CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2006, **15**, 415–425

Indications of vigor loss after fire in Caribbean pine (*Pinus caribaea*) from electrical resistance measurements*

Timothy E. Paysen[A,D], *Andrea L. Koonce*[B], *Edwin Taylor*[C] *and Maria Ouxiliadora Rodriquez*[C]

[A]USDA Forest Service, Riverside Forest Fire Laboratory, Riverside, CA, USA.
[B]San Bernardino National Forest, 602 South Tippecanoe Avenue, San Bernardino, CA 92408, USA.
[C]MARENA, Ministerio del Ambiente y Recursos Naturales, Puerto Cabezas, Nicaragua.
[D]Corresponding author. Email: tpaysen@fs.fed.us

Abstract. In May 1993, electrical resistance measurements were performed on trees in burned and unburned stands of Caribbean pine (*Pinus caribaea* Mor.) in north-eastern Nicaragua to determine whether tree vigor was affected by fire. An Osmose model OZ-67 Shigometer with digital readout was used to collect the sample electrical resistance data. Computer-simulated randomization techniques were used to evaluate the significance of differences in electrical resistance between living trees of burned and unburned stands of various ages. Electrical resistance was used as an index of the general metabolic activity of the tree – our chosen definition of tree vigor. Results indicate a loss of tree vigor in stands that burned in comparison with those that did not.

Additional keywords: fire damage; fire effects; Nicaragua; tropics.

Introduction

Boggy lowlands and pine savannas characterize the Miskito Coast of north-eastern Nicaragua (Fig. 1). This landscape type extends from its eastern limit – the shore of the Caribbean Sea – westward to the mountains of the Cordillera Isabelia, which begin to rise variously from 10 to 50 km inland from the coast. An overstory of Caribbean pine (*Pinus caribaea* Mor.) dominates these savannas. Most of the Caribbean pines in these savannas constitute plantations that have been initiated in an effort to reintroduce forests in these lands, which have a long history of devastating fire (de Dixmude 2001).

Fire is a major source of difficulty in the management of Caribbean pine forests in this region. Fires burn more than 80% of the Proyecto Forestal del Noreste (PFNE) savannas each year (Rodolfo Jaenscthky, Director of Ministerio del Ambiente y los Recursos Naturales [MARENA] in the North-eastern Region, personal communication). This adds credence to Taylor's assertion that the entire savanna region burns each year, with 'only accidental exceptions' (Taylor 1959). The chance of frequent reburns is high for a given stand. Most fires are started by humans. No firm statistics have been kept that would support this assertion in terms of numbers, but sufficient commentary exists to make the statement plausible. Budowski (1966), in a commentary on mid-twentieth century circumstances, felt that 'almost all fires' were set by humans, often to carry out land use practices such as clearing fields for agriculture and ridding an area of pests (Fig. 2). This mirrors a similar statement by

Fig. 1. The Caribbean coast in north-eastern Nicaragua ('Miskito Coast') just south of Puerto Cabezas. A mixture of lowlands and elevated lands can be seen, with associated differences in vegetation. The lowlands here are dominated by grass and other herbaceous plants, with some savannas created by pine plantations. Caribbean pine and a variety of broadleaf species grow in more elevated ground.

* This article was written and prepared by US Government employees on official time and is therefore in the public domain and not subject to copyright.

10.1071/WF05092 1049-8001/06/030415

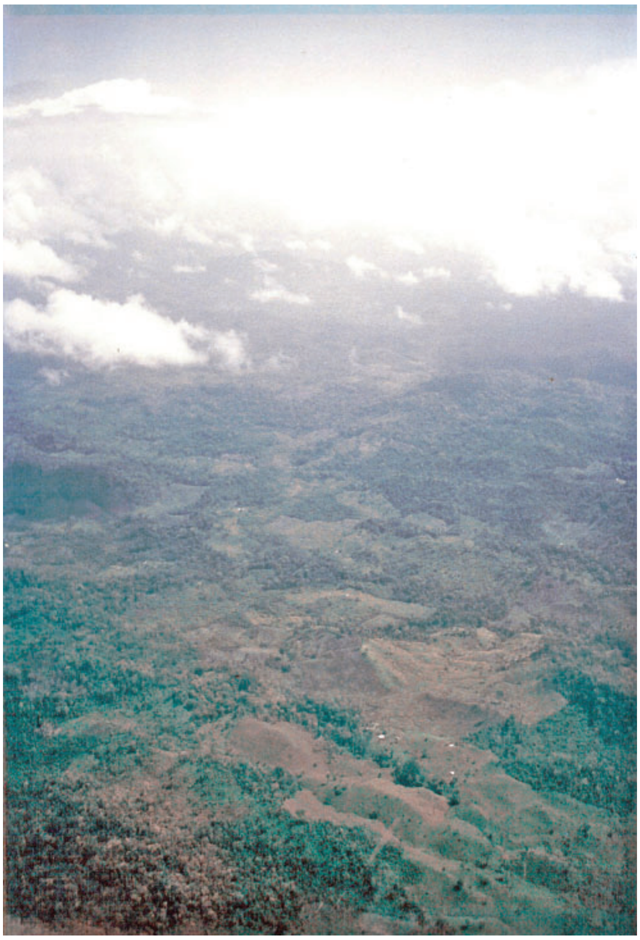

Fig. 2. A patchwork mosaic of agricultural fields and natural forests – the latter a mix of Caribbean pine and hardwoods. The so-called 'slash-and-burn' technique is used for developing agricultural plantations. In the less hilly terrain, the 'burn' part of the technique is sufficient to remove the mostly herbaceous plants that are currently a part of the pine savannas.

Fig. 3. This fire was started by a woman who wanted to gain the attention of a passing truck driver; she wanted a ride into town for herself and her children. The understory vegetation that is burning is wet to the touch.

Taylor (1959). Occasionally, a fire is lit for arbitrary purposes (Fig. 3). None of the fires can be considered prescribed fires, even those that might have a specific purpose. No effort is made to control the extent and damage of the fires that are lit (de Dixmude 2001). Some believe that 'slash-and-burn' agricultural practices have been carried out in north-eastern Nicaragua since pre-Columbian times (de Dixmude 2001), but that current indifference to control measures is largely attributable to non-indigenous people from the western portions of the country. The latter are said to burn off forest for agricultural land at the worst times of the year – times when fire spread is more likely to be problematic (NicaNet 2005).

Fire rarely kills the very fire-resistant mature Caribbean pines, but seedlings and pole-stage pines can suffer high fire mortality (Munro 1966) (Fig. 4). Taylor (1959) places 5 years of age as the cut-off point beyond which the Caribbean pines are rarely killed by fire (Fig. 5). Though specific losses in productivity of these pines after fire are unknown, preliminary growth estimates (from height and dbh measurements – dbh meaning bole diameter at breast height, or 1.37 m above the ground) indicate a loss in volume increment (MARENA and PNFE staff, personal communication). This occurs during the year of the fire and for an undetermined time afterward.

The apparent long history of fire, and the flammable vegetation of the area, can lead to conjecture regarding whether the ecosystem is fire prone, and whether fire can be regarded as a natural component of the system. The answer is that it is no more or less fire prone than any other ecosystem that has vegetation that will burn, given the application of a firebrand. With regard to fire hazard, in its technical sense (the presence of flammable material), the pine savannas of the Región Autonomía Atlántica Norte (RAAN) currently have high hazard levels. With regard to risk, in its technical sense (the propensity for firebrands to be present), the system also has a high level of risk. However, neither factor, taken independently, can define a fire regime, but together they can give a fire regime its character. For the moment, then, the RAAN can be said to be fire-prone. Is fire a natural component of the ecosystem? If the concept 'natural' includes both anthropogenic and non-anthropogenic elements, then, yes, fire is a natural, and common, component of the system.

Fig. 4. A young (post-seedling stage) Caribbean pine plantation that has recently burned (a few months before the photo was taken). New understory herbaceous material can be seen growing around the pine. Based on local experience, this pine is thought to have a good chance of survival.

Fig. 5. A pole-sized Caribbean pine plantation that was burned a few weeks before this photograph was taken. Damage was severe, heat scorch leaving only wisps of green crown. Early predictions of survival were problematic, depending, for the most part, on the effectiveness of the remaining crown material in sustaining tree life.

Fig. 6. At the time of the present study, the fire problem in Nicaragua not only related to the maintenance of forest and savanna vegetation, but to resulting economic losses as well. A crown fire carried by high winds and the crowns of Caribbean pine swept through this area earlier in the year. The town of Slilma-Lila, its lumber mill, and associated equipment were destroyed, along with its lumber production.

If the anthropogenic elements stop lighting fires, then fire will become less common, but will always have to be considered natural. Lightning tends to occur during wet storms, and poses little to no problem with fire ignition. Tumbling rocks have not been cited as a fire ignition issue. Volcanoes, however, are present; however long they may 'sleep', they remain a potential source of firebrands. So, we will say, 'yes', fire is a natural component of the RAAN ecosystem.

The present study arose as an opportunity during a series of assignments given to the first two authors – the first assignment was sponsored by USAID and the US Forest Service – at the request of the Nicaraguan government, to evaluate the fire problem in the north-eastern portion of the country (Fig. 6). A similar evaluation was carried out in 1975 (FAO and UNEP 1975). Intervention of a revolt and a protracted civil war (CIA 2005; Learningcurve 2005; World Vision International 2005) prevented implementation of recommendations from the earlier evaluation, and indeed made forest management in general a difficult task (Heiner *et al.* 1989). Subsequent debate over management responsibility, and even forest ownership, continued to hamper development of a technologically sophisticated management organization (Everingham 2001; FAO 2001; Urbina 2003), but did not prevent highly skilled professionals from carrying out the required work, while under-equipped and under-staffed (Koonce and Paysen 1991).

Caribbean pine growing on optimum sites can achieve heights up to 40 m, and have crown lengths (from the bottom of the green crown to its peak) that are 30–40% of tree height. In north-eastern Nicaragua, crown lengths of less than 30% of height are common (Fig. 7), presumably because of fire injury (MARENA staff, personal communication). Cessation of measurable growth, general decline in crown color, and reduced needle density indicate vigor loss. This general decline may be observed for a few years after fire.

The concept of vigor is ephemeral. It has no concrete, tangible definition, whether applied to pine trees or human beings. The words used to define 'vigor' can often be, themselves, defined by the word 'vigor' (Table 1). We often understand the use of the word if its context is clear. Now and then, a context is presumed: 'the vigorous trees survived' and 'vigorous trees dominated the stand' are statements that could be commonly found in forestry literature. Both statements could imply some predetermined vigor status as something that determined survival or dominance. Conversely, the outcomes, survival and dominance, could be used as indicators of some undetermined vigor characteristic. Note that we used growth rate, crown color, and needle density as indicators of vigor in the above paragraph – all acceptable comparative indicators used by foresters; Keen's crown classes (Keen 1943) for Ponderosa pine (*pinus ponderosa* Laws.) use crown vigor, as indicated by crown size, density, and shape, for determining the tree's susceptibility to bark beetle attack. Clearly, we must define which facet of vigor we are addressing.

Fig. 7. This stand of Caribbean pine suffered from fire at some unrecorded earlier time. Local foresters believe that it was around 7 years before this photograph was taken. Crown development, and needle length and color are poor in comparison with the same characteristics of the occasional tree found growing in the open and known to have been untouched by fire for a few (unspecified) years.

Table 1. Definitions for the word 'vigor' and for related words taken from Webster's *New World Dictionary of the American Language* (Friend and Guralnik 1959)

Qualifying or explanatory subsets of the definitions are left out. Only subsets that comprise single explanatory words are included

Word	Definition
Vigor	Active physical or mental force or strength; vitality
Vitality	Mental or physical ***vigor***; energy
Strength	The state or quality of being strong; force; power; ***vigor***
Force	Strength; energy; ***vigor***; power
Energy	Potential forces; inherent power; capacity for ***vigorous*** action
Power	Great ability to do, act, or affect strongly; ***vigor***; force; strength
Vigor[A]	Vitality, strength, or robustness; degree of health and healthy growth exhibited by an organism
Vigour[B]	The intensity of growth or general metabolic activity of an organism, population or community

To bring the concept closer to the subject of the present paper, definitions from [A]*The Dictionary of Ecology and Environmental Science* (Art 1993), and [B]*A Dictionary of Ecology, Evolution and Systematics* (Lincoln *et al.* 1983) are included.

We followed *The Dictionary of Ecology, Evolution and Systematics* (Art 1993) (Table 1), and state that we were looking at the general metabolic activity of the trees in our study. As an indicator of such activity, we used the concentration of electrolytes in the tree cambium. As a measure of concentration, we used the electrical resistance (ER) of the cambium's cellular material.

The use of bioelectrical techniques, including measurement of ER, as means for assessing various tree growth conditions, which include vigor, is not without precedent. Such techniques have been established in practice (Wargo and Skutt 1975; Tattar and Blanchard 1976; Shortle *et al.* 1977; Cole and Jensen 1979; Davis *et al.* 1979; Cole 1980; Davis *et al.* 1980; Piene *et al.* 1984; Shigo and Shortle 1985; Ostrofsky 1986; Gagnon *et al.* 1987; Bará *et al.* 1992; Paysen *et al.* 1992; Narog *et al.* 1997; Filip *et al.* 2002). Tattar and Blanchard (1976) provided good evidence for the use of electronic technology for evaluating various aspects of plant function and disease. Bará *et al.* (1992) used electrical conductivity and generation of square waves to evaluate fire damage in *Pinus radiata*, and Bara Temes (1993) confirmed the utility of the method on burned and unburned 8-year-old *Pinus pinaster*. He was able to predict survival or mortality with greater than 90% accuracy. Here, we present the results of a study using ER on stands of *P. caribaea* that have different fire histories. The study was initiated to determine whether tree vigor is affected by fire in Caribbean pine.

Our purpose in performing this study was to determine the effect of fire on tree vigor for this species, without the confounding effects of stand-thinning, which often occur as a result of fire, especially prescribed fire (Paysen and Narog 1993; Peterson *et al.* 1994; Narog *et al.* 1997). These thinning effects may mask the specific effects of the fire. There are those who believe that trees belonging to a fire-prone environment cannot be injured by fire if they have survived a fire (particularly a prescribed fire) and show increased activity (height or diameter growth, apparent improvement in crown vigor). We are addressing the notion that such trees are possibly showing a net improvement, based on the logic that virtually any living organism that is burned by fire will suffer damage of one kind or another. Understanding this will improve the expectations of forest managers who contemplate the use of fire as a management tool.

Study location

The study area was located in the portion of north-eastern Nicaragua known as the Región Autonomía Atlántica Norte, or RAAN (Northern Autonomous Atlantic Region) (Fig. 8). The region has 3.4 million hectares of forested area; the pine forests cover ~500 000 ha, or ~15%. In addition, the area has 1.5 million ha of tropical rain forest in the lowlands; most of the tropical rain forest occurs as gallery forests along the major rivers (Fig. 9).

A relatively cool, humid–tropical climate characterizes the region. The mean annual minimum temperature is 22°C and the mean annual maximum temperature is 30°C (Organización de las Naciones Unidas para la Agricultura y Alimentación 1972). The mean annual precipitation is ~3000 mm. A 15-week relatively dry period occurs between February and May when total precipitation ranges between 30 and 60 mm. Between the end of May and the beginning of November, the rain exceeds 250 mm per month (Taylor 1959), although a 7–10-day dry period frequently occurs in September. After November, the rain diminishes; masses of cold air from the north descend over the region, generally bringing dry conditions due to the foehn effect (Organización de las Naciones Unidas para la Agricultura y Alimentación 1972; Portig 1976). In general, winter in this region brings dryer conditions, and an increase in fire danger. Dryer conditions in this area should not be confused with those of Mediterranean-type and Boreal zones of the world. It rains in Nicaragua during the dry periods, but not as much as during the wet periods (Fig. 10). Nevertheless, the dry period is significant from the standpoint of fire activity.

The region's topography is smoothly undulating, and gradually rises towards the west, to 200 m elevation in some places. A complex principal drainage system runs from west to east; it contains a secondary drainage system, resulting in a general dendritic structure, frequently with small U-shaped gullies. Abundant marshes exist, which increase in size and frequency towards the east.

A lateritic alluvium of granitic origin comprises the principle soil of the region. It is a sandy clay silt, nutrient-poor, brownish orange in color, and acidic (pH of 4–5). An A horizon of clayey silt exists in zones of larger vegetation, but is frequently absent in areas that have been exposed to frequent fire and subsequent weathering. Gravel pavements, several centimeters thick, are frequently found throughout

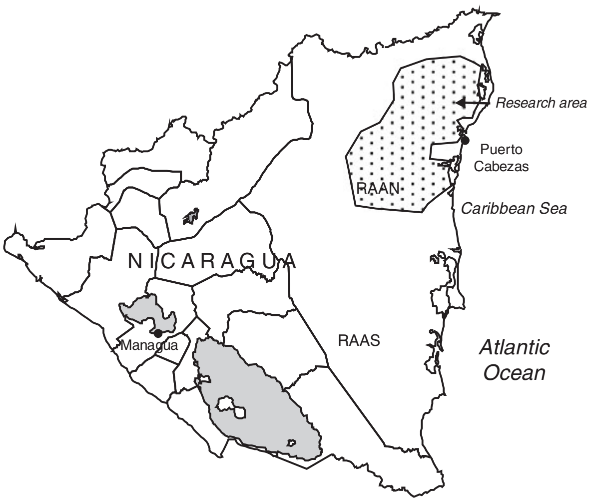

Fig. 8. The research area in the Región Autonomía Atlántica Norte (RAAN) of north-eastern Nicaragua. The present study addressed the condition of the frequently burned stands of Caribbean pine savannas.

Fig. 9. A tropical rain forest growing along a major river in the highlands of north-eastern Nicaragua. Such forests in this area are dominated by hardwoods, including big-leaf mahogany (*Swietenia macrophylla* King), with an element of pine.

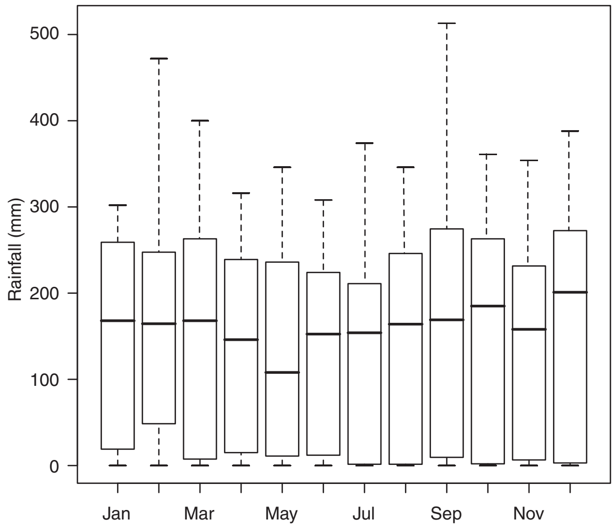

Fig. 10. Average monthly precipitation for the town of Puerto Cabezas, covering the years 1975 to 2005. This particular data set was obtained from the NOAA/NCDC (National Oceanic and Atmospheric Agency, National Climatic Data Center) data set.

the region; these consist of various proportions of quartz and iron concretions.

A mix of true grasses and juncus (*Cyperaceae*) generally cover the area. The best-drained sandy soils are covered only with true grasses, the poorly drained areas, only with juncus. The juncus is found in large (of the order of 0.1–1 m), well-spaced (order of 2–3 m) tufts in areas where drainage is very bad. These tufts invariably indicate the presence of water-logged plastic clays below the soil surface.

The presence of one juncus, a *Bulbostilus* species, depends to a large degree on the frequency of fire. It disappears in places that have been protected from fire for a period of time. When frequent fires do occur, its presence is restricted to areas with iron concretions in the soil.

This mix of grasses and sedges forms a highly flammable understory in the pine savannas and woodlands that are the subjects of the present study. This ecosystem burns even under very moist conditions – not an unknown phenomenon in tropical ecosystems (Fig. 11).

The Caribbean pine, which forms the overstory in the stands being studied, occurs naturally, particularly in the highlands of the RAAN. However, most of the current stands in the savanna lowlands are plantations. Of the stands studied, all were 25 years in age (time since seedlings planted) or less (Table 2).

Fig. 11. The fire resulting from the ignition illustrated in Fig. 3. It was a light underburn in damp understory conditions.

Table 2. Stand locations with ages and fire histories
Stand age refers to time since establishment as a plantation. A seedling stock age of 2 years can be assumed

Stand	Stand age (years)	Time since burn (years)
Krukira	7	Never burned
Trakis	1	Never burned
Panua	11	6.0
Sisin	7	3.5
Torre 8	25	0.3

Methods

The sampled stands were widely scattered throughout the study area. Their selection was purposeful: stands were selected that represented different times since last burn, to the extent possible, and included some that had never burned (few choices were available in the latter case). In total, five stands were selected (Table 2). Within these stands, ER measurements were taken on sample trees using a Shigometer. An Osmose model OZ-67 Shigometer (Osmose Wood Preserving Co., Buffalo, NY, USA) with probes that were 9 cm in length and a digital readout, was used for the measurements.

Fuel conditions during the fires were, of course, not recorded. However, judging from general understory character in the savannas (see Figs 3–5), and from the swelling at the base of the tree boles – a reaction to fire in Caribbean pine – understory depth probably ranged from 10 to 20 cm. We sampled understory vegetation to develop a sense of fuel loading per unit volume in the savannas, but the samples were tainted by the roof that collapsed on them as they were awaiting processing. Nevertheless, we were comfortable assuming that variation in convective heating was within a sufficiently small range that it could be ignored for the level of analytical precision in the present study.

Allocation of measurements to trees within stands was also purposeful: the intent was that tree selection reasonably cover the stand area, not be in clusters, and provide a representation of tree sizes and conditions within the stands. Personal judgment was used in the selection of trees, with an effort to avoid bias. The proportion of trees sampled was of the order of 5%. Variability of tree sizes within a given stand was small, as the stands were all even-aged.

All stands were sampled during a sunny day in May 1993. The weather was constant throughout the day, with little variation in air temperature and humidity. It is particularly important to appreciate the state of the weather in this instance. The sample area lies at 14°N latitude, 9.5° south of the Tropic of Cancer. In the month of May, the sun is effectively overhead at noon, and north/south aspect contrasts mean very little in terms of solar radiation and consequent sensible heat of solid bodies. In the first author's experience in more northern latitudes (Paysen *et al.* 1992), differences in temperature of north and south sides of tree boles can be felt with the hand in winter seasons. Weather conditions and season can affect electrical resistance readings. However, in studies carried out in the USA in areas that have distinctive seasons in terms of weather conditions, conclusions were that comparisons are valid for measurements taken during the same period of the year, or on the same day, provided no dramatic changes in weather variables occur during the measurement period (Cole and Jensen 1979; Cole 1980; Blanche *et al.* 1991; Paysen *et al.* 1992). The latter point is important for the present study. Formal measurements of air temperature and relative humidity were not available; the international weather station in Puerto Cabezas had closed down several years before, and instrumentation for measuring temperature and humidity was just not available. The crucial point, however, is that neither temperature nor humidity changed sensibly during the day, allowing valid comparison between measurements taken from all stands.

The two Shigometer probes of the instrument were pushed horizontally through the tree bark (or, more accurately, in a plane normal to the vertical plane of the bark), until the probe tips were in the cambium. As a rule of thumb, low readings indicate low electrical resistance and are generally associated with healthy trees. The presence of adequate amounts of water and ions in the cambium promotes good electrical conductivity and, therefore, low electrical resistance (Shigo and Shortle 1985). As a corollary, high readings are generally associated with less-than-healthy trees. One caution is that decaying wood that has a high moisture content will give extremely low readings (generally, less than 5 kilo-ohms [KΩ]), because it too acts as a good conductor of electricity. In practice, the difference between decaying and non-decaying wood in standing trees is easily detected, and there is little chance of confusing the two (decaying wood looks and feels rotten, soft, and disorganized). Very high readings (over 30 KΩ or so) are difficult to interpret with mathematical precision because the instrument begins to lose linearity at these levels – an inherent electronic feature of the instrument model that we used. Such high readings, however, generally indicate declining tree health. Extremely high readings (in hundreds of KΩ) can be interpreted as infinite resistance – effectively, air space in the dead cambium area. Obviously dead spots on a tree bole – spots that have no bark or have obvious rot – can be avoided, provided a successful measurement can be taken within the appropriate directional quadrant. However, a high or low reading alone cannot signal the need to search for a reading that fits a preconceived notion of a 'successful' sample effort – one that samples truly living material. Unless there is obvious reason to do otherwise, readings have to be taken at face value. No obviously dead spots were apparent on our sample trees.

Two measurements at breast height (1.37 m) were made on each tree: one on the north side and the other on the south. Our experience in temperate areas has shown that these two sides of a tree trunk represent extremes in possible ER readings for a given tree, probably owing to temperature differences in the trunk itself, a result of solar incidence (Paysen *et al.* 1992). Data was gathered from 10 trees in each stand, but 15 trees were used in the Panua stand, which was larger than the rest. Tree height (ocular estimate to the nearest meter) and dbh (measured to the nearest cm) were recorded for each sample tree.

Analysis

The purposeful stand and tree selection methods that we used are not statistically unsound. They simply mean that tree-level results cannot be statistically inferred to a stand level, and that results achieved on trees from a given stand cannot be statistically inferred to all stands with the same characteristics. This is often an unfortunate reality, dictated by circumstances. However, our subsequent analysis technique was such that significance levels are statistically sound. Inferences from the results can be applied as individual professional judgment dictates.

For visual interpretation of the ER data, we developed Epanechnicov kernel density diagrams (Silverman 1986) for the data. Kernel densities are, in essence, mathematically smoothed histograms. They provide a desirable alternative to the use of standard histograms for sparse data, and also provide a means for estimating statistical density distributions from observed data. We aggregated the data into two classes: burned, and not burned, for each of the north and south aspects of the tree boles. The resulting kernel densities are presented in Fig. 12.

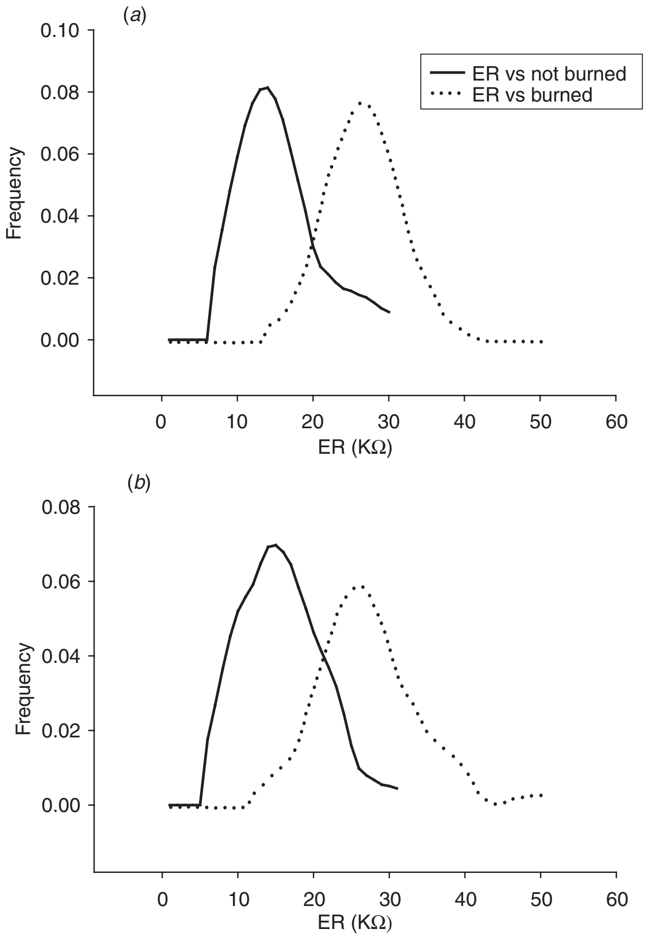

Fig. 12. Kernel density diagrams of electrical resistance readings for Caribbean pine stand data aggregated into classes: burn and no burn. (*a*) Kernel densities for north side electrical resistance readings; (*b*) kernel densities for south side electrical resistance readings.

The objective of the study was to evaluate the vigor of living trees that have or have not burned. Electrical resistance readings taken on the north and south sides of tree trunks were averaged for each tree, and the result taken as representative of the tree's overall vigor. Electrical resistance values over 50 KΩ were assumed to represent dead or dying tissue. We were interested in the vigor of living trees, dead trees representing the trivial case, where vigor is not an issue. We were not evaluating stand condition. Therefore, trees with one or both of the north and south readings over 50 KΩ were treated as outliers and eliminated from the analysis. Such readings would provide meaningless weight to tests of significance between the two classes of data. Two trees were removed from the Panua data set.

Kernel density diagrams were developed for the two resulting average ER data sets (burn and no burn) to provide a basis for useful visual interpretation (Fig. 13). A window width of 2.5 KΩ was used for diagram development. In the judgment of the first author, a window width of 25 times the smallest significant unit in the data (mean differences, in this case) provides decent results under most circumstances. Analyses were performed on the raw data, rather than the synthetic data developed for the kernel densities.

To test the hypothesis that no difference exists between ER readings on trees that have burned and those that have not burned, a test comparing the differences of means between the two data sets was performed. An approximate randomization test (Edgington 1987; Noreen 1989) was used for this purpose. In this instance, the randomization test was functionally equivalent to its parametric counterpart, the *t*-test for two samples with unequal variances.

Approximate randomization tests are analytical equivalents of pure randomization tests as proposed by Fisher (1935), but do not suffer the limitations imposed by the need to specify every possible outcome of a given trial setup. They instead evaluate, through simulation techniques, the uniqueness of a data set by comparing it with a large number of random shuffles of the values of its two components. For this, the data was shuffled, and, in accordance with the shuffling, values were randomly assigned to the burn or no burn categories, regardless of their original identity. The differences between means of the two resulting artificial data set components were then calculated. This was repeated 500 times. The choice of 500 iterations for the simulation was strictly an arbitrary choice by the first author. Generally, the choice of 1000 iterations for a simulation exercise provides a desirable degree of comfort to readers; it provides something analogous to a large sample. Significance achieved with a smaller sample seems to be more interesting.

The set of differences in mean values was then compared to the values obtained from the field data. This is precisely equivalent to comparing a set of means obtained from field samples to values in a *t*-table, or performing its computational equivalent, under parametric analysis conditions. Informally, this type of test asks: 'Given the numbers in my data set, is the configuration of the set unique? Or, could it have been achieved through a random shuffle of the same set of numbers?' In other words, it tests whether the burn and no-burn data values came from different populations, or if instead the burn–no burn dichotomy is meaningless.

Simple allometric relationships can sometimes help to distinguish between populations with inherent differences in growth relations, or with relations that have been affected by site character or by competition. Differences in these relationships are sometimes associated with differences in vigor. However, should such differences have appeared in our data, their source could not have been specified because the burned trees had already burned, confounding the picture (conceivably, vigor loss from damage could cause a change in allometric relationships as well). As a cursory check to see if obvious differences did appear between burned and unburned trees, height and dbh relations were visually inspected with a composite scatter diagram (Fig. 14). A simple linear regression was applied to the height *v.* dbh data using the log to the base 10 of dbh. No specific burn/no burn tests could be validly performed in the regression context. The relative spread and location of the burn/no burn data would indicate a significant

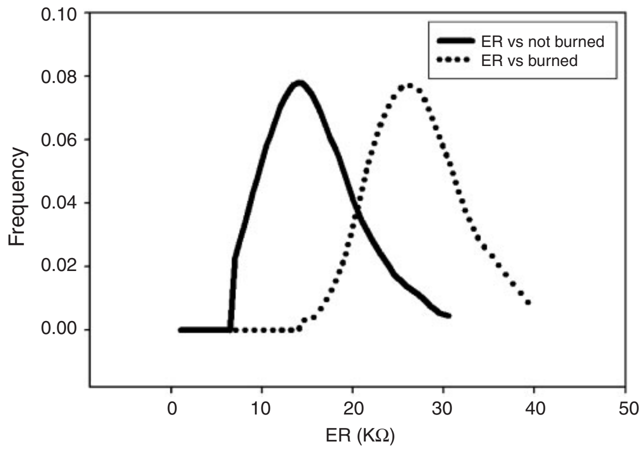

Fig. 13. Kernel density diagrams for the average of the north and south electrical resistance readings for each Caribbean pine tree.

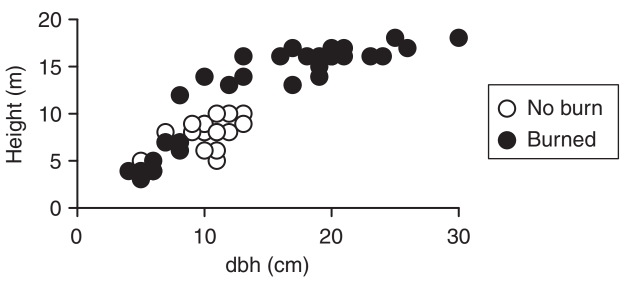

Fig. 14. Scatter plot of tree height *v.* tree diameter at breast height (dbh) for all trees analyzed.

difference between the two, even if they belonged to the same population.

Similarly, the issues of tree size and age can emerge as factors affecting – or reflecting – apparent vigor. All stands were young (7–25 years since establishment), so we only considered tree size as a possible confounding factor. We repeated the randomization test only on trees that were 13 cm dbh or less (13 cm being the largest dbh of the trees in stands that had not burned). It turned out that the majority of the selected trees came from the youngest stands.

Results

The linear regression with height = function ($\log_{10}$ dbh) provided reasonably strong results ($R^2 = 0.83$, with a regression F-ratio significance probability of 0.00). Evidence of any inherent or condition-induced differences in growth relationships is not obvious. If such differences do exist, the spread of the unburned stand data is too small to show it. Simple linear regression points to a height *v.* dbh relationship that is fairly consistent throughout the stands sampled.

Results of the randomization test are presented in Table 3, along with those derived from trees 13 cm or less. The results of the test indicate that the mean differences between the burn and no-burn samples are highly significant, thereby allowing rejection of the hypothesis of no difference. The result reinforces the visual impressions left by Figs 12 and 13 that ER for burned and unburned stands are quite different. The probability (0.002) of obtaining the mean difference statistic of 11.5 KΩ or greater is smaller than those that would be required for significance at the standard levels. Results of the test on trees 13 cm dbh or less do not change the more general results.

Discussion

The issue of stand vigor after fire is filled with confusion. On one hand, we can logically propose that fire damages organisms, and that loss of vigor should be expected. In contrast, we know that fire is often used as a tool to improve tree stand performance, in terms of reproduction, and sometimes in terms of growth. The confusion arises from the fact that we are left to evaluate the net effect of a fire, and in so doing, do not always consider all effects of a fire event.

Table 3. Results of the randomization tests on mean differences between burn and no burn Caribbean pine stands

The statistic being tested is the difference between the means of the two categories; dbh, diameter at breast height

Variable	All trees	Trees < 13 cm dbh
Number of shuffles	500	500
Actual difference (KΩ)	11.5	10.9
Significance level (ϕ)	0.002	0.002
Probability of $\phi \leq 0.01$	1.00	1.00
Probability of $\phi \leq 0.05$	1.00	1.00
Probability of $\phi \leq 0.10$	1.00	1.00

Consider the following: (1) fire, as a damaging agent, can produce vigor loss in trees that have been damaged by fire; and (2) fire, as a damaging agent, can remove competition, resulting in improved vigor in residual trees, damaged or not. Both of these factors can work in a stand of trees affected by fire. The net result – the one that we perceive – will depend on which factor has the strongest effect. We can, therefore, burn a stand of trees, kill some trees, remove understory vegetation, and damage the residual living trees, and have a net increase in stand vigor because the effect of competition removal was more dominant than the damaging effect of the fire.

In the present study, competition was not removed by the fires that burned each stand. No trees were killed, and the understory vegetation, in effect, regenerated immediately (refer to Fig. 4). The measured vigor response was due solely to the damaging effect of fire, and a loss of vigor was detected.

Conclusions

Results from the present study suggest a relationship between tree vigor and the fire history of trees, burned or not burned. Higher ER readings were consistent with trees in stands that had burned. The results suggest that we observed a loss of vigor after fire for trees in these stands.

For the present study, the spread in years since burn was not sufficient to allow evaluation of vigor recovery over time. Stands in the RAAN that can be represented by those in our study will probably have vigor loss that persists for at least 6 years after fire, the longest period of time since fire for the stands that we studied.

To extend this kind of study so that it incorporates stands that have not burned for a time period longer than 6 years will probably require effective fire prevention applications in the RAAN. A substantial number of Caribbean pine stands that have burned in the past, but that have not burned for various periods of time greater than 6 years, will be required. Under these circumstances, evaluation of vigor recovery for Caribbean pine in the RAAN might be established.

Meanwhile, the results of the present study suggest that forest managers, in any ecosystem, should consider trade-offs that may exist in the use of fire as a management tool. Potential damage to residual trees after a fire should be weighed against the benefits to be gained from stand treatment with fire. It may well be that the benefits gained from treatment with fire will outweigh the setbacks that might occur as a result of fire damage. And, in some ecosystems, the use of fire might not be advisable. Under some circumstances, such as may exist in the RAAN, both understory and overstory trees might be well adapted to fire, but fire that occurs too frequently may ultimately lead to a system crash. Under all circumstances, the use of fire as a management tool, and its control as a catastrophic event, must be approached with careful analysis and an understanding of ecosystem dynamics for the systems being managed.

References

Art HW (Ed.) (1993) 'The dictionary of ecology and environmental science.' (Henry Holt and Co.: New York)

Bará S, Vega JA, Alonso M (1992) Estudio de los daños prodúcidos por el fuego en árboles, utilizando métodos bioeléctricos. I. Pino Radiata. *Investigación Agraria, Sistemas y Recursos Forestales* **1**, 21–40.

Bara Temes S (1993) Mettodos bioelectricos para determinar el estado fisiologico de los arboles. In 'Ponencias y communicaciones del Congresso Forestal Español', 14–18 June 1993. pp. 219–224. (Lourizán, Pontevedra, Galicia, Spain)

Blanche CA, Nebeker TE, Hodges JD, Schmitt JJ, Hones CR (1991) The applicability of stem electrical resistance in rating loblolly pine tree vigor. In 'Proceedings of the sixth biennial southern silvicultural research conference', 30 October–1 November 1990, Memphis, TN. (Eds SS Coleman, DG Neary) pp. 314–322. USDA Forest Service Southern Experiment Station, General Technical Report SE-70. (Asheville, NC)

Budowski G (1966) Fire in tropical American lowland areas. In 'Proceedings of the fifth annual Tall Timbers Fire Ecology Conference', 24–25 March 1966, Tallahassee, FL. (Chairmen EV Komarek, J Philips, CH Coulter) pp. 5–22. (Tall Timbers Research Station: Tallahassee, FL)

CIA (2005) Nicaragua. In 'The world factbook'. Available at http://ww.cia.gov/cia/publications/factbook/geos/nu.html [Verified 20 September 2005]

Cole DM (1980) Within-stand comparisons of inner bark electrical resistance in Lodgepole pine – the bark moisture factor. *Forest Science* **26**, 309–312.

Cole DM, Jensen CE (1979) Estimating phloem thickness distribution in lodgepole pine stands using electrical resistance measurements. *Canadian Journal of Forest Research* **10**, 102–106.

Davis D, Shortle W, Shigo A (1980) Potential hazard rating system for fir stands infested with budworm using cambial electrical resistance. *Canadian Journal of Forest Research* **10**, 541–544.

Davis W, Shigo A, Weyrick R (1979) Seasonal changes in electrical resistance of inner bark in red oak, red maple, and eastern white pine. *Forest Science* **25**, 282–286.

de Dixmude AJ (2001) Fire situation in Nicaragua. In 'Global forest fire assessment 1990–2000', Forest Resources Assessment WP 55. (Eds JG Goldammer, RW Mutch, P Pugliese) pp. 427–431. (FAO: Rome)

Edgington ES (1987) 'Randomization tests.' (Marcel Dekker: New York)

Everingham M (2001) Agricultural property rights and political change in Nicaragua. Tierra Americas, Latin American Politics and Society, Fall 2001. Landnet Americas. Available at http://www.findarticles.com/p/articles/mi_qa4000/is_200110/ai_n8959781 [Verified 24 May 2006]

FAO (2001) Informacion sobre manejo forestal, recursos forestales y cambio en el uso de la tierra en America Latina, Anexo 4: Resumen del estado del manejo en los paises de America Latina. In 'Memorias de Talleres "Información sobre Manejo y Recursos Forestales en America Latina" ', 6 September 2001, Lima, Peru, Volume 3. pp. 169–258. (Food and Agriculture Organization of the United Nations: Rome)

FAO and UNEP (1975) 'Detection and control of forest fires for the protection of the human environment: Proposals for a global programme.' UNEP project 0206-74-003. (Food and Agriculture Organization of the United Nations: Rome)

Filip GM, Ganio LM, Oester PT, Mason RR, Wickman BE (2002) Ten-year effect of fertilization on tree growth and mortality associated with Armillaria root disease, fir engravers, dwarf mistletoe, and Western spruce budworm in North-eastern Oregon. *Western Journal of Applied Forestry* **17**, 122–128.

Fisher RA (1935) 'The design of experiments.' (Oliver and Boyd: Edinburgh)

Friend JH, Guralnik DB (Gen. Eds) (1959) 'Webster's new world dictionary of the American language – college edn.' (World Publishing Co.: Cleveland, OH)

Gagnon RR, Bauce E, Pineau M (1987) Relation between air water potential and cambial electrical resistance of balsam fir and white spruce after budbreak. *Canadian Journal of Forest Research* **17**, 105–108.

Heiner H, Heiner D, Lowell K (1989) Forest utilization in war-torn Nicaragua. *Journal of Forestry* **87**, 38–45.

Keen FP (1943) Ponderosa pine tree classes redefined. *Journal of Forestry* **41**, 249–253.

Koonce AL, Paysen TE (1991) 'Wildfire assessment in the pine savannas of northeast Nicaragua, 9–20 June 1991.' USDA Forest Service, International Forestry, and USDA Forest Service, PSW Station, Riverside Forest Fire Laboratory. (Report on file)

Learningcurve (2005) 'Nicaragua.' Available at http://www.spartacus.schoolnet.co.uk/COLDnicaragua.htm [Verified 29 June 2006]

Lincoln RJ, Boxshall GA, Clark PF (1983) 'A dictionary of ecology, evolution and systematics.' (Cambridge University Press: Cambridge)

Munro N (1966) The fire ecology of Caribbean pine in Nicaragua. In 'Proceedings of the fifth annual Tall Timbers Fire Ecology Conference', 24–25 March 1966, Tallahassee, FL. pp. 67–83. (Tall Timbers Research Station: Tallahassee, FL)

Narog MG, Paysen TE, Corcoran BM, Zavala MA (1997) Monitoring fire injury in Canyon live oak with electrical resistance. In 'Proceedings of a symposium on oak woodlands: ecology, management, and urban interface issues', 19–22 March 1996, San Louis Obispo, CA. (Tech. Coords NH Pillsbury, J Verner, WD Tietje) USDA Forest Service Pacific Southwest Research Station, General Technical Report PSW-GTR-16. (Albany, CA)

NicaNet (2005) 'Over 10 000 hectares of protected area destroyed by fire in RAAN.' Nicaragua Network News Service. The Nicaragua Network, a project of the Alliance for Global Justice, 25 April 2005. Available at http://www.nicanet.org [Verified 21 September 2005]

Noreen EW (1989) 'Computer-intensive methods for testing hypotheses: an introduction.' (John Wiley and Sons: New York)

Organización de las Naciones Unidas para la Agricultura y Alimentación (1972) Investigación para el desarrollo de los recursos forestales en el noreste de nicaragua (SF/NIC 9–1/FO), Volume 1. (Forestal, Forestry and Engineering International: Vancouver)

Ostrofsky WD (1986) An evaluation of Red spruce vigor using the Shigometer. Progress Report 28. Cooperative Forest Research Unit, College of Forest Resources, University of Maine. Miscellaneous Report 315. (Maine Agricultural Station, University of Maine: Orono, ME)

Paysen TE, Narog MG (1993) Tree mortality 6 years after burning a thinned *Quercus chrysolepis* stand. *Canadian Journal of Forest Research* **23**, 2236–2241.

Paysen TE, Narog MG, Zavala MA (1992) Monitoring electrical resistance in canyon live oak using a Shigometer. In 'Ecology and management of oak and associated woodlands: perspectives in the south-western United States and northern Mexico', 27–30 April 1992, Sierra Vista, AZ. (Tech. Coords PF Ffolliott, GJ Gottfried, DA Bennett, C Henandez, A Irtega-Rubio, RH Hamre) USDA Forest Service Rocky Mountain Research Station, General Technical Report RM-218. (Fort Collins, CO)

Peterson DL, Sackett SS, Robinson LJ, Haase SM (1994) The effects of repeated prescribed burning on *Pinus ponderosa* growth. *International Journal of Wildland Fire* **4**, 239–247. doi: 10.1071/WF9940239

Piene H, Pensom DS, McIsaac JE, Thompson RG, Alexander KG (1984) Electrical resistance and capacitance measurements on young,

spaced and unspaced, defoliated and protected, balsam fir trees. *Canadian Journal of Forest Research* **14**, 811–817.
Portig WH (1976) The climate of central America. In 'World survey of climatology, vol. 12, Climates of Central and South America'. (Ed. W Schwerdtfeger) pp. 405–478. (Elsevier: Amsterdam)
Shigo AL, Shortle WC (1985) 'Shigometry: a reference guide.' Agriculture Handbook No. 646. (United States Department of Agriculture: Washington, DC)
Shortle WS, Shigo AL, Berry P, Abusamra J (1977) Electrical resistance in tree cambium zone: relationship to rates of growth and wound closure. *Forest Science* **23**, 326–329.
Silverman BW (1986) 'Density estimation for statistics and data analysis.' (Chapman and Hall: New York)
Tattar TA, Blanchard RO (1976) Electrophysiological research in plant pathology. *Annual Review of Phytopathology* **14**, 309–325. doi:10.1146/ANNUREV.PY.14.090176.001521
Taylor BW (1959) Estudios ecologicos para el aprovechamiento de la tierra en Nicaragua (Ecological land use surveys in Nicaragua), Volume 1. Ministerio de Economía, Instituto de Fomento Nacional, y Organización de las Naciones Unidas para la Agricultura y Alimentación. (Editorial Alemana: Managua)
Urbina WT (2003) Fire in reserve of pines in Waspam. In 'La Prensa, el diario de los Nicaraguenses'. Available at http://www.laprensa.com.ni/archivo/2003/abril/25/regioanales/regionales-20030425-01.html [Verified 25 April 2003]
Wargo PM, Skutt HR (1975) Resistance to pulsed electric current: an indicator of stress in forest trees. *Canadian Journal of Forest Research* **5**, 557–561.
World Vision International (2005) 'Nicaragua – country profile.' Available at http://www.wvi.org/wvi/country_profile/nicaragua.htm [Verified 5 July 2006]