated with the parameters that had a significant linear model (Table VI-6). The limited sample size may also have affected the linear relationship. The greater number of significant linear models within the Meyer's Branch riparian forest may be reflective of the subtle microtopography, and fairly uniform soils. The lack of significant linear models in Pen Branch (AR) may be attributed to microtopography, however, the dense herbaceous vegetation in this young riparian forest absorb flood energies and alter distribution of organic matter and sediment.

The size of shrub and tree plots included the range of microtopography positions dismissing a microtopography effect. In general, aboveground biomass did not exhibit a linear relationship with increasing distance from the main stream channel. Therefore, tree and shrub productivity may not be subject to a distance gradient when extensive ridge and swale topography confounds a distance gradient effect. The extensive root system of trees and shrubs also may buffer differences in

microtopography on sites where ridges and swales coexist within a few feet of one another.

A prominent shrub (*Leucothoe axillaris*) which was generally found towards the fringe of the Meyer's Branch riparian forest was included in the herbaceous sampling and accounts for the greater amount of herbaceous biomass with increasing distance from the main stream channel. The general increase in elevation with increasing distance from the main stream channel affects soil moisture and provides favorable growing conditions for the shrub. Also, in the Meyer's Branch riparian forest there was a fairly high correlation between elevation and herbaceous biomass (Table VI-7). In the Meyer's Branch riparian forest herbaceous species richness declined with increasing distance from the main stream channel due to the predominance of the shrub species which inhibited the growth of other species. There was little correlation between herbaceous species richness and elevation.

Table VI-5. P-values of the model for the linear regression models ($y = mx + b$) for four South Carolina Coastal Plain riparian forests where the independent variable is distance from the main stream channel. P-values < 0.10 were considered to be significant.

Dependent Variable	Pen Branch (AR)	Pen Branch (NR)	Fourmile Branch	Meyer's Branch
Shrub Biomass ('97)	0.4332	0.8841	0.1706	0.1173
Tree Biomass ('97)	0.5875	0.5985	0.7046	0.4873
Total Aboveground Biomass ('97)	0.9318	0.6395	0.8154	0.4569
NPP ('97)	0.6153	0.9322	0.4962	0.2082
Shrub Biomass ('99)	0.2537	0.9200	0.1311	0.7533
Tree Biomass ('99)	0.2020	0.9847	0.3938	0.2200
Herb Biomass	0.1370	0.1865	0.3699	< 0.0001 *
Herb % Carbon	0.1837	0.2573	0.1843	0.6639
Herb C Pool	0.1864	0.0248 *	0.0572 *	0.2982
Herbaceous Species Richness	0.8278	0.7012	0.1299	0.0698
Root Biomass	0.1958	0.0783 *	0.1412	0.0019 *
Root C Pool	0.5977	0.0389 *	0.4323	0.5176
Soil % OM	0.4717	0.4148	0.4842	0.2551
Soil % Carbon	0.3672	0.4530	0.7113	0.1343
Bulk Density	0.4260	0.2601	0.9036	0.0094 *
Total Porosity	0.2771	0.2855	0.7987	0.0139 *
Non-capillary Porosity	0.1938	0.7971	0.9292	0.0533 *

* Significant linear models.

Table VI-6. Linear equation and correlation coefficient (r^2) for the variables that had a significant model ($p < 0.10$) in Table VI-5.

Dependent Variable	Pen Branch (AR)	Pen Branch (NR)	Fourmile Branch	Meyer's Branch
Herb Biomass	--	--	--	$r^2 = 0.1939$ $y = 5.5 + 5.2x$
Herb C Pool	--	$r^2 = 0.1323$ $y = 35.8 + 4.2x$	$r^2 = 0.0610$ $y = 81.2 - 4.6x$	--
Herbaceous Species Richness	--	--	--	$r^2 = 0.0168$ $y = 3.5 - 0.05x$
Root Biomass	--	$r^2 = 0.0449$ $y = 738 - 19x$	--	$r^2 = 0.1086$ $y = 1370 - 50x$
Root C Pool	--	$r^2 = 0.1075$ $y = 373 - 14x$	--	--
Bulk Density	--	--	--	$r^2 = 0.2922$ $y = 0.29 - 0.008x$
Total Porosity	--	--	--	$r^2 = 0.2667$ $y = 82.8 + 0.29x$
Non-capillary Porosity	--	--	--	$r^2 = 0.1742$ $y = 12.1 + 0.52x$

A linear increase in the herbaceous carbon pool in the Pen Branch (NR) riparian forest with distance from the main stream channel may be a combination of species composition, associated percent carbon, and biomass due to increased stability (less flood effect) farther from the main stream channel. The increase or decrease in herbaceous carbon pool visually mirrored fluctuations in elevation along the transect. However, correlation between the Pen Branch (NR) herbaceous carbon pool and elevation was low (Table VI-7). This demonstrates that the ridge and swale microtopography was independent of elevation. There was a linear decrease in herbaceous carbon pool in the Fourmile Branch riparian forest. Species composition and percent carbon may still be important factors, but the influence of flood energy probably does not play a significant role. Greater herbaceous carbon pools occurred at slightly higher elevations regardless of the distance from the main stream channel. However, correlation between the Fourmile Branch herbaceous carbon pool and elevation was also

relatively low (Table VI-7). A predominant herb (*Commelina virginica*) which had a relatively low percent carbon (Fig. VI-4) was usually found growing in swales farther from the main stream channel and this may account for the relationship.

Table VI-7. Correlation (r) between elevation and the respective variable for four South Carolina Coastal Plain riparian forests.

Variable	Pen Branch (AR)	Pen Branch (NR)	Fourmile Branch	Meyer's Branch
Herb Biomass	-0.024	0.003	-0.030	0.601
Herb % Carbon	0.362	0.490	0.103	0.050
Herb C Pool	-0.230	0.151	-0.288	0.024
Herbaceous Species Richness	0.254	0.051	0.0978	0.107
Root Biomass	-0.452	0.001	-0.410	0.134
Root C Pool	-0.262	0.068	-0.084	0.288
Soil % OM	0.331	-0.215	-0.396	-0.562
Soil % Carbon	0.322	-0.256	-0.458	-0.469
Bulk Density	-0.451	0.659	0.676	0.146
Total Porosity	0.477	-0.718	-0.674	-0.212
Non-capillary Porosity	-0.304	0.094	-0.247	-0.212

Both the Pen Branch (NR) and Meyer's Branch riparian forests exhibited a linear decrease in root biomass with increasing distance from the main stream channel. The Pen Branch (NR) riparian forest also exhibited a linear decrease in the root carbon pool with increasing distance from the main stream channel. In the Pen Branch (NR) riparian forest most of the root samples were obtained from relatively dry soils. The drier soils may allow more energy to be directed to the production of shoots instead of roots resulting in a decrease in root biomass. Soil chemical and physical properties associated with microtopography or elevation may influence the root carbon pool in the Pen Branch

(NR) riparian forest. However, there was little correlation between either root biomass or root carbon pool and elevation in the Pen Branch (NR) riparian forest (Table VI-7). The decrease in root biomass in the Meyer's Branch riparian forest may be attributed to soil physical properties and a change in vegetation growth form from herbs and shrubs to trees. The general increase in elevation with distance from the main stream channel contributes to vegetation change by influencing soil moisture, but elevation by itself has little correlation with root biomass in the Meyer's Branch riparian forest (Table VI-7). Significant differences in herbaceous and woody vegetation occur with small differences in water table depth (Bledsoe and Shear 2000).

In the Meyer's Branch riparian forest bulk density decreased, and total porosity and non-capillary porosity increased linearly with increasing distance from the main channel. The deposition of coarser sediments along the stream bank during a flood event may produce a higher bulk density and as finer particles are deposited farther from the stream the bulk density may become lower. Porosity (total and non-capillary) is also linked to soil particle size and the same explanation would hold true. The finer particles (clay and silt) would result in greater total porosity and the organic matter component in the soil would increase non-capillary porosity. In the Meyer's Branch riparian forest a distance gradient effect was more evident than the slight changes in elevation which were not well correlated with soil physical properties (Table VI-7). In the relatively mature riparian forest with a more uniform landscape, flooding events have a greater effect on the distribution of organic matter and sediment, thereby affecting soil properties.

Conclusion

Wetland scientists can learn more about landscape scale wetland functions by observing biotic processes that occur at the micro scale, particularly carbon pools. Topographic heterogeneity within a riparian forest creates a complex mosaic of microsites. Microtopography in riparian forests is closely associated with hydroperiod and this microtopography/hydroperiod connection subsequently influences

herbaceous biomass and species richness, root biomass, soil properties, and ultimately carbon pools. The magnitude of landscape change (the number of micro-sites, where they are positioned, and the scale of elevation change) will determine herbaceous species distributions.

Ridge and swale microtopography in riparian forests affected herbaceous and fine root biomass. Although most differences were not significant, there patterns emerged within each site. The greatest differences were between herbaceous and fine root biomass in the younger riparian forests versus upland herbaceous and fine root biomass. There was more herbaceous biomass and less root biomass in the Pen Branch riparian forests than its adjacent upland forests. In these riparian forests there was a lower percent carbon in the herbaceous component of wet areas compared to intermediate, dry and upland areas, however, there was no difference in the percent carbon of the fine roots between any of the areas.

Species richness was influenced by differences in topography. Again the distinction was more prominent between the riparian areas and the adjacent upland forests with the upland forests having greater species richness.

In the young riparian forests which had a significant ridge and swale microtopography, the impact of flood energy was carried throughout the site due to the braided nature of current and old stream channels resulting in a homogeneous heterogeneity within these sites which eliminated a distance gradient. Braided stream channels produce an intricate mosaic of ridge and swale topography that will affect more localized factors and influence forest productivity. In a more mature riparian forest, with relatively uniform landscape and plant community associations, the effects of a distance gradient was more pronounced. The only discernible changes observed along a distant gradient from the main stream channel were an increase in herbaceous biomass with distance and soil physical properties in the mature riparian forest.

An accumulation of organic matter closer to the stream was not observed in any of the sites. The amount of organic matter deposited during flood events and after waters recede appears to be minimal. The interference of an herb stratum, velocity and magnitude of flood waters, and existing organic matter pools affect organic matter distribution to and within the riparian forest.

Changes in elevation, which generally correspond to the microtopography, dictate soil moisture and may influence the ratio of shoot to root growth, and species establishment. However, elevation may not implicitly replace microtopography since it does not necessarily reflect the biotic processes that occur on a ridge or in a swale. As disturbance history plays a role in possibly altering the hydroperiod and soil characteristics, it may result in dissimilar plant community composition and structure. It is important for wetland managers to realize that these braided minor stream systems have different gradients relative to the classic major and minor river bottomlands typically discussed.

Realizing the complexity of riparian forests and the interlocking pieces of the puzzle will provide a basis for understanding the components and processes governing riparian forests and how they recover from disturbances. This will also guide and improve management decisions for restoration efforts. Specifically, knowledge that microtopography affects species establishment will enhance species selection for planting, ensure plant survival, and contribute to restoration success. The general hydrologic and soil properties of the microtopography within a site should be assessed prior to selecting the species to be planted to appropriately match species habitat requirements to site conditions. Time invested up front will decrease the costs of a restoration project. For example recognition of microtopography and appropriate species could be used to enhance survival of planted trees on mitigation sites, where, unfortunately, linear planting in zones has been the rule.

Summary

The importance of this study was two fold. It provided quantitative data, which is often lacking, for the complex carbon pools within riparian forests representing different seral stages. In doing so, this research also uncovered some of the intricate workings of carbon within these pools. Carbon pools and fluxes may serve as indicators of riparian restoration, especially from a vegetation and energy cycling perspective. This study focused on riparian forests bordering 3rd order streams in the Coastal Plain of South Carolina, but the same interactions and connection between terrestrial and aquatic environments could be extrapolated to riparian areas in other regions and larger stream orders as long as there is a strong hydrologic connection. An underlying assumption in restoration is that if the energy dynamics and inherent biogeochemical processes are restored everything else will fall into place.

Succession Succession, or the continuous change in species composition, is different in riparian areas compared to inland terrestrial areas, due to the close association with the aquatic environment and local hydroperiod. The repetitive disturbance from flood events may affect the development and magnitude of carbon pools. Therefore, the more dynamic carbon pools; herbaceous vegetation, litter, and fine roots, were better indices of seral stage, or recovery from disturbance than the less dynamic pools.

Litterfall Litterfall dynamics in riparian forests are very complex due to the close association with the stream. Besides gravity fed inputs of litterfall, the hydroperiod of an area greatly influences the distribution (redistribution) of litter components. Despite their fractal nature, the vegetation within riparian forests adapt to disturbances and proceed in the annual production of litterfall. Litter production rates of these young riparian forests quickly approached that of the older riparian forest. The rapid recovery of litterfall rates in riparian areas indicates that the establishment and protection of vegetation within streamside management zone forests could re-establish litter detritus to food webs more rapidly than expected.

Decomposition The decomposition process in riparian forests often operates under a different paradigm. Less than ideal conditions due to inundation cause the players of the decomposition process to be ingenuous, however they function at a slower rate due to the anaerobic conditions. In the young riparian forests, the decomposition process was not altered by the effects of the thermal disturbance and was independent of seral stage. However, species composition, which is a function of seral stage, does affect decomposition rates due to differences in litter quality. Generally, litter quality of early successional species (i.e., red maple) are designed for rapid incorporation to the energy cycle promoting forward succession or recovery. However, the early successional species in these young riparian forests (i.e., black willow, alder, and waxmyrtle) exhibited slower decomposition rates.

Microtopography The hydrologic interaction with the complex ridge and swale microtopography in the younger riparian forests further demonstrates the ability to use the more dynamic carbon pools for assessing restoration of vegetation. Vegetation establishment and growth is dictated by the micro habitats created. During the thermal disturbance in these riparian forests, the altered hydrology may have critically rearranged the flow patterns and changed substrate configuration to the point that the vegetation recovery pattern may not develop toward a facsimile of its pre-disturbance character. The prominent ridge and swale microtopography also confounds any vegetation patterns that would be based on a distance gradient.

In summation the most important findings of this research are discussed in the following paragraphs.

The carbon pools in these riparian forests indicate that the riparian forests that were severely impacted by thermal pollution were recovering. Vegetation, which is important to riparian functions, partially recovers some major functions within 10 years. In mature Coastal Plain riparian forests of the Southeast, largest to smallest carbon pools are: trees, soil carbon, and fine roots, followed by similar

shrub and litterfall carbon pools and next, the herbaceous carbon pools. Forest floor and woody debris carbon pools comprised a very small percentage of the total mature riparian forest carbon pool. Also in the streams of young riparian forests, submerged aquatic vegetation constituted a fairly important carbon pool.

Carbon pools and carbon allocation patterns vary as riparian forest stands age/develop, particularly with regard to above and belowground patterns. At early seral stages the herbaceous carbon pool was almost equivalent to the fine root carbon pool. However, as riparian forests develop, the herbaceous carbon pool declines and the fine root carbon pool increases.

Carbon sequestration by wetlands (riparian forests) is enhanced by allowing stands to mature. Mature riparian forests store approximately 4 times more carbon than younger riparian forests. The greatest carbon storage was in the soil in the young riparian forests, and associated with trees in the mature riparian forest. Managing stands for carbon storage will require understanding and maintaining the processes that furnish the carbon inputs, i.e. litter dynamics and decomposition.

Litterfall amounts in the disturbed, young riparian forests, except the artificial regeneration site, were comparable to the undisturbed, more mature riparian forest. Once a woody stratum develops, the amount of litterfall was comparable between the riparian forests. The rapid recovery of litterfall suggests that the recycling of nutrients critical for forest growth is occurring. Rapid litterfall recovery also implies that carbon inputs (an important energy source) to the aquatic ecosystem are restored. Due to the nature of litterfall in these riparian forests it can successfully be used as an index of productivity/recovery.

Litter movement within a riparian forest, and to and from the associated stream, is very complex. Overall lateral litter supplied less energy to the stream system than vertical inputs. In the riparian forests where lateral litter movement could be analyzed, more litter was deposited into the

riparian forest from the stream than from the riparian forest to the stream. However, the influx of organic matter did not accumulate closer to the stream and must therefore become redistributed. This demonstrates that the possibility exists for the influx of organic matter (nutrients) necessary for biotic processes, and in riparian forests with distinct ridge and swale microtopography the influx of organic matter is uniformly distributed.

The differences in litter quality (carbon) need to be acknowledged because they will affect decomposition rates and subsequent nutrient incorporation processes. Crediting litterfall components (and other vegetation components) with a set carbon amount (usually 50 percent) will overestimate global carbon models. More accurate global carbon estimates may be obtained by utilizing the appropriate carbon percentages based on forest stand type.

Riparian forest species composition affect decomposition rates. Species with less labile leaves slow the decomposition rate and subsequent incorporation of organic matter to the soil carbon pool as well as the ever sought after nutrients. In riparian forests, decomposition rates are also affected by the local hydroperiod which not only provides undesirable anaerobic conditions, but often during flood events, sediment is deposited blanketing litterfall inputs further slowing the decomposition process.

Sediment accumulation patterns differed in these riparian forests due to differences in vegetation strata and hydroperiod. Lack of a herbaceous layer in the mature riparian forest resulted in greater sediment deposition to the riparian forest which in turn could be returned to the stream during the next flood event and adversely affect water quality. Hydroperiod in conjunction with vegetation and soil type can alter sediment deposition patterns independent of forest age. Therefore, maintenance of an herbaceous layer and knowledge of the current hydroperiod can ensure good water quality by mitigating early sediment removals.

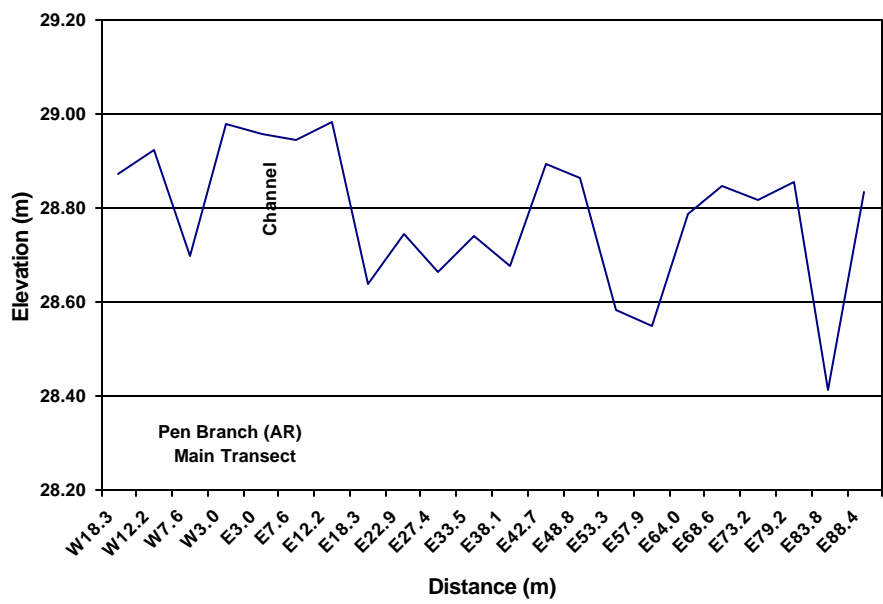
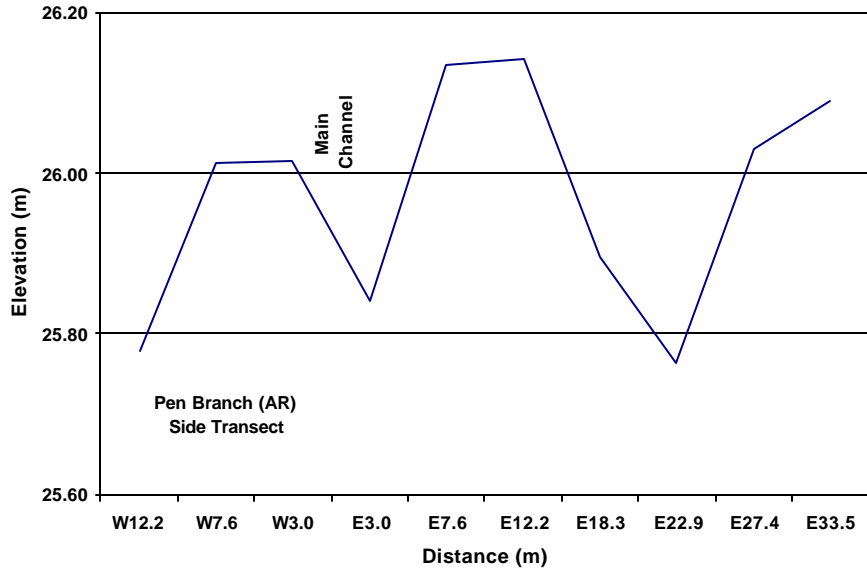
There was a lack of major differences in woody debris in these riparian forests and in all four riparian forests woody debris comprised a relatively small carbon pool. Fine woody debris comprises the greatest percentage and will undergo decomposition in a relatively short time. However, coarse woody debris provides essential habitat conditions and was limiting in all of the riparian forest. Developing a means to increase coarse woody debris may be an important management objective.

It is important for riparian creation/restoration projects to understand that the dynamics (hydrologic, plant community, soil) of a young riparian forest with braided channels and prominent ridge and swale microtopography will differ more than in a mature riparian forest. However, this is not to imply that creation of this type of riparian forest system is not warranted. Creating microtopography may improve recruitment of desirable species by providing a variety of sites favorable for seed germination and establishment. The objectives for the riparian forest restoration/creation need to be thoroughly addressed prior to any constructive activity. Marked differences in microtopography affect subsurface drainage due to differences in soil physical properties, vegetation and local watershed influences and subsequently makes design and implementation of riparian restoration challenging.

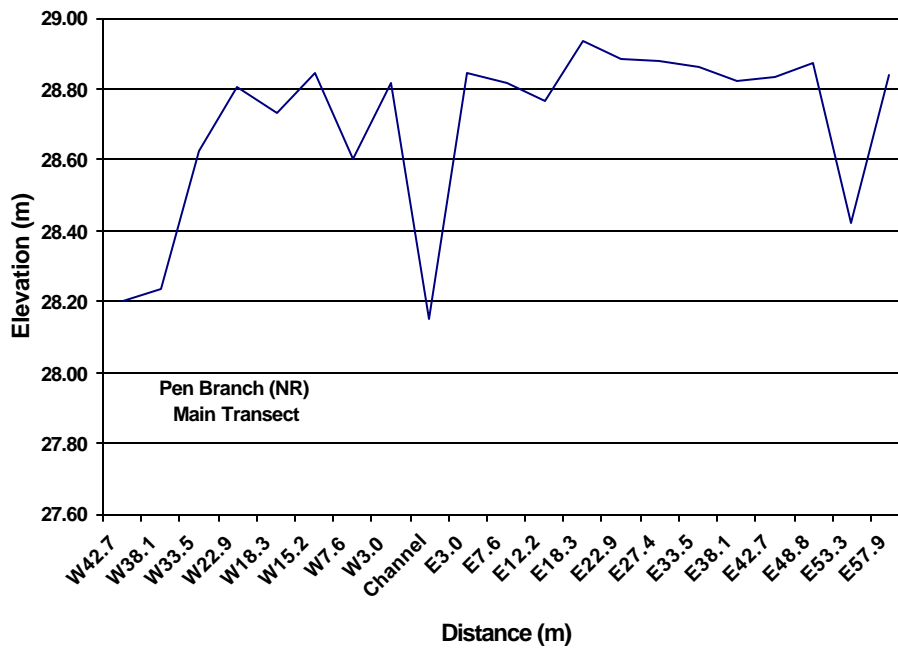
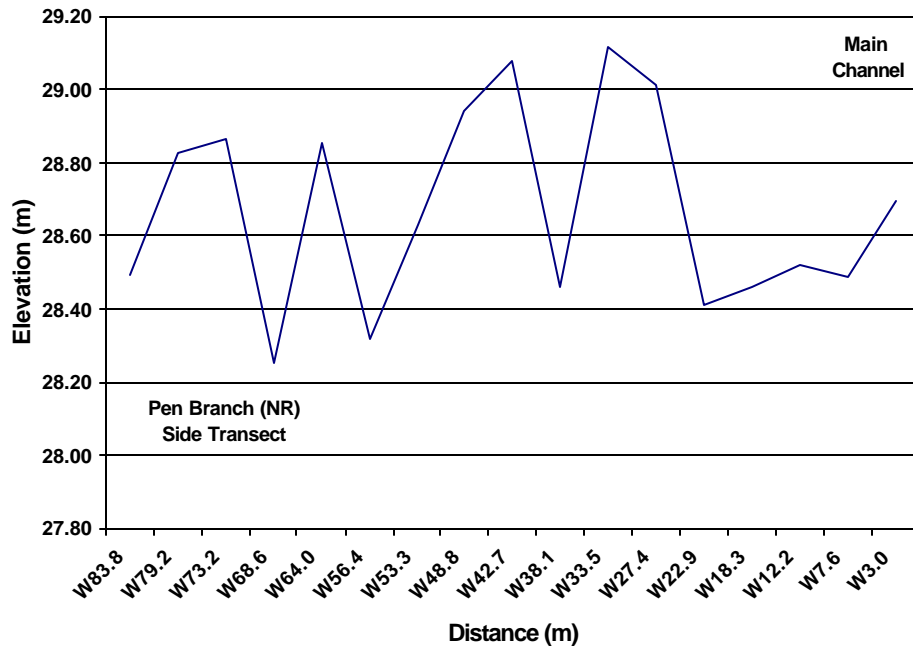
“In science we never actually prove anything, we merely fail to disprove, and hence we accept the hypotheses that make up scientific knowledge only tentatively, which is to say, until something better comes along.”

Unknown

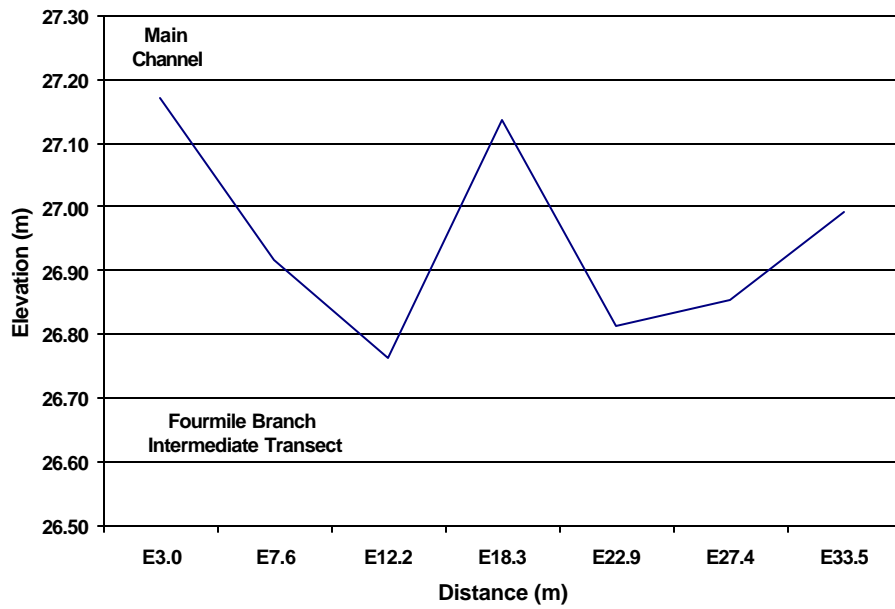
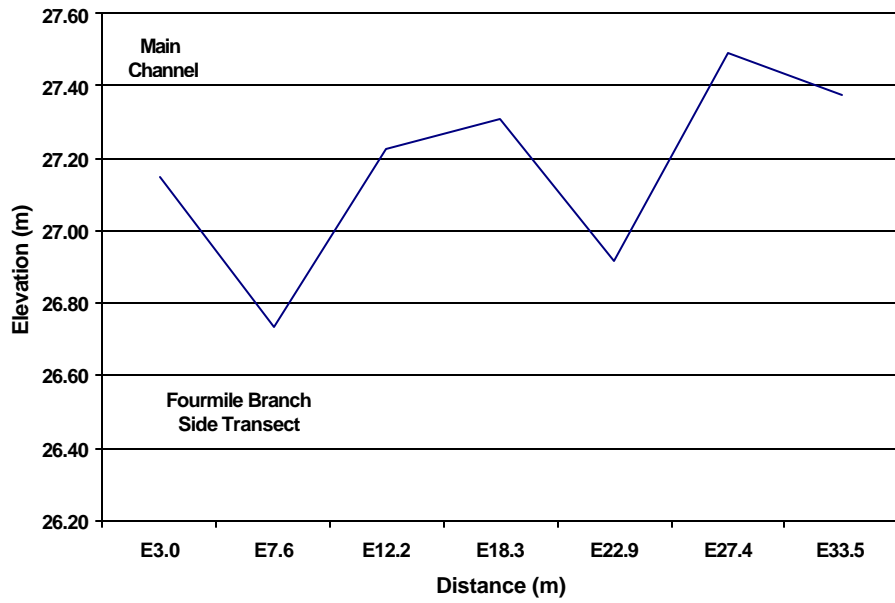
APPENDIX



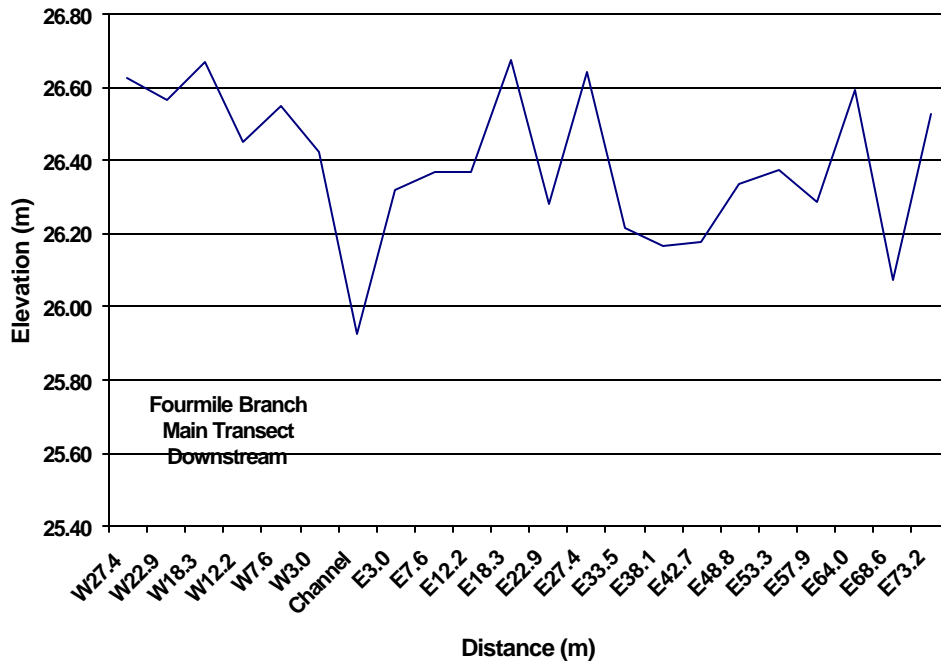
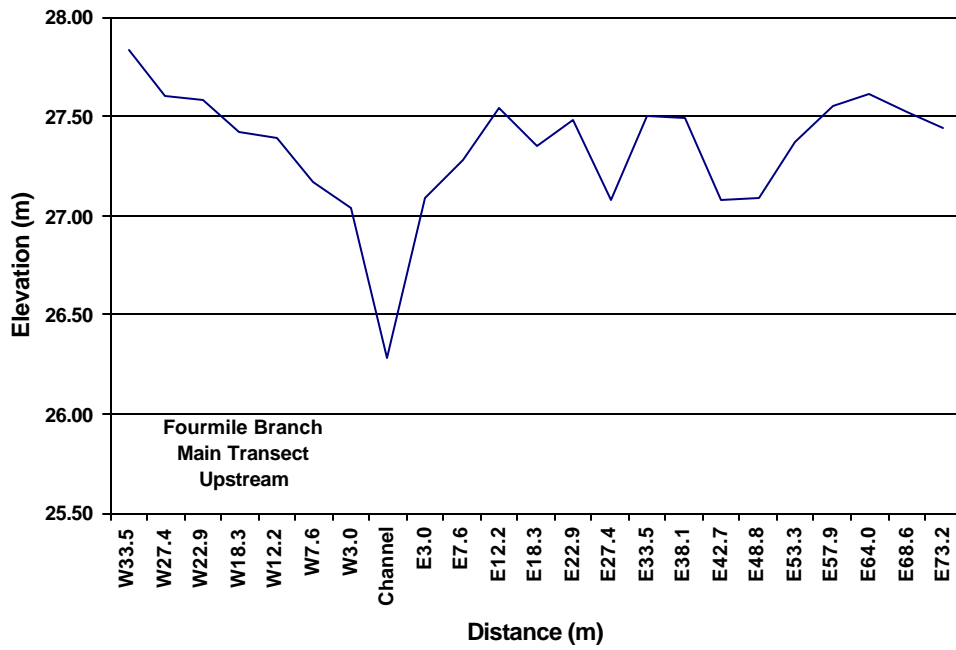
Appendix Figure 1. Elevations for each plot and subplot along the riparian transect based on distance from the main stream channel towards the upland. The letter designation refers to the principle transect direction; west (W), east (E), north (N), and south (S). The x-axis is not necessarily linear. The location of the main channel is labeled either on the figure or x-axis.



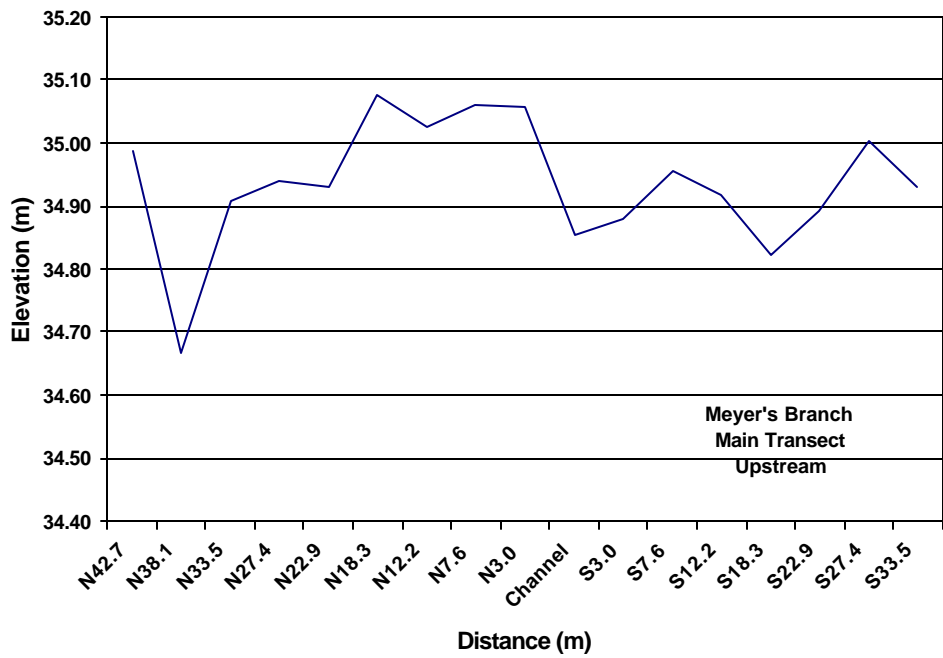
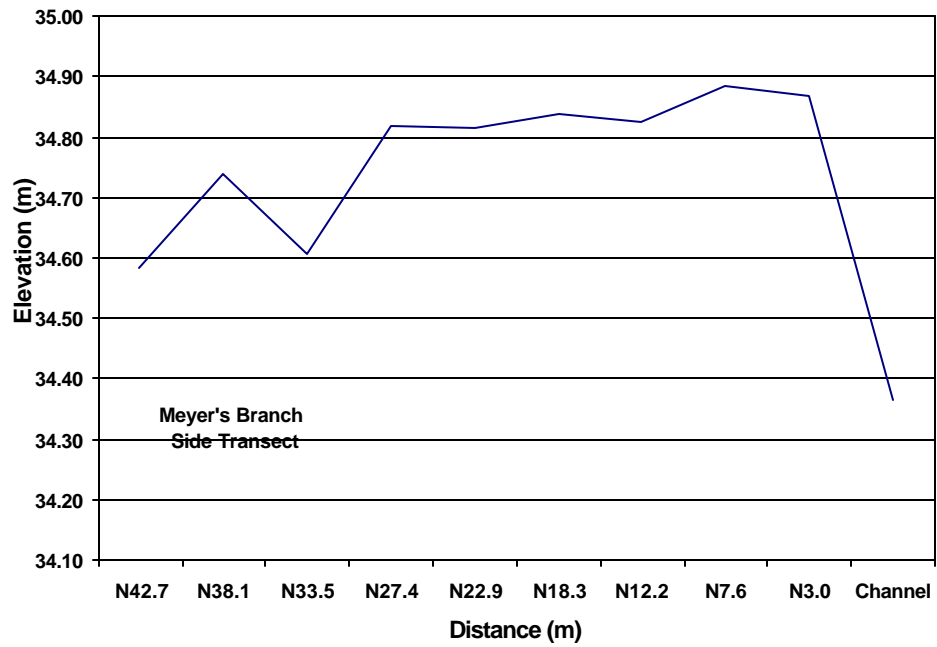
Appendix Figure 1 Continued.



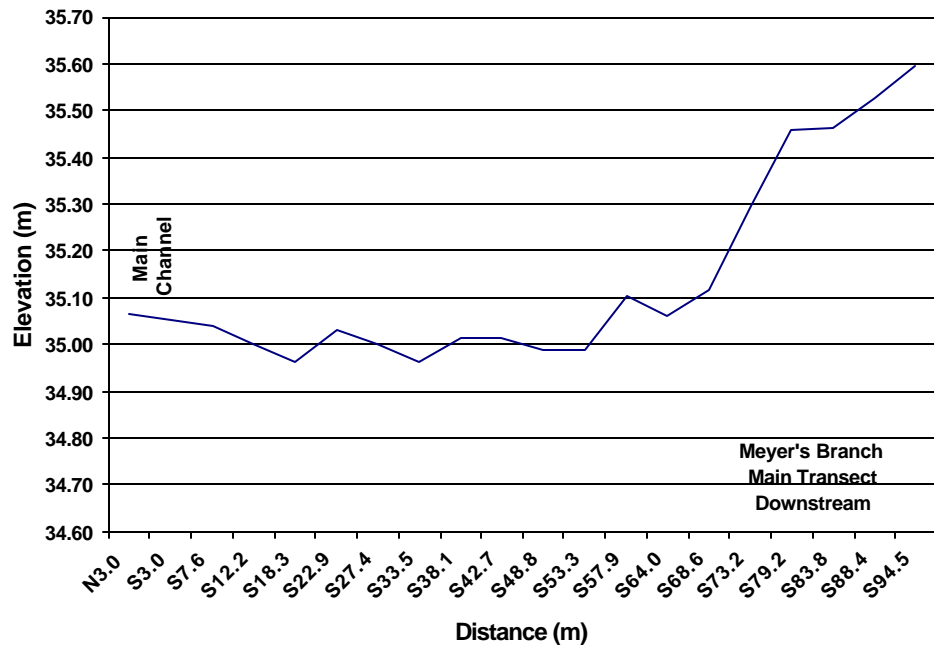
Appendix Figure 1 Continued.



Appendix Figure 1 Continued.



Appendix Figure 1 Continued.



Appendix Figure 1 Continued.

Appendix Table 1. List of all species found within Pen Branch, Fourmile Branch, and Meyer's Branch riparian and upland areas. Form is classified by tree (T), shrub (S), herb (H), and vine (V). The wetland indicator status obtained from the USDI-FWS 'National list of plant species that occur in Wetlands: Southeast (Region 2).'

Species	Code	Form	Wetland Indicator Status
<i>Acer barbatum</i> Michx.	ACBA	T	
<i>Acer rubrum</i> L.	ACRU	T	FAC, OBL
<i>Aesculus pavia</i> L.	AEPA	S	FAC
<i>Agrimonia</i> sp.		H	FAC, FACU
<i>Alnus serrulata</i> (Ait.) Willd.	ALSE	S	FACW+
<i>Alternanthera philoxeroides</i> Griseb.	ALPH	H	OBL
<i>Ampelopsis arborea</i> (L.) Koehne	AMAR	H	FAC+
<i>Anemone</i> sp.		H	
<i>Aronia arbutifolia</i> (L.) Elliott	ARAR	S	FACW
<i>Arundo donax</i> L.	ARDO	H	FACW
<i>Asplenium platyneuron</i> (L.) Oakes	ASPL	H	FACU
<i>Aster</i> spp.		H	
<i>Athyrium Filix-femina</i> (L.) Roth	ALFI	H	NI
<i>Betula nigra</i> L.	BENI	T	FACW
<i>Bidens</i> spp.		H	
<i>Boehmeria cylindrica</i> (L.) Swartz	BOCY	H	FACW+
<i>Callicarpa americana</i> L.	CAAM	S	FACU-
<i>Campsis radicans</i> (L.) Seem.	CARA	V	FAC
<i>Carex lurida</i> Wahlenb.	CALU	H	OBL
<i>Carex</i> spp.		H	
<i>Carpinus caroliniana</i> Walter	CACA	T	FAC
<i>Carya glabra</i> (Mill.) Sweet	CAGL	T	FACU
<i>Carya tomentosa</i> Nutt.	CATO	T	NI
<i>Celastrus scandens</i> L.	CESC	V	NI
<i>Cephalanthus occidentalis</i> L.	CEOC	S	OBL
<i>Chimaphila maculata</i> (L.) Pursh.	CHMA	H	NI
<i>Cicuta maculata</i> L.	CIMA	H	OBL

<i>Commelina virginica</i> L.	COVI	H	FACW
<i>Cornus florida</i> L.	COFL	S	FACU
<i>Cornus foemina</i> Mill.	COFO	S	FACW-
<i>Cuscuta gronovii</i> Willd.	CUGR	H	NI
<i>Cyperus</i> spp.		H	
<i>Daucua carota</i> L.	DACA	H	NI
<i>Dioscorea villosa</i> L.	DIVI	H	FAC
<i>Diospyros virginiana</i> L.	DIVI2	T	FAC
<i>Dulichium arundinaceum</i> (L.) Britton	DUAR	H	OBL
<i>Epigaea repens</i> L.	EPRE	H	NI
<i>Euonymus americanus</i> L.	EUAM	S	FAC-
<i>Fraxinus pennsylvanica</i> Marshall	FRPE	T	FACW
<i>Galium</i> spp.		H	
<i>Gaultheria procumbens</i> L.	GAPR	H	FACU
<i>Gelsemium sempervirens</i> (L.) Ait.	GESE	H	FAC
Grasses		H	
<i>Hexastylis</i> sp.		H	
<i>Hydrocotyle umbellata</i> L.	HYUM	H	OBL
<i>Hypericum densiflorum</i> Pursh	HYDE	H	FACW-
<i>Hypericum mutilum</i> L.	HYMU	H	FACW
<i>Hypericum virginicum</i> L.	HYVI	H	OBL
<i>Ilex decidua</i> Walter	ILDE	S	FACW-
<i>Ilex opaca</i> Soland. in Ait	ILOP	T	FAC-
<i>Ilex verticillata</i> (L.) Gray	ILVE	S	FACW
<i>Impatiens capensis</i> Meerb.	IMCA	H	FACW
<i>Ipomoea</i> sp.		H	
<i>Itea virginica</i> L.	ITVI	S	FACW+
<i>Juncus effusus</i> L.	JUEF	H	FACW+
<i>Juncus</i> spp.		H	
<i>Justica ovata</i> (Walter) Lindau	JUOV	H	OBL
<i>Leersia oryzoides</i> (L.) Swartz	LEOR	H	OBL
<i>Leucothoe axillaris</i> (Lam.) D. Don.	LEAX	S	FACW

<i>Lindera benzoin</i> (L.) Blume	LIBE	S	FACW
<i>Liquidambar styraciflua</i> L.	LIST	T	FAC+
<i>Liriodendron tulipifera</i> L.	LITU	T	FAC
<i>Lobelia cardinalis</i> L.	LOCA	H	FACW+
<i>Lonicera japonica</i> Thunberg	LOJA	V	FAC-
<i>Ludwigia</i> spp.		H	
<i>Lycopus</i> spp.		H	
<i>Lyonia</i> spp.		S	
<i>Magnolia virginiana</i> L.	MAVI	T	FACW+
<i>Mikania scandens</i> (L.) Willd.	MISC	V	FACW+
<i>Mimulus ringens</i> L.	MIRI	H	OBL
<i>Mitchella repens</i> L.	MIRE	H	FACU+
<i>Myrica cerifera</i> L.	MYCE	S	FAC+
<i>Nyssa sylvatica</i> Marsh.	NYSY	T	FAC, OBL
<i>Orchis</i> sp.		H	
<i>Onoclea sensibilis</i> L.	ONSE	H	FACW
<i>Orontium aquatica</i> L.	ORAQ	H	OBL
<i>Osmunda cinnamomea</i> L.	OSCI	H	FACW+
<i>Osmunda regalis</i> L.	OSRE	H	OBL
<i>Ostrya virginiana</i> (Mill.) Koch	OSVI	T	FACU-
<i>Parthenocissus quinquefolia</i> (L.) Planch.	PAQU	V	FAC
<i>Peltandra virginica</i> (L.) Kunth	PEVI	H	OBL
<i>Persea borbonia</i> (L.) Spreng.	PEBO	S	FACW
<i>Pilea pumila</i> (L.) Gray	PIPU	H	FACW
<i>Pinus taeda</i> L.	PITA	T	FAC
<i>Platanus occidentalis</i> L.	PLOC	T	FACW-
<i>Polygonum densiflorum</i> Meisn.	PODE	H	OBL
<i>Polygonum pensylvanicum</i> L.	POPE	H	FACW
<i>Polygonum sagittatum</i> L.	POSA	H, V	OBL
<i>Prunus serotina</i> Ehrhart	PRSE	T	FACU
<i>Quercus alba</i> L.	QUAL	T	FACU
<i>Quercus laurifolia</i> Michx.	QULA	T	FACW

<i>Quercus michauxii</i> Nutt.	QUMI	T	FACW-
<i>Quercus nigra</i> L.	QUNI	T	FAC
<i>Quercus phellos</i> L.	QUPH	T	FACW-
<i>Rhexia</i> spp.		H	
<i>Rhododendrum viscosum</i> (L.) Torr.	RHVI	S	FACW+
<i>Rhynchospora corniculata</i> (Lam.) Gray	RHCO	H	OBL
<i>Rubus</i> spp.		S	
<i>Sagittaria latifolia</i> Willd.	SALA	H	OBL
<i>Salix caroliniana</i> Michx.	SACA2	T	OBL
<i>Salix nigra</i> Marsh.	SANI	T	OBL
<i>Sambucus canadensis</i> L.	SACA	H	FACW-
<i>Saururus cernuus</i> L.	SACE	H	OBL
<i>Scirpus cyperinus</i> (L.) Kunth	SCCY	H	OBL
<i>Smilax</i> spp.		V	
<i>Solidago</i> spp.		H	
<i>Sparganium americanum</i> Nutt.	SPAM	H	OBL
<i>Sphagnum</i> spp.		H	
<i>Taxodium distichum</i> (L.) Rich.		T	OBL
<i>Thelypteris</i> sp.		H	
<i>Toxicodendron radicans</i> (L.)Kuntze	TORA	V	FAC
<i>Tradescantia virginiana</i> L.	TRVI	H	FAC+
<i>Typha latifolia</i> L.	TYLA	H	OBL
<i>Ulmus alata</i> Michx.	ULAL	T	FACU+
<i>Ulmus americana</i> L.	ULAM	T	FACW
<i>Vaccinium elliotii</i> Chapm.	VAEL	S	FAC+
<i>Vaccinium</i> spp.		S	
<i>Viburnum dentatum</i> L.	VIDE	S	FAC
<i>Viburnum nudum</i> L.	VINU	S	FACW+
<i>Viola</i> spp.		H	
<i>Vitis vulpina</i> L.	VIVU	V	FAC+
<i>Vitis</i> spp.		V	
<i>Woodwardia areolata</i> (L.) Moore	WOAR	H	OBL

Appendix-Table 2. Number of species found within each wetland indicator status for the herbaceous clip plots based on topographic position. Species include all forms (tree, shrub, herb and vine).

*Unknown - no species was determined, however, the genus is generally considered a wetland plant.

NI - no indicator status was listed in the USDI-FWS 'National list of plant species that occur in Wetlands: Southeast (Region 2).

	Pen Branch (AR)				Pen Branch (NR)			
Indicator Status	Wet	Int	Dry	Upland	Wet	Int	Dry	Upland
OBL	12	10	5	1	3	7	4	
FACW+	2	1	2	1	1	2	2	
FACW	5	6	3	3	4	5	4	2
FAC+	1	1	1	2		1	2	1
FAC		1		3		1	3	2
FAC-				2				1
FACU				2				2
NI								1
Unknown*	10	8	8	8	3	6	12	8

	Fourmile Branch				Meyer's Branch			
Indicator Status	Wet	Int	Dry	Upland	Wet	Int	Dry	Upland
OBL	8	4	3	2	11	7		1
FACW+	2	3	2	2	5	3		3
FACW	5	6	7	3	6	9	1	3
FACW-			1	1	1	2		
FAC+	1	1	3	1	1	1		3
FAC			5	6	7	5	1	7
FAC-				2	1	1		3
FACU			1	3	1	1		3
NI			3		1	2	1	
Unknown*	7	8	10	9	8	11	1	6

Appendix-Table 3. Species recorded from herbaceous clip plots in June (J) or August (A) of 1997. Species recorded only in 1997 (1) or 1998 (2); i.e. if no number follows four letter code, the species was recorded both years. Four letter code may be found in Appendix Table 1.

Pen Branch Artificial Regeneration (AR)				Pen Branch Natural Regeneration (NR)			
Wet	Int.	Dry	Upland	Wet	Int.	Dry	Upland
Herbs							
ALPH 2	AMAR J1	AMAR 2	ARDO 2	Carex J1	ALPH 2	AMAR A	ARDO 2
AMAR J1	ARDO A	ARDO A	Carex J	CIMA A	AMAR A	Aster 2	Carex 2
BOCY JA	BOCY JA	BOCY J	Galium 2	COVI 2	Bidens 2	Bidens 2	CHMA 2
CALU 2	CALU 2	CALU 2	Grass JA	Grass J	BOCY JA	BOCY JA	Galium 2
Carex JA1	CARA J1	Carex JA1	Hexastylis A	IMCA 2	Carex A	CALU 2	Hexastylis 2
CIMA JA1	Carex J1	CEOC 2	MIRE JA	JUEF A	CIMA J	Carex J	MIRE A
COVI JA	CIMA A1	Galium J1	ONSE A	Juncus J1	COVI A	DUAR 2	TORA JA
Cyperus A1	COVI 2	Grass J1	OSCI 2	LEOR 2	DUAR 2	Galium JA	Viola 2
Galium J1	Cyperus J1	HYVI 2	TORA J1	ONSE 2	Galium J	Grass JA	
Grass JA	DUAR 2	IMCA J	WOAR J	POPE JA1	Grass JA	HYUM J	
HYMU JA1	Galium J1	JUEF J		SALA A1	HYUM 2	IMCA JA	
HYVI 2	Grass A	Juncus J1			IMCA JA	Ipomomea 2	
IMCA 2	HYMU JA	Ludwigia 2			JUEF 2	JUEF 2	
Ipomomea 2	IMCA JA	POPE J1			LEOR 2	Juncus J1	
JUEF JA	Ludwigia J	POSA JA1			Lycopus J1	Lycopus 2	
Juncus J1	PIPU J1	Solidago 2			ONSE J	ONSE JA	
LEOR 2	PODE A1	WOAR 2			PIPU 2	PIPU 2	
Ludwigia JA	POPE JA				PODE 2	POPE JA	
Lycopus 2	POSA JA1				POPE JA1	POSA J1	

MIRI A	Rhexia A1				SACE 2	Solidago 2	
ONSE 2	SACE J1				Solidago 2	Thelypteris 2	
Pen Branch (AR) Herbs Continued				Pen Branch (NR) Herbs Continued			
Wet	Int.	Dry	Upland	Wet	Int.	Dry	Upland
PODE A	SALA A1				TORA 2	TORA 2	
POPE JA	SCCY 2					Viola 2	
POSA J	Solidago 2					WOAR 2	
SALA J	SPAM 2						
SCCY A	TYLA 2						
Solidago JA							
TYLA 2							
WOAR J1							
Shrubs							
Rubus JA	Rubus JA	Rubus JA	EUAM 2		Rubus JA	CEOC 2	EUAM A
			ILOP J			MYCE J1	ILVE 2
			MYCE 2			Rubus JA	Vaccinium 2
			PEBO 2				
			Vaccinium JA				
Trees							
	ACRU J		ACRU 2			ACRU 2	CAGL 2
			Carya 2				Quercus J
			LIST 2				QUNI 2
			Quercus J				
Vines							
			PAQU 2			PAQU 2	Smilax JA
			Smilax J				Vitis JA
			Vitis A				VIVU 2

Appendix Table 3 Continued.

Fourmile Branch				Meyer's Branch			
Wet	Int.	Dry	Upland	Wet	Int.	Dry	Upland
Herbs							
ALPH 2	AMAR 2	ALFI J	AEPA J1	AMAR 2	Agrimony 2	TORA J	AMAR J1
AMAR 2	Aster 2	AMAR 2	AMAR 2	BOCY A	ALFI JA		ARDO 2
BOCY JA	BOCY JA	ARDO 2	ARDO 2	Carex JA	AMAR JA		CHMA A
Carex 2	Carex J1	Aster 2	ASPL 2	GESE J1	ARAR A1		Galium JA
CIMA JA	CIMA JA1	BOCY J	BOCY JA	Grass JA	BOCY JA		GESE 2
COVI JA	COVI JA	Carex JA	Carex J	HYUM JA	Carex A		Grass J
Galium J1	Galium J1	COVI 2	DUAR 2	HYVI A	Galium J1		Hexastylis JA
Grass JA	Grass J1	DACA 2	Galium J	IMCA JA1	Grass JA		IMCA J1
HYMU 2	HYMU JA1	Galium J	Grass JA	JUOV 2	HYUM J		MIRE J
HYVI 2	HYVI 2	GESE J	HYDE A1	LOCA A1	IMCA JA		OSCI JA
IMCA JA1	IMCA JA	Grass JA	HYMU A1	Ludwigia J1	Juncus 2		TORA JA
JUEF A	JUEF J	HYMU A	HYVI 2	Lycopus A	JUOV 2		TRVI 2
LEOR A	Lycopus JA	HYUM J	IMCA J1	MIRE 2	Lycopus A1		WOAR JA
Ludwigia A1	ONSE JA	IMCA JA	Ipomomea 2	ONSE A	MIRE J1		
Lycopus 2	PIPU 2	JUEF JA	JUEF A1	ORAQ JA	ONSE JA1		
ONSE JA	PODE A1	Lycopus 2	MIRE JA	OSCI A1	ORAQ A		
PODE JA	POPE J1	ONSE JA	Solidago J1	OSRE JA	Orchis 2		
POPE 2	Solidago J	PIPU 2	TORA A	PEVI JA1	PEVI A1		
POSA A1	WOAR JA	SACA 2		PIPU JA	PIPU 2		
SACE A		SCCY 2		POPE J1	POPE A1		
SALA 2		Solidago JA		RHCO 2	SACA 2		
Solidago J		TORA J		SACA A	SACE JA		

		WOAR JA		SACE JA	SALA 2		
				SALA 2	Solidago 2		
Fourmile Branch (Herbs Continued)				Meyer's Branch (Herbs Continued)			
Wet	Intermedia te	Dry	Upland	Wet	Intermedia te	Dry	Upland
				Solidago J1	TORA JA		
				Sphagnum 2	Viola A1		
				TORA JA	WOAR A		
				Viola 2			
				WOAR JA			
Shrubs							
Rubus J	ALSE 2	MYCE J1	CAAM J	ALSE 2	ITVI JA	LEAX JA	AEPA 2
	Rubus JA	Rubus JA	DIVI A1	ITVI JA	LEAX JA	Rubus J	Azalea J
			EUAM 2	LEAX JA	LIBE 2		LEAZ JA
			Rubus JA	Rubus JA	Rubus JA		MAVI 2
			Vaccinium 2	VIDE JA	VIDE JA		MYCE J
					VINU A		RHVI 2
							VIDE A
Trees							
		Carya 2	Carya J1	ACRU J	ACRU J		ACRU JA1
		LIST 2	ILOP J1	FRPE A1	BENI J1		Carya J1
		QULA/NI 2	QULA/NI 2	LIST J1	CACA 2		ILOP JA
		Salix 2			QULA J1		LIST J1
					QUPH A		PRSE J1
							QULA/NI JA
Vines							
	Vitis 2	CARA J	CARA J	CARA J1	CESC 2	CESC 2	LOJA 2
		CESC 2	PAQU J1	CESC 2	LOJA 2		PAQU J

		PAQU J	Smilax J	LOJA 2	PAQU J		Smilax JA
		Smilax 2	Vitis JA	PAQU JA	Smilax JA		Vitis JA
		Vitis J		Vitis 2			

Appendix Table-4 Regression equations for determining tree and shrub biomass.

Shrub Species	Equation	DBH Range/r ²	Reference
<i>Acer rubrum</i> , <i>A. bacata</i> <i>Aronia arbutifolia</i>	$380.508 + 31.52 * (DBH_{cm}^2 * Ht_m)$	r ² =0.9562	Hauser
<i>Alnus serrulata</i> , <i>Callicarpa americana</i> , <i>Forestiera acuminata</i> , <i>Itea virginiana</i> ,	EXP (3.124 + (2.7354 * Ln (DBH _{cm}))) <i>Myrica cerifera</i> , <i>Sambucus canadensis</i> , <i>Vaccinium</i> , <i>Viburnum dentatum</i>		Mader
<i>Carpinus Caroliniana</i>	$108.511 + 30.207 * (DBH_{cm}^2 * Ht_m)$ $((3.29895 * (DBH_{in}^2))^{1.19583}) * 450$	r ² =0.9554	Hauser (OXAR) Clark (Carya)
<i>Carya glabra</i>	$((3.299 * (DBH_{in}^2))^{1.196}) * 450$		Clark
<i>Cephalanthus occidentalis</i>	$(10^{(-0.712 + 1.744 * \log (DBH_{cm}))} * 1000)$		Muzika
<i>Cornus foemina</i>	$10^{(2.54 + (1.928 * \log (DBH_{cm})))}$		P&C ¹ (COFL)
<i>Diospyros virginiana</i>	$((1.822 * (DBH_{in}^2))^{1.264}) * 450$		Clark
<i>Fraxinus pennsylvanica</i> , <i>Aesculus pavia</i>	EXP(4.149 + (2.203*Ln (DBH _{cm})))	2-48 mm	Mader (FRCA)
<i>Ilex opaca</i> , <i>I. glabra</i> , <i>I. decidua</i> <i>Persea borbonia</i>	$337.443 + 42.665 * (DBH_{cm}^2 * Ht_m)$	r ² =0.9947	Hauser
<i>Liquidambar styraciflua</i>	$80.364 + 22.603 * (DBH_{cm}^2 * Ht_m)$	r ² 0.9868	Hauser
<i>Liriodendron tulipifera</i>	$10^{(2.165 + (2.363 * \log (DBH_{cm})))}$		P&C
<i>Magnolia Virginiana</i>	$-122.84 + 29 * (DBH_{cm}^2 * Ht_m)$	r ² =0.8840	Hauser
<i>Nyssa sylvatica</i>	$((0.175 * (DBH_{in}^2 * Ht_{ft}))^{0.91}) * 450$ $565.7 + 26.653 * (DBH_{cm}^2 * Ht_m)$	r ² =0.9510	Hauser (soft Hdwd)
<i>Ostrya virginiana</i> HYDE	$755.121 + 42.751 * (DBH_{cm}^2 * Ht_m)$		Hauser
<i>Pinus taeda</i>	$(10^{(-1.029 + 0.988 * \log((DBH_{in}^2 * Ht_{ft})))}) * 450$	r ² =0.9056	Hauser
<i>Quercus velutina</i> , <i>Q. laurifolia</i> , <i>Q. nigra</i> , <i>Q. lyrata</i>	$108.511 + 30.207 * (DBH_{cm}^2 * Ht_m)$ $1280.568 + 39.4 (DBH_{cm}^2 * Ht_m)$	r ² =0.9376	Hauser
<i>Sabal minor</i>	Rachis EXP (-10.38 + (2.72*Ln(Rachis _{cm}))) Fronde -13.31 + (0.85*Fronde _{cm})		Ghoetz
<i>Salix nigra</i> , <i>Betula nigra</i>	$(10^{(-1.017 + 2.07 * \log (DBH_{cm}))} * 1000)$		Muzika
<i>Taxodium distichum</i>	EXP (4.247 + (2.144 * Ln (DBH _{cm})))		Mader
<i>Ulmus americana</i>	$10^{(2.22 + (2.391 * \log (DBH_{cm})))}$		P&C (ULRU)

Appendix Table-4 continued.

Tree Species	Equation	DBH Range/r ²	Reference
<i>Acer rubrum</i> , <i>Fraxinus pennsylvanica</i> , <i>Platanus occidentalis</i> , <i>Sambucus canadensis</i>	$((0.149 * (DBH_{in}^2 * Ht_{ft})) ^ 0.94)*450$ $8.299 + 0.3714*DBH_{cm}$ $9.76 + 3.9*DBH_{in}$	r ² =0.99 r ² =0.3172	Hauser Clark et al.
<i>Alnus serrulata</i> , <i>Myrica cerifera</i>	EXP (3.124 + (2.7354 * Ln (DBH _{cm})))		Mader
<i>Carpinus caroliniana</i> , <i>Ilex opaca</i> , <i>Ostrya virginiana</i>	$((0.2251 * (DBH_{in}^2 * Ht_{ft})) ^ 0.924)*450$	r ² =0.99	Hauser (Hd Hdwd); Clark et al.
<i>Carya glabra</i>	$((3.299 * (DBH_{in}^2)) ^ 1.196)* 450$ $((1.613 * (DBH_{in}^2)) ^ 1.334)* 450$		Clark P&C > 11"
<i>Cephalanthus occidentalis</i>	$(10^{(-0.712 + 1.744 * \log (DBH_{cm}))} * 1000)$		Muzika
<i>Cornus florida</i>	$10 ^ (2.54 + (1.928 * \log (DBH_{cm})))$		P&C
<i>Diospyros virginiana</i>	$((1.822 * (DBH_{in}^2)) ^ 1.264)* 450$		Clark
<i>Liquidambar styraciflua</i> , <i>Tilia americana</i>	$((0.132 * (DBH_{in}^2 * Ht_{ft})) ^ 0.9416)*450$	r ² =0.99	Hauser Clark et al.
<i>Nyssa sylvatica</i> , MAAN	$((0.175 * (DBH_{in}^2 * Ht_{ft})) ^ 0.91)*450$	r ² =0.99	Hauser (soft Hdwd); Clark et al.
<i>Pinus taeda</i>	$(10 ^ (-1.029 + 0.988 * \log((DBH_{in}^2 * Ht_{ft}))) * 450$	r ² =0.99	Hauser; Clark & Taras
<i>Quercus alba</i>	$((0.2 * (DBH_{in}^2 * Ht_{ft})) ^ 0.939)*450$	r ² =0.99	Hauser; Clark et al.
<i>Quercus nigra</i>	$((0.237 * (DBH_{in}^2 * Ht_{ft})) ^ 0.923)*450$	r ² =0.99	Hauser; Clark et al.
<i>Salix nigra</i> , <i>Betula nigra</i>	$(10 ^ (-1.017 + 2.07 * \log (DBH_{cm})) * 1000)$		Muzika
<i>Taxodium distichum</i>	$((0.1066 * (DBH_{in}^2 * Ht_{ft})) ^ 0.935)*450$		Mader
<i>Ulmus americana</i> , <i>U. alata</i>	$10 ^ (2.22 + (2.391 * \log (DBH_{cm})))$		P&C (ULRU)

1) P&C refers to Peet and Council

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