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A Dendroecological Evaluation of the Effects of Coal Ash on Tree Growth, Kingston Fossil Plant, Harriman, Tennessee, U.S.A.

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To the Graduate Council:

I am submitting herewith a thesis written by Niki Ann Garland entitled "A Dendroecological Evaluation of the Effects of Coal Ash on Tree Growth, Kingston Fossil Plant, Harriman, Tennessee, U.S.A.." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

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A Dendroecological Evaluation of the Effects of Coal Ash on Tree Growth, Kingston Fossil Plant, Harriman, Tennessee, U.S.A.

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Niki Ann Garland

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ABSTRACT

Tree growth is a function of many environmental variables, and it is possible to detect differences between natural and human-related factors on tree growth. Radial growth of trees in one year and in subsequent years that follow is influenced not only by climate and other overarching multi-year processes, but also by pulse disturbance events. On December 22, 2008, an embankment at an impoundment for wet storage of fly ash at the Kingston Fossil Plant, Harriman, Tennessee collapsed, releasing 4,434,400 cubic meters of coal ash into the Clinch and Emory Rivers, impacting aquatic life as well as terrestrial flora and fauna. My study assesses the effects of coal ash on tree growth on two particularly impacted islands (Island 1 and Island 2) in the Emory River. I collected increment cores from 106 trees on Island 1 and from 20 trees on Island 2, totaling 126 trees and 143 increment cores. After excluding problematic cores that were too short, too decayed, or too broken, a total of 44 increment cores were analyzed for growth suppressions. No growth suppression events were detected that would indicate adverse effects from the coal ash spill. Possible explanations include : (1) ring widths alone may not be the best evidence of suppression; (2) it could be too early to detect the impact of the spill on tree growth with only three years of tree growth; (3) growth release from competition on the TVA islands could have compensated for any growth suppression; (4) all trees that died or suffered major damage were physically removed by TVA; (5) water level fluctuation and flood potential for the trees growing on the TVA islands could have masked or disrupted the disturbance signal from the spill; (6) soils on Island 2 could have been supplemented with high levels of nutrients that could have enhanced tree growth instead; and (7), the Kingston Ash Spill could have had no detrimental effect on tree growth.

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CHAPTER ONE

1.0 INTRODUCTION

The construction of the Kingston Fossil Plant in Harriman, Tennessee began in 1951 and was completed in 1955. At that time, it was the largest coal-burning power plant in the world and held this distinction for nearly 10 years. Prior to construction, land uses in this area were typical of most other land in the Tennessee Valley (TVA 2009). Subsistence farming with row crops and pastures interspersed with woodlands were the primary land use type for the Tennessee Valley. Woodlands were burned regularly to promote growth of annuals and other forage plants or were grazed by livestock. Construction lumbers were periodically harvested to provide firewood and other wood products, thus leaving these areas susceptible to severe soil erosion. After the acquisition of the TVA property, loblolly and shortleaf pines were planted in open areas while other areas were allowed to return to their natural state, which included hickory (*Carya* spp.), eastern redcedar (*Juniperus virginiana* L.), Virginia pine (*Pinus virginiana* Mill.), and other hardwoods (TVA 2009). Currently, public land surrounding Watts Bar Reservoir can be broken into five broad community types: forest, open/agricultural land, shrub/brush land, wetland, and residential habitats (TVA 2009).

Tennessee Valley Authority's Kingston Fossil Plant is located on Watts Bar Reservoir. This reservoir encompasses parts of the Clinch and Emory Rivers, which flow northeast to southwest, and is used for navigation, flood control, hydroelectric power, and recreation. The Watts Bar Reservoir is located in the Appalachian Ridge and Valley physiographic province of Mideastern Tennessee (TVA 2009) and lies within the ecological subregion referred to as the

Eastern Broadleaf Forest (Oceanic) province (Bailey *et al*. 2004). The primary forest of the Central Ridge and Valley is oak-pine forest with southern oak (*Quercus virginiana* Mill.), post oak (*Quercus stellata* Wangenh.), blackjack oak (*Quercus marliandica* Muenchh.), chestnut oak (*Quercus montana* Willd.), and scarlet oak (*Quercus coccinea* Muenchh.) dominating drier sites, and white oak (*Quercus alba* L.), eastern black oak (*Quercus velutina* Lamb.), and southern red oak (*Quercus falcata* Michx.) dominating more mesic sites. Other tree species that contribute to the composition of the oak-pine forest are several hickory species (pignut (*Carya glabra* Mill.), mockernut (*Carya tomentosa* Sarg.), bitternut (*Carya cordiformis* Wangenh.), and shagbark (*Carya ovata* Mill.)), several pine species (Virginia (*Pinus virginiana* Mill.), white (*Pinus strobus* L.), shortleaf (*Pinus echinata* Mill.), and loblolly (*Pinus taeda* L.)), black gum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.), sweetgum (*Liquidambar styraciflua* L.), slippery (*Ulmus rubra* Muhl.) and American elms (*Ulmus americana* L.), and some large willow oaks (*Quercus phellos* L.). A significant portion of the stands are dominated by hardwoods while pine stands are secondary in coverage area (TVA 2009).

The Tennessee Valley Authority Kingston Fossil Plant currently generates enough electricity yearly to power approximately 540,000 homes in the Tennessee Valley Region. Kingston Fossil Plant uses nine coal-fired units to heat water in a boiler to produce steam. This steam, under extremely high pressure, is forced through a turbine that spins a generator to create electricity. The byproduct of this burning is called coal ash. The components of coal ash vary considerably and are dependent on the source and the makeup of the coal being burned. Both silicon dioxide (SiO_2) and calcium oxide (CaO) are components of all fly ash in varying amounts depending upon the provenance of the coal. Coal ash contains trace levels of arsenic,

barium, beryllium, boron, cadmium, chromium, thallium, selenium, molybdenum, and mercury (Ruhl 2009).

On December 22, 2008, an embankment at an impoundment for wet storage of fly ash at the Kingston Fossil Plant collapsed, releasing 4,434,400 cubic meters of coal ash into the Clinch and Emory Rivers, impacting aquatic life as well as terrestrial flora and fauna. Subsequent to the spill, TVA acquired approximately 364 hectares of potentially affected private land on Watts Bar Reservoir around the Kingston Fossil Plant. Current plans for this property include green space and a community recreation area (TVA 2011). The areas affected by the spill have been undergoing intense restoration in the months and years since the collapse. Furthermore, several studies have been conducted in the vicinity of the Kingston Ash Spill to evaluate the health of the fish, mammals, birds, sediments, and aquatic vegetation (TVA 2011). This study was conducted in the immediate vicinity of the Kingston Fossil Plant on two islands in the Clinch and Emory Rivers, examining trees that would most likely have been impacted by coal ash.

While tree growth is largely a function of environmental conditions, it is possible to detect differences between natural factors and human-caused factors on tree growth (Kim 1995; Boone 2004). Radial growth of trees is influenced not only by climate, but also by pulse disturbance events, such as volcanic eruptions, earthquakes, and insect outbreaks (Fritts and Swetnam 1989). In addition, and especially relevant to this study, ground and air pollutants influence tree growth and forest health (McClenahen and Dochinger 1985; Fox *et al*. 1986; Sutherland and Martin 1990), even here in the Southeastern U.S. (Anderson *et al*. 2000; Webster *et al*. 2004) and on the grounds of the nearby Oak Ridge National Laboratory (McLaughlin *et al*. 1982; Barlar 2000; Cassidy 2004).

Separating the various factors that affect tree growth is possible because growth can be modeled as a function of five major factors, known as the principle of aggregate tree growth (Cook 1985, 1987). This principle states that tree-ring growth in any one year can be decomposed as a function of climate, disturbance events, and random error, and allows researchers to identify those factors that are the topic of study (signal) while accounting for those factors that would be considered noise (Speer 2010). The model states that:

$$R_t = f(G_t, C_t, \delta D_{1t}, \delta D_{2t}, E_t)$$

where tree-ring width in any one year (R_t) is a function of the age-related growth trend (G_t), climate (C_t), any endogenous disturbances that arise within or near the forest stand ($D1_t$), any exogenous disturbance that arise from outside the forest stand ($D2_t$), and any signal that is not controlled by for the other variables (E_t). The delta notation δ indicates presence (1) or absence (0) of that disturbance. The Kingston Ash Spill represents an endogenous disturbance.

My main objectives for this study were to: (1) identify living trees that may have been affected by the Kingston Ash Spill that occurred on December 22, 2008 using aerial photographs that serve as a post-spill reference; (2) extract cores from multiple living trees to determine if a disturbance in radial growth occurred in the years following the coal ash spill; (3) if a disturbance is found, quantify the disturbance by determining the magnitude of impact on the radial growth of living trees; and, (4) examine climate trends from an area physiographically similar to the Kingston Fossil Plant to eliminate climate as a potential growth suppression factor in the trees at the coal ash spill site. I did not focus on tree mortality, but rather on living trees that currently stand on TVA property because this study required multiple years of tree growth to evaluate the magnitude of the possible disturbance on growth rates.

1.1 Research Questions

To meet these objectives, this project seeks to obtain answers to the following specific research questions:

1. Do tree species exist in the area of the Kingston Ash Spill that can be examined using dendroecological techniques?
2. Did the Kingston Ash Spill cause changes in tree growth rates? If so, to what degree were the growth rates altered? If not, what factors could explain this absence of evidence?
3. What is the potential for extending and expanding this research to better understand the effects of the Kingston Ash Spill on the surrounding forests?

CHAPTER TWO

2.0 LITERATURE REVIEW

This literature review addresses groundwater, surface water, and air pollution studies. These studies were chosen as a framework to build upon because current literature does not address the impact of coal ash on tree growth. These studies proved to be the most relevant studies to the current study and provided the methodology to support the development of this investigation.

2.1 Groundwater Pollution

2.1.1 Specific to the Southeastern U.S.

LeBlanc *et al.* (1991) used dendrochronological techniques to examine the effects of contaminated groundwater seepage on tree growth. The project was conducted at two seepage basins (F- and H-Areas) down slope from the Department of Energy's Savannah River Site (SRS) in South Carolina. Localized forest decline occurred downslope from the seepage basins beginning in the early 1980s; groundwater contamination was identified as the probable cause of tree mortality. The objectives of this study were : (1) to determine the historical development of forest decline in the F- and H-Areas; and (2) to evaluate the relationships between growth decline and climatic stresses.

Historically, seepage basins in both areas were constructed to receive effluent from chemical processing operations at SRS beginning in the late 1950s. They received acidic, low level radioactive waste that included nitric acid, sodium hydroxide, tritium, and various heavy

metals (Killian *et al*. 1987) until 1988 when seepage basin operations ceased. Seepage occurred from the basins to the wetland via the unconfined aquifer.

Using standard dendrochronological methods, the most common tree species were sampled by taking tree cores in “dieback areas” and “unaffected areas” in both study sites. Basal area increment (BAI) was used as an index of both vigor and tree growth instead of annual ring width. Environmental stress on tree growth was determined using deviation from expected trends of BAI. The relationships between growth decline and climate was evaluated using correlation analyses between year-to-year variation in tree-ring width and seasonal mean temperature and total precipitation.

All four taxa (*Pinus taeda* L., *Quercus* spp., *Liriodendron tulipifera* L., and *Liquidambar styraciflua* L.) showed growth decline during the post-1970 period using mean BAI curves; however, they differed in the timing and nature of the decline. Radial growth decline was associated with severe droughts in 1977 and 1986 and a significant correlation was found between radial growth and growing season precipitation during the period 1965–1987. The period 1977–1986 had moderate droughts, while two years had severe droughts. Results indicated that tree mortality in forests downslope from the seepage basins of both areas were impacted by the interaction of drought and contaminate-induced stress. Drought may have intensified the concentrations of contaminates in groundwater seeps, resulting in increased mortality and decreased tree growth. However, drought stress appeared to be the most likely cause of localized forest decline.

2.1.2 Outside of the Southeastern US

Edmands *et al*. (2001) examined the uptake and mobility of uranium (U) by two black oak trees (*Quercus velutina* Lamb.) in a Concord, Massachusetts bog. This bog is adjacent to a nuclear industrial facility that had processed depleted uranium (DU) since 1959. DU had been leaking from an onsite holding basin and cooling pond down to the bog from the processing plant. Uptake and mobility were assessed by measuring the isotopic composition of tree rings. Edmands noted that DU is easily discernible from natural U because DU has no outside source other than the industrial facility. The occurrence of DU in bark, heartwood, and sapwood back to 1937, pre-dating the introduction of DU at the site, was confirmed using isotope ratio analysis. DU being present throughout the tree rings suggests that U is mobile, and possibly diffused through the tree wood. The results indicated that concentrations of U in sapwood were approximately equal to the average U concentrations in groundwater onsite over the past 10 years, therefore suggesting that sapwood and bark analyses are an alternative to drilling wells to monitor shallow groundwater U contamination.

2.2 Water Pollution

2.2.1 Specific to the Southeastern U.S.

Latimer *et al.* (1996) constructed a 101-year tree-ring chronology from baldcypress (*Taxodium distichum* (L.) Rich.) growing in Bayou Trepagnier in southern Louisiana. They noted that human activities in recent years had produced higher levels of heavy metals in the environment and that these metals had become more widespread in ecosystems. Heavy metals enter plants through leaves, roots, and bark. Dendrochronological studies assume that the

chemical makeup of the tree rings reflects the chemistry of the environment in which it is growing (Amato 1988). In Bayou Trepagnier, heavy metals and organic pollutants from a local oil refinery polluted the area in the early 1900s.

Latimer *et al.* cored 50 baldcpyress growing in the bayou but were able to crossdate and conduct climate analysis on just 26 trees. Stinking Bayou was chosen as a control site because it was similar to Bayou Trepagnier in ecology. Climate analysis on the 26 trees indicated that precipitation in February of the preceding year and October of the two previous years was most significant for tree growth. Using x-ray fluorescent spectrometry, Latimer *et al*. produced a historical record of pollution examining lead (Pb) and Zinc (Zn) in the Bayou Trepagnier tree cores. Increased levels of both Pb and Zn in the tree cores were correlated with the establishment of the oil refineries (1916) and dredging (1930–1950) which increased levels of heavy metals in the bayou banks. Concentrations of Pb in the trees were highest in the upper portions of the bayou near the refinery (~ 4.5 ppm) while trees in the lower portion of the bayou contained lower Pb levels (~ 2.2 ppm). Concentrations of Zn did not correlate with distance from pollution sources as did Pb. Trees in the upper and lower portions of the bayou showed Zn average levels of 5.5 and 5.4 ppm). Pb and Zn levels in the trees from Stinking Bayou, the control site, were 1.0 and 5.2 ppm, respectively.

At this same bayou, Marcantonio *et al.* (1998) analyzed the Pb isotopic composition of tree rings from seven of the same trees analyzed by Latimer *et al.* (1996). Tree samples were chosen from both highly contaminated areas (spoil banks) of Bayou Trepagnier and from areas that were considered to be less contaminated. This study was considered the first to use Pb isotope tree-ring records to assess the sources and extent of heavy-metal contamination of the

environment through time. Marcantonio *et al.* noted that the distinct isotopic signatures are the key to discriminating between pollutant and natural Pb within cypress wood. Trees that that were gathered from and near the more contaminated areas of the bayou contained the highest fraction of Pb while the trees collected the farthest from the high-contamination spoil banks had the lowest fraction of Pb. They concluded that local hydrological processes as well as chemical processes determined the amount of contaminate Pb metabolized by the tree roots and that high concentrations of Pb in tree wood did not imply a greater extent of pollutant uptake.

2.3 Airborne Pollution

2.3.1 Specific to the Southeastern U.S.

Baes and McLaughlin (1984) explored trace elements in shortleaf pine (*Pinus echinata* Mill.) in Great Smoky Mountains National Park. They noted that increasing levels of trace metals have been found in growth rings from shortleaf pine in the east Tennessee area since the 1950s and that most elements have been serially correlated with growth. However, since the 1970s, as metal content increased, growth rates decreased. During the period 1863–1912, trees up to 88 km away from Copper Hill, Tennessee were exposed to increased levels of Fe and SO_2 due to the fumigation plume moving downwind of the facility.

Baes and McLaughlin searched for evidence of increased regional atmospheric pollution in eight hardwood and six conifer species at sites in Oak Ridge, Tennessee and in the GSMNP. They used inductively coupled plasma optical emission spectroscopy to conduct multi-element analysis of the tree rings and found that, at all sites, the highest trace metals were found in the living phloem and cambium tissues. The levels were known to be toxic in aboveground tissues

of agricultural and herbaceous plants but it was unknown if they were toxic in tree tissue. Baes and McLaughlin concluded that the close temporal relationship between Copper Hill history and reduced tree growth and increased Fe xylem accumulation rates at Cades Cove provided evidence that trees at each site were affected by the smelting operations.

Long *et al.* (1999) examined growth variations of white oak (*Quercus alba* L.) trees that were subjected to historic levels of fluctuating air pollution from a coal-fired power plant in Pennsylvania that began operations in 1954. Growth variations in white oak were compared between 3 in-close sites and 3 control sites located 10–50 km away from the power plant. Long *et al*. noted that stack heights at the plant varied through time and hypothesized that differing stack heights influenced ground pollution levels, primarily SO_2. Results indicated that when the stacks were at the lowest height, pollution was the greatest. White oak at two in-close sites showed a growth reduction during this time, while the third site showed no impact. In 1976, taller stacks were constructed, reducing ground-level contaminants. Increased growth responses at two in-close affected sites were noted from 1976–1985. Growth rates after 1976 for white oak, at all three in-close sites, were comparable to growth rates of white oak growing at the control sites. Long *et al*. noted that the mid-1960s drought could have been an interacting factor that contributed to suppressed radial growth.

Webster *et al.* (2004) explored the interactions between pollutant emissions and climatic variability in growth of red spruce (*Picea rubens* Sarg.) in Great Smoky Mountains National Park. They hypothesized that atmospheric pollutants and/or climatic conditions, both of which have changed beyond ranges of natural variability, were related to a decline in radial tree growth. They evaluated whether: (1) the decline in radial growth, which started in the middle

of the 20th century, reached unprecedented levels in terms of mean and/or standard deviation; (2) radial growth was connected to climatic variables and/or atmospheric pollutants; (3) the sensitivity of radial growth to climate and/or atmospheric pollutants varied with elevation; and (4) dendrochemistry could provide insight into the causes of changes in radial growth during the 20th century.

Webster *et al*. determined that radial growth decline in red spruce was not unprecedented, but that previous declines (1940–1970) could be linked to local smelting operations taking place in the 1940s near the selected sites. By 1970, the Clean Air Act was passed, which helped reduce sulphur dioxide emissions, therefore possibly resulting in a recovery in radial growth. They also concluded that red spruce near mountain ridges appeared to respond faster to atmospheric pollutants than did trees in mountain draws. Since the 1940s, emissions of nitrogen oxide (NO_x) and sulphur dioxide (SO_2) explained 42.9% of the radial growth pattern for trees near the mountain ridges while emissions of NO_x and SO_2 were not related to radial growth of trees in the mountain draws. Webster *et al*. noted that changes in the emissions of NO_x and SO_2 are immediate in the areas near mountain ridges but that recovery is possible if emissions are controlled. However, they also noted that while NO_x and SO_2 are not linked to radial growth decline in mountain draws, the effects could have been delayed and then manifested 20 years later if emissions had not been restricted.

2.3.2 Outside of the Southeastern US

Thompson (1981) explored the interactions between tree rings and air pollution in single-needle pinyon pine (*Pinus monophylla* Torr. & Frém.) in east-central Nevada. Two research sites near a copper smelter in McGill, Nevada were chosen for dendrochronological analysis. Site 1, Duck Creek Range West, was located on a slope just above the smelter and was regularly fumigated by the smelter plume. Site 2, Berry Creek, was located east of Duck Creek Range West and was occasionally fumigated by the smelter plume. Three control sites were chosen that varied in distance from the copper smelter from 15 to 80 km.

Standard dendrochronological techniques were applied to remove the age-related trend thus amplifying signals from pollution, regional climate, and other growth-limiting factors at each site. Site 1 revealed a decrease in mean tree growth that was lower than all of the four other sites from 1910–1930, a time of high mining activity. However, Thompson noted that other periods of high mining activity after 1930 did not result in mean tree growth reduction as measured by ring width. Climatic influences were apparent at all five sites as indicated by high values of mean sensitivity and standard deviations. However, the first order autocorrelation values in the two pollution site chronologies were much higher than the control chronologies, indicating that some non-climatic factor had a lasting effect on tree growth. Only at Site 1 were trees limited by both non-climatic and climatic variables in the pollution period (1908–1964). Ring widths were reduced from approximately 1910–1940, after which ring-width growth greatly increased. This may be attributed to the fact that smelter pollutants decreased around 1933. For the Site 2 chronology, first-order autocorrelation was high, but the amount of low frequency variance in the chronology did not change from the pre-pollution period to the

pollution period. Because of this, Thompson decided to treat Site 2 as another control chronology.

Sutherland and Martin (1990) examined the growth response of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) to air pollution from copper smelting in the Oquirrh Mountains of Utah. Two research sites were chosen because of their proximity to the smelter. One was 9.5 km (close site) from the smelter and the second was 15.5 km distant (intermediate site). The control site, 27.0 km from the smelter, was chosen because no smelter-induced damage to the vegetation was documented, and because it was within the same physiographic region as the research sites. Their objective was to model radial growth response of Douglas-fir to known SO_2 emissions using standard dendrochronological and regression techniques. To determine the relative effect of SO_2 at the polluted sites, a subtraction technique was used to remove climatic variation.

Results showed that SO_2 negatively affected the growth response of trees located at the close and intermediate sites. At both sites, many absent rings in the increment cores were found during the period of smelting (1907–1987). No absent rings were noted in the increment cores at the control site. Autocorrelation was highest at the closest sites and lowest at the control site, suggesting a long term disturbance to polluted trees. SO_2 accounted for 54% of the non-climatic growth variance at the closest site and 6% at the intermediate site.

Boone *et al*. (2004) used dendrochronological techniques to examine the radial growth of bur oak (*Quercus macrocarpa* Michx.) and quaking aspen (*Populus tremuloides* Michx.) near a 132 MW coal-fired generating station in Manitoba, Canada. The objective of this study was to determine if airborne emissions from the power plant inhibited radial growth in trees or could

be linked to forest decline. Boone *et al*. (2004) analyzed climatic and non-climatic variations in radial growth in 18 mixed stands dominated by the two species. Sixteen stands were within a 16-km radius of the station and two control stands were sampled outside of the affected range. A decrease in radial growth was found in all oak and aspen stands as well as in the control stands, which suggested that the decline was not related to heavy metals or sulphur dioxide emissions from the plant, but was more likely a result of age effects and stand dynamics. Boone *et al*. (2004) noted that emissions from this generating station were likely too low and discontinuous to have had widespread effects on tree growth due to the small size of the station as well as operations being less than 20% capacity on average. Thompson (1981) and Fox *et al*. (1986), however, established that ambient sulphur dioxide levels from emissions were linked to decline in radial growth. In addition, Gupta and Ghouse (1987) and Muir and McCune (1988) documented that other, larger coal-fired stations with higher emissions (sulphur dioxide and heavy metals) had negative effects on tree growth.

Liu *et al.* (2007) investigated the accumulation of selenium in tree rings from a high selenium producing coal combustion area in China. They noted that selenium is one of the most toxic and volatile trace elements emitted during coal production and that selenium present in scrubber stockpiles poses an environmental hazard to the health of humans as well as plants and animals. For this study, Liu *et al*. chose trees as bioindicators of enhanced selenium deposition. Two sites were sampled (YV and YM) where high-selenium coal was known to be the primary fuel source both for energy production, cooking and heating.

Liu *et al*. used Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) to assess selenium content in tree rings. At site YV, selenium increased from 1984–2003. From

1984–1988, the average value of selenium was 0.16 ppm while from 1989–1998, the average value was 0.43 ppm, which was twice that in 1984–1988. The highest average value was 1.08 ppm from 1999–2003. In the YM samples, selenium content was almost equal to the constant (0.13 +/– 0.03 ppm) with an average value of 0.137 ppm. Liu *et al.* hypothesized that the content at the YV site was much higher than the selenium content at the YM site because selenium was at a much higher concentration in the soils, water, and air.

Aznar *et al.* (2007) investigated mining and smelting activities that produced anomalies in tree-growth patterns in black spruce (*Picea mariana* (Mill.) BSP) growing on the Gaspésie Peninsula in Québec. They hypothesized that black spruce growing in the study region would experience growth reductions due to the activities of the Murdochville Pyrometallurgical Complex during the period of most intense activity (1960–1990). Sulphur dioxide and heavy metals were the common pollutants emitted in the area and arsenic, cadmium, and lead in the ambient air were relatively high at a distance of 1.5 km from the smelter location. Results showed growth reductions were observed as far as 25 km from the smelting location and growth depletion increased with smelter proximity, slope exposed to smelter emissions, and locations of higher elevation. These findings could not be explained by site elevation or tree age alone, nor was this pattern of decreased growth found in the control period (1930–1950). Aznar *et al*. also noted that climate stress and insect defoliation could have affected hardwood stands that were sampled; however, these stresses cannot account for the observed gradient of growth reductions closer to the smelter.

CHAPTER THREE

A DENDROECOLOGICAL EVALUATION OF THE EFFECTS OF COAL ASH ON TREE GROWTH, KINGSTON FOSSIL PLANT, HARRIMAN, TENNESSEE, U.S.A.

This chapter has been written for submission to the journal *Tree-Ring Research*. The use of "we" in the chapter refers to me and my advisor and second author, Dr. Henri D. Grissino-Mayer. Dr. Grissino-Mayer assisted in site selection, conceptual study design, field collection, and text editing. My contributions to this chapter include research topic formulation, field collection, processing and dating of all samples, data analysis, and interpretation of results.

3.1 Introduction

Tree growth is largely a function of environmental conditions. Anthropogenic activities have also been shown to affect forest health and tree growth patterns, especially in the vicinity of point source pollution (Bunce 1979, Ayräs and Kashulina 2000, Liu *et al.* 2007, Aznar *et al.* 2007). For example, air and water pollutants such as heavy metals and sulphur dioxide have long been understood to be factors that affect forest health and vigor (Sutherland and Martin 1990, Fox *et al.* 1986). Often, these pollutants have long-term effects on tree growth (Fritts 1976) with the effects being discernible in different parts of the tree, particularly in tree stem growth (Boone 2004). For example, Yunus and Iqbal (1996) and McLaughlin *et al.* (1982) noted that reduced photosynthesis caused by pollution exposure slows cambial activity and therefore radial growth. When soil characteristics are modified because of pollution interaction, tree roots could be affected resulting in reduced wood production (Joslin and Wolfe 1992).

Evaluating the natural determinates of tree growth, especially climate, is critical in gaining a clear understanding of pollutant effects on radial growth. Trees integrate many environmental influences, so a human-induced pollution signal may be embedded within a high level of natural environmental signals (Cook and Innes 1989, Boone 2004). Climate and site

level factors are known to influence tree growth; however, trees that are influenced by non-climatic factors, such as pollutants, are expected to produce ring-width patterns different from trees that are limited primarily by climate (Thompson 1981). Separating the various factors on tree growth is possible because tree growth can be modeled as a function of five major factors, known as the principle of aggregate tree growth (Cook 1985, 1987). This principle states that tree-ring growth in any one year can be decomposed as a function of climate, disturbance events, and random error, and allows researchers to identify those factors that are the topic of study (signal) while considering factors that would be considered noise (Speer 2010). The model states that:

$$R_t = f(G_t, C_t, \delta D_{1t}, \delta D_{2t}, E_t)$$

where tree-ring width in any one year (R_t) is a function of the age related growth trend (G_t), climate (C_t), any endogenous disturbances that arise within the stand ($D1_t$), any exogenous disturbance that arise from outside the stand ($D2_t$), and any signal that is not controlled by the other variables (E_t). The δ notation indicates presence (1) or absence (0) of that disturbance.

Among tree species, sensitivity to environmental factors varies greatly. Human-induced stress factors and natural site factors are variables that influence tree growth; therefore, surveys of a single species may not allow valid conclusions in forest health studies (Schweingruber 1990). Two or more species are important to rule out environmental stress factors that are not related to natural site factors. For example, Boone *et al*. (2004) examined bur oak (*Quercus macrocarpa Michx.*) and quaking aspen (*Populus tremuloides* Michx.) near a coal-fired generating station, while LeBlanc and Loehle (1993) sampled multiple species growing in pollution seepage basins, including sweetgum (*Liduidambar styracifula* L.), tulip poplar (*Liriodendron tulipifera* L.),

and oak (*Quercus* spp.). Such studies can then rule out species-specific growth patterns that could be misinterpreted as being caused by disturbances.

This study examined the impact of coal ash on multiple tree species located on two islands in Watts Bar Reservoir at the Tennessee Valley Authority's (TVA) Kingston Fossil Plant in Harriman, Tennessee. The construction of the Fossil Plant began in 1951 and was completed in 1955. At that time, it was the largest coal-burning power plant in the world and held this distinction for nearly 10 years. TVA's Kingston Fossil Plant currently generates enough electricity yearly to power approximately 540,000 homes in the Tennessee Valley Region. The by-product of this burning is called coal ash. The components of coal ash vary considerably and depend on the source and the makeup of the coal being burned. Both silicon dioxide (SiO_2) and calcium oxide (CaO) are components of all coal ash in varying amounts depending upon the provenance of the coal. Coal ash also contains trace levels of arsenic, barium, beryllium, boron, cadmium, chromium, thallium, selenium, molybdenum, and mercury.

On December 22, 2008, an embankment at an impoundment for wet storage of coal ash at the Kingston Fossil Plant collapsed, releasing 4,434,400 cubic meters of coal ash into the Clinch and Emory Rivers, impacting aquatic life as well as terrestrial flora and fauna. Subsequent to the spill, TVA acquired approximately 364 hectares of potentially affected private land on Watts Bar Reservoir, around the Kingston Fossil Plant. Current plans for this property include green space and a community recreation area (TVA 2011). The areas affected by the spill have been undergoing intense restoration in the months and years since the collapse. This study was conducted in the immediate vicinity of the Kingston Fossil Plant on islands in the Clinch and Emory Rivers, where trees would have most likely been impacted by coal ash.

While tree growth is largely a function of environmental conditions, it is possible to detect the differences between natural factors and artificial factors on tree growth (Kim 1995, Boone 2004). Radial growth of trees is influenced not only by climate, but also by pulse disturbance events, such as volcanic eruptions, earthquakes, and insect outbreaks (Fritts and Swetnam 1989). In addition, and especially relevant to this study, ground and air pollutants influence tree growth and forest health (McClenahen and Dochinger 1985; Fox *et al*. 1986; Sutherland and Martin 1990), including here in the Southeastern U.S. (Anderson *et* al. 2000; Webster *et al*. 2004) and on the grounds of the nearby Oak Ridge National Laboratory (McLaughlin *et al*. 1982; Barlar 2000; Cassidy 2004).

The main objectives for this study were to: (1) evaluate the effects of the Kingston Ash Spill on the health and vigor of trees located within the spill radius, and (2) provide the Tennessee Valley Authority with baseline information for evaluating the future health of trees on TVA property. To meet these objectives, this project sought to obtain answers to the following specific research questions:

1. Do tree species exist in the area of the Kingston Ash Spill that can be examined using dendroecological techniques?
2. Did the Kingston Ash Spill cause changes in tree growth rates? If so, to what degree were the growth rates altered? If not, what factors could explain this absence of evidence?
3. What is the potential for extending and expanding this research to better understand the effects of the Kingston Ash Spill on the surrounding forests?

3.2 Study Area

The study area is located on Watts Bar Reservoir at the Tennessee Valley Authority's Kingston Fossil Plant in Harriman, Tennessee (35˚ 53′ 54″ N, 84˚ 31′ 08″ W) (Figure 3.1). The reservoir encompasses parts of the Clinch and Emory Rivers, which flow northeast to southwest, and is used for navigation, flood control, hydroelectric power, and recreation. Watts Bar Reservoir is located in the Appalachian Ridge and Valley physiographic province of Mideastern Tennessee (TVA 2009) and lies within the ecological sub-region referred to as the Eastern Broadleaf Forest (Oceanic) province (Bailey *et al*. 2004).

The primary forest of the Central Ridge and Valley is oak-pine forest with southern oak, post oak, blackjack oak, chestnut oak, and scarlet oak dominating drier sites, and white oak, black oak, beech, birch and southern red oak dominating more mesic sites . Other tree species that contribute to the composition of the oak-pine forest are several hickory species (pignut (*Carya glabra* Mill.), mockernut (*Carya tomentosa* Sarg.), bitternut (*Carya cordiformis* Wangenh.), and shagbark (*Carya ovata* Mill.)), several pine species (Virginia (*Pinus virginiana* Mill.), white (*Pinus strobus* L.), shortleaf (*Pinus echinata* Mill.), and loblolly (*Pinus taeda* L.)), black gum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.) , silver maple (*Acer saccharinum* L.), sweetgum (*Liquidambar styraciflua* L.), slippery (*Ulmus rubra* Muhl.) and American elms (*Ulmus americana* L.), and some large willow oaks (*Quercus phellos* L.). A significant portion of the stands are dominated by hardwoods while pine stands are secondary in coverage area (TVA 2009).

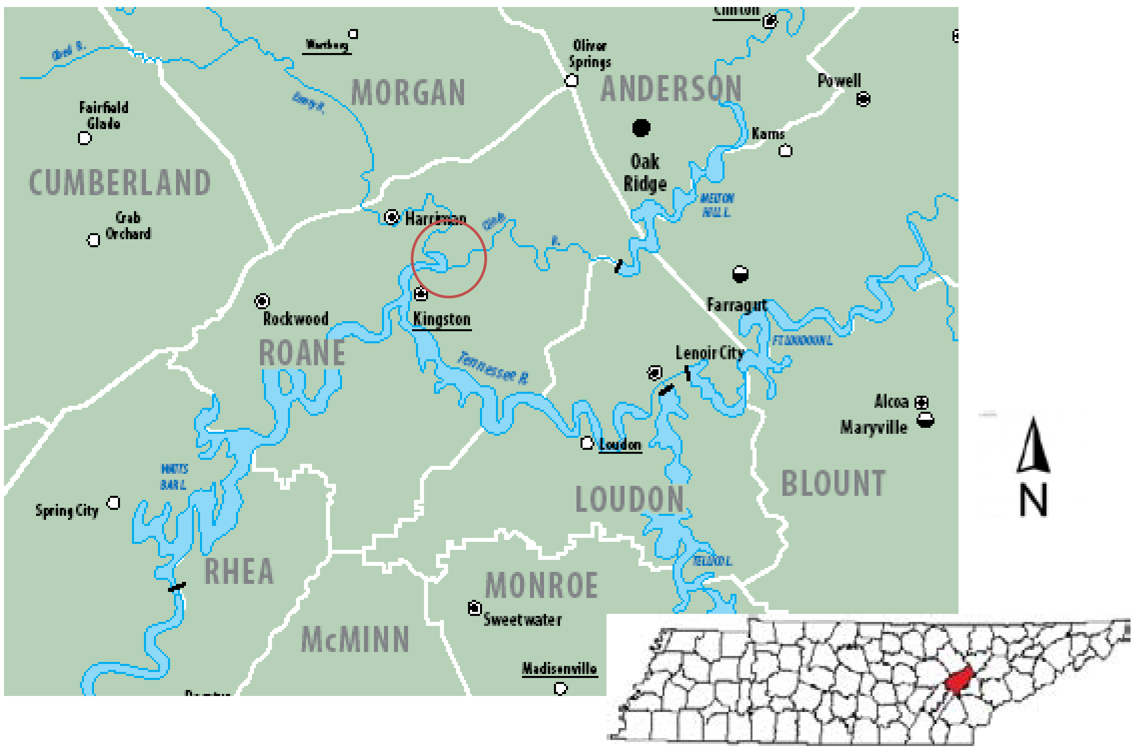

Figure 3.1: Location of the Kingston Fossil Plant, Harriman, Tennessee. Map courtesy of the University of Tennessee Cartographic Services Laboratory.

Using aerial photographs provided by the TVA, we determined the two islands closest to the ruptured embayment in the Emory River were the most impacted by the Kingston Ash Spill (Figures 3.2 and 3.3). Island 1 is located at 35˚ 54′ 38″ N, 84˚ 30′ 16″ W while Island 2 is located at 35˚ 55′ 10″ N, 84˚ 29′ 47″ W. Island 1 is densely populated with underbrush and is primarily dominated by red maple and river birch (*Betula nigra* L.) and secondarily by silver maple, sourwood (*Oxydendrun arboretum L.* (*DC.*)), hickory, black locust (*Robinia pseudoacacia* L.), beech *(Fagus grandifolia* L.), and willow oak (Figure 3.4). Island 2 is covered by dense underbrush but dominated only by river birch; no other tree species are found there.

Visually, Island 1 was more strongly impacted than Island 2 and the coal ash residence time on Island 1 was approximately 15 months. On the western impact edge of Island 1, coal ash reached depths of approximately 3 meters. This height was visually noted because of the coal ash still evident in the crooks of affected trees (Figure 3.5) as well as impact scars on the trees themselves (Figure 3.6). Island 2 was less directly impacted due to the distance from the spill. Coal ash did not have a known residence time on Island 2, but aerial photographs taken immediately after the spill showed that the coal ash extent did reach Island 2. After the Kingston ash spill, the western edge of Island 1 was reconstructed and all dead and downed material was removed by TVA. The islands were largely undisturbed by humans prior to the coal ash impact.

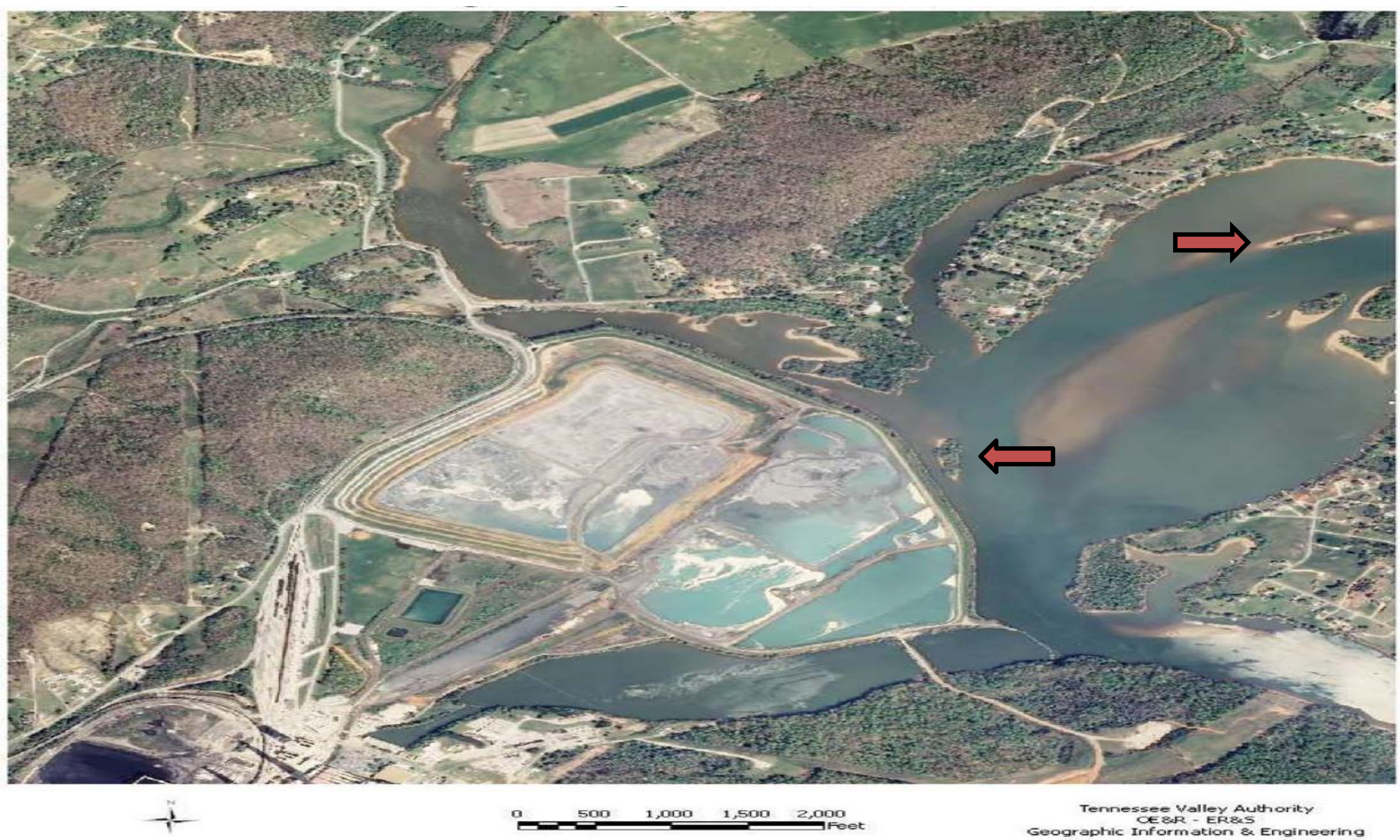

Figure 3.2: TVA's coal ash impoundment pre-spill at the Kingston Fossil Plant, Harriman, Tennessee. Arrows indicate location of Island 1 (bottom) and Island 2 (top right). Photo courtesy of the Tennessee Valley Authority.

Figure 3.3: Image of the ruptured impoundment at Kingston Fossil Plant, Harriman Tennessee. Taken December 23, 2008. Photo courtesy of the Tennesse Valley Authority.

Figure 3.4. TVA Island 1 located in the Emory River.

Figure 3.5: Coal ash in the crook of a tree on the western edge of Island 1.

Figure 3.6. An impact scar on a tree growing on the western edge of Island 1. Height at the top of the scar is approximately 2.5 m above the island ground surface.

3.3 Methods

3.3.1 Control Data Set: Field and Laboratory Methods

To ensure any growth suppression noted in the tree cores taken from the islands were not due to unfavorable climate conditions, we extracted 25 cores from red oak trees at Norris Dam State Park in Norris, Tennessee. This site is located in the same physiographic province as the study sites at the Kingston Fossil Plant, so trees here would be responding to the same climate factors as trees on the two islands. The affected trees on the islands represent multiple hardwood species, so it was not possible for us to develop a reference dataset for all species of trees collected for our study.

All cores from Norris Dam State Park were mounted, sanded, and visually crossdated under a microscope (Stokes and Smiley 1996) and then the tree rings were measured to 0.001 mm accuracy using a Velmex measuring stage interfaced with Measure J2X software (Speer 2010). The accuracy of the visual crossdating was statistically confirmed with the quality control program COFECHA (Holmes 1983, Grissino-Mayer 2001). We used COFECHA to determine the strength of the association between 40-year segments lagged by 10 years for an individual series against the remaining NSP cores using segmented time series correlation analysis. This procedure ensured that all growth rings were assigned to their proper calendar year of formation. ARSTAN was used to standardize the tree-ring series to remove the age-related trend and create a master chronology (Cook 1985). The residual chronology was used because low-frequency trends have been removed, thus retaining the year-to-year fluctuations in tree growth that occur primarily in response to climate.

3.3.2 TVA Islands: Field Methods

Islands 1 and 2 were accessed by boat. We thoroughly scouted the impacted areas and noted a high number of different tree species that have not been commonly analyzed in dendrochronology. To ensure a thorough understanding of the tree composition growing on the islands, and to assist in determining the feasibility of using these tree species for future studies, we identified the species of each tree in the field by examining bark patterns, leaf morphology, and overall tree architecture using standard references (National Audubon Society 1980; Brown *et al*. 2007). All of the trees growing on the TVA islands were conclusively identified and tallied except for the dead standing trees that we were often not able to identify.

We used 16” 3-thread Haglof increment borers to extract increment cores from every tree larger than 5 cm DBH, regardless of species, including dead standing trees if a sound core could be obtained (Grissino-Mayer 2003). Increment cores were taken at 30 cm above ground level, making sure that the outermost tree rings and bark were included in the core (Figure 3.7). Cores were placed in paper straws and labeled with the tree ID, DBH, and species (both common name and Latin binomial). Additionally, we recorded latitude, longitude, estimated residence time of the surrounding coal ash, and whether the tree bole (and therefore the root system also) or root system (only) was likely affected. We also noted any visual impact scars or growth abnormalities on the tree.

3.3.3 TVA Islands: Laboratory Methods

The increment cores were mounted and sanded with progressively finer sandpaper, beginning with ANSI 180-grit and ending with ANSI 400-grit, allowing for easier visual

Figure 3.7. TVA employee, Brandon Thomas, removing an increment core from a red maple (*Acer rubrum* L.) on Island 1.

inspection of the vertically aligned tracheids (Stokes and Smiley, 1996, Orvis and Grissino-Mayer 2002). After the increment cores were sanded, we visually examined each core using a stereo-zoom boom-arm microscope under standard 10X magnification and noted the wood type for that species (Hoadley 1990). Some of the tree species sampled have diffuse porous wood, a wood type in which the ring boundaries are not easily discernible. To accentuate the ring boundaries and to allow the ring boundaries to be more easily identified, the cores were dyed with a phloroglucinol solution (Stewart 1930, Patterson 1961, EPA 1994). This was accomplished by soaking the cores in phloroglucinol solution for one minute and then placing the cores in a hydrochloric acid solution. Once the cores began to turn red, they were removed from solution and rinsed under running water. The increment cores were allowed to dry and then were re-sanded with ANSI 1500-grit sandpaper.

The cores were aged beginning with the last year of growth being 2011, and we marked the decadal rings with established notation (Stokes and Smiley 1996, Speer 2010). Ring widths were measured to the nearest 0.001 mm accuracy using a Velmex measuring system interfaced with Measure J2X software (Speer 2010). Samples were measured from the innermost ring to the outermost ring (2011). The cores were collected in the late fall of 2011; therefore, the latewood of the 2011 ring was intact, ensuring an entire ring measurement for 2011. The cores were also visually inspected for aberrant rings that could indicate a disturbance event (e.g., rings that formed after 2008 that were discolored).

Graphs of the raw ring widths for each tree were created using EXCEL to help visually assess potential growth suppressions for each core measurement series. To statistically evaluate whether or not a reduction in tree growth occurred due to effects of the coal ash, we used

software specifically designed to detect anomalous trends in tree-ring measurement series. The JOLTS computer program (Holmes 1999) can be used to detect growth reductions that could have occurred had the coal ash had a negative impact on tree growth rates. This software is used to detect whether or not a disturbance event has caused the tree to produce either narrower rings than would be expected (for example, from air pollution, water pollution, or an intense wildfire) or wider rings than would be expected (for example, from a low severity wildfire or from the death of a nearby tree that competed for nutrients and sunlight) (Girardin *et al*. 2002, Cseke 2003).

The JOLTS program is designed to compute average growth conditions before a disturbance pulse, and then uses statistical techniques to search for and identify anomalous ring widths that follow the disturbance pulse. Using a running mean based on a suppression factor, JOLTS identifies significant growth changes in each ring series (Girardin *et al*. 2002, Cseke 2003). The running mean window was set at eight years prior to each year tested and four years starting at each year tested, while the suppression factor was set at 1.25. The minimum number of years between detected suppressions was set at 5. Each file containing a single tree-ring series was entered into JOLTS, which produced a statistical file summary and an FHM file (a graphics file in FHX2 format). The FHM file was then used to create an FHX2 chart (Grissino-Mayer 1995, 2001) that displayed JOLTS-detected suppressions.

3.4 Results

3.4.1 Island 1 and Island 2

We collected increment cores from 106 trees on Island 1 and from 20 trees on Island 2, totaling 126 trees and 143 increment cores. A total of 44 increment cores was analyzed for growth suppressions. The remaining increment cores were not able to be analyzed either because the ring boundaries were not discernible, even after staining, or because the core was taken from a dead standing tree and the outermost rings needed to evaluate the effects of the coal ash spill had decayed off. The oldest tree-ring core obtained from Island 1 aged at 1952 and Island 2, 1963. The tree species count on the islands consisted of: river birch (41), red maple (31), black locust (10), silver maple (3), sourwood (3), sycamore (2), red oak (2), American beech (2), tulip poplar (1), willow oak (1), hackberry (1), and, hickory (1). This species count does not include the dead standing trees because often we were not able to conclusively identify the tree species.

When we visually evaluated the 44 island cores, it became clear that crossdating would not be possible because multiple tree species were collected and most all tree species represented the diffuse porous wood type. Further, crossdating the island cores was complicated because many tree-ring series were complacent, meaning the tree-ring widths did not contain enough significant yearly variation to allow crossdating across the tree-ring series. It also became apparent in the visual assessment that tree growth on the islands was not driven primarily by climate because of differences in growth patterns from tree to tree. Crossdating is only possible when climate is the overarching macro-environmental factor to which trees respond. In some sites, however, other factors can override the climate signal, especially sites in

unusual topographic settings such as small islands in the middle of rivers where the stream flow is regulated by a land management agency. Further, we had collected cores from dead standing tress in the hope that we could successfully crossdate the tree rings from them; however, this was not possible.

The JOLTS-derived FHX2 graph composite combined Island 1 and Island 2 and displayed any year with 5 or more suppressions present in any tree-ring series (Figure 3.8). The years 1972, 1977, 1982, 1984, 1987, 1988, 1989, 1997, 1998, 1999, 2001, 2002, and 2004 showed suppression events across multiple tree-ring series. All tree-ring series with suppressions for Island 1 and Island 2 were plotted graphically in Excel (Figures 3.9 a–e). No consistent suppression events were evident among the tree-ring series after 2008, suggesting the 44 trees used for our study were not adversely impacted by the coal ash spill.

3.4.2 Control Data Set

The Norris Dam State Park (NSP) cores were analyzed for climate to ensure that any growth suppressions found in the TVA island cores were not caused by unfavorable climate. Our final data set consisted of 23 dated tree-ring series with an interseries correlation of 0.57, average mean sensitivity of 0.22 and mean series length of 96 years. The NSP chronology spans from 1801 to 2011 and displays average tree growth conditions for the examination period of 2009–2011. The NSP cores revealed no ring patterns indicative of climate anomalies that would have created suppressions caused by unfavorable climate in the years following the Kingston Ash Spill (Figure 3.10). However, in the NSP chronology, six years of below average tree growth correspond to suppressions found in the TVA Island cores prior to the Kingston Ash Spill. The

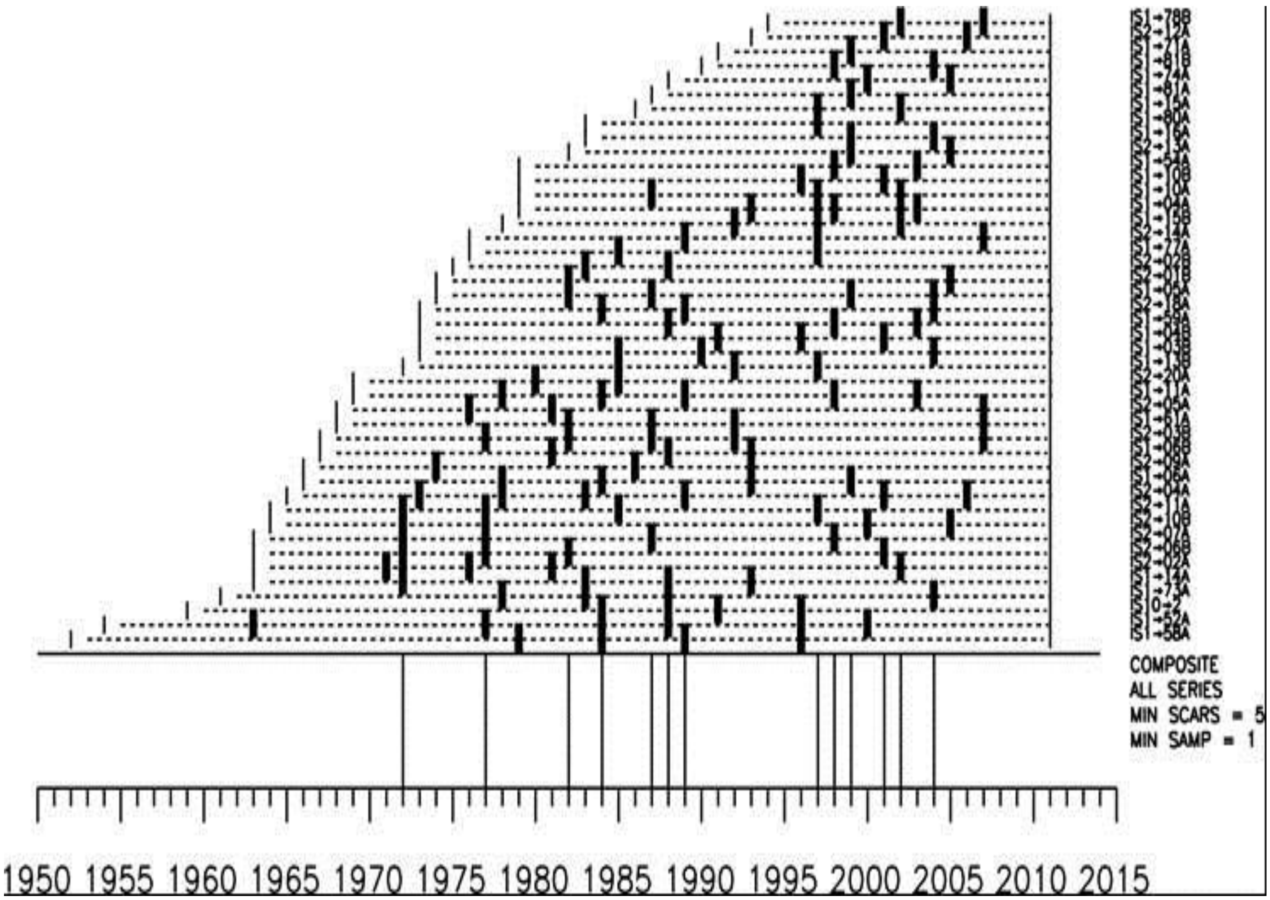

Figure 3.8. FHX2 graph depicting TVA composite (Island 1 and Island 2) suppressions that occurred in more than five tree-ring series.

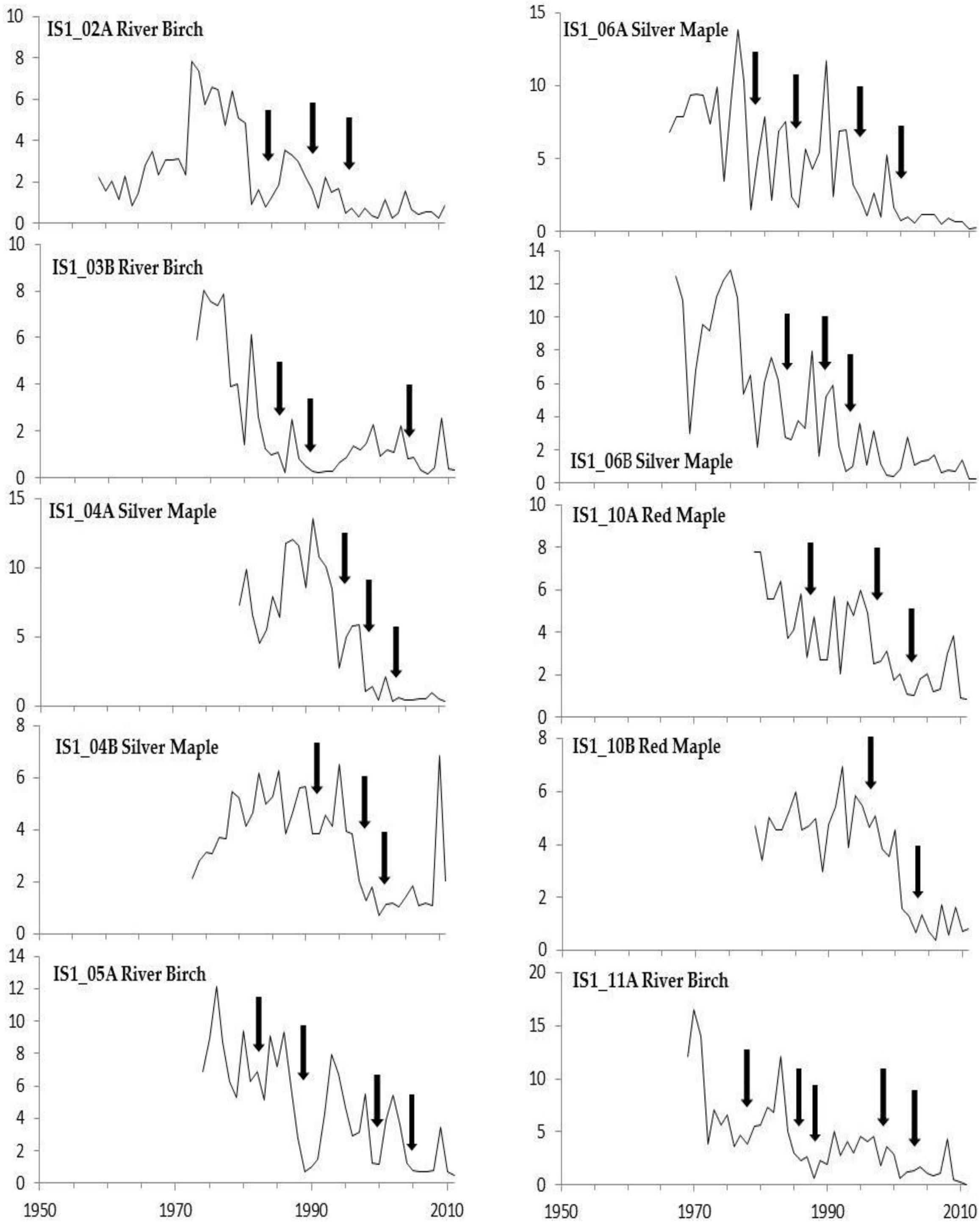

Figure 3.9a. Individual tree-ring series from Island 1 displayed to show suppressions in tree growth. Arrows indicate suppression events. The y-axis is ring width in millimeters.

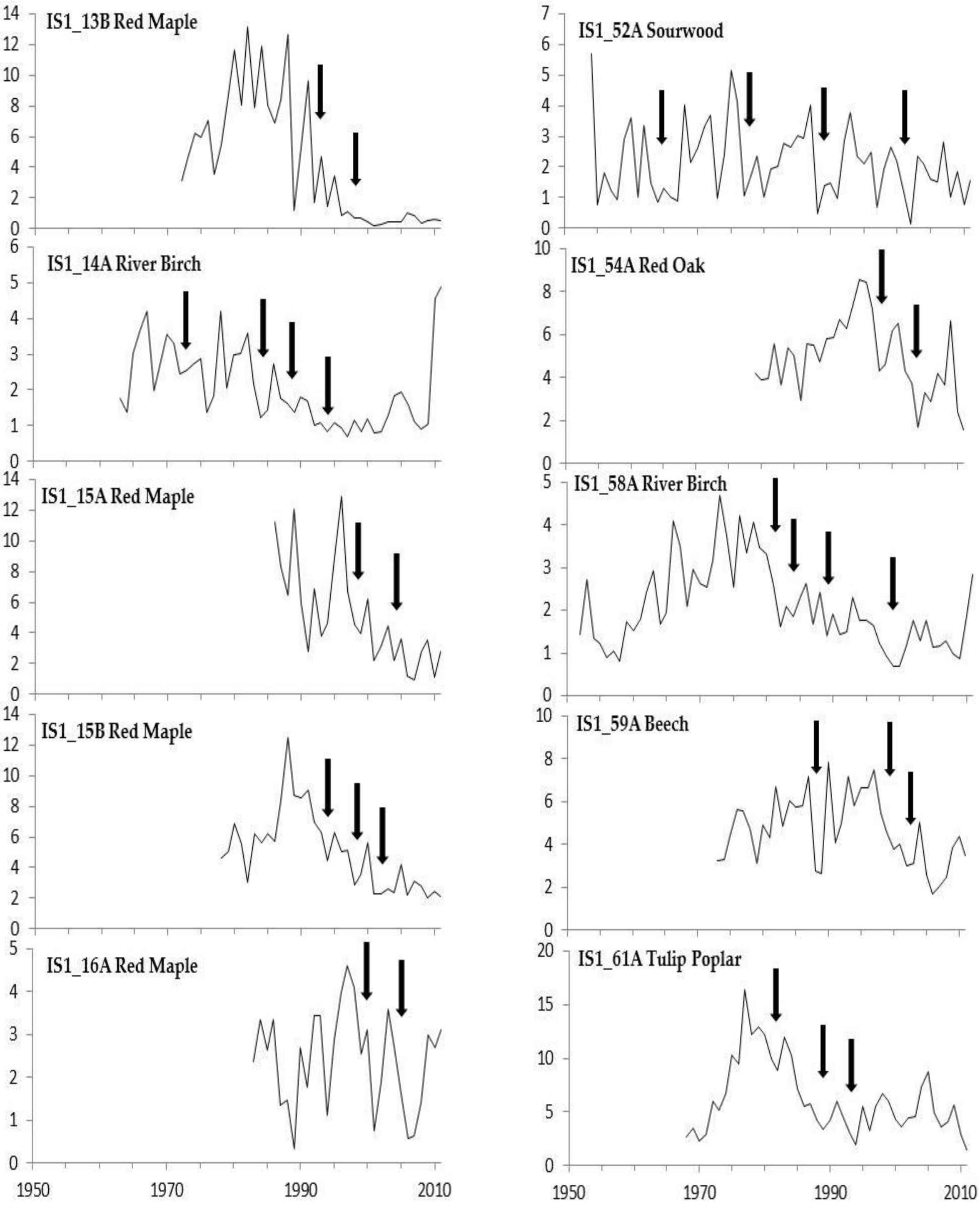

Figure 3.9b. Individual tree-ring series from Island 1 displayed to show suppressions in tree growth. Arrows indicate suppression events. The y-axis is ring width in millimeters.

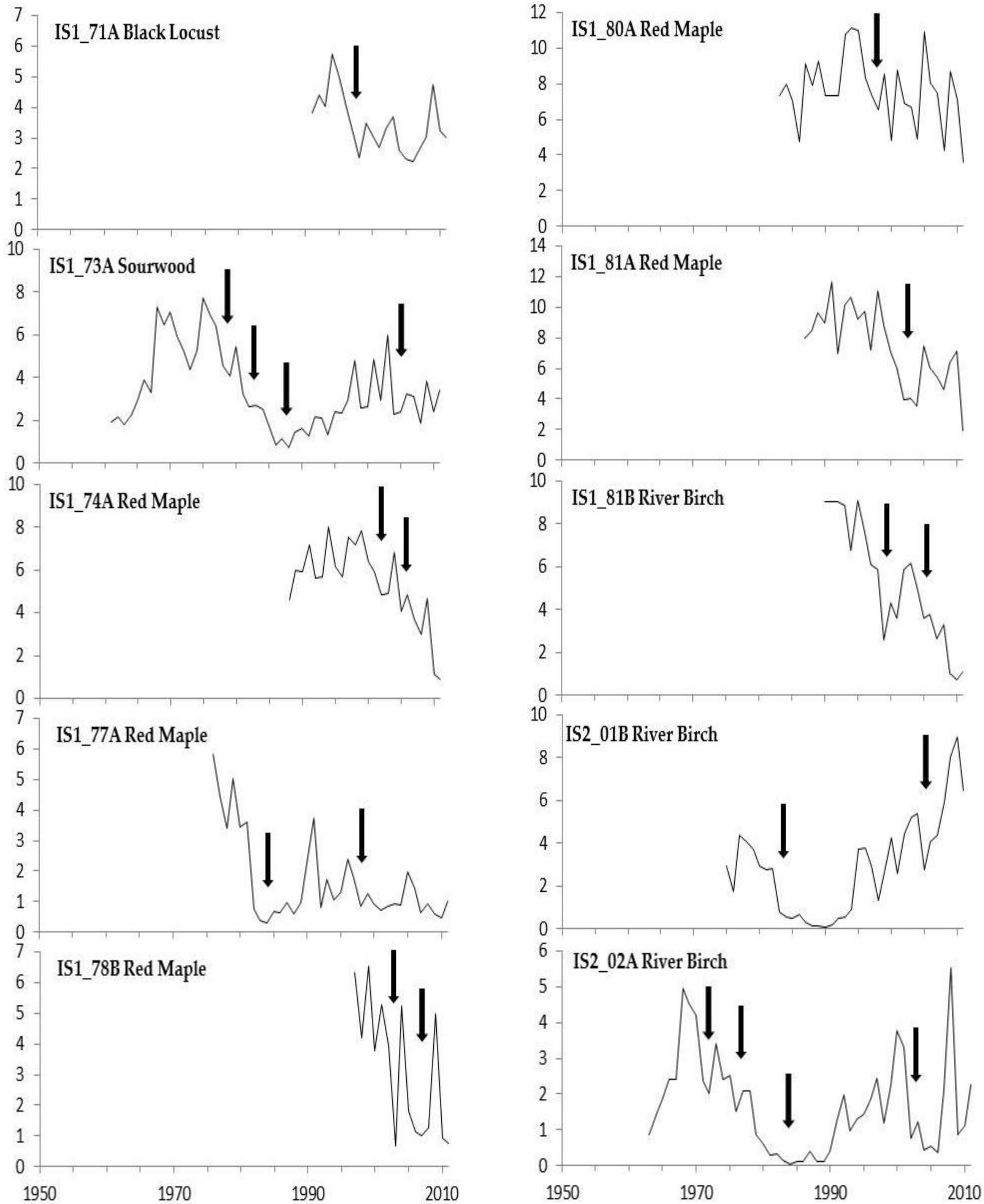

Figure 3.9c. Individual tree-ring series from Island 1 and Island 2 displayed to show suppressions in tree growth. Arrows indicate suppression events. The y-axis is ring width in millimeters.

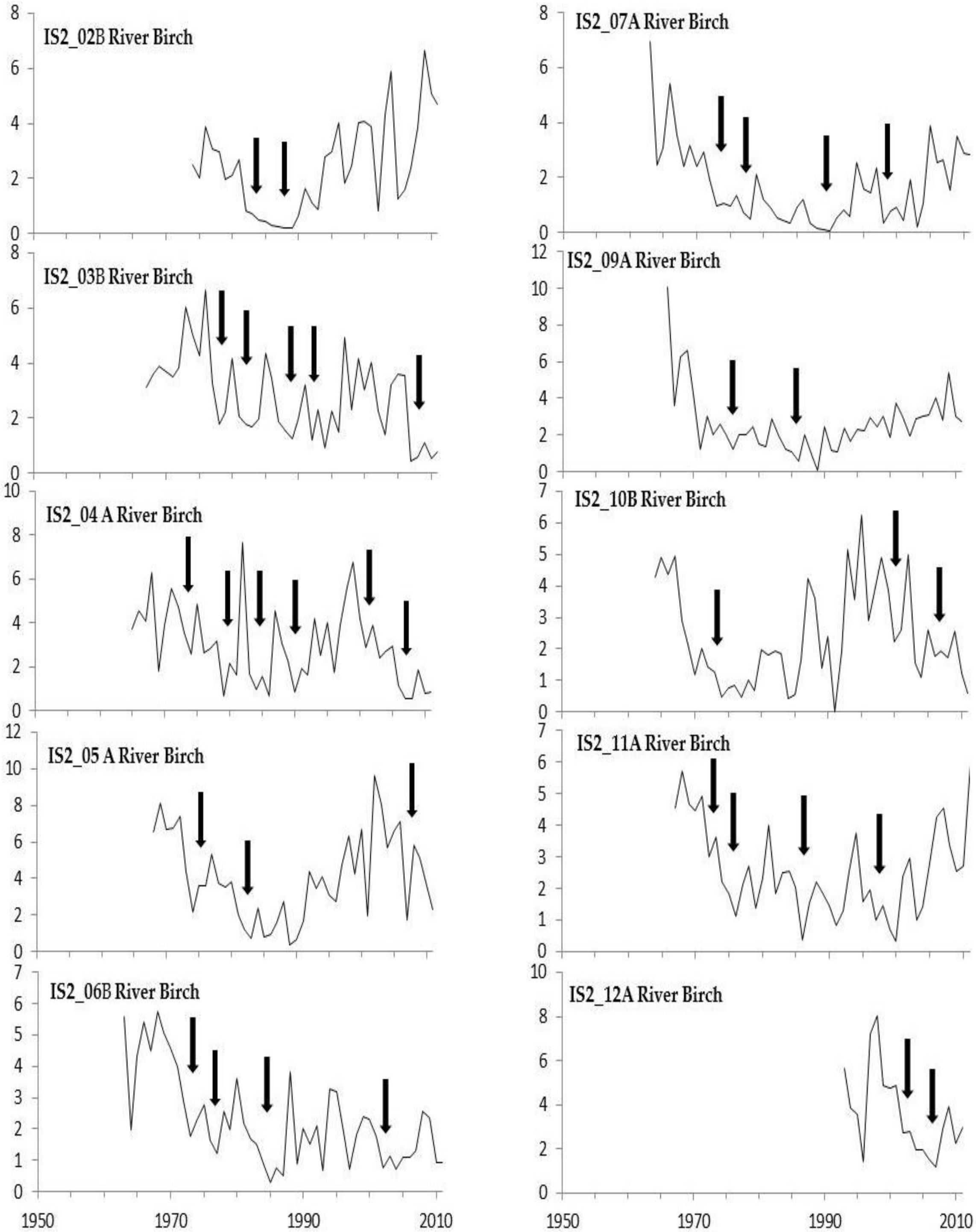

Figure 3.9d. Individual tree-ring series from Island 2 displayed to show suppressions in tree growth. Arrows indicate suppression events. The y-axis is ring width in millimeters.

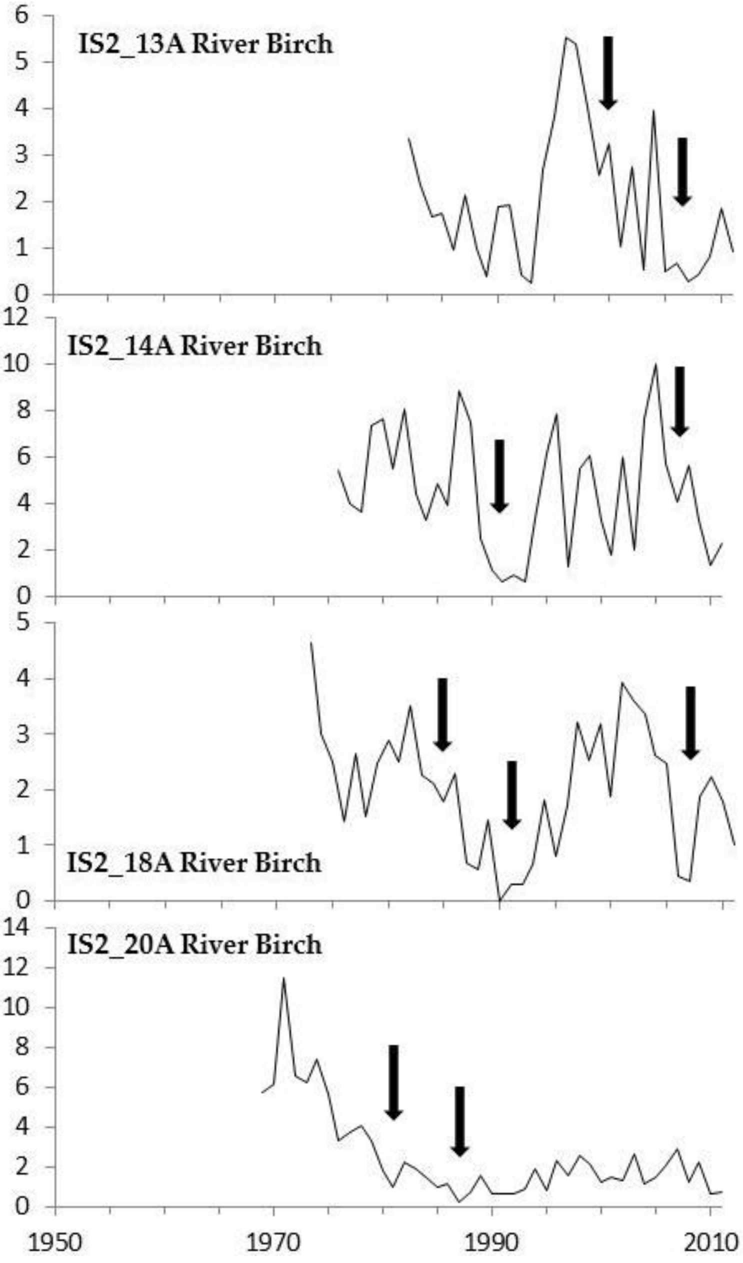

Figure 3.9e. Individual tree-ring series from Island 2 displayed to show suppressions in tree growth. Arrows indicate suppression events. The y-axis is ring width in millimeters.

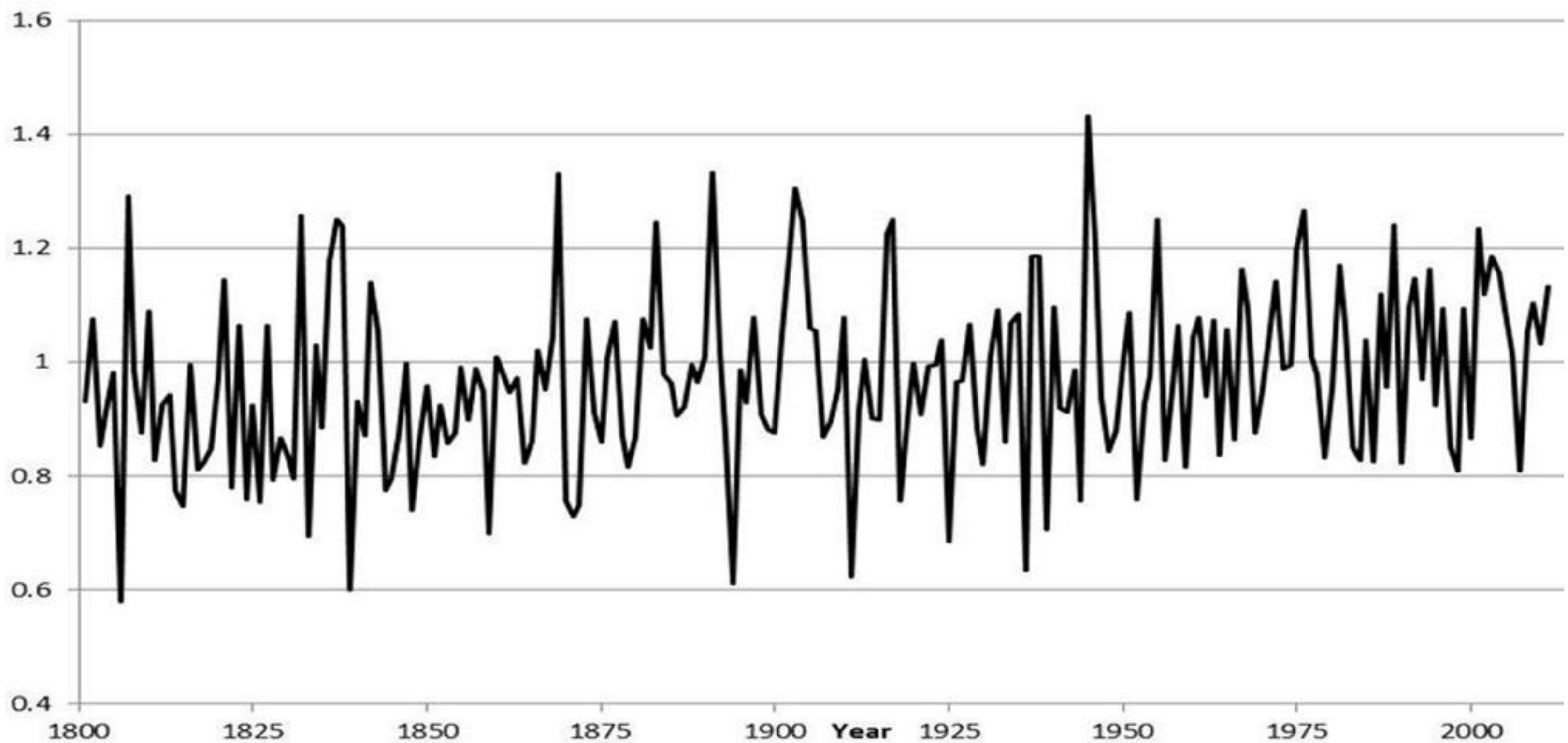

Figure 3.10. ARSTAN tree-ring chronology for oaks sampled at the Norris Dam State Park site.

years 1972, 1977, 1984, 1988, 1997, and 1998 exhibit below average tree growth related to below average climate conditions. Seven other suppressions were detected in the TVA Island cores that do not correspond with climate anomalies detected in the NSP cores and these years are: 1982, 1987, 1989, 1999, 2001, 2002 and 2004.

3.5 Discussion

Tree growth depends on many environmental factors, and assessing all possible sources of variation at a site is not always possible. However, this research sought to examine the potential negative growth effects caused by coal ash on tree growth on the TVA islands. Increment cores from trees growing on Island 1 and Island 2 revealed no tree growth suppressions after the Kingston Ash Spill of December 2008. Tree growth has not currently slowed, and the living trees do not show outward signs of mortality or disease that would impact the future growth of these trees. The trees that did succumb to the effects of the Kingston Ash Spill did so through three mechanisms: (1) direct physical damage by the coal ash spill which tore away the protective bark, effectively girdling the tree; (2) coal ash accumulations around the base of the tree which prevented root aeration needed for tree growth; and, (3) the toxic chemicals found in the coal ash disrupted uptake of nutrients and hindered or prevented photosynthetic capabilities, thereby killing the trees. We next evaluated probable reasons why growth suppressions were not evident.

1. Ring widths alone may not be the best evidence

Rather than obvious changes in ring widths, changes instead could have occurred in the physical (or chemical) properties of the wood formed after the spill event. Three increment cores displayed growth anomalies that were visible in the years following the Kingston Ash Spill (Figure 3.11). Changes in the tree cells themselves, caused by impact disturbance or root uptake of toxic elements, could present as discoloration of the wood and changes in the vessel diameter in the diffuse porous and ring porous wood types.

2. Too early to detect growth suppressions

While tree growth suppressions were not immediately found in the island increment cores after the Kingston Ash Spill, we could analyze only three years of annual tree-ring growth. It could still be too early to detect the effects of the Kingston Ash Spill on surviving trees. Some tree species have delayed reactions to disturbance processes, especially those for which changes in the surrounding environment may be intermediate rather than catastrophic. For example, trees that survived and were growing in the vicinity of volcanic eruptions often displayed delayed responses to eruptions that have been documented and dated to a specific year. The stratovolcano Tambora erupted in 1815, yet trees displayed growth anomalies in 1816 through 1819 (Fye and Cleaveland 2001). In addition, many European oaks show suppression events lasting 7 to 10 years after major volcanic eruptions around the world, especially the A.D. 536 eruption (Baillie 1999). The same is true for the New Madrid earthquake of 1811–1812 where trees impacted by this event registered the disturbance event by forming very wide rings beginning in 1814 (Stahle *et al.* 1992).

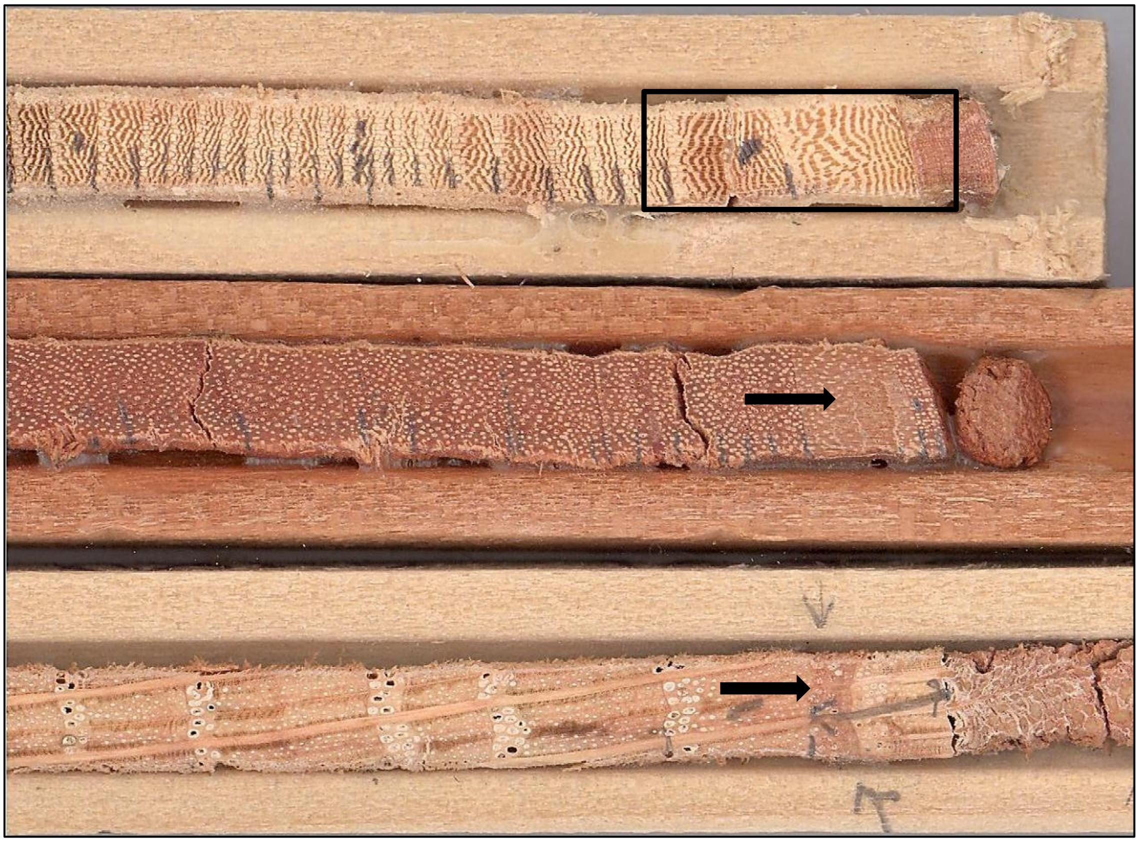

Figure 3.11. Increment cores displaying anomalies in tree growth from the Kingston Ash Spill. IS1114 (top core) exhibits abnormally wide rings in years 2009 to 2011 (box) in relationship to the tree-ring widths seen in the rest of the increment core, indicating a possible release rather than suppression event. IS111A (middle core) exhibits an abnormally wide ring for 2009, indicated by the arrow. IS1051A (bottom core) exhibits a false ring (a return to earlywood vessels) for the 2011 ring, indicated by the arrow.

3. Physical removal of trees most affected

Trees at the TVA site can be placed into two categories that reflect TVA management of the post-spill area: (1) all trees that died or suffered major damage were physically removed by TVA, and (2) TVA personnel retained trees which received minimal or no discernible visual impact from the coal ash spill. Based on discussions with TVA personnel and aerial photographs (before and after the spill), it became obvious that the majority of trees that were impacted by the Kingston Ash Spill were physically removed. Following the spill, a very thorough removal of coal ash debris in the Emory River, on the river banks, and on the islands commenced. More than 2.7 million cubic meters of coal ash were recovered from the Emory River alone, and additional coal ash was removed from the embayment, tributaries, and islands. The western edge of Island 1 was completely resurfaced, removing all trees (living and dead) that could have shown a direct impact by the coal ash. The trees on the islands that were either toppled or died soon after the coal ash spill offered the greatest amount of evidence of the impact of the Kingston Ash Spill on tree growth.

4. Growth suppressions were counteracted by growth releases

The physical removal of the trees on the islands that were impacted by the coal ash made available to the surviving trees on the islands more sunlight and nutrients. Competition for these key factors can influence tree growth suppressions and releases in forest stands. It is possible that the release from competition, after the removal of the impacted trees on the TVA islands, compensated or counteracted any growth suppression that may have occurred as a result of the Kingston Ash Spill.

5. Water levels in a managed river could mask disturbance effects

Despite Island 1 and Island 2 being located in a TVA regulated river, the water levels still fluctuate. Water level fluctuation and flood potential for the trees growing on the two islands are two important factors that could have masked or disrupted the disturbance signal from the Kingston Ash Spill. Watts Bar Reservoir is 226 meters above sea level at full pool (typically from May through October) with an average fluctuation of only 1.5 meters from summer to winter (The Roane County Alliance, 2012). When the water table was higher than normal, the tree root systems have a more consistent water supply that could enhance growth rates and possibly counteract suppression caused by the Kingston Ash Spill. Conversely, the two TVA islands consist primarily of flood tolerant tree species (river birch, silver maple, willow oak, beech, elm, and hackberry) that are accustomed to disturbances such as floods and channel migration. It is possible that the trees growing on Island 1 and Island 2 did not register the Kingston Ash spill as a catastrophic disturbance (Shankman 1993).

6. Nutrient supplements could counteract growth suppression

Other factors in the surrounding environment of trees can potentially impact tree growth. For example, Island 2 is well known to TVA personnel as a site home to a multitude of nesting birds which deposit organic (fecal) material and possibly supplement the pattern of nutrient deposition in the soil. Bird manure is known to add high amounts of nutrients to soils, especially ammonium, phosphorus, and potassium (Zublena 1986). These supplements could enhance tree growth, thus masking any detrimental effects caused by the Kingston Ash Spill.

7. The coal ash had no detrimental effect on tree growth

While we find it unlikely that the Kingston Ash spill had no impact at all on tree growth, it is an explanation that must be considered. Perhaps the coal ash residence time on the islands was not long enough to impact tree growth or perhaps the remaining trees growing on higher ground were not impacted as heavily as those that were removed by TVA. The components that we think of as toxic in coal ash possibly were not taken up by the tree root system and distributed throughout the tree, causing a reduction in tree growth.

Differences between the control data set and the island cores

Our original intent was to use the NSP increment cores to ensure that any suppression found in the tree-ring patterns in the island cores were not related to climate. After investigation, we found that there were distinct differences in growth patterns between the trees growing at Norris Dam State Park and the trees growing on the TVA islands. Some years of reduced growth were noted in the NSP increment cores that corresponded to reduced growth in the island cores (e.g., 1972, 1977, 1984, 1988, 1997, and 1998). However, the island cores displayed reduced growth in years when tree growth was above average as shown in the NSP cores (e.g., 1982, 1982, 1987, 1989, 1998, 1999, 2001, 2002, and 2004).

Further explanations to clarify the possible causes of differences in the tree-ring patterns between the NSP control data set and the TVA island cores can be offered. Trees that are growing in island environments often are not responding to climate alone. Their growth can also be impacted by topographical features of their ecosystem, such as terrain change, low soil depth, and nutrient availability (Pregitzer *et al.* 1998). Trees on both TVA islands are growing in

a sandy loam, and while this is beneficial in preventing disease development by allowing water to drain easily, it also requires more water to sustain plant growth and serves to exaggerate low water level impacts on tree growth. Secondly, as water percolates through the soil, nutrients (particularly nitrogen and potassium) are washed out and unavailable for use by the tree, which results in a potentially different growth response (Tucker 1999) than was found in the NSP increment cores. Additionally, the NSP trees are growing in Ultisols which are typically deficient in calcium and potassium. The trees growing on the islands and at Norris Dam State Park are growing in different soil types, which could explain why the two data sets do not show the same tree growth patterns.

Furthermore, within the eastern deciduous forest, ice and snow storms are among the most frequent forest disturbances (Hauer 2006). Tree species vary in their resistance to ice and snow accumulation; however, broken tree crowns, damaged limbs, and weak branch junctures increase the susceptibility to ice and snow storm damage (Hauer 2006). Ice damage inflicted to a tree can damage the tree in such a way as to slow cambial activity and decrease nutrient uptake, therefore affecting radial growth. For example, Cseke (2003) used dendrochronology to reconstruct major storm events that caused either suppressions or releases in growth of trees growing in Great Smoky Mountains National Park. Major storm events occurred in 1969, 1979, 1980, 1993, and 1994 and caused large-scale disturbances in the forest composition. Tree-ring records have noted snow storms and ice accumulation to be detrimental to tree growth (Lafon and Speer 2002). Ice accumulation and snow damage could explain differences in the stand-wide suppression events found in trees growing on the TVA islands and at Norris Dam State Park.

It is reasonable to assume that disturbance processes were occurring prior to the Kingston Ash Spill and therefore could have added a large measure of noise to the datasets that contributed to the differences between the NSP control chronology and TVA islands dataset. The noise in the TVA island increment cores also affected our ability to crossdate the tree-ring series from the two islands and possibly could have masked the signal from the Kingston Ash Spill.

Future Research

While field scouting around the lake margin to better assess the impacts of the Kingston Ash Spill on surviving trees, we saw impact scars on several pine and hardwood trees not too far from the current river boundary, in an area that was known to have been heavily impacted by the spill. Using aerial photography, one can see that both the islands were impacted, and the coal ash extended to the river banks and subsequent trees. Future research could be expanded to the trees surrounding the impacted river bank that have visual evidence of impact scars, as well as collecting samples from trees deeper into the TVA forests to examine the potential impacts of airborne ash particles on tree photosynthesis. Future studies could also examine the spatial variability of tree growth across Island 1, moving from the western edge (impact edge) to the eastern (furthest from the impact) edge of the island. One would expect tree growth on the western edge of Island 1 to show a higher change in growth rates moving to a lesser change as the eastern edge is reached. Along with this expanded study, a more thorough, in-depth analysis of climate response in multiple tree species could be accomplished to help isolate the possible effects of coal ash on tree growth.

CHAPTER FOUR

4. SUMMARY AND CONCLUSIONS

4.1 Do tree species exist in the area of the Kingston Ash Spill that can be examined using dendroecological techniques?

The major impetus of this pilot study was to establish whether growth was affected in trees directly impacted by the Kingston Ash Spill. After thoroughly scouting the impacted areas, we noted a wide variety of tree species that could be examined using dendroecological techniques as well as species that are not commonly studied in dendrochronology. On the islands, the primary species are river birch and red maple, both diffuse porous species. Silver maple, yellow poplar, and sweetgum are other diffuse porous species growing on TVA property. The diffuse porous genera of trees have small vessels distributed throughout the ring that hold no relationship to the ring boundary (Speer 2010). It is this distribution of vessels throughout the tree ring that can obscure the ring boundary itself. While the diffuse porous type wood is not the easiest to work with, it is possible through a variety of dendroecological techniques to determine the ring boundary and age the tree.

Other tree species growing on TVA property include hickory, elm, oak, and conifer. Apart from conifers, these species are ring porous wood types and lend themselves to dendroecological techniques. Ring porous wood structure is defined by many large earlywood vessels tapering off to smaller vessels ending in the ring boundary. The ring boundary is usually very well defined and easy to discern and requires only standard dendrochronological techniques to see the wood very clearly. While the TVA forest is not dominated by conifers, they are still present in the stands, although in lower numbers. Conifers have nonporous wood

structure in which ring boundaries are easily discernible by examining the size and cell wall thickness of the tracheids (Speer 2010). Conifers are known to have simpler wood structure than hardwoods, therefore lending themselves to dendroecological evaluation as easier tree species to examine. All of the conifer and ring porous tree species growing on TVA property are excellent candidates for further research that examines the impact of coal ash on tree growth.

4.2 Did the Kingston Ash Spill cause change in tree growth rates and, if so, to what degree were the growth rates altered? If not, which factors could explain this absence of evidence?

Evaluating the natural determinants of tree growth is important when separating normal tree growth patterns driven by the primary limiting factor, usually climate, and a possible impact on tree growth from a catastrophic pulse event. The NSP increment cores provided the control for climate, and ensured growth suppression years in the island cores after the coal ash spill did not arise due to severe climate events. The trees that we sampled growing on the TVA Islands 1 and 2 showed no suppressions in tree growth that were a result of the Kingston Ash Spill. Several factors may have contributed to the absence of evidence:

(1) TVA land managers were under intense pressure to remove evidence of the spill and in doing so, removed a considerable number of trees that were impacted by the coal ash. They therefore removed primary evidence that would have provided more information about the impact of coal ash on tree growth.

(2) The action of removing the trees that were impacted by the coal ash made available to the surviving trees on the islands more sunlight and nutrients. Competition for

these key factors can influence tree growth suppressions and releases in forest stands. It is possible that the release from competition on the TVA islands compensated for any growth suppression that may have been found as a result of the Kingston Ash Spill.

(3) The western edge (impact edge) of Island 1 was completely resurfaced in an attempt to remove the coal ash from the ecosystem. Trees that had died on the islands soon after the Kingston Ash Spill offered the greatest amount of evidence of the impact of the Kingston Ash Spill on tree growth.

(4) We were only able to examine three years of annual tree growth after the Kingston Ash Spill that occurred in December 2008. It could be too early to detect the effects of the impacts on tree growth because some tree species have delayed reactions to disturbance processes, especially when the impact is intermediate and not catastrophic.

(5) The dead trees on the interior of the Island 1 were not removed by the TVA and died from the impacts of the coal ash 1 to 2 years prior to our sampling in Fall 2011. Therefore, it was not possible to correctly age the tree, determine a year of death, and assess the impacts of coal ash on the radial growth of these trees.

(6) Island 1 and Island 2 are located in a TVA regulated river, but the water levels still fluctuate. Water level fluctuation and flood potential for the trees growing on the two islands are two important factors that could have masked or disrupted the disturbance signal from the Kingston Ash Spill. When the water table was higher than normal, the tree root systems have a more consistent water supply that could

enhance growth rates and possibly counteract suppression caused by the Kingston Ash Spill. Conversely, the two TVA islands consist primarily of flood tolerant tree species (river birch, silver maple, willow oak, beech, elm, and hackberry) that are accustomed to disturbances such as floods and channel migration. These trees can survive and propagate despite environmental disturbances. It is possible that the trees growing on Island 1 and Island 2 did not register the Kingston Ash spill as a catastrophic disturbance.

(7) Island 2 is well known to TVA personnel as a site home to a multitude of nesting birds which deposit organic (fecal) material and possibly supplement the pattern of nutrient deposition in the soil. Bird manure is known to add high amounts of nutrients to soils, especially ammonium, phosphorus, and potassium (Zublena 1986). These supplements could enhance tree growth, thus masking any detrimental effects caused by the Kingston Ash Spill.

4.3 What is the potential for expanding this research to better understand the effects of the Kingston Ash Spill on surrounding forests?

Environmental disasters are unfortunate when they occur, and they often alter the landscape and ecosystem in ways that cannot be repaired. The impact on flora and fauna alike is often long lasting and detrimental; however, when land managers begin mitigation and intervention immediately, often the impacts can be lessened or at least contained. Results from this pilot study suggest that living trees currently on the TVA islands did not sustain significant impact or damage from the Kingston Ash Spill that would inhibit tree growth. However,

opportunities for further research and better collaboration are evident between governmental agencies and the scientific community. By maintaining closer and timelier communication and collaboration with TVA personnel, we could have ensured the immediate collection of cross-sections and increment cores that could have shown suppressions before the impacted trees died and/or were removed. TVA was under intense pressure to remove evidence of the Kingston Ash Spill, including the damaged trees as well as the trees that were in decline. However, by working early with the scientific community in ways that relate to the health of the ecosystem, evidence could have been recovered before the removal of the evidence itself. This important information could have provided a better understanding of the impacts of coal ash on tree growth and could have given TVA land managers a more thorough understanding of how to mitigate such a catastrophic event.

4.4 Future Research

Further study is possible by evaluating the chemical or isotopic signature that would be present in the tree cores obtained from Island 1 and Island 2. While I investigated radial growth that could have been affected, dendrochemical analysis could examine the chemical properties (via tree root uptake) in tree cores from trees that remain after the Kingston Ash spill. Potentially, dendrochemistry would allow us to identify elements that are not normally found in trees, such as lead, arsenic, and higher levels of other trace elements that could impact tree growth.

While this study did not detect growth suppressions in the trees growing on the TVA islands, future study is possible by examining the potential growth releases rather than growth

suppressions. It is possible that the coal ash, either through removal of tree competition or through a possible nutrient effect, caused the examined trees to produce wider than average growth rings instead of narrow growth rings following the Kingston Ash Spill. The computer program used in this study, JOLTS, can also be used to statistically evaluate whether growth releases have occurred in tree growth patterns.

Finally, future research is possible by revisiting and re-sampling the trees on the islands at a later date. While this pilot study did not currently find a significant impact to tree growth, studies conducted later may reveal impacts that were not immediately obvious so soon after the Kingston Ash Spill. By re-evaluating tree growth in the future, both the scientific community and TVA land managers can better understand and mitigate the impacts of coal ash on tree growth.

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APPENDICES

APPENDIX 1

COFECHA output for the Norris Dam State Park chronology

Year	Value	No	Ab	Year	Value	No	Ab	Year	Value	No	Ab	Year	Value	No	Ab	Year	Value	No	Ab	Year	Value	No	Ab
				1850	.115	2		1900	-.860	8		1950	-.111	17		2000	-1.561	22					
1801	-.026	1		1851	-1.366	2		1901	-.156	8		1951	.541	17		2001	.691	22					
1802	1.361	1		1852	-.504	2		1902	.480	8		1952	-1.358	18		2002	.390	22					
1803	-.194	1		1853	-1.404	2		1903	1.327	9		1953	-.356	19		2003	.920	22					
1804	-.032	1		1854	-.499	3		1904	1.272	9		1954	-.174	19		2004	.957	22					
1805	.507	1		1855	.067	3		1905	.871	9		1955	1.429	19		2005	.841	22					
1806	-5.487	1		1856	-.280	3		1906	1.198	10		1956	-.824	19		2006	.235	22					
1807	1.730	1		1857	1.164	3		1907	.431	10		1957	.052	20		2007	-1.525	22					
1808	.990	1		1858	.941	3		1908	.062	10		1958	.406	21		2008	-.217	22					
1809	.438	1		1859	-2.507	3		1909	.158	10		1959	-1.259	21		2009	-.033	22					
1810	1.883	1		1860	.285	3		1910	.493	10		1960	.232	21		2010	-.336	22					
1811	.595	1		1861	.136	3		1911	-1.956	10		1961	.821	21		2011	.623	22					
1812	.996	1		1862	.501	3		1912	-.557	10		1962	.037	21									
1813	1.178	1		1863	.933	3		1913	-.483	10		1963	.786	21									
1814	-.207	1		1864	-.780	3		1914	-.755	11		1964	-.844	21									
1815	-1.443	1		1865	-.790	3		1915	-1.073	11		1965	.218	22									
1816	.504	1		1866	.672	3		1916	.717	11		1966	-1.218	22									
1817	-.862	1		1867	.467	3		1917	1.620	11		1967	.592	22									
1818	-1.188	1		1868	1.050	3		1918	-.441	11		1968	.471	22									
1819	-1.266	1		1869	2.930	3		1919	.206	11		1969	-.827	22									
1820	.056	1		1870	.266	3		1920	.401	11		1970	-.472	22									
1821	1.838	1		1871	-.343	3		1921	-.136	11		1971	-.170	22									
1822	-.062	1		1872	-1.519	3		1922	.464	12		1972	.809	22									
1823	1.622	1		1873	.705	3		1923	.507	12		1973	-.148	22									
1824	-.225	1		1874	-.518	3		1924	.855	12		1974	-.099	22									
1825	.395	1		1875	-.446	3		1925	-1.632	12		1975	.900	22									
1826	-1.136	1		1876	.397	3		1926	.004	12		1976	1.764	22									
1827	.588	1		1877	.355	3		1927	-.178	12		1977	.718	22									
1828	-.876	1		1878	-1.654	3		1928	.669	12		1978	.460	22									
1829	-.849	1		1879	-1.877	3		1929	-.147	12		1979	-.764	22									
1830	-1.346	1		1880	-1.308	3		1930	-.962	12		1980	-.491	22									
1831	-1.971	1		1881	-.234	3		1931	-.022	12		1981	.742	22									
1832	.349	1		1882	.784	3		1932	.517	13		1982	.731	22									
1833	-1.794	1		1883	1.345	3		1933	-.431	13		1983	-.551	22									
1834	-.633	1		1884	.718	3		1934	.564	13		1984	-1.363	22									
1835	-.896	2		1885	.616	4		1935	.563	13		1985	-.231	22									
1836	.940	2		1886	.742	4		1936	-1.784	13		1986	-1.484	22									
1837	1.410	2		1887	.718	4		1937	1.065	14		1987	.263	22									
1838	1.905	2		1888	.098	5		1938	1.080	15		1988	-.564	22									
1839	-.206	2		1889	-.307	5		1939	-.910	15	1	1989	1.017	22									
1840	.813	2		1890	-.179	5		1940	.532	15		1990	-1.033	22									
1841	.286	2		1891	1.324	6		1941	-.327	17		1991	.464	22									
1842	1.038	2		1892	.629	6		1942	-.389	17		1992	.827	22									
1843	1.552	2		1893	.138	6		1943	-.072	17		1993	.293	22									
1844	-.858	2		1894	-1.810	7		1944	-1.586	18		1994	1.062	22									
1845	-.682	2		1895	-.652	7		1945	1.596	18		1995	.058	22									
1846	.013	2		1896	-.880	8		1946	1.400	18		1996	.800	22									
1847	.073	2		1897	.046	8		1947	.473	18		1997	-.610	22									
1848	-1.584	2		1898	-.665	8		1948	-.251	18		1998	-1.504	22									
1849	-1.045	2		1899	-.723	8		1949	-.460	18		1999	-.065	22									

Correlations of 40-year dated segments, lagged 10 years
Flags: A = correlation under .3665 but highest as dated; B = correlation higher at other than dated position

Seq	Series	Time_span	1830 1869	1840 1879	1850 1889	1860 1899	1870 1909	1880 1919	1890 1929	1900 1939	1910 1949	1920 1959	1930 1969	1940 1979	1950 1989	1960 1999	1970 2009	1980 2019
1	NSP001A	1944 2011												.47	.38	.41	.41	.43
2	NSP001B	1941 2011												.45	.45	.31A	.49	.30A
3	NSP002A	1938 2011											.59	.58	.42	.30A	.21B	.22A
4	NSP02B	1937 2011											.60	.59	.49	.35A	.30A	.28A
5	NSP003A	1957 2011													.57	.56	.79	.80
6	NSP003B	1965 2011														.52	.56	.56
7	NSP004B	1835 2011	.62	.54	.56	.50	.44	.62	.74	.84	.75	.69	.61	.51	.57	.52	.59	.60
8	NSP005A	1903 2011								.63	.70	.78	.71	.73	.72	.68	.74	.74
9	NSP006A	1891 2011							.49	.51	.57	.70	.70	.65	.60	.61	.64	.65
10	NSP007	1896 2011							.80	.88	.86	.78	.60	.45	.43	.48	.70	.67
11	NSP008	1801 1949	.67	.57	.62	.52	.39B	.59	.68	.52	.51							
12	NSP009	1894 2011							.61	.61	.68	.67	.66	.74	.73	.77	.71	.72
13	NSP010	1941 2011												.73	.76	.71	.73	.73
14	NSP011B	1932 2011											.68	.54	.51	.32B	.43B	.44
15	NSP012	1922 2011										.59	.65	.67	.65	.72	.65	.67
16	NSP013A	1854 2011			.33A	.40	.34B	.62	.61	.67	.68	.65	.73	.67	.65	.59	.61	.62
17	NSP013B	1906 2011								.32B	.31B	.41	.49	.52	.40	.51	.38	.38
18	NSP014A	1953 2011													.68	.72	.78	.78
19	NSP014B	1958 2011													.78	.78	.73	.73
20	NSP016A	1952 2011													.61	.64	.60	.61
21	NSP16B	1914 2011									.50	.59	.58	.51	.56	.63	.67	.66
22	NSP019	1888 2011						.48	.48	.47	.50	.49	.47	.46	.33B	.37A	.33A	.35A
23	NSP020	1885 2011						.62	.65	.63	.68	.69	.70	.68	.71	.72	.75	.78
Av segment correlation			.65	.56	.50	.48	.39	.59	.63	.61	.61	.64	.63	.59	.57	.56	.58	.58

```
For each series with potential problems the following diagnostics may appear:

 [A] Correlations with master dating series of flagged  40-year segments of series filtered with  32-year spline,
     at every point from ten years earlier (-10) to ten years later (+10) than dated

 [B] Effect of those data values which most lower or raise correlation with master series
     Symbol following year indicates value in series is greater (>) or lesser (<) than master series value

 [C] Year-to-year changes very different from the mean change in other series

 [D] Absent rings (zero values)

 [E] Values which are statistical outliers from mean for the year
=====================================================================================================================

 NSP001A   1944 to  2011      68 years                                                                     Series   1

 [B] Entire series, effect on correlation (  .477) is:
       Lower   2009< -.073   1981< -.040   1952> -.027   1975< -.013   1988> -.008   1970> -.007  Higher   2000  .045   1944  .033

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2009 -4.6 SD
=====================================================================================================================

 NSP001B   1941 to  2011      71 years                                                                     Series   2

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1960 1999    0   -.14  .04 -.20 -.07  .05  .07 -.32 -.19 -.27  .12  .31* .01  .03 -.02  .20  .12 -.02  .29  .06  .13 -.07
    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    1972 2011    0   -.08 -.03 -.28 -.12 -.15  .03  .05 -.28 -.07  .06  .30*  -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .342) is:
       Lower   2011< -.106   1991< -.025   1966> -.024   1965< -.022   1964> -.021   2007> -.019  Higher   1959  .039   1952  .029
     1960 to 1999 segment:
       Lower   1991< -.055   1966> -.055   1964> -.050   1965< -.049   1969> -.021   1970> -.014  Higher   1990  .053   1976  .047
     1972 to 2011 segment:
       Lower   2011< -.198   1991< -.040   2007> -.035   2000> -.009   2010> -.009   1988> -.008  Higher   1990  .042   1976  .037

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       2011 -5.7 SD
=====================================================================================================================

 NSP002A   1938 to  2011      74 years                                                                     Series   3

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1960 1999    0   -.05  .01 -.22 -.11 -.19  .20 -.01 -.23  .05  .01  .30* .29 -.04  .17 -.21  .28 -.23  .00 -.23 -.32  .09
    1970 2009    1   -.02  .14 -.23 -.02 -.16  .19 -.03 -.24 -.08  .01  .21| .32* .02    -    -    -    -    -    -    -    -
    1972 2011    0    .02  .09 -.24 -.08 -.17  .16  .04 -.19 -.09  .03  .22*  -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .379) is:
       Lower   2000> -.059   1985< -.041   1986> -.031   1990> -.013   1950< -.009   1956> -.008  Higher   1944  .045   1952  .035
     1960 to 1999 segment:
       Lower   1985< -.073   1986> -.062   1990> -.024   1967< -.014   1998> -.013   1970> -.013  Higher   1983  .025   1972  .023
     1970 to 2009 segment:
       Lower   2000> -.094   1985< -.055   1986> -.047   1990> -.016   2005< -.013   1970> -.010  Higher   2007  .033   1983  .032
     1972 to 2011 segment:
       Lower   2000> -.098   1985< -.052   1986> -.050   1990> -.018   2005< -.011   2011< -.009  Higher   1983  .032   2007  .029
```

```
[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      2000 +4.5 SD
====================================================================================================================================

NSP02B    1937 to  2011      75 years                                                                                   Series   4

[A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
   ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
   1960 1999    0   -.14  .04 -.26 -.12 -.25  .20  .13  .09 -.10  .16  .35* .14  .05  .06 -.05  .12 -.30 -.07 -.37 -.01  .15
   1970 2009    0   -.16  .12 -.35  .02 -.20  .28  .06 -.04 -.13 -.01  .30* .19  .11    -    -    -    -    -    -    -    -
   1972 2011    0    .09  .06 -.31 -.03 -.27  .18 -.03  .18 -.10 -.03  .28*   -    -    -    -    -    -    -    -    -    -

[B] Entire series, effect on correlation (  .386) is:
      Lower   2000> -.052   2010< -.031   1966> -.028   1960< -.023   2003< -.016   1979> -.013  Higher   1945  .026   1955  .022
    1960 to 1999 segment:
      Lower   1966> -.064   1960< -.046   1979> -.030   1990> -.029   1961< -.017   1989< -.013  Higher   1976  .044   1969  .023
    1970 to 2009 segment:
      Lower   2000> -.090   2003< -.033   1979> -.021   2005< -.018   1990> -.017   1989< -.015  Higher   1976  .039   2001  .023
    1972 to 2011 segment:
      Lower   2000> -.082   2010< -.031   2003< -.025   1979> -.020   1990> -.018   2005< -.014  Higher   1976  .035   2001  .022

[E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
      2000 +3.8 SD;    2001 +3.5 SD
====================================================================================================================================

NSP003A   1957 to  2011      55 years                                                                                   Series   5

[B] Entire series, effect on correlation (  .656) is:
      Lower   1967< -.050   1961< -.032   1998> -.022   1964> -.014   2006> -.013   1968< -.011  Higher   2007  .048   2000  .037

[E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      2006 +3.3 SD
====================================================================================================================================

NSP003B   1965 to  2011      47 years                                                                                   Series   6

[B] Entire series, effect on correlation (  .542) is:
      Lower   1998> -.028   1966> -.027   1983> -.023   2009< -.018   1986> -.015   2006> -.012  Higher   2000  .048   2007  .041

====================================================================================================================================

NSP004B   1835 to  2011     177 years                                                                                   Series   7

[B] Entire series, effect on correlation (  .600) is:
      Lower   1878> -.016   1990> -.016   1844< -.014   1987< -.010   1890> -.009   1948< -.008  Higher   1859  .017   1869  .012

[E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
      1890 +3.4 SD;    1951 +3.6 SD;    1990 +3.5 SD
====================================================================================================================================

NSP005A   1903 to  2011     109 years                                                                                   Series   8

[B] Entire series, effect on correlation (  .677) is:
      Lower   1903< -.028   1918> -.019   1933> -.011   1968< -.011   1944> -.009   1909< -.007  Higher   1936  .023   1925  .016

====================================================================================================================================

NSP006A   1891 to  2011     121 years                                                                                   Series   9
```

```
 [B] Entire series, effect on correlation (  .601) is:
       Lower   1911> -.042   1973< -.014   1995> -.012   1971< -.010   1959> -.009   2001< -.008  Higher   2007  .022   1925  .014

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1911 +4.3 SD;    1995 +3.9 SD
==================================================================================================================================

 NSP007    1896 to  2011     116 years                                                                                    Series  10

 [B] Entire series, effect on correlation (  .658) is:
       Lower   1965< -.039   1960< -.024   1898< -.014   1979> -.009   1955< -.007   2011< -.007  Higher   1936  .025   1925  .016

==================================================================================================================================

 NSP008    1801 to  1949     149 years                                                                                    Series  11

 [*] Early part of series cannot be checked from 1801 to 1834 -- not matched by another series

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1870 1909   -1   -.23 -.16 -.32 -.05 -.25 -.04 -.01 -.17  .02  .40* .39| .15  .23  .07  .18 -.01  .05 -.20 -.08 -.14 -.13

 [B] Entire series, effect on correlation (  .530) is:
       Lower   1935< -.042   1844> -.028   1878> -.015   1942< -.014   1890< -.013   1891< -.010  Higher   1859  .043   1911  .020
     1870 to 1909 segment:
       Lower   1878> -.052   1890< -.040   1891< -.028   1900> -.016   1909< -.015   1889> -.012  Higher   1894  .064   1904  .028

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1844 +4.3 SD;    1935 -6.1 SD
==================================================================================================================================

 NSP009    1894 to  2011     118 years                                                                                    Series  12

 [B] Entire series, effect on correlation (  .599) is:
       Lower   1939< -.055   1936> -.032   1898> -.020   1968< -.011   1907> -.007   1900> -.007  Higher   1911  .018   1925  .011

 [D]    1 Absent rings:  Year   Master  N series Absent
                         1939    -.910      15       1

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
       1898 +3.4 SD;    1936 +3.1 SD;    1939 -8.7 SD
==================================================================================================================================

 NSP010    1941 to  2011      71 years                                                                                    Series  13

 [B] Entire series, effect on correlation (  .726) is:
       Lower   1992< -.038   1944> -.032   1978< -.018   1983> -.013   1997> -.009   2002< -.005  Higher   2007  .024   1952  .014

==================================================================================================================================

 NSP011B   1932 to  2011      80 years                                                                                    Series  14

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1960 1999   -2   -.31  .09 -.22  .03 -.25 -.28  .10 -.34  .34* .09  .32|-.05  .15  .23  .10  .17 -.13 -.26 -.23 -.06  .09
    1970 2009   -2   -.16  .25 -.38 -.09 -.39 -.26 -.12 -.21  .44* .14  .43| .02  .07    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .570) is:
```

```
      Lower   1990> -.027   1960< -.025   1975< -.023   1998> -.023   1979> -.015   2007> -.014  Higher   1936  .047   1986  .013
    1960 to 1999 segment:
      Lower   1960< -.064   1975< -.060   1990> -.055   1998> -.043   1981< -.033   1979> -.031  Higher   1986  .067   1976  .041
    1970 to 2009 segment:
      Lower   1975< -.063   1990> -.056   1998> -.044   1981< -.034   1979> -.032   1999< -.017  Higher   1986  .054   2000  .050

====================================================================================================================================

 NSP012    1922 to  2011      90 years                                                                                    Series  15

 [B] Entire series, effect on correlation (  .640) is:
      Lower   2006< -.020   1938< -.019   1959> -.012   1989< -.012   1947< -.010   2007> -.010  Higher   1944  .014   1966  .012

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
      1960 +3.1 SD
====================================================================================================================================

 NSP013A   1854 to  2011     158 years                                                                                    Series  16

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1854 1893    0   -.12 -.42  .12 -.09  .21 -.07 -.05 -.01  .04  .17  .33* .11 -.22  .03 -.01 -.07 -.02  .00 -.02 -.07 -.07
    - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    1870 1909    1    .03 -.45  .02 -.18  .18 -.20  .14 -.02  .08  .26  .34| .44*-.04 -.06 -.05 -.17 -.15 -.09 -.23 -.15 -.02

 [B] Entire series, effect on correlation (  .538) is:
      Lower   1859> -.029   1878< -.028   1879> -.011   1888> -.009   1984< -.009   1925> -.008  Higher   1911  .017   2000  .014
    1854 to 1893 segment:
      Lower   1878< -.081   1888> -.029   1855< -.018   1859> -.018   1879> -.015   1870> -.010  Higher   1869  .061   1857  .014
    1870 to 1909 segment:
      Lower   1878< -.091   1879> -.039   1888> -.036   1870> -.016   1872> -.010   1889< -.010  Higher   1894  .029   1903  .027

 [E] Outliers     4   3.0 SD above or -4.5 SD below mean for year
      1859 +4.3 SD;    1878 -5.3 SD;    1888 +3.1 SD;    1984 -6.9 SD
====================================================================================================================================

 NSP013B   1906 to  2011     106 years                                                                                    Series  17

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1906 1945   -3   -.17 -.03 -.09 -.24  .08  .03 -.14  .45* .04 -.17  .32|-.18  .08  .00 -.09  .26 -.38 -.19  .17 -.08  .10
    1910 1949   -3   -.18  .01 -.07 -.25  .11  .00 -.13  .38* .00 -.15  .31|-.20  .13 -.09 -.09  .37 -.38 -.25  .23  .03 -.02

 [B] Entire series, effect on correlation (  .362) is:
      Lower   1916< -.022   2000> -.018   1959> -.017   1955< -.014   1917< -.014   1977< -.011  Higher   1944  .017   1936  .016
    1906 to 1945 segment:
      Lower   1916< -.046   1917< -.028   1918> -.023   1915> -.016   1928< -.015   1921> -.011  Higher   1944  .040   1936  .038
    1910 to 1949 segment:
      Lower   1916< -.048   1917< -.029   1918> -.022   1939< -.016   1928< -.016   1915> -.015  Higher   1944  .041   1936  .040

 [E] Outliers     3   3.0 SD above or -4.5 SD below mean for year
      1939 -5.6 SD;    1985 +3.3 SD;    1990 -4.6 SD
====================================================================================================================================

 NSP014A   1953 to  2011      59 years                                                                                    Series  18

 [B] Entire series, effect on correlation (  .718) is:
      Lower   1966< -.029   1976< -.012   1969> -.010   1959> -.008   1987< -.008   2008< -.008  Higher   2007  .024   1956  .010
```

```
===================================================================================================================================

 NSP014B   1958 to  2011      54 years                                                                                    Series  19

 [B] Entire series, effect on correlation (  .765) is:
       Lower   1990> -.035   2006< -.011   1987< -.011   2000> -.010   1958< -.010   2002< -.010  Higher   2007  .017   1986  .013

===================================================================================================================================

 NSP016A   1952 to  2011      60 years                                                                                    Series  20

 [B] Entire series, effect on correlation (  .639) is:
       Lower   2000> -.027   1979> -.027   1990> -.018   1972< -.018   2004< -.017   1962< -.014  Higher   2007  .024   1998  .020

===================================================================================================================================

 NSP16B    1914 to  2011      98 years                                                                                    Series  21

 [B] Entire series, effect on correlation (  .579) is:
       Lower   1975< -.029   1915> -.013   1939> -.010   1966> -.009   1964> -.008   2010> -.008  Higher   2007  .023   1986  .016

 [E] Outliers     1   3.0 SD above or -4.5 SD below mean for year
       1967 +3.4 SD
===================================================================================================================================

 NSP019    1888 to  2011     124 years                                                                                    Series  22

 [A] Segment   High   -10   -9   -8   -7   -6   -5   -4   -3   -2   -1   +0   +1   +2   +3   +4   +5   +6   +7   +8   +9  +10
    ---------  ----   ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---  ---
    1950 1989   -7    .26  .08 -.22  .38*-.26  .30 -.15 -.05 -.22 -.12  .33|-.10 -.05 -.10 -.18  .32  .08  .20 -.02  .02  .13
    1960 1999    0    .15 -.06 -.28  .35 -.03  .33  .08 -.12 -.01 -.28  .37*-.23 -.02 -.18 -.17  .23 -.06  .18  .17  .09  .26
    1970 2009    0    .00 -.02 -.03  .24  .12  .19 -.09 -.18  .00 -.23  .33*-.05  .11    -    -    -    -    -    -    -    -
    1972 2011    0    .08 -.05 -.01  .21  .13  .16 -.11 -.10 -.02 -.23  .35*   -    -    -    -    -    -    -    -    -    -

 [B] Entire series, effect on correlation (  .422) is:
       Lower   2007> -.026   2006< -.019   1983> -.018   1963< -.015   1921< -.012   1905< -.011  Higher   1944  .020   1925  .017
     1950 to 1989 segment:
       Lower   1983> -.057   1963< -.055   1961< -.033   1978< -.028   1956> -.022   1957< -.021  Higher   1959  .086   1955  .032
     1960 to 1999 segment:
       Lower   1983> -.054   1963< -.047   1961< -.028   1978< -.022   1997> -.021   1986> -.019  Higher   1990  .068   1994  .028
     1970 to 2009 segment:
       Lower   2007> -.071   2006< -.048   1983> -.047   1978< -.020   2005< -.020   1997> -.017  Higher   1990  .065   2000  .038
     1972 to 2011 segment:
       Lower   2007> -.073   1983> -.048   2006< -.047   1978< -.019   2005< -.019   1997> -.018  Higher   1990  .061   2000  .035

 [E] Outliers     2   3.0 SD above or -4.5 SD below mean for year
       1983 +3.7 SD;    2006 -4.6 SD
===================================================================================================================================

 NSP020    1885 to  2011     127 years                                                                                    Series  23

 [B] Entire series, effect on correlation (  .680) is:
       Lower   1915> -.016   1888< -.014   1904< -.013   1922< -.006   1913> -.006   1962< -.006  Higher   2000  .014   1911  .010
```

						Corr	//-------- Unfiltered --------\\					//---- Filtered -----\\			
			No.	No.	No.	with	Mean	Max	Std	Auto	Mean	Max	Std	Auto	AR
Seq	Series	Interval	Years	Segmt	Flags	Master	msmt	msmt	dev	corr	sens	value	dev	corr	()
1	NSP001A	1944 2011	68	5	0	.477	3.13	6.28	1.462	.827	.220	2.52	.504	-.070	1
2	NSP001B	1941 2011	71	5	2	.342	2.78	5.20	1.022	.722	.217	2.59	.502	-.012	1
3	NSP002A	1938 2011	74	6	3	.379	3.66	7.50	1.176	.811	.155	2.64	.563	-.030	1
4	NSP02B	1937 2011	75	6	3	.386	4.55	9.88	1.810	.855	.128	2.76	.512	-.065	1
5	NSP003A	1957 2011	55	4	0	.656	5.03	8.45	1.201	.615	.163	2.60	.545	-.111	1
6	NSP003B	1965 2011	47	3	0	.542	3.11	5.56	1.146	.781	.184	2.57	.509	-.115	1
7	NSP004B	1835 2011	177	16	0	.600	1.68	3.40	.550	.684	.195	2.74	.411	-.032	1
8	NSP005A	1903 2011	109	9	0	.677	2.33	5.12	.976	.752	.236	2.74	.470	-.073	1
9	NSP006A	1891 2011	121	10	0	.601	2.05	7.18	.787	.659	.202	2.69	.504	-.045	1
10	NSP007	1896 2011	116	10	0	.658	2.44	4.42	.649	.577	.190	2.69	.477	.011	1
11	NSP008	1801 1949	149	9	1	.530	1.24	2.89	.514	.784	.219	2.51	.337	-.060	1
12	NSP009	1894 2011	118	10	0	.599	2.33	4.84	.714	.453	.248	2.43	.304	.015	1
13	NSP010	1941 2011	71	5	0	.726	3.40	11.15	1.663	.688	.286	2.65	.519	-.095	1
14	NSP011B	1932 2011	80	6	2	.570	3.76	7.49	1.490	.683	.206	2.46	.427	-.080	1
15	NSP012	1922 2011	90	7	0	.640	2.36	3.90	.653	.393	.244	2.56	.431	-.045	1
16	NSP013A	1854 2011	158	14	2	.538	1.82	4.07	.852	.721	.290	2.56	.400	-.017	1
17	NSP013B	1906 2011	106	9	2	.362	2.55	5.49	1.226	.784	.266	2.46	.388	-.083	1
18	NSP014A	1953 2011	59	4	0	.718	3.35	6.91	1.252	.715	.232	2.47	.447	-.022	1
19	NSP014B	1958 2011	54	4	0	.765	4.90	7.92	1.288	.712	.170	2.53	.477	.054	1
20	NSP016A	1952 2011	60	4	0	.639	4.96	8.51	1.562	.733	.196	2.51	.417	-.019	1
21	NSP16B	1914 2011	98	8	0	.579	3.17	7.18	1.177	.631	.198	2.80	.465	-.051	1
22	NSP019	1888 2011	124	11	4	.422	1.70	4.88	.917	.799	.236	2.66	.432	-.043	1
23	NSP020	1885 2011	127	11	0	.680	1.98	3.69	.631	.592	.239	2.62	.413	-.008	1
Total or mean:			2207	176	19	.567	2.64	11.15	.977	.688	.219	2.80	.441	-.040	

Appendix 2

Raw ring width measurements
for the 44 increment cores from TVA Islands 1 and 2.

The ring width measurements are in international decadal format at 0.001 mm accuracy with the decimal point removed. Each line contains the ring series ID, the first year, then the measurements for that particular decade. For example, a measurement of 833 indicates an absolute value of 0.833 mm. The value of "-9999" is an end-of-series sentinel.

IS1_02A	1959	2227									
IS1_02A	1960	1537	2064	1124	2305	845	1431	2838	3502	2345	3064
IS1_02A	1970	3088	3114	2332	7826	7347	5735	6616	6494	4755	6416
IS1_02A	1980	5118	4835	893	1648	799	1279	1842	3558	3316	2989
IS1_02A	1990	2284	1603	736	2228	1531	1688	459	733	298	716
IS1_02A	2000	394	224	1120	270	505	1544	693	435	556	520
IS1_02A	2010	247	834	-9999							
IS1_03B	1973	5912	8047	7546	7399	7894	3888	4030			
IS1_03B	1980	1400	6124	2601	1263	959	1111	201	2485	843	474
IS1_03B	1990	272	213	301	300	644	894	1355	1196	1480	2289
IS1_03B	2000	904	1219	1116	2213	836	870	347	194	445	2527
IS1_03B	2010	403	340	-9999							
IS1_04A	1979	15947									
IS1_04A	1980	7293	9899	6559	4568	5501	7924	6404	11771	12082	11620
IS1_04A	1990	8582	13575	10787	10073	8516	2789	4983	5749	5846	1056
IS1_04A	2000	1368	466	2090	324	561	384	459	482	510	990
IS1_04A	2010	519	311	-9999							
IS1_04B	1973	2128	2825	3142	3103	3720	3677	5487			
IS1_04B	1980	5236	4129	4662	6189	4991	5266	6289	3850	4647	5602
IS1_04B	1990	5646	3843	3859	4566	4143	6541	3953	3829	2030	1282
IS1_04B	2000	1819	691	1127	1202	1042	1418	1865	1084	1189	1073
IS1_04B	2010	6841	2032	-9999							
IS1_05A	1974	6859	8951	12121	8696	6260	5302				
IS1_05A	1980	9386	6317	6925	5172	9109	7208	9295	5957	2772	724
IS1_05A	1990	1008	1518	4295	7933	6717	4717	2918	3146	5484	1278
IS1_05A	2000	1172	3958	5407	3629	1232	789	744	713	833	3489
IS1_05A	2010	700	485	-9999							
IS1_06A	1966	6801	7843	7885	9362						
IS1_06A	1970	9390	9344	7368	9947	3501	8909	13867	10298	1512	5028
IS1_06A	1980	7848	2139	6885	7534	2412	1672	5634	4253	5393	11713
IS1_06A	1990	2429	6905	7000	3186	2342	1066	2613	1006	5241	1654
IS1_06A	2000	794	998	633	1210	1206	1170	545	960	672	675
IS1_06A	2010	238	314	-9999							
IS1_06B	1967	12442	11012	2974							
IS1_06B	1970	6805	9533	9200	11264	12247	12815	11164	5359	6475	2153
IS1_06B	1980	6033	7574	6174	2790	2609	3743	3314	7952	1664	5221
IS1_06B	1990	5872	2227	759	1049	3613	1072	3148	1177	524	454
IS1_06B	2000	872	2766	1099	1307	1399	1691	647	769	705	1419
IS1_06B	2010	286	277	-9999							
IS1_10A	1979	7797									
IS1_10A	1980	7783	5578	5581	6428	3727	4140	5832	2833	4744	2716
IS1_10A	1990	2689	5720	2065	5455	4782	6003	4920	2548	2616	3094
IS1_10A	2000	1761	2069	1098	1034	1779	2033	1188	1335	3006	3841
IS1_10A	2010	926	859	-9999							
IS1_10B	1979	4699									
IS1_10B	1980	3411	5033	4558	4553	5222	5995	4551	4686	4968	2988
IS1_10B	1990	4727	5398	6945	3905	5852	5475	4658	5065	3858	3541
IS1_10B	2000	4531	1596	1317	697	1333	712	378	1726	579	1629
IS1_10B	2010	744	823	-9999							
IS1_11A	1969	12061									
IS1_11A	1970	16482	13961	3790	7061	5666	6563	3633	4660	3850	5536
IS1_11A	1980	5686	7293	6863	12133	5024	3063	2239	2643	607	2324
IS1_11A	1990	1947	5058	2815	4123	3015	4607	4057	4597	1778	3594
IS1_11A	2000	2849	593	1204	1323	1673	1154	855	1122	4293	500
IS1_11A	2010	300	69	-9999							
IS1_13B	1972	3081	4657	6237	5954	7061	3567	5493	8752		
IS1_13B	1980	11676	8040	13166	7893	11873	8012	6841	8347	12679	1168
IS1_13B	1990	5324	9652	1711	4691	1464	3412	826	1092	658	720
IS1_13B	2000	420	160	276	452	418	401	1015	870	319	519
IS1_13B	2010	569	515	-9999							
IS1_14A	1963	1747	1372	3026	3674	4222	1987	2712			
IS1_14A	1970	3566	3320	2438	2564	2731	2885	1378	1854	4204	2038

IS1_14A	1980	2977	3028	3588	2165	1228	1437	2745	1748	1605	1362
IS1_14A	1990	1785	1705	1023	1077	816	1066	955	697	1170	835
IS1_14A	2000	1183	782	817	1315	1842	1961	1582	1113	897	1041
IS1_14A	2010	4576	4870	-9999							
IS1_15A	1986	11253	8334	6442	12106						
IS1_15A	1990	5966	2781	6864	3751	4593	8898	12929	6729	4551	3957
IS1_15A	2000	6201	2149	3135	4418	2178	3596	1212	941	2794	3541
IS1_15A	2010	1074	2759	-9999							
IS1_15B	1978	4601	5035								
IS1_15B	1980	6900	5559	3012	6218	5613	6241	5691	8396	12523	8691
IS1_15B	1990	8548	9031	6953	6301	4469	6333	5049	5156	2850	3507
IS1_15B	2000	5615	2265	2241	2637	2374	4232	2189	3075	2757	2030
IS1_15B	2010	2402	2100	-9999							
IS1_16A	1983	2382	3346	2638	3343	1355	1468	345			
IS1_16A	1990	2696	1760	3433	3447	1115	2870	3991	4605	4110	2551
IS1_16A	2000	3123	750	1880	3601	2717	1606	562	637	1402	3007
IS1_16A	2010	2693	3110	-9999							
IS1_52A	1954	5715	757	1804	1228	921	2894				
IS1_52A	1960	3596	1006	3348	1452	828	1296	1001	866	4015	2141
IS1_52A	1970	2615	3328	3678	987	2395	5145	4153	1068	1729	2352
IS1_52A	1980	1015	1953	2010	2777	2638	3036	2946	4012	451	1370
IS1_52A	1990	1493	965	2871	3756	2364	2099	2497	687	1928	2642
IS1_52A	2000	2171	1179	134	2366	2115	1577	1524	2831	1006	1868
IS1_52A	2010	771	1541	-9999							
IS1_54A	1979	4207									
IS1_54A	1980	3918	3939	5585	3633	5390	5050	2963	5545	5526	4764
IS1_54A	1990	5836	5891	6705	6264	7305	8590	8415	7198	4314	4594
IS1_54A	2000	6189	6545	4287	3701	1688	3280	2872	4179	3682	6644
IS1_54A	2010	2391	1588	-9999							
IS1_58A	1952	1446	2714	1336	1241	906	1057	821	1741		
IS1_58A	1960	1537	1793	2419	2931	1673	1949	4103	3514	2091	2955
IS1_58A	1970	2625	2542	3166	4695	3732	2560	4218	3358	4082	3471
IS1_58A	1980	3318	2614	1628	2090	1846	2309	2624	1686	2416	1423
IS1_58A	1990	1934	1428	1497	2317	1766	1780	1664	1234	944	702
IS1_58A	2000	696	1168	1781	1283	1774	1131	1185	1283	1002	872
IS1_58A	2010	1896	2848	-9999							
IS1_59A	1973	3231	3305	4444	5616	5571	4750	3121			
IS1_59A	1980	4897	4294	6727	4866	6051	5761	5810	7185	2763	2666
IS1_59A	1990	7838	4085	4987	7210	5785	6674	6668	7513	5444	4542
IS1_59A	2000	3793	4027	3029	3103	5031	2552	1677	2073	2446	3854
IS1_59A	2010	4367	3486	-9999							
IS1_61A	1968	2610	3545								
IS1_61A	1970	2288	2884	5958	5223	6760	10365	9446	16435	12182	12965
IS1_61A	1980	12183	9947	8907	11926	10332	7148	5511	5768	4174	3357
IS1_61A	1990	4161	5949	4560	3019	1958	5523	3213	5574	6703	6015
IS1_61A	2000	4385	3608	4422	4587	7335	8731	4939	3591	4081	5645
IS1_61A	2010	2845	1407	-9999							
IS1_71A	1991	3837	4422	4040	5753	4997	4009	3289	2357	3501	
IS1_71A	2000	3122	2682	3315	3675	2593	2293	2240	2601	3036	4740
IS1_71A	2010	3230	3016	-9999							
IS1_73A	1961	1937	2187	1776	2251	2857	3916	3270	7298	6457	
IS1_73A	1970	7050	5936	5190	4358	5286	7732	6921	6382	4547	4087
IS1_73A	1980	5433	3220	2648	2729	2522	1772	831	1119	725	1419
IS1_73A	1990	1599	1253	2149	2088	1314	2383	2352	2925	4767	2575
IS1_73A	2000	2624	4848	2945	6017	2276	2432	3252	3145	1846	3831
IS1_73A	2010	2426	3428	-9999							
IS1_74A	1988	4630	5978								
IS1_74A	1990	5905	7172	5642	5664	8051	6188	5684	7560	7165	7823
IS1_74A	2000	6397	5916	4841	4903	6807	4089	4846	3746	3023	4657
IS1_74A	2010	1141	916	-9999							
IS1_77A	1976	5816	4434	3387	5047						
IS1_77A	1980	3434	3609	753	393	286	690	650	961	579	974
IS1_77A	1990	2252	3716	818	1718	1073	1304	2386	1756	857	1272

IS1_77A	2000	935	729	847	939	897	1954	1433	615	928	596
IS1_77A	2010	458	1008	-9999							
IS1_78B	1994	11006	5974	7796	6335	4191	6542				
IS1_78B	2000	3791	5294	3956	687	5243	1808	1156	998	1270	4982
IS1_78B	2010	944	750	-9999							
IS1_80A	1983	7298	8008	7055	4751	9152	7882	9302			
IS1_80A	1990	7302	7330	7307	10770	11143	10993	8355	7426	6554	8588
IS1_80A	2000	4838	8790	6928	6661	4878	10954	8054	7505	4282	8669
IS1_80A	2010	7153	3615	-9999							
IS1_81A	1987	7998	8479	9610							
IS1_81A	1990	8947	11637	7000	10108	10650	9210	9696	7230	11063	8803
IS1_81A	2000	7077	6050	3976	4016	3538	7504	6083	5448	4595	6403
IS1_81A	2010	7141	1964	-9999							
IS1_81B	1990	9043	9027	9067	8892	6792	9119	7626	6136	5861	2600
IS1_81B	2000	4289	3626	5874	6166	5105	3617	3790	2637	3285	1049
IS1_81B	2010	746	1101	-9999							
IS2_02A	1963	869	1410	1835	2407	2416	4962	4529			
IS2_02A	1970	4197	2371	2003	3414	2416	2527	1513	2079	2103	880
IS2_02A	1980	621	310	326	139	54	96	104	386	106	121
IS2_02A	1990	407	1245	1986	982	1295	1453	1866	2429	1204	2283
IS2_02A	2000	3763	3324	746	1217	446	532	366	2124	5520	879
IS2_02A	2010	1128	2270	-9999							
IS2_02A	1974	2507	2001	3896	3066	2957	1988				
IS2_02A	1980	2118	2697	836	712	498	451	284	237	212	196
IS2_02A	1990	608	1626	1125	848	2807	2957	4034	1840	2448	4037
IS2_02A	2000	4065	3897	811	4296	5891	1253	1596	2366	3840	6672
IS2_02A	2010	5077	4713	-9999							
IS2_02B	1975	2954	1759	4386	4084	3742					
IS2_02B	1980	2961	2759	2838	778	523	499	651	318	136	140
IS2_02B	1990	83	181	465	573	910	3731	3773	2958	1306	2644
IS2_02B	2000	4281	2596	4440	5185	5394	2750	4101	4364	5934	8049
IS2_02B	2010	8989	6452	-9999							
IS2_03B	1967	3108	3585	3899							
IS2_03B	1970	3672	3482	3859	6061	5052	4271	6676	3259	1765	2210
IS2_03B	1980	4150	2056	1760	1660	1950	4343	3454	1884	1534	1266
IS2_03B	1990	1980	3200	1222	2287	910	2244	1487	4922	2290	4188
IS2_03B	2000	3008	4018	2269	1408	3215	3585	3530	428	565	1087
IS2_03B	2010	549	751	-9999							
IS2_04A	1965	3713	4527	4084	6301	1792					
IS2_04A	1970	3917	5579	4738	3511	2588	4849	2645	2808	3193	692
IS2_04A	1980	2190	1618	7686	1706	981	1568	654	4545	3072	2267
IS2_04A	1990	828	1951	1615	4204	2498	4013	1774	3913	5612	6741
IS2_04A	2000	4200	2886	3889	2390	2705	2945	1132	534	577	1866
IS2_04A	2010	765	863	-9999							
IS2_05A	1968	6554	8108								
IS2_05A	1970	6717	6779	7419	4399	2181	3567	3607	5300	3717	3545
IS2_05A	1980	3832	2006	1214	704	2373	835	970	1556	2709	356
IS2_05A	1990	639	1635	4364	3440	4131	3064	2709	4764	6303	4268
IS2_05A	2000	6706	1973	9657	8079	5699	6626	7122	1715	5825	5093
IS2_05A	2010	3615	2306	-9999							
IS2_06B	1963	5592	1982	4308	5404	4472	5741	5079			
IS2_06B	1970	4592	3989	2907	1785	2321	2777	1646	1225	2575	1992
IS2_06B	1980	3610	2180	1681	1494	869	288	751	500	3808	903
IS2_06B	1990	2034	1515	2112	660	3276	3194	1896	712	1827	2390
IS2_06B	2000	2316	1748	745	1149	707	1092	1103	1291	2543	2369
IS2_06B	2010	927	924	-9999							
IS2_07A	1963	6924	2450	3093	5417	3529	2412	3175			
IS2_07A	1970	2423	2909	1907	948	1075	969	1347	747	491	2092
IS2_07A	1980	1186	921	532	431	346	935	1203	324	154	94
IS2_07A	1990	62	520	803	568	2531	1564	1421	2330	357	768
IS2_07A	2000	940	455	1932	199	1075	3866	2532	2639	1535	3516
IS2_07A	2010	2890	2830	-9999							
IS2_09A	1966	10029	3635	6292	6592						

IS2_09A	1970	4219	1201	2991	2024	2624	1999	1197	2020	2040	2477
IS2_09A	1980	1518	1341	2907	1949	1223	1075	617	2009	958	92
IS2_09A	1990	2450	1164	1085	2412	1698	2299	2236	2957	2446	3056
IS2_09A	2000	1868	3732	2977	1930	2886	3050	3131	4028	2803	5409
IS2_09A	2010	3006	2720	-9999							
IS2_10B	1964	4281	4909	4346	4943	2903	2150				
IS2_10B	1970	1171	2021	1424	1269	466	771	840	453	1009	695
IS2_10B	1980	1971	1812	1935	1857	428	570	1634	4257	3606	1394
IS2_10B	1990	2389	0	1945	5166	3560	6258	2908	3821	4922	3869
IS2_10B	2000	2214	2618	4998	1568	1104	2606	1752	1945	1740	2555
IS2_10B	2010	1207	589	-9999							
IS2_11A	1964	5123	5921	4321	4542	5721	4671				
IS2_11A	1970	4471	4907	2986	3603	2197	1824	1122	2103	2708	1347
IS2_11A	1980	2320	3975	1826	2510	2518	2034	351	1551	2211	1883
IS2_11A	1990	1437	827	1278	2535	3744	1595	1971	971	1435	715
IS2_11A	2000	322	2360	2938	973	1411	2785	4250	4558	3369	2554
IS2_11A	2010	2695	5928	-9999							
IS2_12A	1993	5673	3831	3588	1440	7177	8021	4888			
IS2_12A	2000	4742	4861	2732	2794	1925	1940	1538	1161	2889	3918
IS2_12A	2010	2228	2949	-9999							
IS2_13A	1982	3359	2353	1667	1744	958	2124	1008	387		
IS2_13A	1990	1887	1936	417	259	2687	3829	5530	5386	4032	2551
IS2_13A	2000	3238	1021	2738	544	3973	503	679	260	438	816
IS2_13A	2010	1860	938	-9999							
IS2_14A	1976	5423	3988	3599	7379						
IS2_14A	1980	7632	5457	8090	4403	3306	4860	3920	8841	7475	2514
IS2_14A	1990	1135	620	890	650	3349	6116	7834	1283	5516	6059
IS2_14A	2000	3299	1755	5982	1993	7654	9996	5691	4089	5625	3274
IS2_14A	2010	1374	2303	-9999							
IS2_18A	1973	4645	3017	2501	1428	2641	1512	2452			
IS2_18A	1980	2877	2487	3502	2251	2105	1776	2290	690	568	1454
IS2_18A	1990	4	282	291	654	1803	800	1731	3215	2535	3194
IS2_18A	2000	1860	3920	3586	3352	2611	2475	434	364	1876	2217
IS2_18A	2010	1779	1010	-9999							
IS2_20A	1969	5739									
IS2_20A	1970	6151	11504	6597	6214	7408	5652	3294	3762	4040	3344
IS2_20A	1980	1776	978	2202	1870	1450	994	1139	255	705	1594
IS2_20A	1990	648	624	671	933	1884	824	2308	1546	2544	2132
IS2_20A	2000	1243	1503	1356	2608	1178	1501	2071	2901	1220	2224
IS2_20A	2010	670	696	-9999							

VITA

Niki A. Garland grew up in the beautiful Appalachian region of East Tennessee. Geographically surrounded by the scenic mountains that bordered her rural upbringing, Niki learned to love nature at an early age. She studied at East Tennessee State University and McNeese State University (Louisiana) then eventually entered The University of Tennessee-Knoxville as an adult student with two children. Attending The University of Tennessee, she earned her Bachelor of Arts degree in Geography with a concentration in dendrochronology and biogeography in 2010 and was awarded the Michelle D. Pfeffer Outstanding Senior Award. She continued on at the University of Tennessee to pursue a Master's degree in Geography, focusing on dendroecology, biogeography, and environmental assessment.

At The University of Tennessee, she enjoyed working as a Graduate Teaching Assistant and participated in multiple research trips to the American Southwest, the eastern U.S., and southern Florida. Her research focused on dendroecological assessment at Tennessee Valley Authority's Kingston Fossil Plant and palaeoclimate analysis in the Southwest. Her time in the Laboratory of Tree-Ring Science was under the instruction of Dr. Henri Grissino-Mayer. She completed this research and earned her Master of Science degree in the spring of 2013. She plans on entering the private environmental business sector and continuing to preform environmental risk assessment.