PRESCRIBED BURNING EFFECTS ON GULLY HYDROLOGY, EROSION, AND SOIL PHOSPORUS POOLS IN THE PIEDMONT REGION OF SOUTH CAROLINA

by

MARCO A. GALANG

(Under the direction of Daniel Markewitz and Lawrence A. Morris)

ABSTRACT

Gullies found today in the Piedmont of South Carolina are legacies of past land abuse and erosion. Although currently covered with forest vegetation, issues related to gully contribution in nonpoint source pollution, particularly when forests are prescribed burned or otherwise disturbed, remain unanswered. This research was conducted with the goals of determining: 1) the influence of land use change on the morphological and current status of gullies; 2) the effect of prescribed burning on the hydrologic behavior of gullies; and 3) the effect of heating on the phosphorus (P) pools in soil. Three separate studies were conducted targeting these individual objectives. For the first goal, a field survey of gullies in the South Carolina Piedmont was conducted following an analysis of land cover in the area. For the second, eight individual gullies were hydrologically instrumented and monitored one year before and one year after a prescribed burning treatment. For the last objective, soil samples were heated with different temperature by duration regimes then analyzed with the modified Hedley fractionation procedure. Results from this controlled experiment were compared with results obtained for soils collected before and after prescribed burning that were similarly extracted. Results showed that: 1) legacy gullies found in older forested sites were deeper and wider than gullies found in more recently forested areas but all gullies included in the study are relatively stable; 2) not all gullies flowed during rain events but when they did flow, there was no evidence of adverse impacts of prescribed burning on hydrologic properties as inter-annual variation was greater than treatment effect; and 3) temperature and heating duration interaction play an important role in the release of P to solution.

INDEX WORDS: land cover change, nonpoint source pollution, surface runoff, water perching, P fractionation, soil heating, mineralization

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DEDICATION

To my wife, MHATIE and my son, MAX

My life, joy, inspiration, and strength

To NANAY, the greatest mother a person could ask for

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Land use change is well recognized as one of the major factors affecting soil erosion rates. In a forested area where gullies formed due to past agricultural practice but are now under forest vegetation, typical of the Piedmont region, the following questions arise:

a. Are gullies still actively eroding?
b. Is there a difference in the morphological properties of gullies based on time of reforestation?
c. How do gullies behave hydrologically under the present land cover?
d. Does prescribed burning affect the hydrologic behavior of these gullies?
e. How does soil heating affect the release of soil phosphorus that can potentially contribute to nonpoint source pollution?

These questions have not been dealt with in past studies of water erosion, where most research has concentrated on sheet (interrill) and rill erosion processes operating at the runoff scale (Poesen et al., 2003). Many scientists claim that the presence of gullies provides continuity in the transport of sediments, nutrients, and pollutants from the hillslope to the valley bottom or perennial streams. This is exemplified by the study of Rivenbark and Jackson (2004) where 50% of the occurrences of sediment extending through the Streamside Management Zone (SMZ), from observed clearcut and site prepared management units, were found in converging (swales) and gullied areas. Interest in ephemeral gully erosion, particularly in cultivated areas, has increased recently as evidenced by numerous publications on this topic (e.g. Poesen et al., 2003; Bennett et al, 2000; Valcarcel et al., 2003).

The use of prescribed fire for land management purposes and the incidence of wildfire have increased substantially since 1984 (Neary et al., 1999). Fire managers have reported an increase in area burned, fire frequency, and fire severity (Cromack et al., 2000). The effects of prescribed fire on a gullied landscape have not been fully explored. Prescribed burning could pose a serious threat to gully stability, and gullies could facilitate transport of nutrients and sediments to perennial streams.

Chapters presented in this dissertation address these five questions and are arranged to progress from a landscape perspective down to a soil chemical level. Together, these chapters present a holistic view of the effect of prescribed burning on gullies in lands returned to forest cover after agricultural abuse and abandonment.

Chapter 2 of this dissertation addresses the first two questions by examining land use change on a portion of the Long Cane Ranger District, Sumter National Forest, South Carolina. Sets of aerial photographs were digitized and a broad classification of land use as cultivated or forested was performed. Thereafter, a field survey of gullies found in “continually forested” and “cultivated-to-forested” sites was conducted and the abundance and morphological difference of gullies in each site were compared.

Chapter 3 focused on the third and fourth questions. Eight gullies under loblolly pine stands were hydrologically instrumented. The gullies were monitored and measured for one year to provide baseline information. Afterward, the stand was subjected to prescribed fire and the gullies were monitored for one year of post-burn data collection.

In Chapter 4, the effect of soil heating on the soil phosphorus pools was investigated to address the final (fifth) question. A laboratory experiment was conducted in which composite soil samples were heated at various temperatures and time intervals to mimic conditions that could occur during prescribed burn. After heating, samples were chemically analyzed using the Hedley sequential phosphorus analysis (Tiessen and Moir, 1993), and the results obtained were compared to that of the pre-burn and post-burn samples taken from the actual burn sites.

Chapter 5 summarizes and highlights the significant findings in this work.

Literature Review

Concept of gully erosion

Soil erosion refers to the detachment of soil particles and rock fragments and subsequent transport by an agent into an area of deposition. It is a natural process that has shaped the landscape and led to formation of fertile alluvial and loess soils. However, accelerated erosion resulting from human activities can have severe impacts on soil and environmental quality (Lal, 2001). With respect to the forces acting on soil, erosion can be classified as gravity erosion, wind erosion, or water erosion. In countries receiving high rainfall, water erosion is the dominant type. Water erosion is further classified into splash, rill, gully, and streambank erosion depending on the condition, amount and effect of water in soil.

“Gully erosion is defined as the erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes the soil to considerable depths from this narrow area” (Poesen et al., 2003). Poesen (1993) distinguishes rills from gullies by a critical cross-sectional area of 929 cm^2. In some cases, researchers used a minimum width of 0.3

m and a minimum depth of 0.6 m (Brice, 1966) or a minimum depth of 0.5 m (Imeson and Kwaad, 1980) to define gullies and distinguish these related features.

Gully erosion can be classified as permanent, ephemeral, or bank. The Soil Science Society of America Terminology Committee (2001) defined permanent gullies for agricultural land as “channels too deep to easily ameliorate with ordinary farm tillage equipment, typically ranging from 0.5 m to as much as 25-30 m in depth.” Ephemeral gully erosion was a classification introduced in the 1980’s to include concentrated flow erosion larger than rill erosion, but less than classical gully erosion (Poesen et al., 2003). Wherever concentrated runoff crosses an earthen bank, bank gullies develop (Poesen et al., 2003).

Gully erosion is a threshold phenomena that occurs only when a threshold of specified flow hydraulics, rainfall, topography, pedology, and land use have been exceeded (Poesen et al., 2003). Vandekerckhove et al. (2000) found that vegetation type and cover were far more important than climatic conditions for explaining differences in topographic thresholds for different areas. Valcarcel et al. (2003) stated that maintenance of vegetation cover completely prevented soil surface incision and channel formation in northwestern Spain. In Racaka, Hungary, because of deforestation and extension of agricultural areas, the average length of existing gullies rose from 21.3 to 38.2 km (Gabris et al., 2003). Gully systems may develop even if the slope gradient is below 12% (Gabris et al., 2003). Patton and Schumm (1975) found that “for a given drainage area it is possible to define a critical valley slope above which the valley floor is unstable, but variations in vegetative cover prevent recognition of a critical threshold slope.” Valcarcel et al. (2003) observed that main gullies tend to reappear at the same position in the landscape. The typical stages in gully evolution are: initiation, headward migration, channel widening, channel slope reduction, reduction of bank angles, deposition of sediment, and establishment of vegetation (Harvey et al., 1985).

Poesen et al. (2003) stated that soil loss rates by gully erosion can represent from 10 to 94% of total sediment yield caused by water erosion. In addition, they stated that the rate depends on gully type, soil type, land use, climate, and topography. Sediments transported from gullies do not originate from upslope but rather in the gully itself (Collison, 1996). Although not migrating rapidly (relatively stable), gully headcuts can nevertheless produce significant amounts of sediment during overland flow events (Hessel and van Asch, 2003). When the frequency of gullies increases in a particular catchment, specific sediment yield increases (Poesen et al., 2003). However, the mere presence of gullies does not always equate to high sediment yields (Harvey et al., 1985).

Gully erosion in the Southeastern United States

Ireland et al. (1939) and Trimble (1974) provided thorough accounts of erosion in the South Carolina Piedmont. Ireland et al. (1939) made a detailed survey of gully erosion in South Carolina, while Trimble provided a historical account of the relation between land use and erosion in the Piedmont region. Highlights of their results are:

Ireland et al. (1939):

a. In South Carolina, there was a close relation between the type of bedrock and the soil erosion conditions. In addition, precipitation intensity is also correlated to the rate of gully erosion.

b. The character and the distribution of gullies in the southern Piedmont are closely related to past and present land use. Most of the areas of severe erosion were directly related to roads, ditches, terraces, and other water channels, or type of cultivation practiced.
c. The steepest slope suitable for any form of cultivation in most Piedmont soils is approximately 12%.

Trimble (1974):

a. The conditions contributing to extensive erosion of the Piedmont have not been clear.
b. South Carolina has an average soil loss depth of 9.5 inches (24 cm).
c. On a regional basis, maximum soil erosion in the Piedmont occurred in the lower (southeast) Piedmont of South Carolina and Georgia, while the least erosion was found in the eastern Piedmont of North Carolina.

Effects of erosion

Erosion may lead to declines in soil quality and subsequent degradation of a land (Lal, 2001). In dry climates, if left unabated, this could result in desertification. With water erosion, selective removal of soil particles can occur due to the variation in size and density of particles. As a result, soil erosion by water gradually leads to a selective re-distribution of mineral nutrients. Kisic et al. (2002), working in the eroded tilled area of Croatia, found a higher soil pH, greater organic matter content, and more available P and K in erosional drifts compared to the eroded area.

“Erosion generally decreases productivity of forests by decreasing the available soil water for forest regrowth, and through loss of nutrients in eroded sediment” (Elliott et al., 1999).

With a decrease in soil depth, the amount of water the soil can hold also decreases. Sediments carried by running water usually contain considerable amounts of nutrients rendering eroded areas less fertile and the bottomlands increasingly fertile. This can make growth on the eroded sites marginal.

In a forest ecosystem, disturbances can be natural, such as wildfire, or human-induced, such as harvesting or prescribed burning (Elliott et al., 1999). Reported soil erosion rates for undisturbed or carefully managed forest land, is 0.05 to 0.10 ton acre^{-1} year^{-1} (0.1 to 0.25 tons ha^{-1} year^{-1}), which when compared to erosion from agricultural land of 1 to 5 tons acre^{-1} year^{-1} (2.5 to 12 tons ha^{-1} year^{-1}), is very low (Patric, 1976). Irresponsible timber harvest can quickly increase erosion of particulate matter to unacceptable levels (Patric, 1976). Wildfire and management practices such as timber harvest and prescribed burning carry the risk of producing unacceptable erosion rates due to the removal of soil cover.

Forest fire impacts on soil and nutrient loss

Fire in a forest ecosystem has positive and negative impacts. Fire is necessary for maintaining some species, and is the most rapid means for bringing about nutrient turnover (Cromack et al., 2000). Low intensity burning can promote herbaceous flora, increase plant available nutrients and thin overcrowded forests (Neary et al., 1999). Fire, however, removes vegetative cover and consumes organic material exposing the soil to erosion. In the United States, the stage for significant losses of nutrients and reduced soil quality is set due to increase in acreage and frequency of severe wildfires (Cromack et al., 2000).

The overall effects of fire on ecosystems range from the reduction or elimination of aboveground biomass to impacts on belowground physical, chemical and microbial-mediated processes (Neary et al., 1999). “The forest ecosystem characteristics that can increase vulnerability to the effects of fire are relative flammability of forest floor, the location of nutrient storage (above or below ground), depth of soil, site quality, steepness of slopes, propensity to produce hydrophobic soils, and likelihood of mass movement” (Cromack et al., 2000).

Soil properties that determine hydrologic functioning, such as infiltration rate, porosity, conductivity, and storage capacity, can be adversely affected by fire (Neary et al., 1999). During fire, nutrients in the vegetation and soil can be lost by direct combustion of organic matter and nutrient volatilization, or by erosion and mass movement (Cromack et al., 2000). S and N are the most easily volatilized, with volatilization temperatures often less than 375^oC. P and K volatilize at over 774^oC (De Bano and Conrad, 1978). Biological activity in soil begins to be disrupted in the $40\text{-}70^oC$ range (Neary et al., 1999). Helvey et al. (1985) reported that the total N losses to erosion in the Cascade Range of Washington increased from a pre-fire level of 0.004 kg ha^{-1} $year^{-1}$ to 0.16 kg ha^{-1} $year^{-1}$ post fire. Available P losses increased from 0.001 kg ha^{-1} $year^{-1}$ to 0.014 kg ha^{-1} $year^{-1}$, and the combined erosion losses of Ca, Mg, K, and Na increased from 1.98 kg ha^{-1} $year^{-1}$ to 54.3 kg ha^{-1} $year^{-1}$. However, they stated that “nutrient losses were insignificant for site productivity and stability compared with the physical effects of channel scouring associated with greater runoff, higher peak flows, and debris torrents following fire.” The beneficial release of nutrients, such as P resulting from fire has also been reported in various studies (e.g. Giardina et al., 2000).

Erosion can be severe after fires, particularly where soils are subject to formation of a hydrophobic surface, and there are one or more subsequent intense precipitation events. As a result of hydrophobic surface formation, there is an increase in downslope and downstream soil movement during precipitation events, which also increases runoff (Cromack et al., 2000). Fire-induced hydrophobic layers are of primary concern when they cause infiltration rates to drop below precipitation intensity.

Several studies have examined the effect of forest management practices on erosion after fire occurrence. For instance, Providoli et al. (2002) studied the effect of fire without post-fire treatment, fire followed by clear-cutting, and fire followed by clear-cutting after 1 year, and found that clear cutting did not increase the rate of splash erosion compared with the untreated, burned coppice. Furthermore, they did not find a deterioration of aggregate stability, although mean weight diameter of aggregates decreased for fire-affected sites. The loss of aggregate stability could lead to lower infiltration due to crusting and reduction of macropores. The strongest decrease in splash erosion occurred on plots subject to immediate clearcutting, which was attributed to the rapid development of vegetative cover protecting the soil from raindrop impact. Shahlaee et al. (1991) investigated fire effects on runoff production and soil loss in a cutover and burned mixed pine-hardwood site using rainfall simulation and natural rain events and found low yield for both runoff and sediments primarily due to residual forest floor (root mat layer) protection. However, they observed relatively higher runoff production at the onset of rain when antecedent moisture condition was dry due to a temporary hydrophobic condition in the residual forest floor.

There has been a lack of research focusing specifically on the effect of prescribed fire in a gullied landscape. Douglass and Van Lear (1983) investigated watersheds containing gullies but not individual gullies. Poesen et al. (2003) emphasized the role gullies play in the continuity of water and sediment flow from the uplands to valley bottoms and permanent channels. Gullies, therefore, could be significant contributors to nonpoint source pollution, currently a key issue in the southern United States (Baker, 1992). Thus, there is a need to characterize the hydrologic properties of gullies, as well as to quantify nutrients and sediment movement toward gullies following a prescribed burning.

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CHAPTER 2

LAND USE CHANGE AND GULLY EROSION IN THE PIEDMONT REGION OF SOUTH CAROLINA[1]

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ABSTRACT

Land use change played an important role in the formation of gullies present today in the Piedmont of the Southeastern United States. Forested areas that were once cleared to cultivate cotton and consequently gullied are now, once again, covered with forest vegetation. Despite this forest cover, gullies are still considered to be important contributors of sediment to streams, and restoration efforts are still ongoing. However, the data available to assess the extent of gully contributions of sediment are limited. This study assessed the present day stability of these gullies relative to the land use conditions from 1939 to 1999. Based on 1939, 1954, 1970, and 1999 aerial photographs land areas were classified into those found to be open or cultivated in 1939 that had converted to forest by 1999 (cultivated-to-forested) versus areas that were forested throughout this period (continually forested). An analysis was then conducted that quantified the number and morphological characteristics of gullies in these areas. Characteristics assessed during the field surveys that quantified the presence of recent erosion, such as percent bare soil or forest floor displacement, revealed that the majority of the gullies in both areas are stable. Surprisingly, more frequent (4 vs. 2 per transect), deeper (54 vs. 46 cm), and longer (36 vs. 30 m) gullies were found in the continually forested areas. This equated to a higher estimated average total volume eroded in the continually forested areas (299 m^3) compared to the cultivated-to-forested areas (107 m^3). It is believed that the continually forested areas, which had steeper average slopes, were cultivated but abandoned prior to 1939 due to severe gully formation.

Key words: cover change, erosion, gully survey, reforestation

INTRODUCTION

A change in land use from forest to agriculture can cause accelerated erosion. This is especially true if other factors, like slope and rainfall, are conducive to soil erosion. Gully erosion is considered a threshold phenomenon. It arises only when thresholds of flow hydraulics, rainfall, topography, pedology, and land use have been exceeded (Patton and Schumm 1975; Poesen et al. 2003). Patton and Schumm (1975) stated that “for a given drainage area it is possible to define a critical valley slope above which the valley floor is unstable” and susceptible to gullying. However, they have added that this critical slope is difficult to identify due to variation in vegetation, soil erodibility, and land use within the landscape. Land use has, in fact, been consistently investigated as a key driver of gully formation (Gabris et al. 2003; Harvey et al. 1985; Ireland et al. 1939; Poesen et al. 2003; Strunk 2003). For example, in Racaka, Hungary, deforestation and cultivation caused the average length of existing gullies to increase from 21.3 to 38.2 km (13.2 mi to 23.7 mi) (Gabris et al. 2003).

Reforestation is a common approach to controlling erosion in sloping lands. Forests stabilize soils through root proliferation (Ziemer 1981; Rice 1977), forest floor protection from raindrop impacts, increasing aggregate stability due to organic matter addition, and increasing infiltration rates due to forest floor accumulation and improvement in soil structure (Stuart and Edwards 2006). In the southeastern United States, fertilization of pine trees to promote faster growth of foliage and increase litterfall has even been proposed as a soil protection strategy (Duffy 1977).

There are numerous studies that have demonstrated the negative impacts of deforestation and harvesting on soil erosion (e.g. Klepac, Reutebuch, and Rummer 1999; Grace 2004; Lakel et al. 2006). On the other hand, limited research has been reported on gully response to reforestation. In a case study conducted on the effects of 50 years of reforestation on the eroded Copper Basin in Tennessee, soil erosion by sediment detachment decreased within a decade of reforestation, mainly due to rainfall interception and litter layer formation (Harden 2002). Another study in the 50,000 ha Murder Creek basin of the lower Georgia Piedmont conducted a retrospective sediment budget and found that erosion rates have declined from 18.05 Mg ha^{-1} yr^{-1} pre-1930 to <0.1 Mg ha^{-1} yr^{-1} post-1930 (7,287 Mg ac^{-1} yr^{-1} pre-1930 to <0.04 Mg ac^{-1} yr^{-}1 post-1930). The Southern Piedmont has benefited from reforestation, which has clearly slowed erosion throughout the region (Jackson et al. 2005; Lamon et al. 2005; Krishnaswamy et al. 2000).

Nevertheless, these previous studies largely account for the declines in sheet erosion. None of the above studies, however, have specifically investigated the potential continuing role of persistent gullies. In fact, gully erosion is often left unaccounted for in erosion studies (Poesen et al. 2003). For example, in the Murder Creek study, watershed erosion inputs were estimated through the Universal Soil Loss Equation (USLE) and the WEPP model, which only account for sheet erosion (Jackson et al. 2005). The authors of this work specifically highlighted that erosion channels along dirt roads (i.e., nascent gullies) were largely unmeasured but might be an important source of sediment. If we are to promote the rehabilitation of gullied lands, we should be able to explain the changes reforestation could bring to gully formation, morphology and function, and understand the impacts of land use conversion on erosion from forest to agriculture and back to forest.

The Piedmont Province of the southeastern United States suffered a long period (~1820-1920) of erosion and gullying due primarily to cotton cultivation (Trimble 1974; Richter and Markewitz 2001). The classic study by Trimble (1974) described this history of land use practice using a macroanalysis based on cultural factors such as tenancy and slavery. Utilizing this culturally based composite index of “erosive land use or ELU” in the South Carolina piedmont, the region was classified mostly as “cotton plantation area” and “cotton-general farming area.” These regions had an increasing to very high ELU throughout the period of 1860 to 1920. After this time, a decreasing ELU was observed due to agricultural decline, as well as a transition of cropland to pasture and forest, and the widespread implementation of soil conservation practices (Trimble 1974). At present, much of the previously cleared Piedmont landscape is under forest vegetation, although many gullies formed during the row-crop agriculture era are still readily identifiable.

During the cotton-farming era, formation of gullies was investigated. Ireland et al. (1939) documented permanent gullies and the factors (soil type, land use, etc) that contributed to their formation. Highlights of their results include: 1) an account of gully formation through the following stages: channel-cutting, B horizon and weak parent material penetration, period of adjustment, and period of stabilization; 2) demonstration of high correlation of rock type, soil series and erosion hazard in the Piedmont region; 3) initiation of gully formation by construction of ditch, road, and improper terraces which resulted in concentration of water flow; and 4) attribution of gully clearing and deepening to intense local rains, and shallower and wider gullies to gentle, prolonged, and widespread rains. This research did not quantify the contribution of gullies to erosion nor did it investigate gully functions or morphological condition during post-agricultural land conversion (Ireland et al. 1939).

More recently, two studies in the South Carolina Piedmont within the Sumter National Forest (SNF) have focused on forested gullies. The first of these gully assessments is trying to apply new LIDAR technology for mapping gullies up to ephemeral sizes in areas under forest vegetation (James et al. 2005). The other study focused on the fact that sediment delivery information from ephemeral gullies is weak and tried to estimate sediment movement in a small ephemeral gully under forest vegetation (Hansen and Law forthcoming). The rates of sediment movement from the studied (n=1) small ephemeral gully demonstrated the importance of large tropical storm events in mobilizing sediment and estimated an average of 5 Mg yr^{-1} of sediment delivered over ten years from the 0.1 hectare drainage. These studies emphasized the need to characterize the impact of land use change on gully frequency and morphological properties in order to determine the extent of gully types formed under different land uses and the impact on the overall hydrological function of the watershed.

The current study characterizes the number, size, and current conditions of gullies in the Long Cane Ranger District of Sumter National Forest, South Carolina. Most areas in the study had been gullied in the past. The study uses a comparative description of gullies found in areas with varying periods of reforestation- i.e. gullies that are currently under forested conditions and have been so since 1939, and gullies currently under forest but were open, nonforested in 1939. How reforestation has affected gully development and function within this region has not been previously investigated.

MATERIALS AND METHODS

Location of the study

The 168,000 ha (415,137 ac) Long Cane Ranger District of the SNF lies at the western edge of South Carolina in a region that included areas that were intensively cotton farmed from 1860 to 1920 (Figure 2.1). In general, this area had less intensive farming and less severe gully erosion and development than the Enoree Ranger District on the eastern portion of the SNF. At the height of agriculture, most of the area produced 190 kg ha^{-1} (170 lbs $acre^{-1}$) cotton (Trimble 1974). Trimble (1974) classified the area based on ELU as region III, characterized as having a "high ante-bellum ELU with post-bellum continuation." Cotton farming began declining in this region at the turn of the century due to farm abandonment, but the greatest decline has occurred since 1920 (Trimble 1974). In July 1936, the SNF was established from eroded and gullied farm fields and extensively cutover forest areas (USDA Forest Service 2006).

This study focused on the 7,532 ha (18,612 ac) Lick Fork Section (LFS) of the Long Cane Ranger District, SNF (Figure 2.1). Elevation ranges from 61 to 150 m (200 to 500 ft). The average annual total of rainfall energy-intensity (EI) values is about 250 (Trimble 1974). In general, the soil is classified as Cecil sandy loam (Fine, kaolinitic, thermic Typic Kanhapludults), with a few gradations of Cecil-Pacolet complex, and Cataula sandy loam (Fine, kaolinitic, thermic Oxyaquic Kanhapludults) (Jennings 2006). This Cecil soil type has a 0.28 erodibility factor in the USLE.

Land use change evaluation

Analysis of forest-cover development and land use was estimated from available aerial photographs. Four sets of aerial photographs, representing 1939, 1954, 1970, and 1999 were available and were used to evaluate land use trends in the region. The aerial photographs were scanned and georeferenced using ERDAS Imagine 8.7 (Leica Geosystems 2001). Areas considered open or under cultivation were delineated from forested lands in each set of photos using ESRI Arcview 3.2 software (Environmental Systems Research Institute 1999). Areas under cultivation in 1939 and forested in 1999 were selected for the gully survey and are referred to as "cultivated-to-forested." Likewise, areas forested during 1939 that remained forested through

1999 were also surveyed and are referred to as “continually forested.” Periodically we also refer to “continually cultivated/open” sites. These are areas that were nonforested in 1939 and remain nonforested today.

Gully survey

Twenty sites within the US Forest Service land, ten for the cultivated-to-forested area and ten for the continually forested sites, were randomly selected for survey from the mapped polygons of each land use type. The existing road network was used to access the selected sites. A majority of the roads are, in fact, located along ridgelines with sloping sides where gullies are most likely to form. In each location, a 200 m (656 ft) transect running across the mid-point of the planar slope was established at least 20 m (66 ft) away from the nearest road. This ensured that recent erosion due to road runoff was avoided and use of the midpoint increased the likelihood of intersecting a variety of gully sizes. The direction of the transect was established perpendicular to the slope direction. The criterion proposed by Poesen (1993) (i.e., cross-sectional area of 929 cm^2 [1 ft^2]), was used to separate observed gullies from rills.

Gully characterization

Gullies encountered along transects were individually measured. Three slope readings, 45^o to the left, middle, and 45^o to the right, were taken above the headcut/scarp of the gully to help characterize the “contributing slope” leading to the gully. Gully head width and height were measured. Four sections were established within each gully at 12.5, 37.5, 62.5, and 87.5% of the total length of the defined channel, beginning at the headcut, extending downstream, and ending at the point that depth was 30.48 cm (1 ft). In each segment, width and depth was measured. A profile of the gully cross section was constructed by taking seven depth readings along the gully width (Figure 2.2). Percentage ground cover of the gully was estimated by sampling transects and calculated by counting the number of points covered with litter in the depth measurements. Average counts of points for the whole gully length was multiplied by a factor of 14.3% (1/7 * 100%) to determine total percentage ground cover. Gully slope was determined following the procedure used by Jha (1990). This is done by taking a slope reading using a clinometer from the base of the headcut to the gully length downstream, where a range pole is positioned in the middle of the gully. Gully length was measured using a meter tape, through a series of traverses along the gully extent, from the headcut towards downstream, ending at the point that depth was less than 30.48 cm (1 ft).

Site characterization

Three slope measurements were made adjacent to the gullies using a clinometer and averaged to describe the general slope of each site. The general vegetative cover was characterized as pure pine, mixed pine and hardwood, or pure hardwood. Stand age was approximated using increment borer readings from three randomly selected trees belonging to the dominant crown class. Canopy cover was assessed using a spherical densiometer following the procedure of Lemmon (1957) at the four locations where the gully cross-sections were measured.

Statistical analysis

The morphological properties and site parameters measured on the two land use categories were statistically compared using *t*-tests. Regression analysis was performed to evaluate the role of site on gully characteristics.

RESULTS AND DISCUSSION

Land cover change

Land cover analysis of the 1939 aerial photographs showed that the cultivated/open area covered 30% (2,249 ha or 5,557 ac) of the LFS. During 1954 and 1970, this was reduced to 18% (1,374 ha or 3,395 ac) and 14% (1,064 ha or 2,629 ac), respectively. However, in the year 1999, the cultivated/open area increased to 17% (1,308 ha or 3,232 ac) (Figure 2.3 and Table 2.1). A closer analysis of the photographs and verification with the US Forest Service showed that this increase is mainly due to recent forest harvest. A majority of the lands within the LFS are, in fact, still privately owned in holdings and along with the US Forest Service land are undergoing the normal silvicultural practices of planting and harvesting, including the practice of controlled burning.

In general, the land use classification indicates that the extent of cultivated/open area is decreasing and the area of forested lands is increasing. The area covered by forest in 1939 (5,283 ha or 13,055 ac) had risen 22% by 1970 (6,468 ha or 15,983 ac) (Table 2.1). In addition, if the harvested area in 1999 were to be classified as forested land, the same area of forest has been maintained for the last 30 years. This time period should be sufficient to stabilize existing gullies in the region through development of the forest floor (i.e., the soil O horizon) and through root anchorage (Duffy 1977; Stuart and Edwards 2006). Vegetation establishment is considered the last stage in gully evolution (Harvey et al. 1985). A reconnaissance survey of the lands classified as continually cultivated/open revealed that the majority of these areas are in relatively flat terrain, are largely ungullied, and currently are serving as pastureland. This suggests that sustainable farming best be maintained in relatively flat terrain to avoid severe erosion such as gullying.

A majority (80%) of the cultivated-to-forested areas are now under loblolly pine vegetation that has a mean age of about 40 years. The other 20% is covered with mixed loblolly pine and hardwood tree species. Conversely, 7 out of the 10 surveyed transects of the continually forested sites are now under mixed forest vegetation while the remaining 3 are under loblolly pine cover. Loblolly pine is a relatively aggressive early successional forest species that eventually has hardwoods develop in the understory. The mean age of trees on the continually forested sites is about 47 years. The relatively low mean age of trees determined for both land uses compared to the actual time the area was reforested is probably a function of the tree selection process and harvesting.

Site and gully characteristics

The general slope of the continually forested areas (about 15%) is steeper than the cultivated-to-forested areas (about 7%) ($p = <0.0001$). Seventy percent (7 of 10 sites) of the surveyed cultivated-to-forested areas exhibited gully formation while 100% (10 out of 10) was observed for the continually forested sites. Of all the gully morphological parameters measured, only gully headcut width was found to be significantly different between the two land use classifications ($p = <0.0001$) (Table 2.2). As might be expected on the steeper continually forested areas, gully headcut width (1.8 m [5.9 ft]) is narrower than the cultivated-to-forested sites (2.4 m [7.9 ft]). Although not statistically different, on average, there are about four gullies per 200 m (656 ft) transect found in the continually forested areas, double that in the cultivated-to-forested areas, which has about two per 200 m (656 ft) transect. Likewise, almost all the parameters measured are larger in the continually forested sites than in the cultivated-to-forested sites with the exception of mean gully width, which is 3.6 m (11.8 ft) in the latter compared to 2.4 m (7.9 ft) in the former. The average eroded soil volume for the continually forested sites (299 m^3 or 10,566 ft^3) is twice as great as the cultivated-to-forested sites (106 m^3 or 3,771 ft^3) although again this difference is not statistically significant due to high variability of gully parameters observed in the continually forested sites.

Correlation with slope

Two significant findings between gully characteristics and slope were found (Figure 2.4). The number of gullies in the cultivated-to-forested area exhibited a high positive correlation with the slope (R^2=0.90). In the continually forested areas this relationship was only weakly and insignificantly correlated (R^2=0.10). A strong negative correlation was also observed for contributing slope and gully width under the cultivated-to-forested classification (R^2=0.85). In the continually forested areas this relation also explained 50% of the observed variance (Figure 2.4). In the absence of sloped topography (i.e., flat lands), the gully density and developed morphology, even on continually farmed or open areas, was not observed to be as severe as that found under the continually forested land use with more slope. These relationships highlight that slope is a major determinant of gully formation.

The degree of gullying in these areas, however, might also result from variations during the past in time of initial cultivation or in time of abandonment. Unfortunately, there are no records available as to the time a specific area was cultivated. Trimble (1974) mentioned that the most erosive land use practices in the region were from 1860-1920, although cotton cultivation started prior to that era and continued in many areas beyond that time. Similarly, available historical records do not provide information as to the year a specific area was abandoned and reverted to forests. W. Hansen (personal communication 2006) stated that a lot of areas in the Long Cane Ranger District were planted with pine in the 1930s for gully stabilization. As such, the inferences that can be made from the current analysis are limited by a lack of control for the timing of these land use change factors.

The total eroded gully volume was calculated using the gully width, depth, and length measured for each gully. It was observed that the eroded volume is best predicted by the gully length, although since this variable is used in the total eroded volume calculation a good correlation is expected (data not shown). This relationship persisted regardless of whether the data is pooled or separated into the two land uses. In general, eroded soil volume increases as the gully length increases. This supports the statement of Nachtergaele et al. (2001) that predicting gully length is most important in assessing total eroded ephemeral gully volume.

Current gully stability

Currently, the canopy cover and soil cover in the gullies, as well as the land use, do not differ between the two areas. The average forest floor cover for the cultivated-to-forested areas is 86% while that of continually forested areas is ~83%. Canopy cover was similar for the two sites (~87%). It was observed during the survey that the majority of the gully headcuts (i.e., nick point) are no longer vertically oriented but are sloping. Similarly, gully side slopes are smooth and have a gentle slope. Harvey et al. (1985) described the last stage of gully development (i.e., phase of stabilization) as having a widening gully with side-slopes declining to about 40^o (range of 26^o to 42^o). Thus, based both on side slope and cover, the measured forested gullies are now stable. The extent that strong tropical storms or hurricanes that regularly pass this region can initiate sediment movements within these gullies, as suggested by measurements in one gully in this area (Hansen and Law forthcoming), should be further investigated.

Ireland et al. (1939) stated that in most Piedmont soils, the steepest slope suitable for any form of cultivation is 12%. On the other hand, Gabris et al. (2003) have shown in Racaka, Hungary the development of gully systems on lands cultivated for 50 to 60 years with slopes below 12%. Most of the continuously forested sites in this study exceeded this 12% threshold, which could explain the extensive gullying observed in this area, particularly if there was an earlier time when these lands were under cultivation. Cultivation alone, however, does not always produce extensive gullying. Conditions such as high rainfall intensity, summer thunderstorms, and deeply weathered, erodible soils should also be present- conditions that characterize the southeastern United States (Ireland et al. 1939).

SUMMARY AND CONCLUSION

Land use in the Piedmont region of South Carolina and other southeastern regions of the United States has changed from forest to cultivated and back to forest. In some instances, this change has occurred more than once as the land was deforested, farmed, abandoned and reforested, eventually to be resettled. Consequently, gullies are found beneath forest cover as evidence of the impacts caused by intensive agriculture. In this study we found that deeper, wider, and longer gullies were found in areas already under forested cover by 1939 than those reforested after that time. Reconnaissance survey of the area under continuously cultivated/open area classification since 1939 showed that the majority of these remaining lands are under pasture with flat slopes, and without evidence of gullying. At present, however, in general the gullies under all land covers are well protected by forest vegetation, through O horizon formation and canopy cover, and can be regarded as stable. Whether they are still contributing sediments and nutrients to the streams and floodplains during large, intense rain events (e.g., hurricanes) is an issue worthy of further study.

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Table 2.1. Temporal changes in land use cover based on aerial photographs of Lick Fork Lake, Long Cane Ranger District, Sumter National Forest, South Carolina.

Year	Forested Area		Cultivated/Open Area	
	ha	Percent	ha	Percent
1939	5,283	70	2,249	30
1954	6,158	82	1,374	18
1970	6,468	86	1,064	14
1999	6,224	83	1,308	17

Table 2.2. Gully attributes measured for two land use categories in Lick Fork Lake section, Long Cane Ranger District of the Sumter National Forest in South Carolina. Cultivated-to-forested areas were cultivated or open (i.e., nonforested) in 1939 but forested in 1999. Continually forested areas were forested in 1939, 1954, 1970, and 1999 aerials photographs. Data were collected in 2005 from 10 transect surveys in each land cover category.

Attribute	Cultivated-to-forested		Continually forested	
	Range	Mean	Range	Mean
No. of gullies	0 to 7	2	1 to 7	4
Slope	2.0% to 13.0%	7.0%*	7.7% to 20.0%	14.5%
Contributing slope	5.1% to 12.1%	8.7%	4.0% to 21.0%	14.1%
Headcut height (cm)	26.5 to 46.3	37.5	16.0 to 65.7	34.0
Headcut width (m)	1.6 to 3.2	2.4*	0.9 to 2.8	1.8*
Gully length (m)	8.1 to 90.1	30.0	9.4 to 82.0	35.8
Gully slope	3.0 % to 12.7%	8.0%	6.0% to 21.7%	12.3%
Gully width (m)	2.2 to 5.3	3.6	1.0 to 4.6	2.4
Gully depth (cm)	38.3 to 56.0	46.2	27.8 to 100.5	54.1
Gully soil cover	55.1% to 100.0%	86.0%	28.6% to 100.0%	82.6%
Gully crown cover	77.4% to 96.0%	86.9%	77.6% to 96.3%	86.8%
Total volume eroded (m^3)	15.5 to 284.0	106.8	1.9 to 1734	299.2

* p-value <0.0001

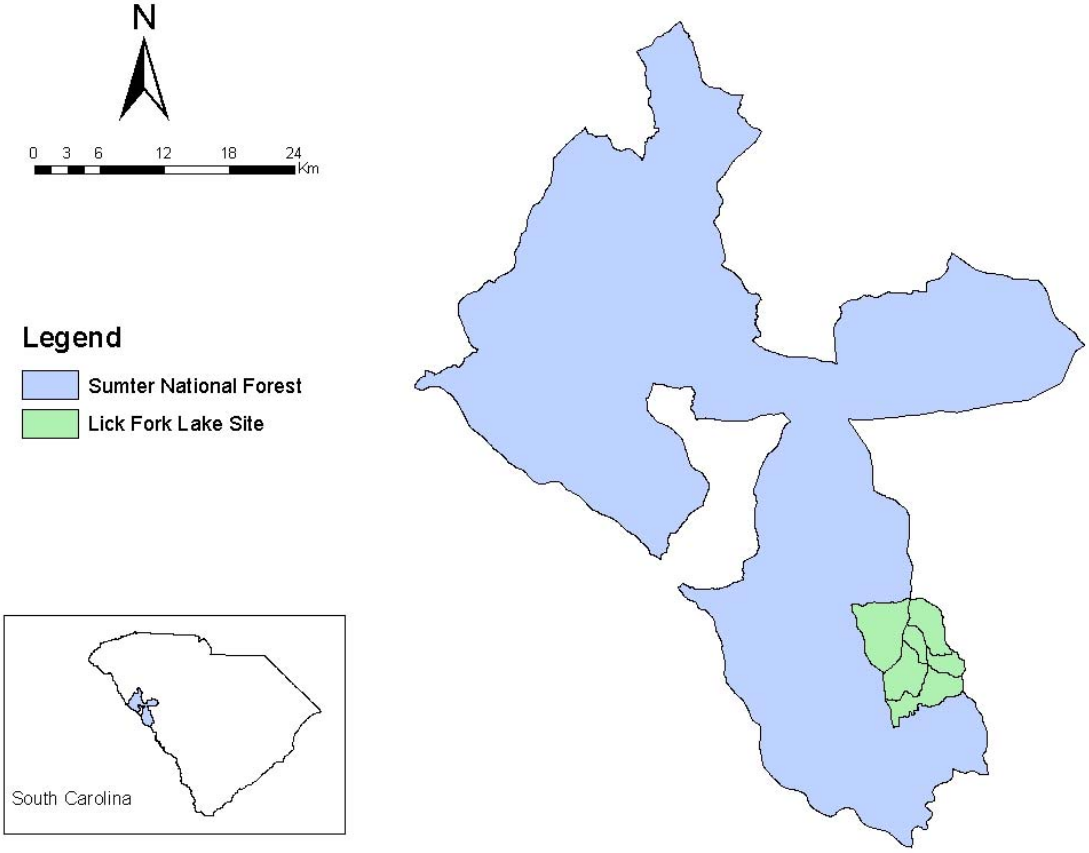

Figure 2.1. The Long Cane Ranger District (blue) of the Sumter National Forest (SNF) found in the western side of South Carolina. Highlighted in green is the Lick Fork Site (LFS) with an area of 7,532 ha (18,612 ac).

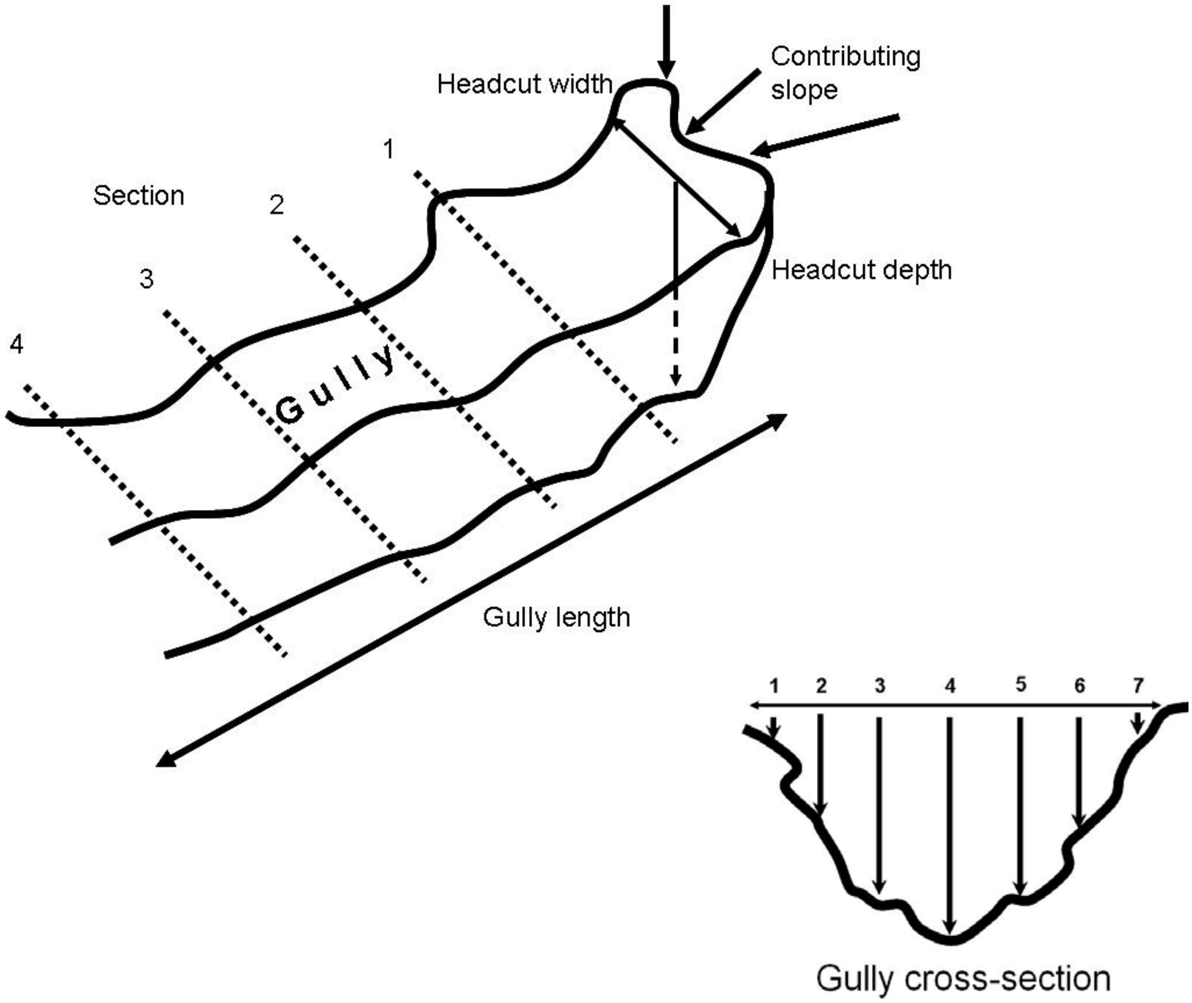

Figure 2.2. Schematic diagram of the gully parameters measured in each gully simplified through exclusion of nickpoints along the gully length. Gully length was divided into four equal sections (12.5%, 37.5%, 62.5%, and 87.5% of the total length) for better representation of gully width and depth. The figure at the bottom represents the seven depth readings conducted for the gully profile. Each gully profile was used to quantify forest floor depth and a line-transect analysis for percent bare soil.

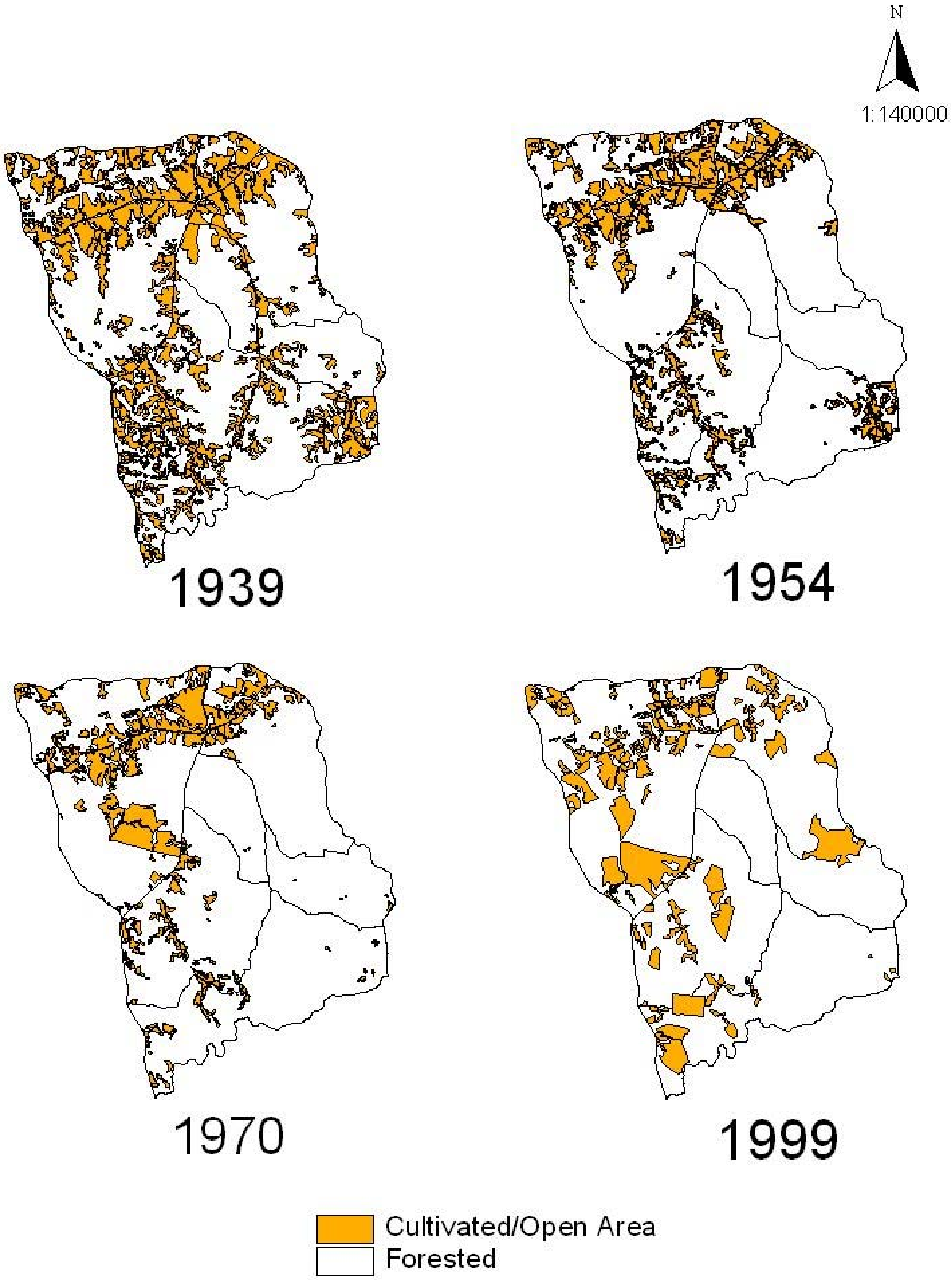

Figure 2.3. Land use change pattern at Lick Fork Lake, Long Cane Ranger District, Sumter National Forest, South Carolina. Evident are a decreasing trend in cultivated/open areas and an opposite trend for the forested areas. Some of the large cultivated/open blocks in the 1999 classification are actually recent forest clear cuts.

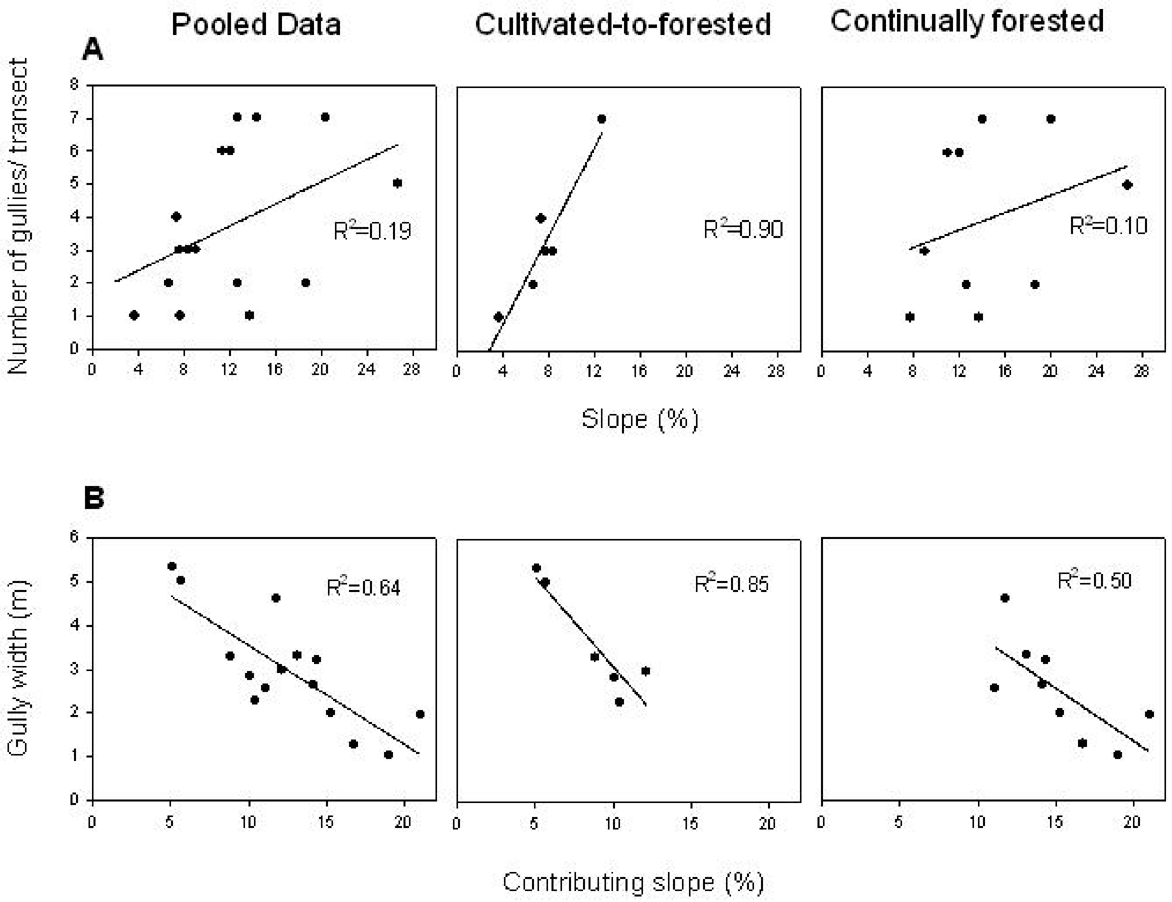

Figure 2.4. Regression analysis of A) Slope vs. number of gullies and B) Gully width vs. contributing slope, grouped according to land use history or for the pooled data. Cultivated-to-forested areas were cultivated or open (i.e., non-forest) in 1939 but forested in 1999. Continually forested areas were forested in 1939, 1954, 1970, and 1999 aerials photographs. Gully measurements were conducted in 2005 at the Lick Fork Section, Long Cane Ranger District, Sumter National Forest, South Carolina.

CHAPTER 3

PRESCRIBED BURNING EFFECTS ON THE HYDROLOGIC BEHAVIOR OF GULLIES IN THE SOUTH CAROLINA PIEDMONT[2]

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[2] M.A. Galang, L. Morris, D. Markewitz, C.R. Jackson, and E.A. Carter. To be submitted to the Hydrological Processes Journal

ABSTRACT

Gullies found today in the Piedmont of South Carolina are legacies of past land abuse and erosion. Although the majority of these gullies are now under forest vegetation and perceived as geomorphologically stable, the question of gully contribution to nonpoint source pollution remains unmeasured, especially when these gullies are subjected to prescribed burning or other forest disturbance. Six prescribe burned and two reference gullies draining mature pine stands grown on former cotton fields were instrumented at the Long Cane Ranger District, Sumter National Forest, South Carolina to characterize the hydrologic behavior of these gullies and to investigate response to prescribed burning. Flow in the gullies was observed for one year of pre-burn and one year of post-burn conditions. During this period, 48 rainfall events exceeding 12.7 mm were recorded, but one reference gully never produced flow and three treatment gullies flowed during three events or less and only in the pre-burn period. The other four gullies flowed between 9 and 19 times distributed fairly evenly between the pre- and post-burn periods. Although significant storm events occurred throughout the year, all gully flow events occurred between December and March. Observations of local groundwater conditions with piezometers and electrical resistivity surveys indicated that gully flows were controlled by the presence of a flow-restricting layer below the gully bed. This restrictive layer caused water perching above the layer and induced saturation overland flow during the wet winter months. The relative behavior of the reference and treatment gullies did not indicate a significant effect of the controlled burn on flow behavior, but the post-burn year was characterized by extreme drought. In general, the observed inter-annual variation in gully behavior was much greater than any treatment effect that might have occurred. Furthermore, increased nutrient availability after burning, as indexed by soil core leachates, showed that even given rains immediately after the burn, the increase in dissolved reactive phosphorus (DRP) should not be a concern in nonpoint source pollution.

Key words: gully erosion, nonpoint source pollution, water perching, surface runoff

INTRODUCTION

The Piedmont region of South Carolina suffered severe soil erosion from 1860 to 1920 due to deforestation and cultivation (Trimble, 1974; Richter and Markewitz, 2001). Evidence of this history is recognizable in the turbid conditions of today's rivers and streams that are unlike those of pre-European colonization described by William Bartram (Jackson et al., 2005; Harper, 1998). Large gullies are present today under secondary forest vegetation growing on land once cultivated for cotton. The role these gullies play in the overall hydrologic function of a site is not known (Hansen and Law, in press). Likewise, the contribution of these gullies, through continued erosion, to the overall sediment production of a watershed is typically unaccounted for in erosion models (e.g. WEPP and USLE; Poesen et al., 2003) and yet could play a significant role in producing nonpoint source pollution.

Nonpoint source pollution associated with sediment is a key issue in the southern United States (Neary et al., 1989; Baker, 1992). In forested watersheds, best management practices are implemented to minimize sediment input to streams. These practices often focus on activities proximal to streams (Lynch et al., 1985) with little regard to gully networks. If gullies behave like ephemeral streams, policies pertaining to prevention of sediment movement might logically be extended to include these land features. This is especially true for gullies that connect directly to perennial streams and, thus, can readily facilitate direct transport of sediments and nutrients from upslope areas. In a survey of recently clearcut and site prepared forest management units, Rivenbark and Jackson (2004a) found 50% of the "breakthrough of sediment" observations that passed the Streamside Management Zones (SMZ) entered stream channels in areas where there was convergence (swales) and gullies. Currently, South Carolina Best Management Practices (BMP; South Carolina Forestry Commission) defines a gully as "an eroded channel (generally at least 12 inches deep), which has deepened to the point that it cannot be removed by tillage" and recommends the maintenance of vegetation and minimal soil disturbance during forest operation.

Prescribed burning is a forest management strategy practiced in many managed pine stands in the southeastern United States for fuel reduction and wildlife management. Prescribed burning is also used to restore the fire-regime associated with longleaf pine stands long suppressed by previous policies (Youngblood et al., 2005; Wade and Lunsford, 1989). Re-introducing fire to southern hardwood forest is also under consideration (Fire and Fire Surrogates Study, 2008). Some studies have shown negative impacts of prescribed burning on sediment and nutrient movement. Wright et al. (1976) found adverse effects of prescribed burning on soil loss and water quality on moderate to steep slopes covered with Ashe juniper (*Juniperus ashei*). Townsend and Douglass (2000) observed higher total suspended sediments and volatile suspended sediments in catchments of Australia as a result of reduction in ground cover from burning. In contrast, other studies have shown that prescribed fire has little effect on soil erosion and can increase soil nutrient content. Van Lear and Danielovich (1988) recorded insignificant soil movement in a logging slash burn in the southern Appalachians. An increase in soil nutrient content occurred after the burn, and was mostly attributed to the combustion of organic materials (Carter and Foster, 2004; Certini, 2005). In the case of nitrogen (N), the influx of native herbaceous N-fixing legumes can compensate for the amount volatilized during the burn (Hendricks and Boring, 1999; Boring et al., 2004). Discrepancies between results of these studies may be attributed to the range of fire intensity and severity (Neary et al., 1999).

Previous evaluations of the effect of prescribed burning on a gullied landscape are limited. Douglass and Van Lear (1983) investigated the effect of prescribed burning on watersheds with "healed" gullies and found no significant effect on storm runoff, sediment concentration, and transport. However, their investigation was conducted at a watershed level and the contribution and behavior of individual gullies were not measured. Cushwa et al. (1971) studied individual gullies in South Carolina and concluded there was no significant effect of prescribed burning on soil movement.

There is a clear need for further investigation of individual gullies, especially after a prescribed burn, to determine the role gullies play in the transport of sediment and nutrient from upslope to downslope areas. The overall objectives of this study were to 1) characterize the hydrologic behavior of a set of gullies under forest vegetation in the Piedmont region of South Carolina, and 2) to determine if prescribed burning altered this behavior and, in so doing, increased sediment and nutrient inputs to streams. We hypothesized that prescribed burning would increase runoff, sediment, and nutrient export from the gullies.

MATERIALS AND METHODS

Location and description of the study site

This study was conducted at the north end of the Long Cane Ranger District, Sumter National Forest, South Carolina (34° 7' 55.36"N, 82°18' 36.17"W). The region was subjected to deforestation and intensive cotton cultivation from the late 1800’s to early 1900’s, which resulted in massive gully formation (Trimble, 1974). The site is in the Piedmont physiographic region and is dominated by the Cecil soil series (fine, kaolinitic, thermic Typic Kanhapludults), characterized as “very deep, well-drained moderately permeable soils formed in residuum weathered from felsic, igneous and high-grade metamorphic rocks” (Soil Survey Staff, Natural Resources Conservation Service, U. S. Department of Agriculture, 2007). Associated soil series include Pacolet (fine, kaolinitic, thermic Kanhapludults; shallower B horizon) and Hiwassee (fine, kaolinitic, thermic Rhodic Kanhapludults; alluvium parent material) soils. Elevation ranges from 120 to 180 meters above sea level (masl), slope varies from 2 to 12%, and average annual rainfall is 1,210 mm distributed evenly throughout the year (U.S. Department of Agriculture, 1980). Vegetative cover consists of mature loblolly pine (*Pinus taeda*) of about 40 years old with occasional mature hardwood trees established in the gully bed and side slope. The understory vegetation is mostly sweetgum (*Liquidambar styraciflua*) and briars (*Rubus* spp.). Forest floor depth ranges from 3 to 5 cm. Previous silvicultural treatments include intermediate thinning in 1997 and 1999 and prescribed burning with the last prescribed burn on February 20, 2004 (S. Wilhelm, personal communication, April 3, 2008).

Gully description and instrumentation

Eight gullies ranging in size from 36 to 90 m long, 2.4 to 9.5 m wide, and 0.9 to 3.0 m deep were instrumented with 90^o V-notch weirs between November and December, 2005 (Table 3.1). Morphological properties of the individual gullies were measured following the procedure outlined in Galang et al. (2007), with the exception of conducting the measurements between the headcut and weir instrumentation point instead of to the gully mouth. The contributing area for each gully, based on the relief and observed source of surface runoff, was mapped using a Trimble GeoExplorer 3 Global Positioning System (GPS) device (Trimble Navigation Limited, Sunnyvale, California). Gully bed cover was assessed also following Galang et al. (2007), where four transects perpendicular to the gully length were established in the gully bed and determination of bare or litter-covered soil at points along these transects is noted. A spherical densiometer was used to measure canopy cover at each transect locations. Six treated gullies were adjacent to each other, within two management compartments, while the two control gullies were in a separate location <5 km from the other six that was not scheduled for burning (Figure 3.1).

Data-logging pressure transducers and stormwater samplers (Global Water Sampler WS750, Global Water Instrumentation, Gold River, California) were installed in each gully to measure stage height and collect runoff samples for analyses (Figure 3.2). In each gully, the nadir of the weir's V-notch was set at about 15 cm above the soil surface, resulting in a dead storage space below this height. As such, below 15 cm stage height, a volume-stage relationship was developed using the gully slope and width at the point of weir instrumentation to estimate runoff volume. The positive change in stage was considered an influx of runoff (i.e., a flow event) and the flow rate was determined by dividing the change in volume by the time interval. A negative change in stage height after a flow event was considered "no flow." Stage height above 15 cm was converted to a flow rate using the Cone equation (Water Measurement Manual, 2001). Runoff volume was calculated from the hydrograph area of each flow event, integrating flow rate by each time step (Volume at time i = Flow rate at time i x 2 minutes), then adding up all the volumes at each time step ($\sum_{i=1}^{n}$ Volume$_i$). Runoff volume for each gully was converted to depth by dividing by the contributing area of the gully.

Two HOBO® data-logging raingauges (Onset Computer Corporation, Pocasset, Massachusetts) were installed on site for local rainfall measurements. In addition, three ECH$_2$O EC-20 soil moisture sensors (Decagon Devices Incorporated, Pullman, Washington) connected to HOBO® microstation data loggers (Onset Computer Corporation, Pocasset, Massachusetts) were installed atop the side slope of three selected gullies, recording soil moisture content in the 0-20 cm depth.

Runoff collection and analysis

Sampling and gully observations were conducted from April 1, 2006 to March 12, 2007 for pre-burn data and from March 14, 2007 to March 12, 2008 for post-burn data. Since the majority of these gullies behave ephemerally, runoff sampling was conducted during events when the gullies flowed and activated the sampler. The number of days between sample collection range from 2 to 10 days. During sampling, containers with samples were taken out and replaced with newly acid-washed containers. Collected unfiltered samples were preserved frozen prior to analyses. Samples were analyzed for pH, conductivity, total suspended solids (TSS), and dissolved reactive phosphorus (DRP) following standard techniques (Clesceri et al., 1998). Runoff samples were also analyzed for Ca, Mg, and K using ion chromatography (DX 500, Dionex Corporation, Sunnyvale, California).

Water table investigation

The role of the water table on gully runoff events was investigated following two techniques. First, maximum-rise piezometers were installed at 50 (shallow) and 275 cm (deep) depth in November 2006, two to three feet away from the weir on the downstream side. The rise in water line, as recorded by floating cork pieces, from each piezometer was measured every sample collection. Second, soil resistivity-transect surveys were conducted perpendicular to gullies using a SuperSting R8 IP resistivity meter (Advanced Geosciences Inc., Austin, Texas) from December to January 2006 (Winter) and in June 2007 (Summer). Soil electrical resistivity is a technique used to investigate spatial and temporal variability in subsurface properties such as in groundwater exploration (Samouëlian et al., 2005). A resistivity survey was used in this research to determine the groundwater table depth in the area and to determine if it rose sufficiently during the wet winter season to initiate gully flow.

Field saturated hydraulic conductivity (Kfs) at the 25 and 50 cm depths were also measured at the downstream side of each weir using a Guelph Permeameter (SoilMoisture Equipment Corp., Santa Barbara, Ca). Soil samples were taken at 0 to 25 cm, and 25 to 50 cm depths and analyzed for texture using the hydrometer method (Day, 1965).

Prescribed burn treatment

Gullies designated for treatment were burned on March 13, 2007 following the standard operating procedures of the United States Department of Agriculture (USDA) Forest Service. Burning on a compartment scale was initiated using a helicopter drop of “ping-pong” balls filled with potassium permanganate and injected with glycol solution for ignition at about 10 m intervals. Drip torches were used for ignition along the compartment perimeters. Weather conditions during the burn were mostly clear skies, maximum air temperature of 80^{o}F, relative humidity of 32% and wind speed of 11 km h^{-1} moving to the southwest. Flame height reached 3.5 m but averaged approximately 1 m. Weirs and other instruments were protected from the burn by removal of fuels on the forest floor with a light leaf blowing. Just prior to the burn, eight HOBO® Type K thermocouples (Onset Computer Corporation, Pocasset, Massachusetts) were randomly installed on site, within the contributing areas of the six treated gullies and in between the mineral soil and forest floor.

Two weeks after the burn, ground cover of the contributing areas of each treatment gully was estimated using a point-transect method. At each side of the contributing area, two transects perpendicular to the gully were established at the 25 and 75% mark of the gully length. One transect following the orientation of the gully length was also established from the headcut to the contributing area boundary. From the gully to the boundary of the contributing area, points at 1 m intervals were assessed as covered with fully consumed dark litter layer (A), covered with partially consumed litter layer (P), not covered and mineral soil exposed (M), covered with rock or stone (S).

Soil core leaching

Soil core leaching was performed to investigate the potential of prescribed burning to mobilize nutrients. Using the same transects as for the post-burn cover estimates, which were established prior to the burn, pre-burn intact soil core samples were collected on the left side, moving at a direction away from the gully, of each of the transect midpoints. One week after the burn (1-week post-burn), intact soil core samples were collected on the right side of the transect midpoint. Three months after the burn (3-month post-burn), intact soil core samples were again taken on the right side of the transect midpoints, but one foot above where the 1-week post-burn samples were collected. Pre-burn sample cores were either mineral soil only (MS) or forest floor + mineral soil (FF + MS). Post-burn sample cores were charred organic material + mineral soil (Char + MS). Soil core sampler dimension was 5 cm (height) x 7.5 cm (diameter). The top and bottom of each core was secured using a cardboard cut out of the same circumference. Overall, 80 intact soil cores were collected in each sampling period.

Soil core leaching was performed by placing an empty core sleeve on top of the collected intact soil core sleeve to create a single larger column. The joint was secured by Parafilm® M and the bottom of the intact core was supported by a Whatman® 42 filter paper. The vertical orientation of the column was checked using a level. Deionized water equivalent to 5 cm rainfall

(~1.5 pore volume) was added at the core surface and allowed to leach until the ponded water was gone and leachate loss was approximately one drop every two minutes. The collected leachate was analyzed for the same constituents as that of the runoff samples and using the same analytical procedures.

Data Analyses

Hydrologic behavior, treatment effects, and inter-annual variation were examined graphically. Soil core leachate data were analyzed using an Analysis of Variance (ANOVA; SAS Institute, 1999). Treatment mean comparisons using Tukey's Honestly Significant Difference (HSD) were conducted for results that were significant ($\alpha = 0.05$).

RESULTS

Rainfall and soil moisture

During the second year of this study, the research site suffered from severe to extreme drought conditions (U.S. Drought Monitor). Average annual rainfall from 1971 to 2000 at the nearest weather station in Greenwood, South Carolina, 14 miles from the research site, was 1,176 mm [National Oceanic and Atmospheric Administration (NOAA), National Weather Service]. In 2006, the site received a total of 1,020 mm, a 15% deficit (150 mm) from the 30-year average. In 2007, annual rainfall was only 660 mm, barely exceeding half of the average for the site. Although the 2006 total was near the long term average, several winter and spring months were well below their long term averages. In 2007, all 12 months fell below monthly averages, with the lowest comparative rainfall occurring in September, when a 76 mm deficit was recorded. Drought conditions continued into 2008, with a 40 mm deficit. February 2008, on the other hand, exceeded the February monthly average (Figure 3.3). Overall, the average monthly deficit for 2006 was 13 mm while that for 2007 was 43 mm. During the pre-burn period, 34 rainfall events exceeded 12.7 mm depth, while only 14 did so in the post-burn period.

The soil volumetric moisture content in the 0 to 20 cm depth atop the gully bank was consistent with the rainfall inputs (Figure 3.4). Soil moisture content fell to below 5% during the driest month (September) of 2007.

Prescribed fire effectiveness

The prescribed burn succeeded in impacting nearly 100% of the existing forest floor cover. A summary of the post-burn cover estimate in the contributing area of each gully two weeks after the burn is presented in Table 3.1. On the average, 33 and 46% of the area post-burn was covered with fully (A) and partially (P) consumed litter layer, respectively. Mineral soil exposure (M) was observed for 20% of the area and 1% of the area was covered with rocks and stones (S). Variance across the gullies was greatest for S and M with a coefficient of variation of 118 and 42% respectively. Fire temperature was measured in only two locations but peak temperature lasting for about five minutes varied six-fold from 100 and 1200^{o}C.

Gully flow

Gully flow events occurred as a series of ephemeral pulses from December to March of each observation period (Figure 3.5). There were no recorded flow events from April to November during either pre-burn or post-burn sampling, although the number of rainfall events exceeding 12.7 mm depth was about equal for December to March and April to November periods (Figure 3.6).

During the two-year study period, 48 rainfall events exceeding 12.7 mm depth were recorded (Table 3.2). Despite this rainfall, one of the reference gullies never produced flow, and three of the treatment gullies flowed three times or less. None of these relatively inactive gullies flowed during the post-burn period (Table 3.2). In the other four gullies, flow was recorded for from 9 to 19 events, and the number of flow events were approximately equal for the pre- and post-burn periods.

Although gully flows were infrequent, peak flow rates of the gullies were considerable. For the six gullies for which flow rates were recorded, these rates ranged from 45 L s^{-1} to 512 L s^{-1} (223 L s^{-1} ha^{-1} to 731 L s^{-1} ha^{-1})(Tables 3.2 and 3.3). The relationships between the peak flow rate and runoff volume of the actively flowing treatment gullies (gullies D to F) and a control (gully G) are presented in Figure 3.7. In general, peak flow rate and runoff volume in the flowing burned gullies decreased after the burn.

Runoff quality

The relationship of six water quality parameters [pH, conductivity, total suspended solids (TSS), and Ca, Mg, and K concentration] is compared between one of the burned gullies and one control gully in Figure 3.8. The small number of flow events and the large inter-annual variation in flow limits the power of statistical analysis for these data. However, it is clear that post-burn samples were either below or fell within the range of the pre-burn samples, with the exception of pH, which was higher, and TSS, which was lower than the pre-burn samples. Dissolved reactive phosphorus (DRP), which is of primary concern in nonpoint source pollution, was also analyzed but not presented in the graph because most samples registered below the detection limit of 5 μg L^{-1}. Of the 19 pre-burn samples analyzed for the burned gullies, only 9 samples (47%) contained

DRP above the detection limit. For post-burn samples, 9 out of 16 samples (56%) were above the detection limit. The highest concentrations of DRP measured in pre-burn and post-burn samples from all the treated gullies were 27.3 and 30.7 μg L^{-1}, respectively.

In comparison to the gully flow chemistry, the analysis of the soil core leachate demonstrated a significant increase in nutrient concentrations immediately after the burn, which diminished to non-significant levels three months after burning (Figure 3.9). Although no "mineral soil only" (MS) core was collected immediately after the burn due to the difficulty of separating ash from the mineral soil, this trend persisted regardless of whether the soil core had organic material (char and ash) or not. The trend presented hereafter are for the FF + MS cores.

Soil core leachate pH increased from 4.7 before the burn to 5.6 one week after the burn, but returned to pre-burn levels three months later. Leachate conductivity increased by 9.4 μS cm^{-1} as a result of prescribed burning and remained 5.9 μS cm^{-1} higher after three months. Leachate Ca concentration one week after the burn was three-fold higher, at 1.57 mg L^{-1} compared to pre-burn levels (0.44 mg L^{-1}), but decreased to 0.79 mg L^{-1} after three months. Magnesium concentration following prescribed burning follows a trend similar to that of Ca concentration. The trend in K leachate concentration deviated from that of Mg and Ca. Potassium concentration doubled (from 0.79 to 1.93 mg L^{-1}) immediately after the burn and further increased three months later (2.17 mg L^{-1}). DRP concentration tripled (from 4 μg L^{-1} to 12 μg L^{-1}) as a result of prescribed burning. Three months later, it had returned to the pre-burn level.

Groundwater profile

Soil electrical resistivity profiles for two of the relatively active gullies (i.e., gullies E and G) is presented in Figure 3.10. In general, the image shows two regions of contrasting resistivity values. From the surface up to about six to eight meters depth, high resistivity values ranging from about 500 to 3000 ohm-m is recorded. Below six to eight meters depth, a low resistivity zone (<500 ohm-m) is observed. Within this low resistivity zone, an area of much lower resistivity (48 to 170 ohm-m) is embedded. The resistivity image generated for summer (August) was similar to that of winter (January), although resistivity was generally lower in winter; consistent with greater soil moisture and higher groundwater.

Piezometer readings indicated varying levels of water saturation in the gully beds during rain events and seasons (Figure 3.11). Of the eight gullies instrumented, only four (i.e., gullies D to G) showed consistent signs of subsurface water activity in the shallow piezometer and in some instances, in the deep piezometer. Breakthroughs of the perched water table to the soil surface were also observed in some rain events (e.g., gully E in January 8 and March 2, 2007).

DISCUSSION

Prescribed burn impacts

Four out of eight gullies (i.e. gullies D to G) consistently flowed during the pre-burn and post-burn sampling. For this reason, the analysis of treatment effects focused on these four relatively active gullies. This should not, however, obscure the fact that within our study 50% of the gullies played no role in sediment or nutrient movement on the landscape.

Of those gullies that did flow, the relationship between the timing of flow events in the treatment gullies and control gully did not change after the prescribed burn treatment. There were still rain events for which the control gullies flowed and the treatment gullies did not. Both peak flow rate and runoff volume decreased during the post-burn period, although this is likely a result of the severe drought condition at the site and not of prescribed burning. Hewlett and

Hibbert (1967) stated that aside from soil mantle depth, slope, slope length, and land use, the average size and number of larger storms determine response of small watersheds to precipitation. Therefore, the lack of larger storm events, especially during the post-burn period, greatly affected runoff production and the investigation of prescribed burn impact in this study. Nevertheless, post-burn peak flow and runoff volume relationship between the burned and control gullies seems to fall within the range as that of pre-burn conditions (Figure 3.7).

We anticipated that there would be an increase in the nutrient concentrations in gully runoff resulting from prescribed burning as has been shown in several previous studies of the same nature (e.g. Wright et al., 1976; Chorover et al., 1994; Boerner et al., 2004) but none was observed in this study. This may be as a consequence of the timing of rainfall or the lack thereof immediately after the burn. Gully runoff quality parameters measured for post-burn samples did not deviate from that of the pre-burn samples. DRP, which is important to nonpoint source pollution, was barely traceable. Using 30 $\mu g\ L^{-1}$ as the threshold concentration of DRP that could contribute to eutrophication of water bodies (Brady and Weil, 2002), all pre-burn samples were below this mark. Similarly, only 1 out 16 (6%) post-burn samples (30.7 $\mu g\ L^{-1}$) barely exceed this threshold.

Our soil core leaching study demonstrated the importance of the timing and intensity of rain in the transport of the nutrients in runoff following burning. Neary et al. (1999) stated that “impacts of fire on hydrology and sediment loss can be minimal in the absence of an immediate precipitation event.” All water quality parameters measured for the leachate were significantly higher one week after the burn but back to pre-burn level three months later.

The increase in leachate concentrations as a result of burning is most likely due to the mineralization of nutrients resulting from combustion of the forest floor material (Neary et al., 1999; Carter and Foster, 2004; Certini, 2005). Higher cation concentrations consequently resulted in higher pH and conductivity. The increase in leachate DRP immediately after the burn is also likely due to ash addition (Van Lear and Danielovich, 1988; Giardina et al., 2000) rather than the release of P from soil. The subsequent decrease in P could be due to the immobilization of P by microorganisms or the binding to Ca, iron (Fe), and aluminum (Al) in soil (DeBano and Klopatek, 1988). Nonetheless, the magnitude of increase in DRP is not significant in terms of nonpoint source pollution as it is below the critical concentration of 30 $\mu g\ L^{-1}$ that would contribute to pollution (Brady and Weil, 2002).

Mechanism for gully flow

The seasonal occurrence of gully flow events coincided with seasonally higher water table and stream flow characteristics of the area and suggests contribution of groundwater in flow events. Estimates of the runoff depth in each flowing gully showed that in a few events (e.g., January 8 and March 2, 2007), runoff depth greatly exceeds rainfall depth. Clearly, the subsurface contributing areas to these active gullies must be larger than the surficial contributing areas for these results to occur.

A groundwater table that rises to the surface may also generate event based flow in excess of rainfall inputs (Dunne and Black, 1970). Soil electrical resistivity profile for two of the relatively active gullies (i.e., gullies E and G), indicated that the groundwater table is approximately 6 to 8 m below the surface (Figure 3.10). This groundwater depth was determined following the Samouëlian et al. (2005) explanation that freshwater resistivity ranges from 5 to 100 ohm-m. Therefore, the low resistivity area beneath the layer of high resistivity values was designated as the groundwater table. The resistivity image generated for summer (August) clearly had higher resistivity than that of winter (January). This higher resistivity indicates the soil was drier. This soil moistening during the winter of study, however, did not demonstrate a rising groundwater table that reached the gully bed and thus was not solely responsible for initiation of gully flow during the wet winter months. In summer images, the drier soil profile, as indicated by higher resistance, helps explain the lack of flow events during summer to fall periods. Frequent rain events of high intensity would be necessary to compensate for evapotranspiration loss during summer to saturate the soil and induce gully flow. This situation is possible during tropical depression or hurricanes, which are not uncommon in the region (Hanson and Law, forthcoming).

The timing of flow of the actively flowing gullies correlates well with the groundwater activity recorded in the piezometers. These observations provided evidence for the mechanism of gully flow initiation. For gullies that flowed during wet winter months (gullies D to G), water rise was recorded in all shallow piezometers and in some cases, in deep piezometers (gully G), indicating perched water between the 0 to 0.5 m depth. The measured water level rise in deep piezometers also indicates possible contribution of groundwater in the saturation of soil at shallow depths. This condition is most likely true for gully G where the estimated depth to the water table based on resistivity imaging is about 6 m from the uneroded (bank) surface. Factoring the depth of gully G at 1.3 m and the depth of deep piezometer installed at the gully bed (2.75 m), the bottom of the piezometer actually reaches the 4 m depth.

The perched water table, in some instances, breaks through the soil layer contributing to gully flow. The timing and incidence of these breakthroughs also coincide with the flow events observed in the actively flowing gullies. Dunne and Black (1970) stated that “where water table intersects the ground surface before and during a storm, water escapes from the soil surface and ran quickly to the stream.” Furthermore, they emphasized the importance of poorly drained soils, saturated stream floor and subsurface lateral inflow in the production of storm runoff. Many studies have proved the importance of subsurface flow in generating runoff through surface saturation (e.g. Ragan, 1967; Freeze, 1972; and Dunne et al. 1975).

Auger boreholes and measurement of saturated hydraulic conductivity (Kfs) in the gullies revealed that gullies that regularly flowed (gullies D, E, F, and G) have sandy clay loam texture at the 25 to 50 cm depth with an average Kfs of 0.49 cm hr^{-1}. Gullies A and C, which flowed only two to three times in the 2-year observation period also have sandy clay loam texture at the 25 to 50 cm depth with an average Kfs of 1.07. Gully B, which did not record any activity in either the shallow or deep piezometer had a 50-cm Kfs of 18.14 cm hr^{-1} (Table 3.4). These values support the formation of a perched water table in the gully bed subsurface through water percolation impedance within this zone. Greco (2008) observed a formation of a thin transient water table across hillslopes over a restrictive argillic horizon in an investigation of interflow. Gully H has a low Kfs at 50 cm depth but didn’t flow during the study possibly as a result of its small contributing drainage area.

Gully flow characterization

Gully flow initiation can be summarized as follows: During summer, evapotranspiration between rain events is so high or rain intensity and duration is insufficient such that the gully bed (with or without the restrictive clay substrate) does not saturate to induce flow; water collected in the gullies infiltrates, in which case, the gullies serve as recharge zones. During winter, rain events coupled with low evapotranspiration allow for the saturation of the gully bed with low Kfs layer, upon which, runoff collected in gullies further saturates the bed. Subsequent rain on a saturated gully bed readily yields runoff, and runoff from the contributing area draining to the saturated gully is readily transported downslope. If the gully bed is close to the groundwater table, saturation is readily facilitated and gullies flow more frequently. If a restrictive layer is absent from a gully, rain intensity and/or runoff accumulation do not exceed water infiltration and percolation rate and the gully behaves as a recharge zone. Finally, small contributing areas limit flow occurrence in the gullies regardless of other conditions.

CONCLUSIONS

This study provides evidence of the varying nature of gullies under mature loblolly pine in the Piedmont region of Sumter National Forest, South Carolina. Not all of the eight gullies studied flowed during rain events, even during the wet winter months of each year, indicating that some gullies are conduits for runoff transport downslope while others are not. Flow occurrence in these gullies seems to be controlled by the formation of a perched water table in the restrictive zone below the gully bed, although in some cases, there is also evidence of possible contribution of the groundwater table. Post-burn observations provided no evidence to support claims that prescribed fire affects the hydrologic behavior of gullies. Nutrient mobilization immediately after rain, as approximated by soil core leaching, was insufficient to cause significant contribution to nonpoint source pollution. Overall, the inter-annual variation in the behavior of the gullies was greater than the treatment effect.

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Table 3.1. Morphological properties for instrumented gullies within the Sumter National Forest in the Piedmont of South Carolina. Initial measurements were taken in 2007 prior to a March 13 prescribed burn.

Gully	Treatment	Area (ha)	Slope (%)	Headcut (m)		CS*	Length	Width	Depth	*Gully bed* *Pre-burn* cover (%)[‡]		*Contributing area* *Post-burn* cover (%)[+]			
				Depth	Width	(%)	(m)	(m)	(m)	FF	CC	A	P	M	S
A	Burned	0.3	6	0.8	3.9	14	68	5.9	1.5	100	92	33	57	8	2
B	Burned	0.3	6	2.9	12.3	5	40	9.5	2.7	96	94	46	40	14	0
C	Burned	0.3	15	2.1	5.2	11	54	9.2	3.0	100	95	26	50	23	1
D	Burned	0.8	7	2.7	11.5	9	68	6.2	2.1	96	93	47	36	17	0
E	Burned	0.3	8	0.8	2.1	11	50	2.4	0.9	96	92	23	46	31	0
F	Burned	0.2	4	1.6	2.0	6	52	4.3	1.2	100	89	21	49	28	1
G	Unburned	0.7	7	1.3	4.8	17	90	7.9	2.0	96	92	na[†]	na	na	na
H	Unburned	0.1	16	1.3	4.4	6	36	4.3	1.4	96	92	na	na	na	na

* Contributing slope, measured above the headcut

[‡] FF = Forest Floor, CC = Canopy cover

[+] A = fully consumed litter layer, P = partially consumed litter layer, M = mineral soil exposed, S = rock or stone

[†] Not applicable

Table 3.2. Summary of gully flow events and rainfall amount and intensity before and after the March 13, 2007 prescribed burn of a 40-yr old loblolly pine stand at the Long Cane Ranger District, Sumter National Forest, South Carolina.

Gully	Number of flow events				Maximum recorded flow (L s^{-1})	
	Pre-burn†		Post-burn‡		Pre-burn	Post-burn
	Apr to Nov	Dec to Mar	Apr to Nov	Dec to Mar		
A	0	3	0	0	120.0	0
B	0	1	0	0	na+	0
C	0	2	0	0	na	0
D	0	3	0	6	113.3	0.03
E	0	6	0	4	95.9	1.3
F	0	4	0	7	44.7	4.2
G	0	10	0	9	511.7	48.8
H	0	0	0	0	0	0

Note: Number of rain events >12.7 mm for pre-burn Apr to Nov and Dec to Mar is 22 and 12, respectively
Number of rain events > 12.7 mm hr^{-1} for pre-burn Apr to Nov and Dec to Mar is 19 and 5 respectively
Number of rain events > 12.7 mm for post-burn Apr to Nov and Dec to Mar is 6 and 8 respectively
Number of rain events > 12.7 mm hr^{-1} for post-burn Apr to Nov and Dec to Mar is 8 and 5 respectively

† April 2006 to March 12, 2007
‡ March 14, 2007 to March 10, 2008
+ Not available due to instrument malfunction

Table 3.3. Summary of the 19 flow-producing events before and after the prescribed burn treatment of actively flowing gullies at the Long Cane Ranger District, Sumter National Forest, South Carolina.

	Pre-burn									
	10/27/06	11/16/06	11/22/06	12/22/06	12/25/06	01/08/07	01/24/07	02/06/07	02/13/07	03/02/07
Rainfall (mm)	67.8	19.6	28.2	38.9	40.1	18.3	24.9	21.6	13.2	67.1
Rainfall intensity (mm hr^{-1})	22.9	9.7	6.6	8.6	13.7	13.2	7.6	7.6	13.2	14.7
Peak flow (L s^{-1})										
D	0	0	0	0	3	0	0	0	0	113
E	0	0	0	0	9	9	1	0	0	96
F	0	0	0	0	11	7	2	0	0	45
G	13	1	13	13	212	113	13	113	1	512
Peak flow (L s^{-1} ha^{-1})										
D	0	0	0	0	3	0	0	0	0	142
E	0	0	0	0	31	29	2	0	0	320
F	0	0	0	0	54	34	9	0	0	223
G	19	1	19	19	304	162	19	162	1	731
Storm runoff volume (L)										
D	0	0	0	5	7,206	0	0	0	0	455,573
E	0	0	0	197	69,165	249,065	12,330	2	0	730,952
F	0	0	0	0	54,068	137,069	66,475	0	0	632,247
G	47,831	10,127	110,508	100,604	538,246	1,024,006	255,249	206,645	39,719	2,240,345
Storm runoff depth (mm)										
D	0	0	0	0	1	0	0	0	0	57
E	0	0	0	0	23	83	4	0	0	243
F	0	0	0	0	54	69	33	0	0	316
G	7	1	16	14	77	146	36	29	6	320

Table 3.3……….continued.

	Post-burn								
	12/30/07	01/17/08	01/19/08	02/01/08	02/18/08	02/22/08	02/26/08	03/04/08	03/07/08
Rainfall (mm)									
	31.5	27.4	14.7	24.9	25.4	22.1	11.9	31.5	25.7
Rainfall intensity (mm hr^{-1})									
	8.1	6.1	3.1	8.6	21.8	5.1	10.2	31.0	17.3
Peak flow (L s^{-1})									
D	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	1
F	0	3	1	1	0	2	0	1	4
G	13	49	1	13	1	13	1	13	49
Peak flow (L s^{-1} ha^{-1})									
D	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	1	0	1	4
F	1	13	5	5	0	10	0	4	21
G	19	70	1	19	1	19	1	19	70
Storm runoff volume (L)									
D	5	39	0	5	0	172	0	20	31
E	0	1,082	0	0	0	10,078	0	6,599	19,439
F	556	26,589	29,070	13,508	0	35,276	0	15,617	50,112
G	29,052	434,795	4075	59,149	3,793	184,593	7,316	58,161	270,969
Storm runoff depth (mm)									
D	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	3	0	2	6
F	0	13	14	7	0	17	0	8	25
G	4	62	0	8	0	26	1	8	39

Table 3.4. Textural class and field saturated hydraulic conductivity (Kfs) at the 0-25 cm and 25-50 cm depth of eight instrumented gullies at the Long Cane Ranger District, Sumter National Forest, South Carolina.

Gully	Depth (cm)	Sand	Silt	Clay	Textural class	Kfs (cm hr^{-1})
		--------	%	--------		
A	0-25	69	15	16	Sandy loam	0.39
	25-50	59	16	25	Sandy clay loam	1.56
B	0-25	52	21	28	Sandy clay loam	19.01
	25-50	66	15	18	Sandy loam	18.14
C	0-25	76	13	11	Sandy loam	2.81
	25-50	65	15	20	Sandy clay loam	0.58
D	0-25	59	20	21	Sandy clay loam	1.23
	25-50	59	20	21	Sandy clay loam	0.82
E	0-25	61	23	16	Sandy loam	16.65
	25-50	51	19	30	Sandy clay loam	0.03
F	0-25	54	16	30	Sandy clay loam	13.2
	25-50	53	13	34	Sandy clay loam	0.45
G	0-25	57	21	21	Sandy clay loam	0.17
	25-50	67	11	22	Sandy clay loam	0.64
H	0-25	35	30	36	Clay loam	29.95
	25-50	47	15	38	Sandy clay	0.35

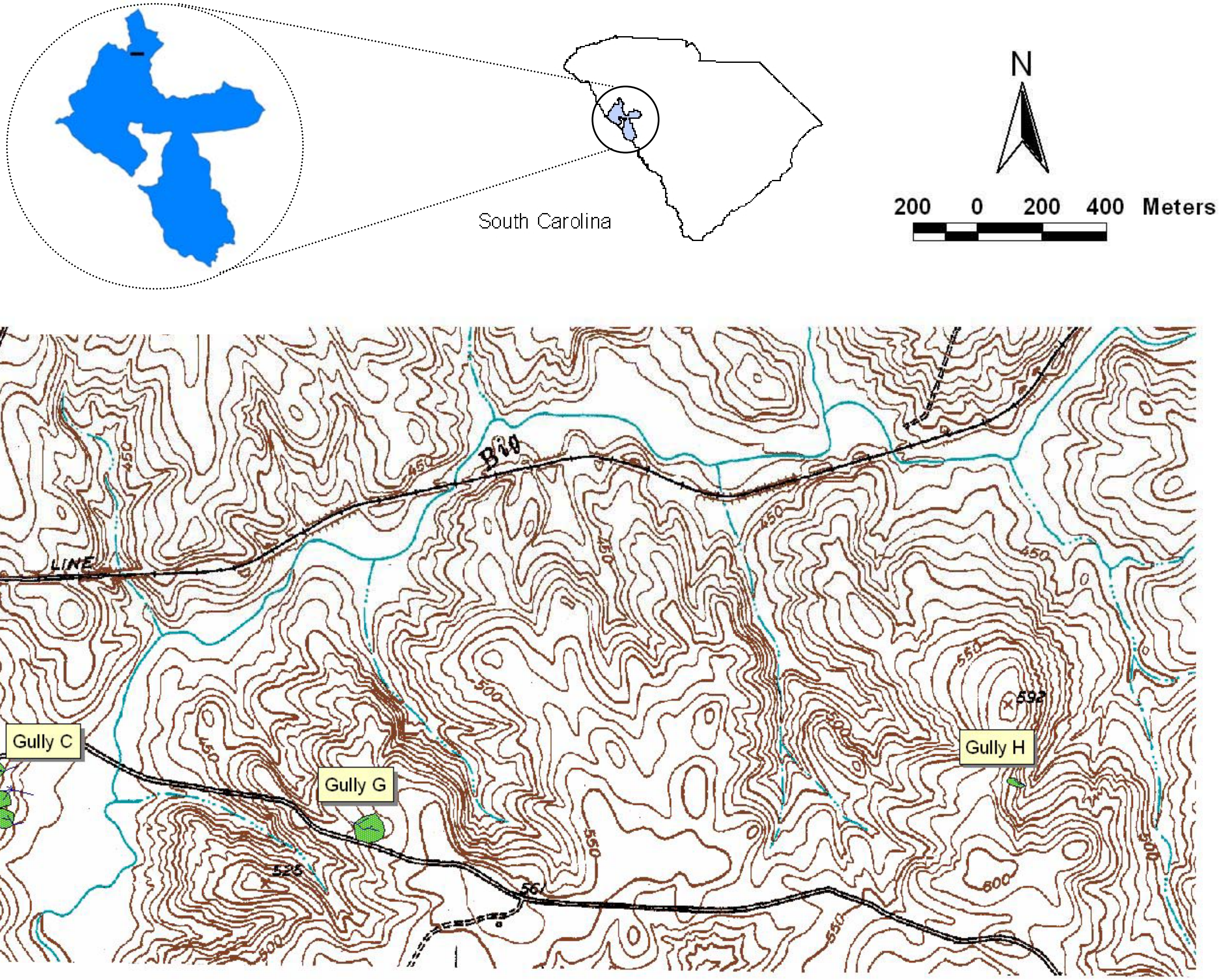


Figure 3.1. Gullies instrumented with 90^o V-notch weir and stormwater sampler at the Long Cane Ranger District, Sumter National Forest, South Carolina. Gullies A to F were burned March 13, 2007 while gullies G and H served as control.

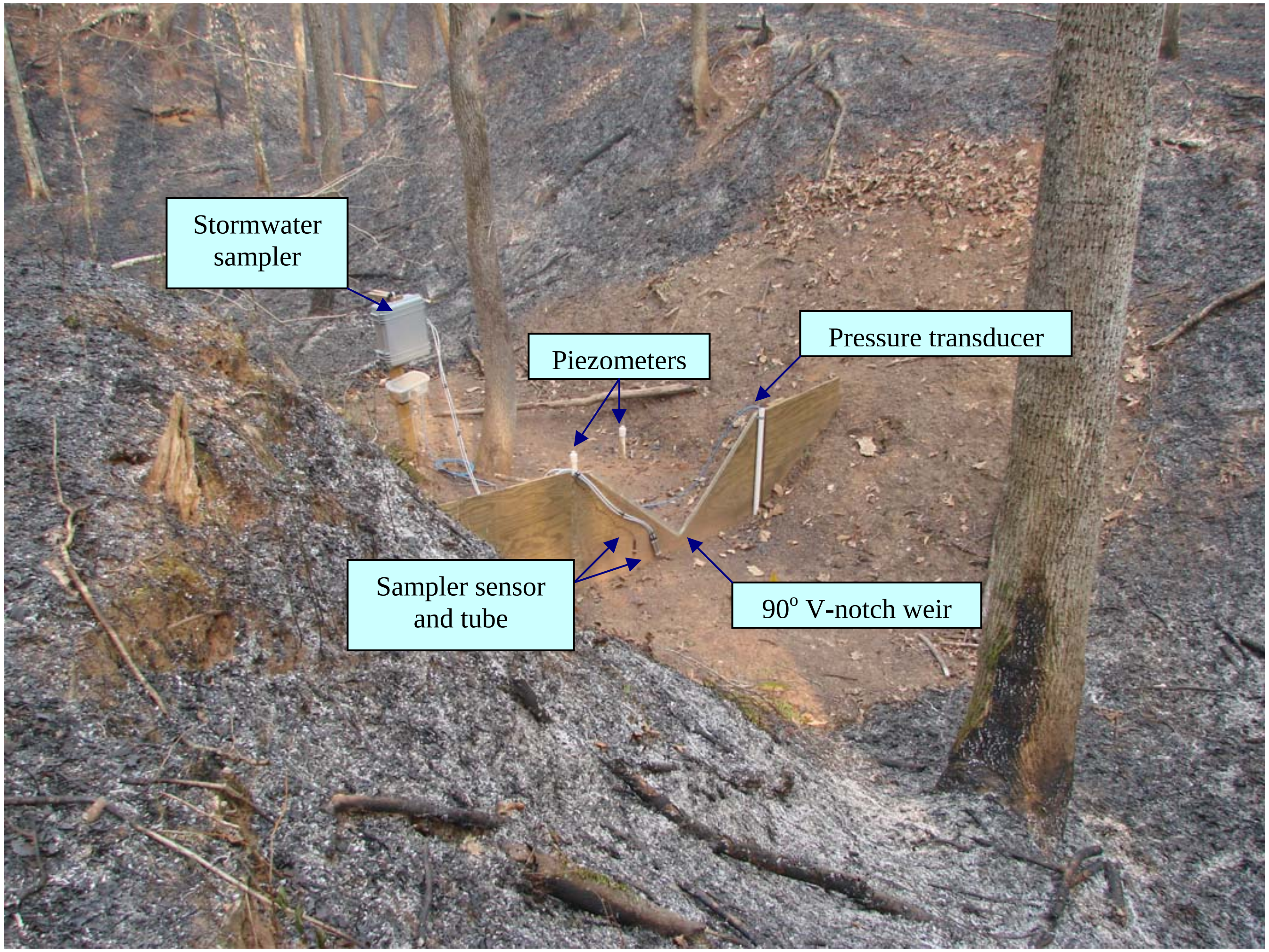


Figure 3.2. Instrumented gully with a 90° V-notch weir, pressure transducer, piezometers, and stormwater sampler shortly after a prescribed burn at the Long Cane Ranger District, Sumter National Forest, South Carolina. Note: The weir was protected from fire while the gully was allowed to burn as evidenced by the ashen forest floor in the gully.

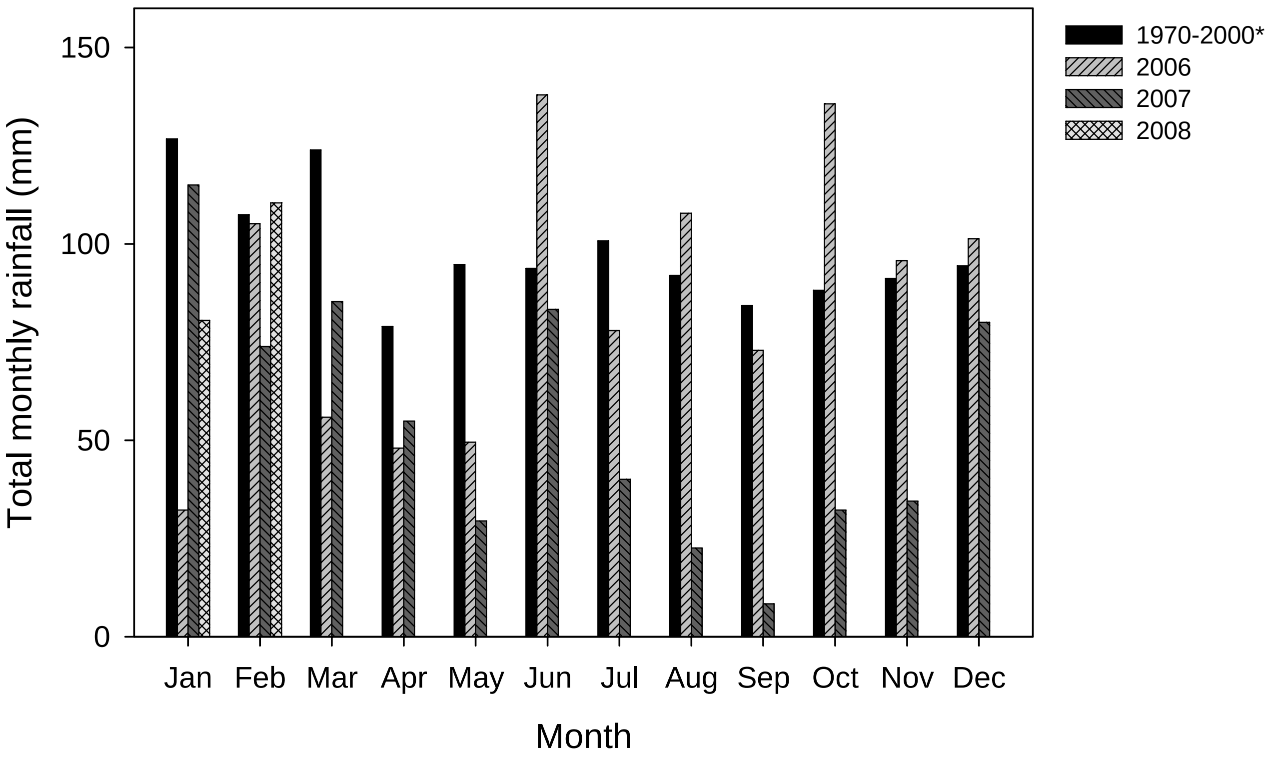


Figure 3.3. Monthly distribution of rainfall at the north end of Long Cane Ranger District, Sumter National Forest, South Carolina during the observation period compared with the previous 30-year monthly average (*Source: National Oceanic and Atmospheric Administration @ www.weather.gov accessed March 11, 2008)

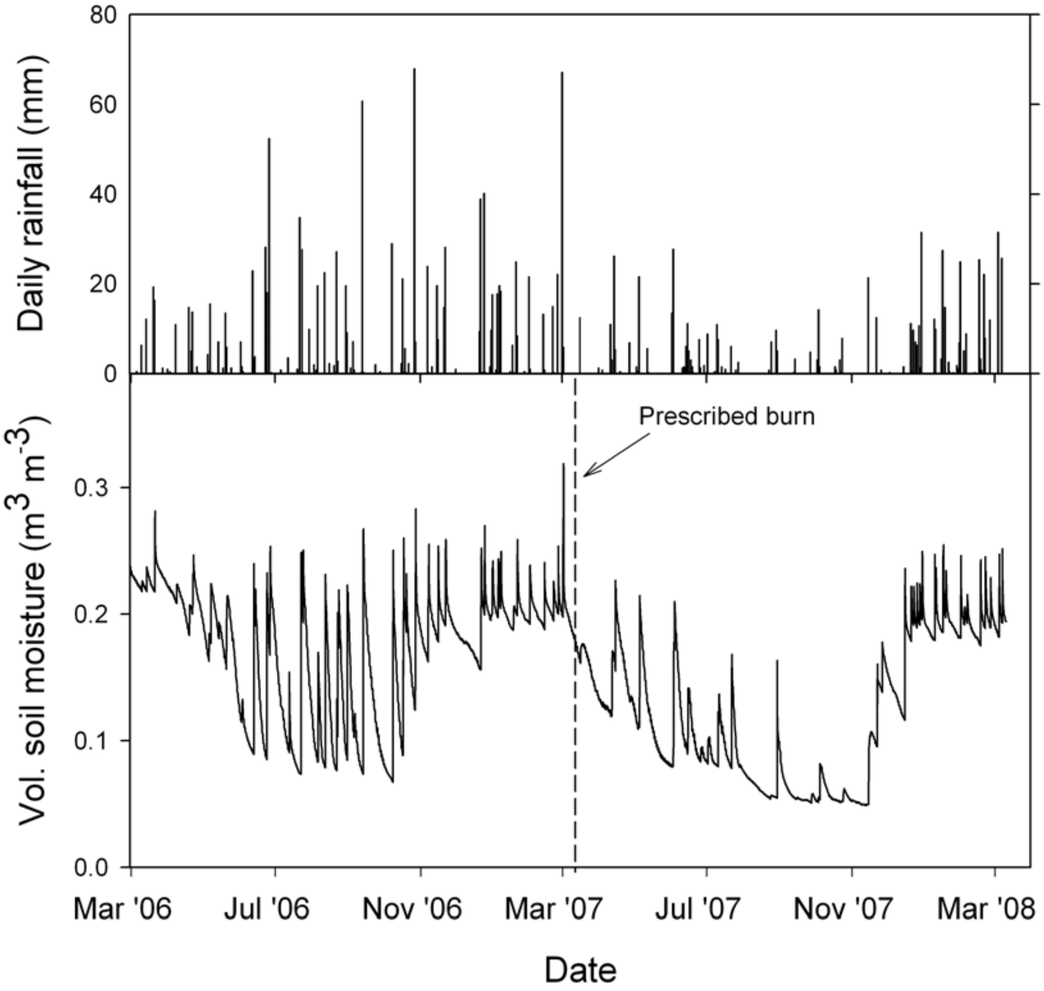


Figure 3.4. Soil volumetric moisture content for the 0-20 cm depth on the bank of an instrumented gully in Long Cane Ranger District, Sumter National Forest, South Carolina.

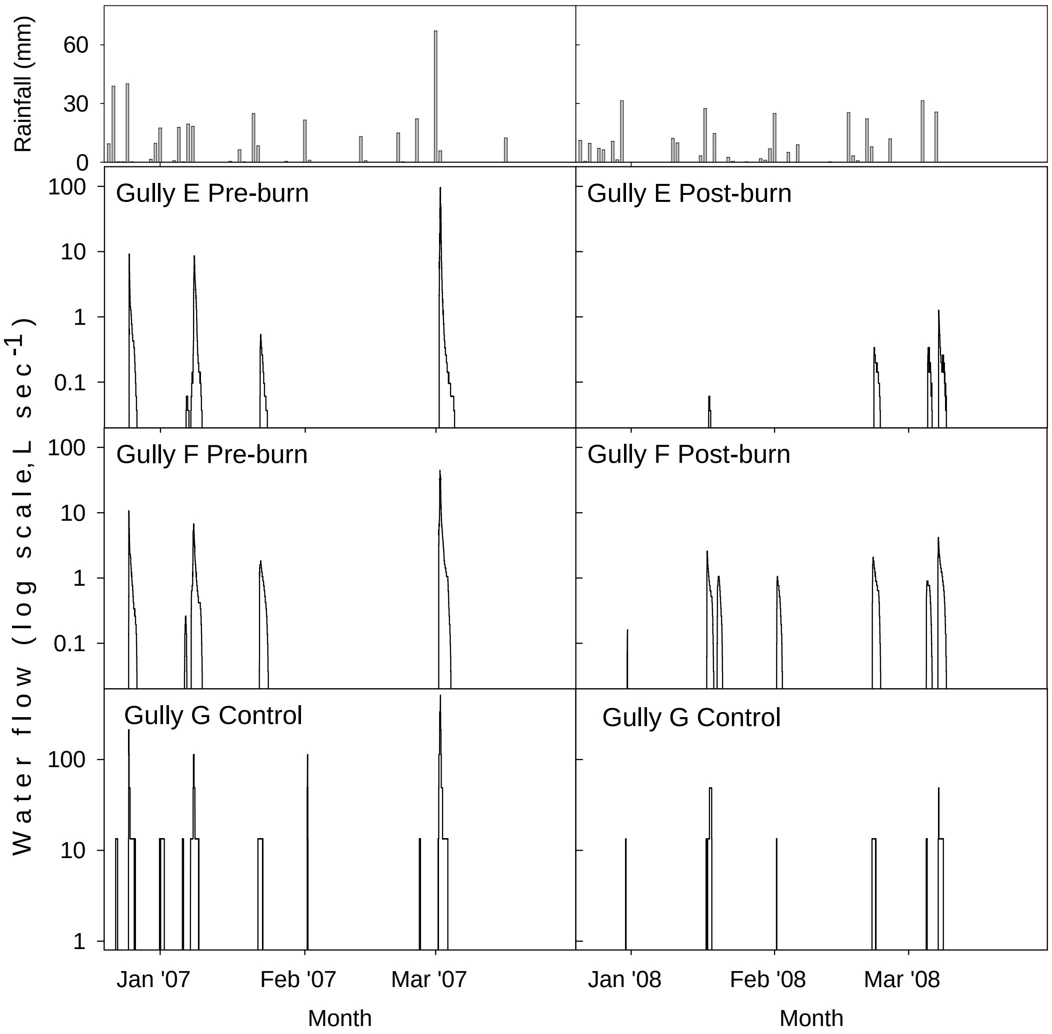


Figure 3.5. Hydrographs for three flowing gullies and rainfall at the Long Cane Ranger District, Sumter National Forest, South Carolina where runoff events occur as pulses only from December to March.

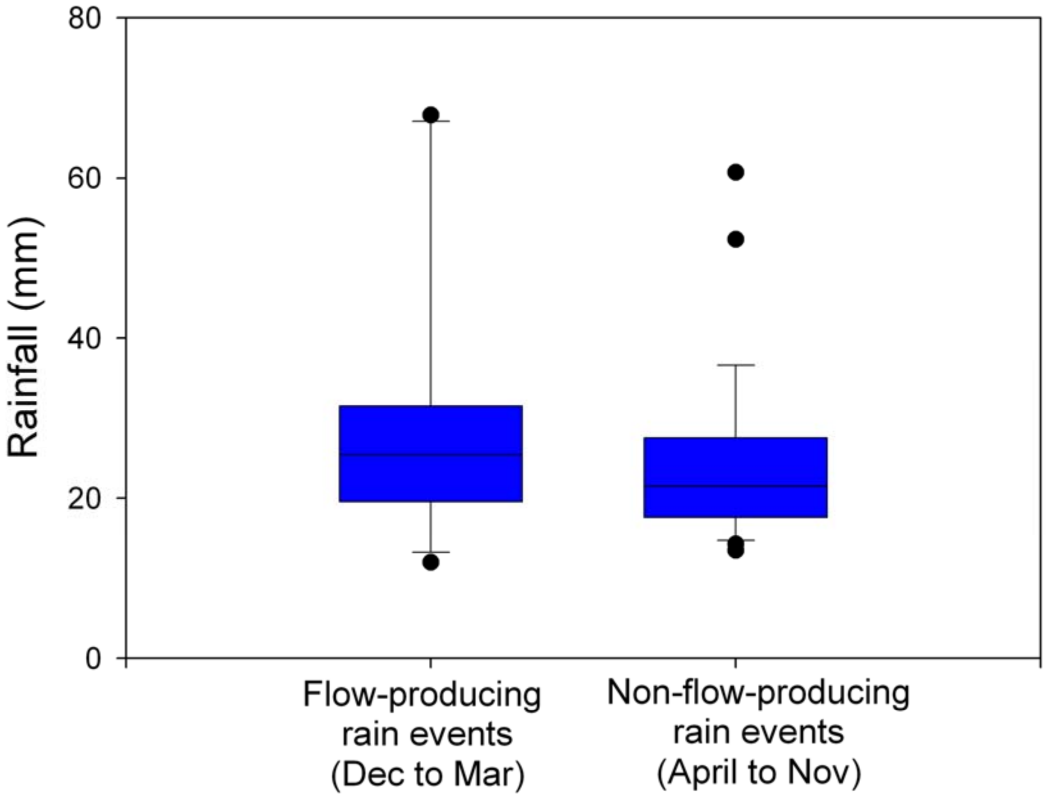


Figure 3.6. Box-plot of gully flow-producing and non-flow-producing rain events greater than 12.7 mm depth during the 2-year duration at the Long Cane Ranger District, Sumter National Forest.

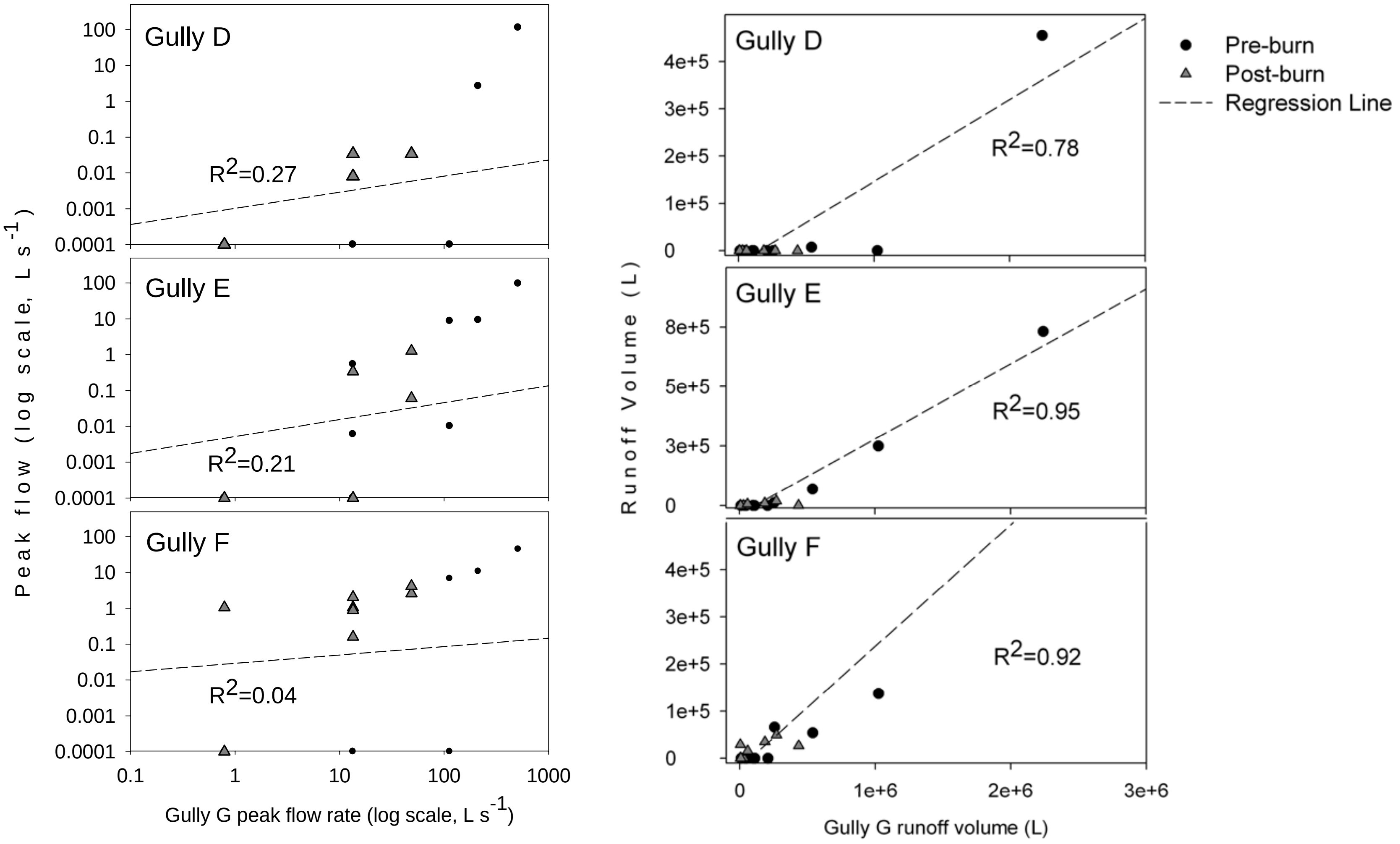


Figure 3.7. Peak flow and runoff volume comparison of three burned gullies (D, E, F) to one control gully (G), Long Cane Ranger District, Sumter National Forest, South Carolina. Values equal to zero were graphed at the lowest point (0.0001) in the log scale presentation for peak flow. Regression line is for pooled (pre- and post-burn) data.

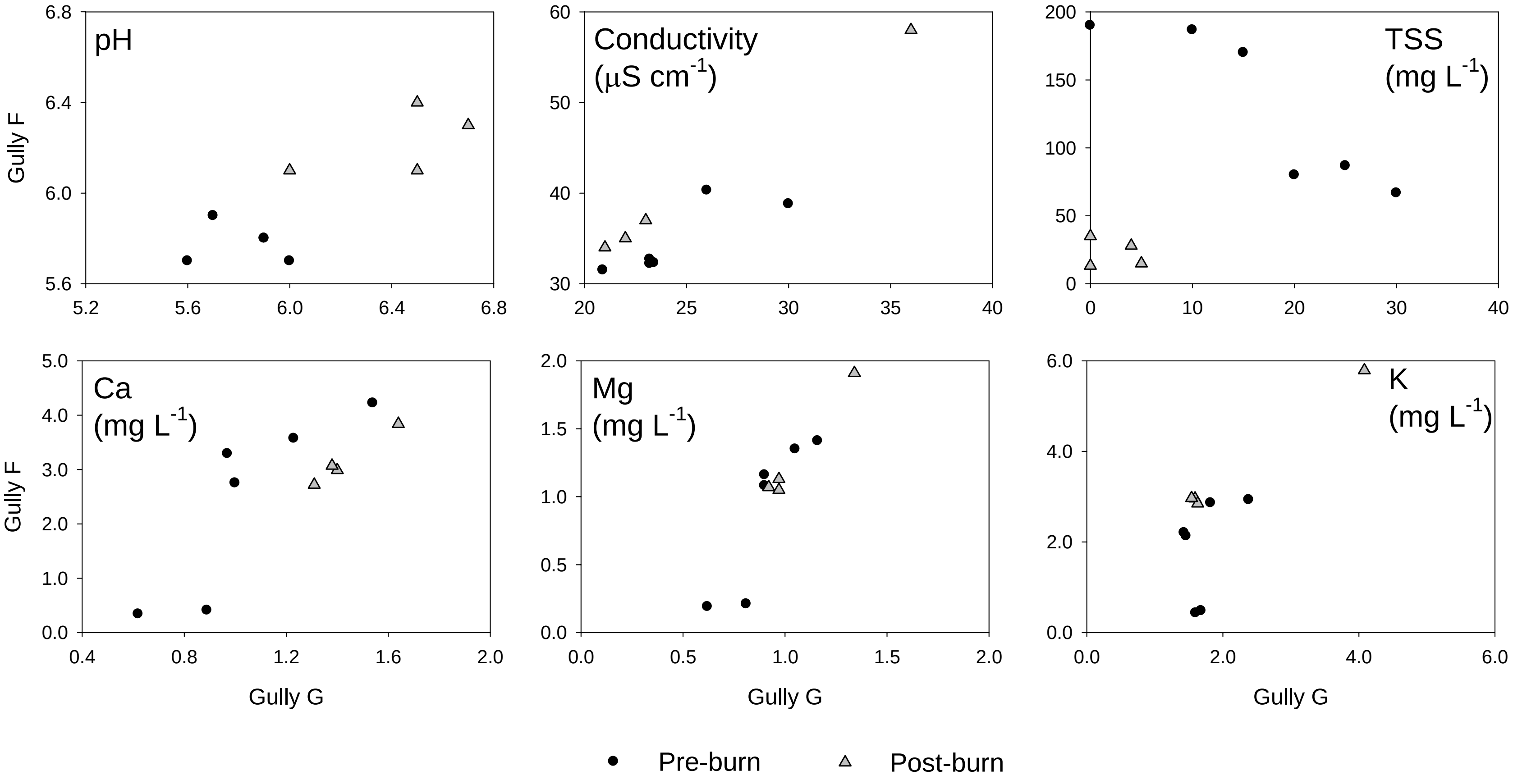


Figure 3.8. Pre- and post-burn relationship of six runoff water quality parameters between a representative of the burned gully (F) and a control gully (G) at the Long Cane Ranger District, Sumter National Forest, South Carolina.

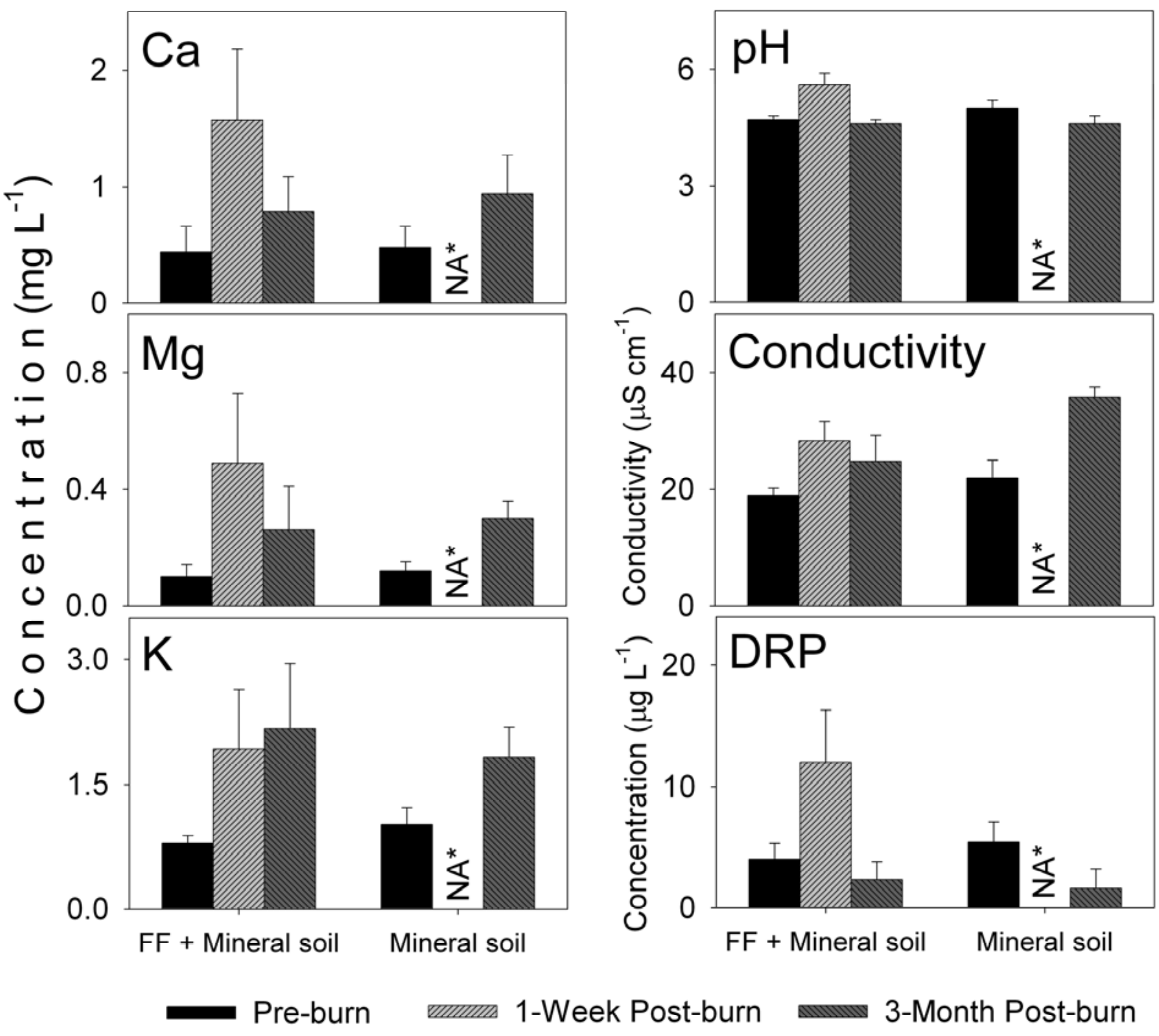
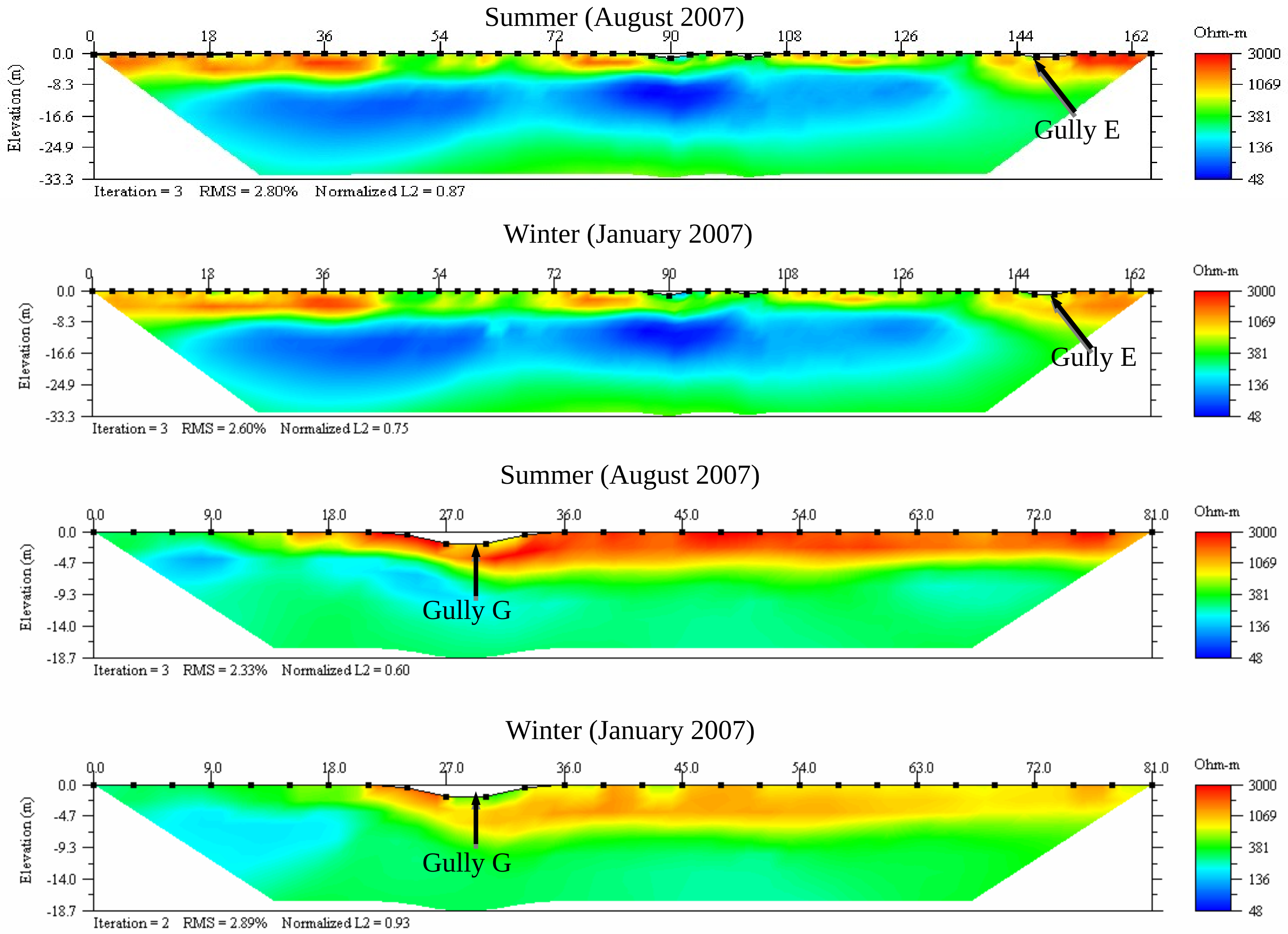


Figure 3.9. Soil core leachate chemistry (mean±1SD) before (Pre-burn), a week after (1-Week Post-burn), and three months after (3-Month Post-burn) prescribed burn treatment at Long Cane Ranger District, Sumter National Forest, South Carolina. *NA indicates no data are available because it was impossible to separate ash from mineral soil in the 1-Week Post burn. FF = Forest floor; DRP = Dissolved Reactive Phosphorus.


Summer (August 2007)

Winter (January 2007)

Summer (August 2007)

Winter (January 2007)

Figure 3.10. Cross-sectional image of soil resistivity created following a transect survey across two instrumented gullies at the Long Cane Ranger District, Sumter National Forest, South Carolina.

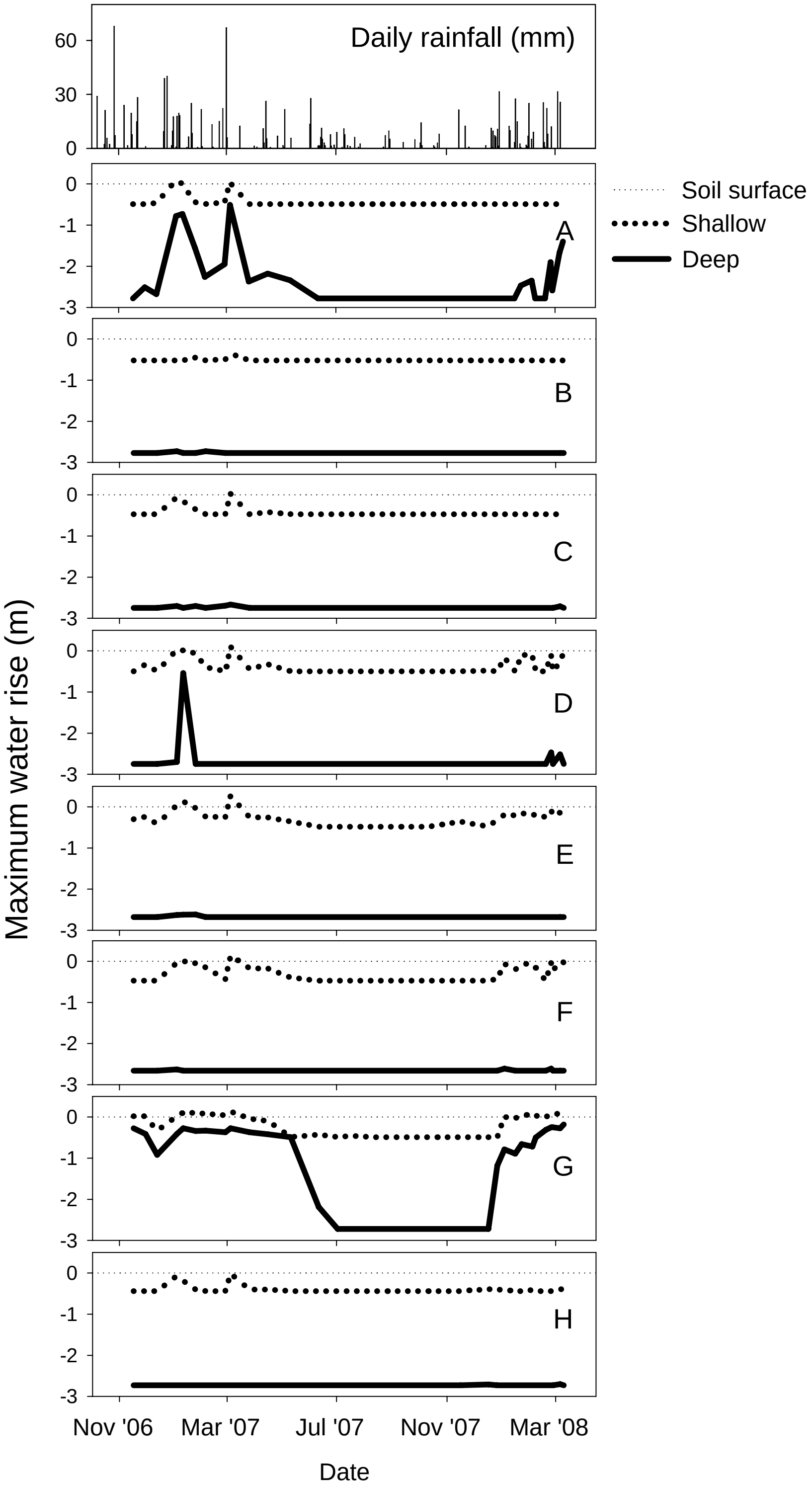


Figure 3.11. Maximum water rise recorded in shallow (50-cm) and deep (275-cm) piezometers installed at the eight gullies on Long Cane Ranger District, Sumter National Forest.

CHAPTER 4

SOIL P TRANSFORMATIONS UNDER PRESCRIBED BURNING AND SIMULATED HEAT TREATMENT CONDITIONS[3]

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[3] M.A. Galang, D. Markewitz, and L. A. Morris. To be submitted to the Soil Science Society of America Journal

ABSTRACT

Natural and prescribed burning is a common occurrence for pine and mixed-pine forests in the southeastern United States. The present high fuel load conditions of many forests has renewed concerns about the potential effects of hot fires on soil nutrients and on nonpoint sources of pollution (i.e. sediments and phosphorus). Variation in temperature and velocity of fire due to unequal fuel loading and soil moisture can affect the extent of sediment and nutrient loss. Unfortunately, this variation is difficult to capture in the field, and laboratory soil heating studies have often focused on long duration events (1 to 24 hours) which may not be applicable to a prescribed burn site, where soils may be heated for only several minutes. The objectives of this study were to investigate soil phosphorus (P) changes in relation to short-duration soil heating. Soil samples were collected before and after a prescribed burn treatment in a mature loblolly pine stand at the Sumter National Forest, South Carolina. Composite pre-burn soil samples were also subjected to different temperature (100, 200, 300, 500, and 1000^{o}C) and heating durations (2.5, 5, 15, 30, and 45 minutes) under laboratory conditions. In both cases, a sequential P extraction following the Hedley procedure was performed. In the field, a significant increase of 3.1 kg-P ha^{-1} was observed only in the inorganic P sodium bicarbonate ($NaHCO_3$ Pi) fraction one week after the burn, likely due to ash addition. Results from the laboratory demonstrated a change in all soil P pools as a result of heating with the combination of temperature and duration determining the extent of change in the different pools. A high temperature-short duration (e.g., 1000^{o}C x 2.5 min) burn can have the same impact on soil P as a medium temperature-longer duration burn (e.g., 300^{o}C x 45 min). An increase in labile P could prove to be significant in nonpoint source pollution in the event of precipitation and runoff immediately after a high temperature burn.

INTRODUCTION

Prescribed burning is a common practice in pine and mixed-pine forest management in the southeastern United States. Previous studies have shown that prescribed burning can provide beneficial effects to ecosystems in the form of organic material combustion resulting to nutrient mineralization and faster post-fire organic material decomposition that renders nutrients available to plants (Schoch and Binkley, 1986; Neary et al., 1999; Carter and Foster, 2004). However, depending on fire conditions such as maximum temperature, burning can also have negative consequences. For example, hot fires that leave soil surfaces bare can increase soil erosion (Cromack et al., 2000). A build up of fuel loads combined with dry conditions can result in the hot fires that create these conditions. This was demonstrated by fires in south Georgia and northern Florida in 2007 (Georgia Forestry Commission, 2008).

Effects of catastrophic or prescribed fires with high fuel load conditions are major concerns in US forest management. Much recent research on the effects of fire under these conditions has focused on fire effects on soil C and N (Johnson and Curtis, 2001). The Fire and Fire Surrogates (FFS) study established in 2003 in US National Forests was specifically designed to investigate treatment options for reducing fuel loads. Also of concern, however, is the effect of these hot fires on nonpoint sources of pollution (i.e. sediments and phosphorus). Phosphorus (P) is a major water quality concern throughout the US. Phosphorus can be delivered to water bodies after fire either with sediment or in soluble forms (Carpenter et al., 1998; Smil, 2000).

Fire can alter the form of soil P, converting relative nonlabile or non-mobile forms of P, such as organic P (Po), to labile and mobile forms (i.e. inorganic P [Pi]) (Giardina et al., 2000). Clearly, variation in temperature and velocity of fire, due to natural variation of the site (e.g. unequal fuel loading and soil moisture) can affect the extent of these changes. Neary et al. (1999)

stated that during forest fires, ground temperatures typically range from 200^{o} to 300^{o}C but can reach in excess of 1500^{o}C. Capturing this variation in the field is often very difficult, so, several studies have utilized simulated soil heating to assess changes in organic and inorganic soil P (e. g., Sertsu and Sanchez, 1978; Kang and Sajjapongse, 1980; Giovannini et al., 1990). Previous results have generally found that at higher temperatures (>200^{o}C), a marked increase in available P is observed. This is likely due to the complete combustion of organic materials, which results in the mineralization of organic P. Results of these previous studies, however, are for a soil heated for 1 to 24 hours, which may not be applicable to a prescribed burn site, where soils may be heated for only several minutes.

In a recent study in the Sumter National Forest in South Carolina, observed soil temperatures during a prescribed fire in the surface 0-2.5 cm of soil ranged from 100 to 1200^{o}C (Galang, Chapter 3). Although most soil temperatures were likely low, there were clearly hot spots within the soil, and extraction of pre- and post burn soil cores demonstrated a small but significant increase in water soluble P (Galang, Chapter 3). Clearly, some component of this P was derived from combustion of forest floor materials, but in hot spots, combustion of soil organic P might contribute to this pool of soluble P. For example, Giardina et al. (2000) working in a dry tropical forest, found that soil heating played a significant role in influencing soil P availability, particular in relation to litter layer ash inputs. A better understanding of the impact of hot (i.e. >200^{o}C) but brief episodes of burning on the solubility of P is needed. With this in mind, the objective of this research was to assess changes in P fractions under prescribed burning and under simulated heat treatment conditions. The goal was to determine the effect of temperature regime and heat duration on the different P fractions, which would enable us to develop a better understanding of stand level and landscape level changes in available P following burning.

MATERIALS AND METHODS

Operational prescribed burn study

Site description

The field portion of this study was conducted at the Long Cane Ranger District, Sumter National Forest, South Carolina as part of a project on assessing impacts of prescribed burning on gully hydro-chemistry. The site is in the Piedmont physiographic region and is dominated by the Cecil soil series (fine, kaolinitic, thermic Typic Kanhapludults), characterized as "very deep, well-drained moderately permeable soils formed in residuum weathered from felsic, igneous and high-grade metamorphic rocks" (Soil Survey Staff, Natural Resources Conservation Service, U. S. Department of Agriculture, 2007). Associated soil series including Pacolet (fine, kaolinitic, thermic Kanhapludults; shallower B horizon) and Hiwassee (fine, kaolinitic, thermic Rhodic Kanhapludults; alluvium parent material) are also present. The area is characterized by a loblolly pine (*Pinus taeda*) overstory of about 40 years old. The understory vegetation is mostly sweet gum (*Liquidambar styraciflua*) and briars (*Rubus* spp.). The average weight of forest floor is 11.1 Mg ha^{-1}. Previous silvicultural treatments include intermediate thinning in 1997 and 1999 and prescribed burning with the last prescribed burn on February 20, 2004 (S. Wilhelm, personal communication, April 3, 2008).

The loblolly pine stand was burned on March 13, 2007 using a combined drip torch and helicopter burn method. The weather conditions that day were mostly clear, with a maximum temperature of 80^{o}F, relative humidity of 32% and wind speed of 11 km h^{-1} moving in a southwest direction. Flame height during the burn reached 3.5 m but, on average, was about 1

m. During the burn, eight HOBO® Type K thermocouples (Onset Computer Corporation, Pocasset, Massachusetts) were randomly setup on site between the forest floor and the mineral soil, but unfortunately, only two functioned properly and recorded maximum temperatures of 100 and 1200°C for a period of 5 minutes, respectively.

Experimental and sampling design

The field experiment focused on the effect of prescribed burning on the hydrochemical functioning of gullies. The approach was a modified paired watershed design comparing six burned gullies. Soil samples were collected before (pre-burn) and a week after (post-burn) the prescribed burn treatment on a 3-ha mature loblolly pine stand, to investigate the effect of prescribed burn on P fractions. Soil samples were collected from 0 to 5 cm depth with an auger. Sample points were on the mid-point of five transects at the top of the gully perpendicular to the gully length. Overall, 60 soil samples (30 pre-burn, 30-post-burn) were collected from the site. Soil samples were air-dried and passed through a 2 mm sieve. Twenty-four of these samples were randomly selected (12 pre-burn and 12 post-burn) and subjected to soil P fractionation as described below. Pre-burn and post-burn results of the soil P fractionation were compared using a t-test and significance level is determined if $p<0.05$.

Prior to the burn, forest floor samples using a 90 cm^2 frame were also collected at the same points where soil samples were taken. These samples were brought to the laboratory, ovendried, and ground using a Wiley Mill. A 250 mg subsample was taken from each sample and digested following the sulfuric-peroxide acid digestion method (Parkinson and Allen, 1975). P concentration in the digest was analyzed using an ALPKEM FS 3000 auto-analyzer (OI Analytical, College Station, Texas).

Soil P fractionation

The sequential soil P fractionation was conducted following the procedure of Hedley as outlined in Tiessen and Moir (1993). Both the 1 *M* HCl and concentrated HCl and sonicated NaOH extraction sequence in the original Hedley fractionation were eliminated in this study and the residual P pool was redefined to include P remaining in the soil after the 0.1 *M* NaOH extraction. The residual P fraction was determined by digesting soil samples that have undergone sequential P fractionation with resin, 0.5 *M* $NaHCO_3$ and 0.1 *M* NaOH. These residual P values were verified by subtracting the sum of all fractions from the P values obtained from the analysis of a digested soil that had not undergone the sequential fractionation. All sample extracts were put in cold storage (4^{o}C) until analysis. The resin-extractable P, 0.5 *M* $NaHCO_3$ inorganic P (Pi), 0.5 *M* $NaHCO_3$ organic P (Po), 0.1 *M* NaOH Pi, and 0.1 *M* NaOH Po extracts were analyzed using the Murphy-Riley chemistry and the Spectronic Genesys 2 (Thermo Fisher Scientific Inc., Waltham, Massachusetts) while all digested samples were analyzed using an ALPKEM FS 3000 auto-analyzer (OI Analytical, College Station, Texas). The resin-extractable Pi, 0.5 *M* $NaHCO_3$ Po, and 0.5 *M* $NaHCO_3$ Pi were pooled to constitute the labile or plant-available P fraction (Hedley et al., 1982; Cross and Schlesinger, 1995) while that of the 0.1 *M* NaOH Pi, 0.1 *M* NaOH Po, and the residual P were pooled to constitute the nonlabile P.

Heat simulation study

Experimental design

This heat simulation study was performed to gain a better understanding of how temperature regime and heating duration affect P fractions in the soil. The experiment was set-up as a factorial in a Completely Randomized Design (CRD) with three replications. The first factor was temperature (Temp) with five levels: 100, 200, 300, 500, and 1000°C. The second factor was heating duration (Dur), also with five levels: 2.5, 5, 15, 30, and 45 minutes (min). In addition, a control (0°C x 0 min) sample was included in the analysis. The temperatures selected are representative of the temperature range observed in a burning forest (Neary et al, 1999; Certini, 2005; DeBano et al., 1998) and those observed in the prescribed burn for the current study. The heating duration, on the other hand, was designed to mimic the exposure to a moving fire that is dependent on type of fire, fuel load and moisture content, wind speed, relative humidity, and topography (see Neary et al., 1999; and DeBano et al., 1998).

Sample collection and treatment application

For this experiment, a composite sample of the pre-burn soils collected in the prescribed burn study was used. The soil was air-dried and passed through a 2-mm sieve. A 50-g subsample of soil was placed in a porcelain crucible and the soil surface leveled such that the average thickness of soil at the deepest and shallowest portion of the crucible was about 2.5 and 0.2 cm, respectively. Heat treatment was applied using a Thermolyne Sybron Type 30400 Automatic furnace (Barnstead International, Dubuque, Iowa). Temperature settings were verified using a HOBO® Type K thermocouple with data logger (Onset Computer Corporation, Pocasset, Massachusetts) and were found to have a ± 10°C error. Heating duration was measured by stopwatch from the time the crucible with soil was placed inside the pre-heated muffle furnace and the time it was removed. Heat-treated soils were cooled in desiccators. Upon cooling, soil samples removed from crucibles were stored in individual Whirl Pack plastic bags and then stored in a 1-gallon re-sealable plastic storage bags with desiccant until extraction. The sequential soil P fractionation was conducted following the same procedure described previously for the operational prescribed burn study.

Statistical Analysis

An Analysis of Variance (ANOVA) was performed on the different P pools using the mixed model procedure of SAS. Treatment differences were determined using Tukey's Honestly Significant Differences (HSD) (SAS Institute, 1999). All the tests were conducted at level of significance $\alpha = 0.05$.

RESULTS

Operational prescribed burn study

There were no significant differences between the pre-burn and post-burn soil samples in any P fraction with the exception of $NaHCO_3$ Pi ($p = 0.0079$, Figure 4.1). $NaHCO_3$ Pi doubled in concentration from a pre-burn level of 1.3 $\mu g\ g^{-1}$ to 2.6 $\mu g\ g^{-1}$ post-burn. Given no significant change in soil bulk density of 1.2 $Mg\ ha^{-1}$, determined using intact soil core (see Galang, Chapter 3), this is equivalent to an increase in plant-available $NaHCO_3$ Pi of 3.1 $kg\ ha^{-1}$. Analysis of forest floor P content shows a mass of 4.1 kg-P ha^{-1}. Overall, the labile pool only increased by about 5% while the nonlabile pool increased by 17%, primarily as result of the increase in the NaOH Po fraction. Total P also increased by about 16% (Table 4.1).

Heat simulation study

Changes in P fractions following soil heating differed among treatments. In general, there was no significant change in any of the fractions when soil was heated at 100°C for any of the measured durations. The results are comparable to control soils (i.e., the unheated check samples). In contrast, heating the soil to temperature $\geq$ 200°C produced significant differences that depended on both the P fraction and the heating duration (Figure 4.2).

The resin-extractable P had a significant Temp x Dur interaction ($p < 0.0001$). The 100°C heat application did not produce a significant change in resin-extractable P at any heating duration level. At 200°C, an increase in resin P was observed only after heating the soil for 30 minutes, which persisted up to 45 minutes. This increase in resin-extractable P occurred earlier, after only 15 minutes, at the 300°C but declined over the next 30 minutes of heating at this temperature. Heating the soil at 500 and 1000°C produced a release of resin-extractable P at 2.5 minutes. However, the magnitude of the increase is no higher than that observed for the 200 and 300°C treatments. The decrease in the 500°C pulse leveled off to that of the 100°C after 15 minutes. In contrast, at 1000°C, the pulse dipped below that of the 100°C level after 15 minutes.

Response of $NaHCO_3$ Pi differed significantly ($p < 0.0001$) among treatments. At 200°C, $NaHCO_3$ Pi started to increase at the 30-minute mark. Similar to the trend in resin-extractable P, the increase in $NaHCO_3$ Pi in the 300°C treatment again occurred earlier, at 15 minutes, and continued to rise through 45 minutes of heating. A similar increasing trend was observed for the 500°C treatment, but at a higher magnitude and earlier time (2.5 min) of occurrence. At 1000°C, the increase appeared as a rapid pulse peaking at 2.5 minutes and diminishing below the 100°C treatment after 30 minutes.

The $NaHCO_3$ Po also differed significantly among treatments ($p < 0.0001$). In general, the trend in $NaHCO_3$ Po is the reverse of that of the $NaHCO_3$ Pi. The heating duration needed to fully combust organic P (i.e., $NaHCO_3$ Po) decreased as temperature increased. However, this seems to be only critical starting at the 300°C temperature. The apparent decrease in $NaHCO_3$ Po and the consequent increase in the $NaHCO_3$ Pi were no longer evident at the 1000°C x 15-minute treatment.

Results of analyses of the NaOH Pi and NaOH Po fractions also differed ($p < 0.0001$) among treatments. The NaOH Pi fraction followed the same trend as that of the $NaHCO_3$ Pi. Likewise, the NaOH Po fraction also followed the same pattern as that of the $NaHCO_3$ Po with one exception. At the 300°C and 500°C temperature, the NaOH Po was not totally consumed even at the 45-minute duration.

Residual P, determined by digestion of soil that has undergone the sequential P fractionation, differed among treatments ($p < 0.0001$). In general, the residual P values decreased with increasing temperature and heating duration. Surprisingly, however, at the 45-minute mark, an observed increase in residual P concentration was observed for 200, 300, 500, and 1000°C. At the 15-min mark, the decrease in residual P seems to taper off at about 150 $\mu g\ g^{-1}$, as evident in the lack of significant difference between 500 and 1000°C.

Labile P tended to increase in soil heated at 200, 300, and 500°C as heating duration increased (Table 4.2). In contrast, labile P in soil heated at 1000°C decreased when subjected to longer heating durations. The labile pool of soil heated to 100°C did not vary significantly by heating duration and soil heated to 200°C differed only slightly from soil heated to 100°C. Overall, the maximum labile P was recorded for the 500°C x 45-minute treatment. The trend in nonlabile P is dictated by the amount of residual P in soil, which constitutes the bulk of the pool. Nonlabile P is reduced by half at 1000°C x 15-minute treatment and continues to decline thereafter. Total P (sum of all fractions or labile and nonlabile P) in the soil remained the same even at 500°C. At 1000°C, total P started to decline at 15-minute mark (Figure 4.3).

DISCUSSION

The increase in $NaHCO_3$ Pi observed in the prescribed burning study agrees well with the observations of Giardina et al. (2000) and DeBano and Klopatek (1988). The overall increase in labile P as a result of soil heating has also been demonstrated in a number of previous studies and was expected (e.g., Sertsu and Sanchez, 1978; Kang and Sajjapongse, 1980; and Giovannini et al., 1990). Giardina et al. (2000) stated that the increase in plant-available P after the burn could be a result of two processes: 1) ash addition, and 2) soil heating that results in mineralization of Po to Pi. Giardina et al. (2000) suggested that in a low temperature burn, "Po and Pi volatilize at the surface, move down into the soil, and condense 2 cm below the soil surface" resulting in an increase in soil Pi in the 0 to 2.5 cm layer.

In the operational prescribed burn study, the increase in $NaHCO_3$ Pi was most likely due to ash addition. Although an effort was made to remove ash from the surface soil after the burn, prior to collection, by scraping the ash off the topsoil with a spatula during sample collection, it was not perfect. As such, the input from ash is not due to extraction of surface ash with soil in the laboratory but forest floor ash material that has already been incorporated in 0-5 cm soil. The insignificant change in $NaHCO_3$ Po and NaOH Po fractions further supports the likely contributions due to ash, since these organic fractions are the other most likely sources of additional Pi especially during high temperature burns. Lawrence and Schlesinger (2001) observed a reduction in $NaHCO_3$ Po and NaOH Po coupled with an increase in $NaHCO_3$ Pi in Indonesian soil heated with $250^{o}C$ for 60 minutes. This reduction in $NaHCO_3$ Po to Pi after burning is believed to be an important source of P for growing trees (Frizano et al., 2003). Surprisingly however, the resin-extractable P did not reflect the same trend as that of the $NaHCO_3$ Pi. An increase in labile P as a result of ash addition is likely to be evident first, especially just days after the burn, in resin-extractable P than the rest of the P fractions as the resin-extractable P is the readily soluble form of P in soil.

The lack of difference observed among the other P fractions in the operational prescribed burn study is partly due to the high variability observed among samples. This variability reflects field conditions (i.e., the soil was subjected to different fire temperatures and durations) partly from varying fuel moisture, fuel load, and soil moisture condition during the burn. It is unfortunate that as a result of equipment malfunction, only two temperature readings were recorded on site during the burn. However, the recorded temperatures of 100^{o} and 1200^{o}C demonstrate the possible range of temperatures that could have occurred on site during the burn. These temperatures are similar to the 60^{o} to 812^{o}C temperature range observed by Giardina et al. (2000) in their study of low-, medium-, and high-intensity burning on a dry tropical forest. Likewise, Raison et al. (1985) stated that the flaming combustion of wood could reach a temperature of 1100^{o}C. It is evident that soils subjected to hotter temperatures will have different P fractions than that subjected to lower temperature. It is expected that at temperatures $>700^{o}$C, more P will be lost through volatilization (Giovannini et al., 1990; DeBano et al., 1998).

Another source of variability may be due to different amounts of ash inclusion during sampling (i.e., ash-induced variability). Soil samples were collected on the site after carefully scraping off the ash. This, however, did not totally eliminate ash inclusion. Giardina et al. (2000) used a vacuum to separate ash from soil but still estimated a 1 kg P ha^{-1} addition from ash inclusion. A final aspect creating variability may be caused by the depth of soil sampling (i.e., sampling depth-induced variability). In this study, soil samples were collected from 0 to 5 cm depth. This sampling depth could have diluted the effect of soil heating at the 0 to 2 cm depth. The effect of heating during the burn is dependent on the extent of thermal progression or influence with depth and is affected by soil moisture. Other studies have tried to resolve this by dividing the 0 to 5 cm depth into 0 to 2 and 3 to 5 cm increments (e.g., Giardina et al., 2000). The operationalization of this sampling collection, however, is difficult and is still subject to errors. The designation of the 2 cm depth as the lower depth limit of condensation of volatilized Po and Pi from burning also needs further investigation. Several studies have used a 0 to 5 cm sampling depth (e.g., Frizano et al., 2003) to investigate the effects of shifting agriculture (with cyclical burning) on P pools.

Results of the heat simulation study clearly demonstrate the importance of the interaction between temperature and heating duration on the release of P in soil and on the conversion of P from one pool to another. At 100^{o}C, a change in the P pool is only evident after 45 minutes. Continued heating at 100^{o}C can result in further alteration of the P pools. For example, Kang and Sajjapongse (1980) observed an increase in extractable P in two Nigerian soils after heating soil at 100^{o}C for six hours. Clearly, conditions of the burn are important but here the focus was on the impacts of short duration heating that is most likely to happen in prescribed burns.

The increase in resin-extractable P, $NaHCO_3$ Pi, and NaOH Pi, and the decrease in NaOH Po observed in this study is similar to the pattern observed by Giardina et al. (2000). Likewise, the general trend of increasing Pi and decreasing Po as a result of soil heating observed in other studies (e.g., Kang and Sajjapongse, 1980) was also evident in this study. Results obtained in this study provide insight into understanding when P response to burning will occur. For example, Giardina et al. (2000) did not observe a decrease in $NaHCO_3$ Po but observed an increase in $NaHCO_3$ Pi after burning at an average temperature of 200^{o}C. We observed that this only occurred after the soil was heated for 30 minutes at 200^{o}C. The same effect could be observed for a shorter duration at higher temperature, as shown in Figure 4.2. Similarly, Saa et al. (1994)

observed altered P distribution (pools) and near-conversion of Po to Pi in a severely burned soil (estimated at 250 to 420^{o}C) but not in a moderately burned (50^{o}C) soil. Clearly, the moderate fire they are referring to did not reach the critical temperature and heating duration combination that would induce changes in the P pool fraction compared to the severe fire they investigated.

The decrease in $NaHCO_3$ Po and NaOH Po coincides with the increase in $NaHCO_3$ Pi and NaOH Pi and is likely the source of the increase in Pi (Sertsu and Sanchez, 1978). However, this apparent increase in Pi has a threshold at higher temperature and heating duration combinations (e.g. 1000^{o}C x 5 min). At this combination of higher temperature and longer heat exposure, P (Pi and Po) is lost through volatilization. It has been demonstrated that at temperatures above 774^{o}C, Pi can be volatilized (DeBano et al, 1998).

In several soil-heating studies using different heating durations, maximum Pi was observed at 400^{o}C and 48 hours heating (Sertsu and Sanchez, 1978), 460^{o}C and 1 hour heating (Giovannini et al., 1990), and <500^{o}C with 6 to 24 hours heating (Kang and Sajjapongse, 1980). This study has shown that heating duration is critical for temperature $\geq$200^{o}C. At 200^{o}C, mineralization of Po was not observed until 30 minutes of heating. Five minutes is enough to induce P mineralization at 300^{o}C. At 500^{o}C, 2.5 minutes proved to be significant in P mineralization. Lastly, temperature above 774^{o}C, in this case 1000^{o}C, results in P loss with volatilization of P starting at 774^{o}C (Neary et al., 1999).

A lack of significant change in total P between 100 and 500^{o}C shows that at this high temperature and to a maximum of 45-minute heating duration, the main effect of heating is the redistribution of P within its different pools (Figure 4.3). $NaHCO_3$ Po and NaOH Po fractions are mineralized resulting in an increase in the inorganic fractions. However, some of these inorganic components originated from the residual P fraction (Giardina et al., 2000). The mechanism for the release of residual P could be the "dehydration of the mineral crystal lattice and resulting breakdown of the lattice reducing cation exchange capacity" (Giovannini et al., 1990). The release of residual P upon heating occurs readily at 1000^{o}C, at least until the soil is heated a minimum of 15 minutes. Beyond this condition, P is volatilized, emphasizing the importance of heating duration in projecting the effect of temperature on soil P mobilization.

The release of P on site after the burn is not only important to plants but also to the growing concern on nonpoint source pollution. Resin-extractable P can be regarded as an indicator of P that can easily be transported in runoff. As such, a significant increase in resin-extractable P after soil heating could contribute to nonpoint source pollution. The heating experiment showed that high temperature-short duration burns favor the release of P to solution. Similarly, a mid-temperature (300^{o}C) and longer duration burn can produce the same effect. The potential release of P into solution after the soil is heated during the burn is, however, dependent on post-burn precipitation events. In the event of a large or intense precipitation event immediately after high-severity fire, impacts can be severe. Under other conditions, the effects can be minimal (Neary et al. 1999) and short-lived (DeBano and Klopatek, 1988).

CONCLUSION

The operational prescribed burn conducted during this study did not significantly alter P fractions in soil, with the exception of the $NaHCO_3$ Pi fraction. The $NaHCO_3$ Pi fraction increased primarily as a result of ash addition, and was not a result of heat-induced breakdown of soil organic P fractions. Although the $NaHCO_3$ fraction is readily soluble, increase in $NaHCO_3$ Pi resulting from the prescribed burning doesn't appear likely to cause significant effect on nonpoint source pollution. The heating experiment proves that aside from ash addition, soil heating can have a profound effect on soil P. The combination of temperature and heating duration is important in determining the extent of change in the different P pools. A high temperature-short duration (e.g., 1000^{o}C x 2.5 min) burn can have the same impact as a medium temperature-long duration burn (e.g., 300^{o}C x 45 min). The extent to which soil is subjected to a given temperature and heating duration can affect plant-available P. Though not shown to be a significant source of nonpoint pollution, this increase in labile P could be important for plant growth. The results of this study will be useful to land managers in: a) assessing the effect of a wildfire or prescribed fire on possible P loss through runoff or release of P for plant growth; and b) planning the burn prescription in an area to avoid hotter burns that could result in P loss through volatilization and runoff transport.

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Table 4.1. Change in labile and nonlabile soil P after a prescribed burn treatment in 2007 in a 40-yr-old loblolly pine forest at the Long Cane Ranger District, Sumter National Forest, South Carolina (N=24).

Pool	Pre-burn	Post burn	Change	P value
	--------μg g^{-1} --------		-----%-----	
Labile[†]	23.0	24.2	5.2	0.861
Nonlabile[‡]	199.6	234.1	17.3	0.017
Total	222.6	258.3	16.0	0.110

[†] Sum of resin-extractable P, $NaHCO_3$ Pi, and $NaHCO_3$ Po

[‡] Sum of NaOH Pi, NaOH Po, and residual P

Table 4.2. Change in labile† and nonlabile‡ (Non) P (µg g^{-1}) of Typic Kanhapludult soil (Cecil series) of the Piedmont region upon heating at different temperatures and durations. Labile and nonlabile P of unheated (control) soil were 18.7 and 288.4 µg g^{-1}, respectively.

Time (min)	Temperature														
	100°C			200°C			300°C			500°C			1,000°C		
	Labile	Non	Total	Labile	Non	Total	Labile	Non	Total	Labile	Non	Total	Labile	Non	Total
2.5	18.3	254.2	272.5	18.2	248.8	267.0	17.8	271.6	289.4	34.4	261.6	296.0	42.9	280.7	323.6
	(1.2)	(29.1)	(29.9)	(1.7)	(28.1)	(29.5)	(1.3)	(42.9)	(44.2)	(3.3)	(29.0)	(30.9)	(6.2)	(9.4)	(4.3)
5	18.7	278.3	297.0	19.2	292.3	311.5	21.3	284.5	305.8	40.7	236.9	277.6	39.5	238.3	277.8
	(0.1)	(9.3)	(9.3)	(0.8)	(21.1)	(21.9)	(1.0)	(37.9)	(38.3)	(0.4)	(16.3)	(16.1)	(2.4)	(14.3)	(12.9)
15	19.4	294.2	313.6	20.3	265.4	285.7	39.0	240.8	279.8	42.0	215.8	257.8	10.5	144.2	154.7
	(0.8)	(4.3)	(4.8)	(0.6)	(15.3)	(15.9)	(3.6)	(40.5)	(36.9)	(3.7)	(11.6)	(14.2)	(0.2)	(13.4)	(13.7)
30	19.5	269.8	289.3	29.4	249.2	278.6	40.9	213.3	254.2	43.6	237.2	280.8	5.7	112.2	117.9
	(0.2)	(13.1)	(13.2)	(1.5)	(15.0)	(14.1)	(1.3)	(10.4)	(9.1)	(5.3)	(6.6)	(11.9)	(0.3)	(10.1)	(10.2)
45	18.8	247.4	266.2	31.7	295.4	327.1	42.2	255.7	297.9	44.3	254.6	298.9	5.0	124.2	129.2
	(0.8)	(5.3)	(6.1)	(1.0)	(8.4)	(7.8)	(3.2)	(15.6)	(19.5)	(1.6)	(32.9)	(32.3)	(0.7)	(30.3)	(30.2)

† Sum of resin-extractable P, $NaHCO_3$ Pi, and $NaHCO_3$ Po

‡ Sum of NaOH Pi, NaOH Po, and residual P

Numbers in parenthesis are 1 standard deviation of n=3

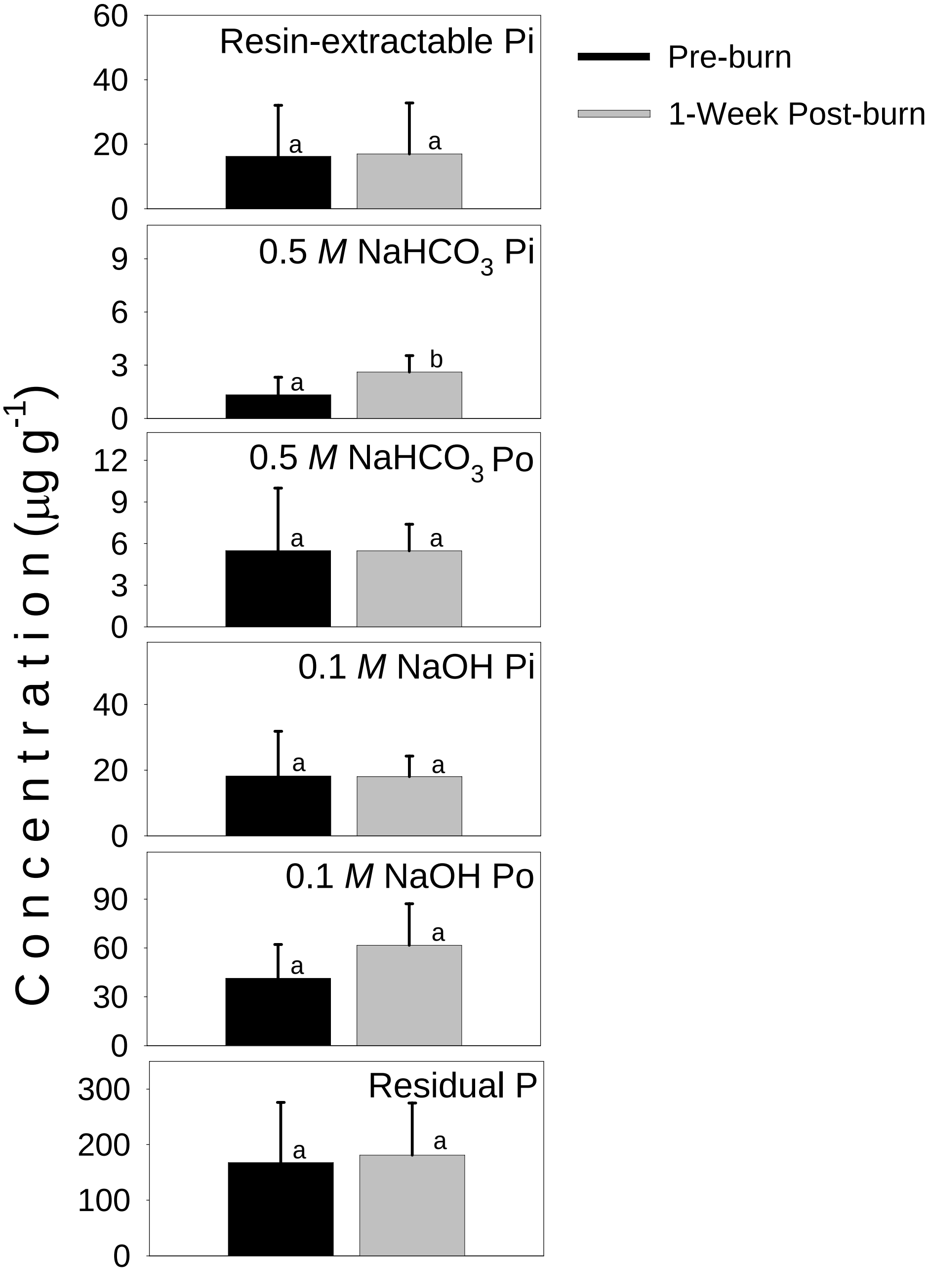

Figure 4.1. Soil P fractions before (pre-burn) and after (post-burn) a prescribed burn of a 40-yr-old loblolly pine stand at the Long Cane Ranger District, Sumter National Forest, South Carolina. Pi and Po refer to inorganic P and organic P respectively. Point bars are mean and error bars are 1 standard deviation (SD) of n=12. Different letters indicate statistically significant differences at p=0.05 level.

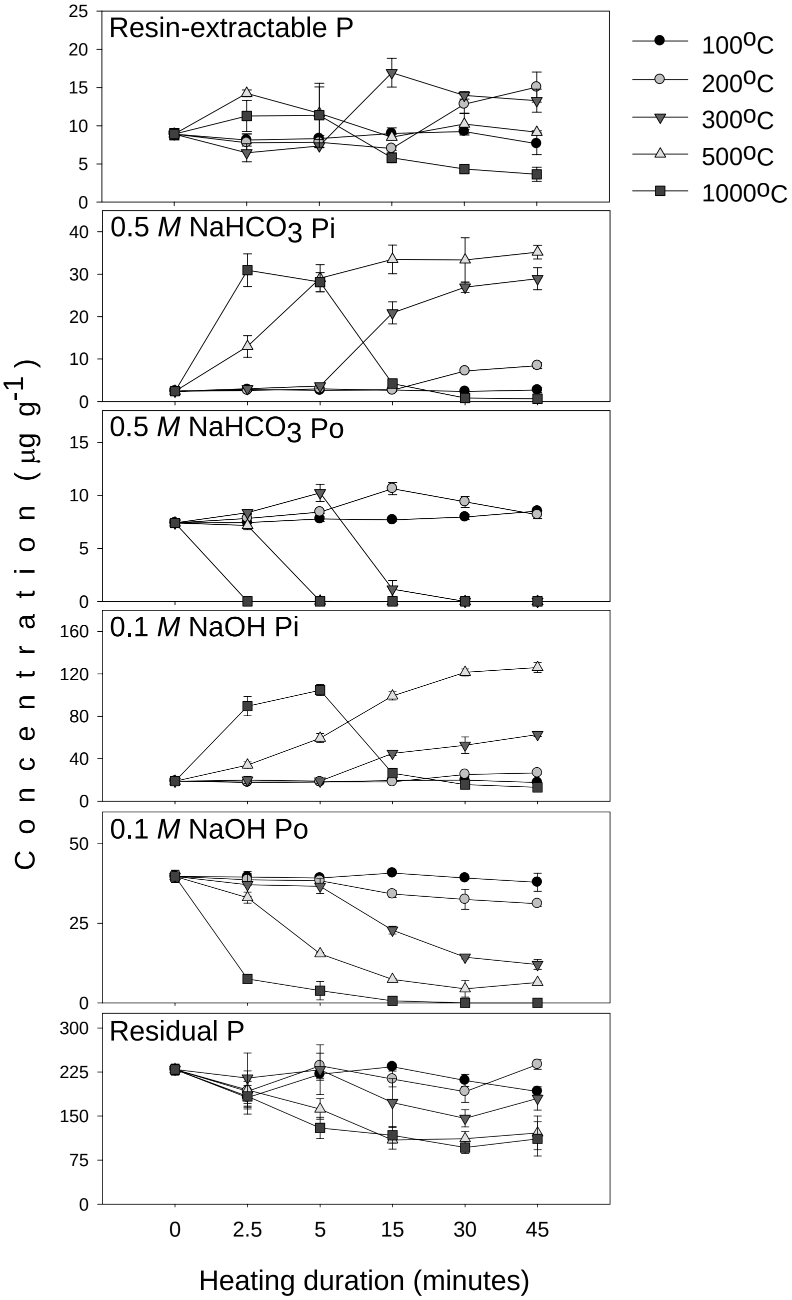

Figure 4.2. Trends in 0-5 cm soil P fractions for a time-temperature laboratory experiment. Typic Kanhapludult soil (Cecil series) was collected in 2006 under a 30 to 40-yr-old loblolly pine stand in South Carolina. Points are mean and bars are 1SD for n=3.

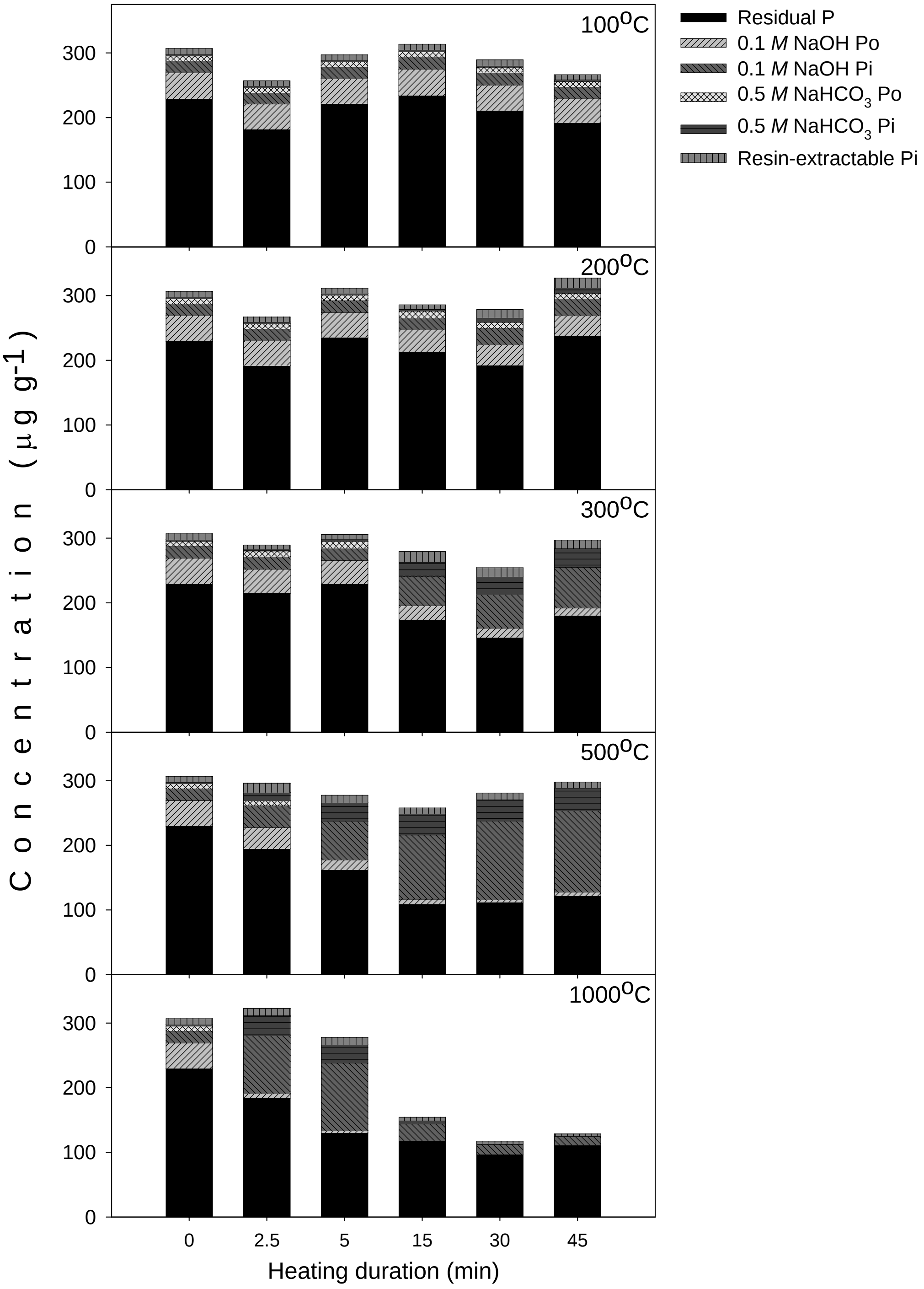

Figure 4.3. P fraction distribution in a Typic Kanhapludult soil (Cecil series) collected at a 30 to 40-yr old loblolly pine stand in South Carolina upon laboratory heating at different temperatures and durations.

CHAPTER 5

CONCLUSION

This study investigated gullies in the Piedmont region of South Carolina to answer questions related to gully contribution to non-point source pollution. Specifically, we examined gullies under forest cover where management practices include periodic burning. With this in mind, three separate studies were devised and conducted ranging from a landscape- to a soil-level scale to: 1) relate land use change with the morphological and current stability of gullies in loblolly pine and mixed hardwood cover, 2) characterize the hydrologic behavior of gullies and assess how it is impacted by prescribed burning, and 3) assess change in soil P pools that could eventually be transported through streams through the gullies. These studies were individually addressed in the three chapters of this dissertation.

Land use change on the Long Cane Ranger District, Sumter National Forest was determined by comparing four sets of aerial photographs taken in 1939, 1954, 1970, and 1999. A land survey of gullies on areas already forested in 1939 and still forested today (continually forested) and on areas that were cultivated/open in 1939 but are now forested (cultivated-to-forested) was conducted. Forest cover in the region has been increasing coupled with a subsequent decrease in open/cultivated area through time. The survey of continually forested areas revealed gullies that are deeper and wider than gullies found at cultivated-to-forested areas, most likely the reason for its early reforestation. In both cases, however, relatively stable gullies are found protected by leaf litter and forest cover.

Eight gullies were instrumented to investigate prescribed burn impacts on gully hydrology. Six of the gullies were subjected to prescribed burning while the remaining two served as controls. Pre-burn sampling showed that seven of the eight gullies generated intermittent flow from December 2006 to March 2007. Three of these gullies, however, flowed only once or twice as a result of a large rain event (67 mm). The flow events seem to be initiated by the formation of perched water table below the gully bed. Post-burn sampling and monitoring was hampered by persistent severe drought in the area. Only four of the eight gullies generated intermittent flows during this period (December 2007 to March 2008). Gullies that do not flow cannot transport runoff and nutrients downslope towards perennial streams or floodplains. Runoff and flow analysis demonstrated a lack of significant effect of prescribed burning on the hydrologic behavior of these gullies. The potential for nutrient mobilization immediately after rain, determined through soil core leaching, was also insufficient to cause significant effect on nonpoint source pollution. Overall, the inter-annual variation in the behavior of the gullies was much greater than the treatment effect.

Phosphorus (P) is a nutrient of concern in nonpoint source pollution. The amount of P in runoff that could be transported to streams and cause eutrophication is determined by how much P is readily soluble. Changes in P resulting from prescribed burning were assessed with both field and laboratory experiments. Soil samples were taken before and after the prescribed burn of a loblolly pine stand and subjected to the Hedley sequential P analysis. Pre-burn samples in the lab were heated at 100, 200, 300, 500, and 1000^{o}C for 2.5, 5, 15, 30, and 45 minutes to simulate different conditions that could occur in a forest fire, then cooled and subjected to the same P analysis. Results showed that prescribed burning increases only sodium bicarbonate ($NaHCO_3$) extractable inorganic P (Pi) primarily due to the addition of ash. The soil heating experiment provided insight into the dynamic combination of or interaction between the heat of fire and length of time the soil is subjected to heating upon the availability and potential release of P. A high temperature-short duration (e.g., 1000^{o}C x 2.5 min) burn can have the same impact as a medium temperature-long duration burn (e.g., 300^{o}C x 45 min). The measured increase in labile P associated with prescribed burning was not enough to be of concern in nonpoint source pollution but could prove to be significant for plant nutrition and soil microorganisms. This information will be useful to land managers in: a) assessing the effect of a wildfire or prescribed fire on possible P loss through runoff or release of P for plant growth; and b) planning the burn prescription in an area to avoid a hotter burn that could result to P loss through volatilization and runoff transport.

APPPENDIX

Summary of the gully survey data for the cultivated-to-forested and continually forested sites.

	Landuse		# of gullies	# of gullies	Stand age	Ave. TD
Site No.	Former (1939)	Current (2005)	incl branch	excl branch	(yrs)	(cm)
1	Cultivated	Mixed	2	1	44	46.2
3	Cultivated	Loblolly	0	0	10	18.3
5	Cultivated	Loblolly	0	0	41	41.6
7	Cultivated	Loblolly	3	3	49	51.4
8	Cultivated	Loblolly	0	0	52	53.4
10	Cultivated	Loblolly	10	7	44	46.7
11	Cultivated	Loblolly	6	4	20	38.2
12	Cultivated	Loblolly	4	3	42	45.5
13	Cultivated	Mixed Lob	0	0	50	51.7
14	Cultivated	Loblolly	2	2	47	46.2
Ave			2.70	2.00	39.90	43.92
2	Forested	Mixed	3	3	50	54.0
4	Forested	Mixed	8	7	47	47.1
6	Forested	Mixed	8	7	51	48.8
9	Forested	Mixed Lob	6	6	49	55.3
15	Forested	Mixed	19	5	52	67.7
16	Forested	Mixed	9	6	48	52.0
17	Forested	Mixed	2	2	51	48.2
18	Forested	Loblolly	5	2	22	24.7
19	Forested	Loblolly	1	1	44	42.5
20	Forested	Loblolly	1	1	55	57.3
Ave			6.20	4.00	46.90	49.76

	Landuse		Ave. slope (%)	Contributing slope (%)	Ave. Headcut	
Site No.	Former (1939)	Current (2005)			Height (cm)	Width (m)
1	Cultivated	Mixed	3.67	5.67	33.0	2.60
3	Cultivated	Loblolly	5.67			
5	Cultivated	Loblolly	9.33			
7	Cultivated	Loblolly	7.67	10.11	46.3	2.80
8	Cultivated	Loblolly	7.00			
10	Cultivated	Loblolly	12.67	12.14	38.5	2.36
11	Cultivated	Loblolly	7.33	10.42	26.5	1.60
12	Cultivated	Loblolly	8.33	5.11	42.7	3.20
13	Cultivated	Mixed Lob	2.00			
14	Cultivated	Loblolly	6.67	8.83	38.0	2.10
Ave			7.03	8.71	37.5	2.44
2	Forested	Mixed	9	11.78	65.7	2.77
4	Forested	Mixed	20	21.00	27.7	1.71
6	Forested	Mixed	14	15.24	38.0	1.62
9	Forested	Mixed Lob	11	11.14	36.5	2.04
15	Forested	Mixed	27	14.33	30.8	1.82
16	Forested	Mixed	12	16.72	43.7	1.87
17	Forested	Mixed	18.67	14.17	27.0	1.80
18	Forested	Loblolly	12.67	13.17	24.5	1.58
19	Forested	Loblolly	7.67	4.00	16.0	1.45
20	Forested	Loblolly	13.67	19.00	30.0	0.85
Ave			14.53	14.06	34.0	1.75

Site No.	Landuse		Ave. gully length (m)	Ave. gully slope (%)	Ave. gully width (m)	Ave. gully depth (cm)
	Former (1939)	Current (2005)				
1	Cultivated	Mixed	90.05	4.0	4.99	38.25
3	Cultivated	Loblolly				
5	Cultivated	Loblolly				
7	Cultivated	Loblolly	12.30	12.7	2.84	45.50
8	Cultivated	Loblolly				
10	Cultivated	Loblolly	27.76	11.6	2.98	52.61
11	Cultivated	Loblolly	20.09	7.0	2.28	40.81
12	Cultivated	Loblolly	21.52	9.7	5.31	56.04
13	Cultivated	Mixed Lob				
14	Cultivated	Loblolly	8.14	3.0	3.29	43.75
Ave			29.98	8.0	3.62	46.16
2	Forested	Mixed	48.77	6.00	4.61	80.83
4	Forested	Mixed	19.18	21.71	1.97	39.46
6	Forested	Mixed	32.8	13.43	2.01	45.54
9	Forested	Mixed Lob	16.86	13.92	2.56	40.63
15	Forested	Mixed	61.5	10.00	3.21	100.50
16	Forested	Mixed	26.73	13.67	1.29	46.21
17	Forested	Mixed	26.15	17.5	2.64	42.63
18	Forested	Loblolly	81.93	9.3	3.30	84.88
19	Forested	Loblolly	34.70	10.0	1.25	27.75
20	Forested	Loblolly	9.40	7.0	1.03	32.50
Ave			35.80	12.3	2.39	54.09

	Landuse		Gully cover (%)	Above cover (%)	Total Vol. Eroded (m^3)
Site No.	Former (1939)	Current (2005)			
1	Cultivated	Mixed	100.00	77.38	132.62
3	Cultivated	Loblolly			
5	Cultivated	Loblolly			
7	Cultivated	Loblolly	61.90	91.05	27.25
8	Cultivated	Loblolly			
10	Cultivated	Loblolly	55.10	83.78	284.01
11	Cultivated	Loblolly	100.00	83.12	57.51
12	Cultivated	Loblolly	98.81	89.9	124.21
13	Cultivated	Mixed Lob			
14	Cultivated	Loblolly	100.00	96.04	15.46
Ave			85.97	86.88	106.84
2	Forested	Mixed	79.76	96.3	343.95
4	Forested	Mixed	99.49	91.23	66.64
6	Forested	Mixed	80.61	81.92	130.34
9	Forested	Mixed Lob	90.48	90.21	62.38
15	Forested	Mixed	81.43	93.38	1733.99
16	Forested	Mixed	79.76	81.93	170.44
17	Forested	Mixed	100.00	83.88	40.78
18	Forested	Loblolly	85.71	91.97	433.69
19	Forested	Loblolly	100.00	79.01	7.73
20	Forested	Loblolly	28.58	77.64	1.89
Ave			82.58	86.75	299.18