Measurement and Research Methods

Moderator:

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ANALYSIS OF TREE DAMAGE FROM HURRICANE HUGO IN THE CARIBBEAN NATIONAL FOREST, PUERTO RICO

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Abstract—Hurricanes strongly influence the structure, composition, and successional processes of many forests. In September of 1989, Hurricane Hugo struck the eastern part of Puerto Rico causing considerable disturbance within the subtropical wet forests. Four areas in the Caribbean National Forest were surveyed: Cubuy, Río Grande, Sabana 4, and Sabana 8. Individual trees were rated for damage and tree and plot characteristics such as d.b.h., crown class, ground slope, and topography were recorded. Tree damage was rated as: (1) none, (2) loss of small branches, (3) loss of large branches, (4) trunk snapped, and (5) uprooted. Two-way contingency tables of damage type against crown class, d.b.h. class, plot topography, tree topography, and slope class were constructed. Chi-square tests and Spearman correlations were computed. The general results are that proportions in each damage type are not the same among crown class and d.b.h. class, but chi-square tests were not significant with plot topography, tree topography, and slope class. There was moderate correlation of damage type with crown class and d.b.h.. Discriminant analyses were conducted with data from the four areas. Using d.b.h., crown class, and species importance values (relative species frequency, density, and basal area), trees were correctly classified into damage categories with an error rate of 48 percent for Cubuy, 43 percent for Riogrande, 39 percent for Sabana 4, and 44 percent for Sabana 8. Understanding hurricane disturbance helps in assessing the volume of hurricane-related mortality and damage, and in assigning trees and species into damage/risk classes.

INTRODUCTION

We report on individual tree damage from a large-scale disturbance (Hurricane Hugo) in the Caribbean National Forest (CNF) in northeastern Puerto Rico. Hurricanes strongly influence the structure, composition, and successional processes of many forests (Boucher 1990, Lugo and others 1983). Hurricanes have regularly traversed the Caribbean Basin and are recognized as one of the major natural disturbance factors shaping the forest ecology of all the islands of the Antilles (Salivia 1972, Weaver 1989). Wind damage serves as an important source of landscape-level patterning in forests and in initiating vegetation dynamics (Boose and others 1994).

Hurricane Disturbance

Puerto Rico has experienced more than 70 hurricanes since 1700 with an estimated 14 severe storms (category 3 or higher) (fig. 1) during this time period (Salivia 1972, Weaver 1987). The most recent severe storm, Hurricane Hugo, passed over the CNF on September 18, 1989 with winds exceeding 200 kilometers per hour at the wall of the hurricane eye, which had a diameter of 25 kilometers. The strength of the winds declined as the storm passed over land (Zimmerman and others 1995) and, as will be seen, there was a decreasing gradient of damage with westward distance from the hurricane track.

WIND RESEARCH

Before quantifying the damage we want to briefly review some recent work on factors that affect both the type and amount of wind damage sustained by trees. Both Mitchell (1995) and Ruel (1995) report that wind damage depends on a number of factors interacting with each other. Gross tree variables that affect the critical wind speed needed to

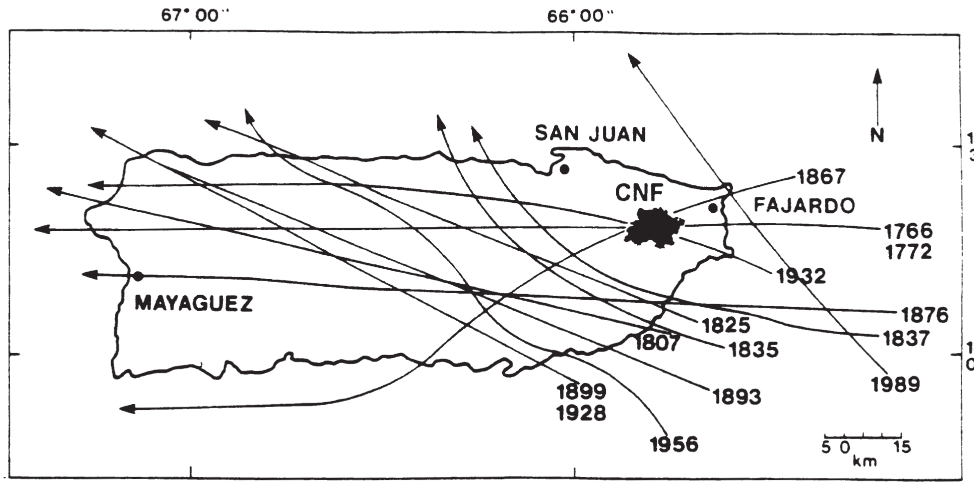

Figure 1—Tracks of the 14 most severe hurricanes striking Puerto Rico since 1700. CNF = Caribbean National Forest. 1989 = Hurricane Hugo.

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either remove branches, snap a trunk, or uproot a tree include: tree height, crown size and density, stem thickness, wood strength, wood elasticity, root-soil mass, root strength, and soil shear strength. Gross stand factors that affect the probability of a wind of critical speed acting on a tree include: topographic exposure, canopy structure, canopy density, and position in canopy. Francis and Gillespie (1993) related gust speed to tree damage in Hurricane Hugo from 18 sites in the Antilles. The results of their logistic regression indicated that the probability of a tree suffering some form of damage increased with both increasing gust speed and increasing tree diameter at breast height (d.b.h.). They found that damage was nil below gust speeds of about 60 kilometers per hour, damage increased rapidly as gust speed increased from 60 to 130 kilometers per hour, and beyond 130 kilometers per hour damage was highly variable, depending upon the gross tree and stand variables previously listed. They also confirmed what many tropical ecologists have reported upon, and that is that some tree species have the ability to quickly reduce crown surface area (i.e., wind resistance) by easily shedding leaves and twigs and thus avoiding severe forms of damage.

THE STUDY AREAS

The Caribbean National Forest is located in a mountainous area of northeastern Puerto Rico known as the Luquillo Cordillera. We studied four areas located between 300 and 600 meters elevation and at increasing distances from the path of Hurricane Hugo. The locations in the CNF are shown in figure 2. Sabana 4 and Sabana 8 are near the eastern boundary of the forest and are physically close to one another. Sabana 8 is an area that had been farmed prior to 1947, when it was acquired. Sabana 4 appears to be an older, less disturbed site. Río Grande has no record of cultivation, but a 1934 map showed cutover forest at intermediate elevation and sierra palm (*Prestoea montana*) forest on slopes and at higher elevations. The forest site at Cubuy is located in original Spanish crown lands. The presence of bamboo, a few coffee plants, and ornamental trees at the Cubuy site indicates the area was not entirely free of human disturbance. There were probably illegal homesteads in this crown land abandoned prior to 1936, when the area was surveyed.

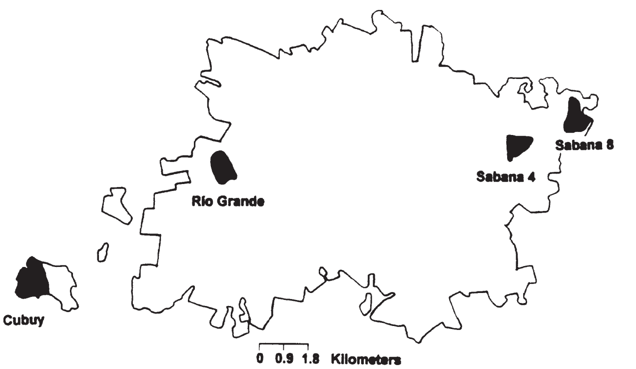

Figure 2—Locations of the four study areas within the Caribbean National Forest.

DATA COLLECTION

In 1991, a little over a year after the storm, a systematic sampling design of plots was established in each of the four study areas. Cubuy had 116 plots, Río Grande had 104 plots, Sabana 4 had 106 plots, and Sabana 8 had 108 plots. Each plot consisted of two areas (fig. 3). The inner area (area A) was a 1/10-acre circular subplot with a radius of 11.35 meters. All trees with a d.b.h. > 9.1 centimeters were measurement trees. The outer area (area B) was a 1/5-acre circular subplot with a radius of 16.05 meters. All trees with a d.b.h. >= 24.2 centimeters were measurement trees. Each measurement tree was visually rated for damage type as: (1) none, (2) loss of small branches, (3) loss of large branches, (4) trunk snapped (50 percent or more of tree trunk down), and (5) uprooted. Tree variables taken were crown class (dominanat, codominant, intermediate, suppressed), ground slope (percentage from horizontal), d.b.h., and topography (convex, bottom, terrace, ridge, slope, concave). Overall plot topography was recorded as ridge, slope, upland valley, or riparian valley.

ANALYSIS AND RESULTS

There were 3 types of analyses performed: (1) descriptive (charts and graphs), (2) two-way contingency tables (chi-square tests) of damage type versus tree and plot variables, and (3) discriminant analysis whereby we tried to correctly assign trees into their damage class based on tree and plot variables. All sample trees were weighted to express their contribution on a per-hectare basis for the entire sample area. Thus, if d.b.h. < 24.2 centimeters then plot area = π (11.35 meters)^2 = 404.71 square meters or .0405 hectares. So each of these trees was weighted by 1/.0405/n or 24.71/n, where n=number of plots. For trees with d.b.h. $\geq$ 24.2 centimeters plot area = π (16.05 meters)^2 = 809.28 square meters or .0809 hectares. So each of these trees was weighted by 1/.0809/n or 12.36/n.

Descriptive Analyses

The two areas closest to the hurricane track, not surprisingly, suffered the greatest amount of damage. The

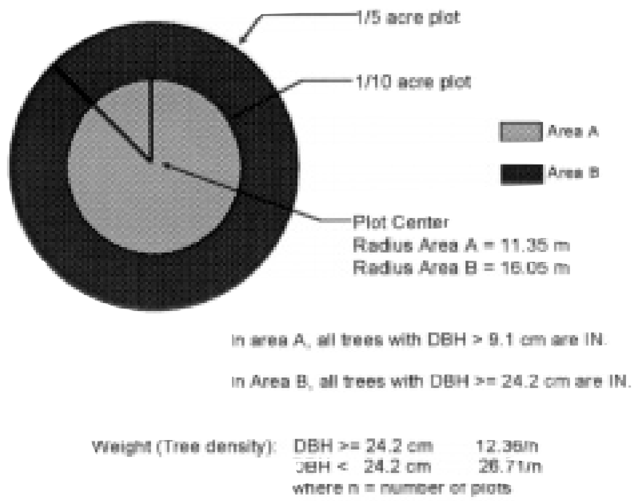

Figure 3—Plot layout in the hurricane tree damage study, Caribbean National Forest.

Sabana 8 study area had 86.35 percent of the trees sustain damage. The breakdown by damage type is: None—13.65 percent, loss of small branches—32.4 percent, loss of large branches—29.62 percent, trunk snap—8.87 percent, and uprooted—15.47 percent (fig. 4). For Sabana 4, 79.37 percent of the trees sustained damage. The breakdown by damage type is: None—20.63 percent, loss of small branches—23.92 percent, loss of large branches—27.61 percent, trunk snap—7.88 percent, and uprooted—19.96 percent (fig. 4). For Río Grande, 61.06 percent of the trees sustained damage. The breakdown by damage type is: None—38.94 percent, loss of small branches—34.95 percent, loss of large branches—19.68 percent, trunk snap—2.26 percent, and uprooted—4.17 percent (fig. 4). The least hit area, Cubuy, had 50.6 percent of the trees sustain damage. The breakdown by damage type is: None—49.4 percent, loss of small branches—31.81 percent, loss of large branches—12.83 percent, trunk snap—3.09 percent, and uprooted—2.87 percent (fig. 4).

In figure 5 we see a breakdown of damage type by diameter class for Sabana 8. All trees larger than the 37.5 centimeter d.b.h. class were damaged. Ten percent or more of the trees in all size classes (except 72.5 centimeters) were uprooted. A large proportion of the trees in all size classes, especially the two largest, suffered loss of large branches. In figure 6 we see results for Sabana 4. Nearly all trees above the 17.5 centimeter class were damaged. Similar to Sabana 8, 10 to 15 percent or more of the trees in each size class were uprooted. It appears in areas heavily impacted by the hurricane, there is a somewhat uniform distribution of uprooting across all diameters of trees. The same seems to be true for trunk-snapped trees. There seems to be a fairly uniform 5- to 10-percent proportion across all diameter classes in Sabana 4 and Sabana 8. In Río Grande, an area about 10 kilometers west of Sabana 4 (fig. 2), we still see uprooting and trunk snapping basically across all d.b.h. classes, but the percentage of trees in these classes has dropped off to about 5 percent for uprooting and about 2 to 3 percent for

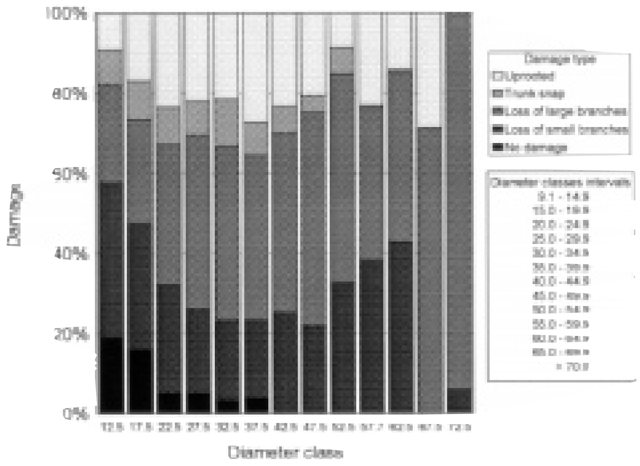

Figure 5—Diameter classes (in centimeters) and percent of damage type for all trees in Sabana 8.

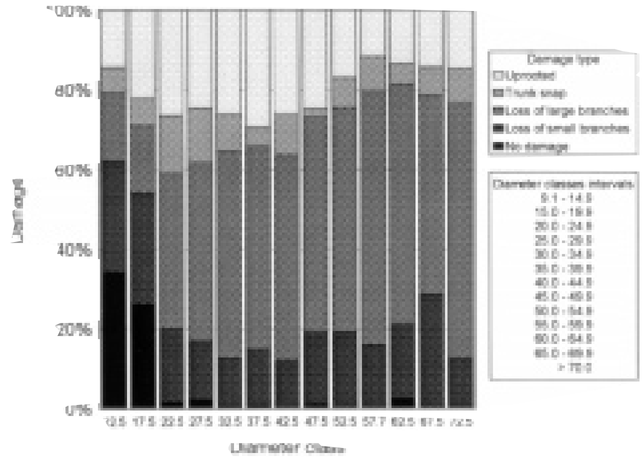

Figure 6—Diameter classes (in centimeters) and percent of damage type for all trees in Sabana 4.

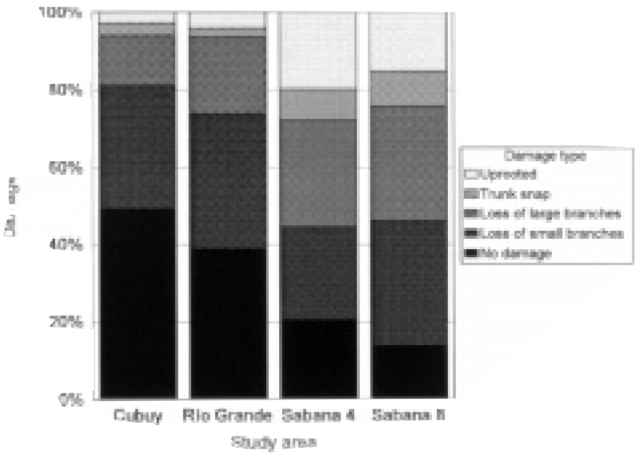

Figure 4—Five damage type classes and their tree damage percent for each study area.

trunk snap (fig. 7). Though Cubuy, an area about 8 kilometers southwest of Río Grande, was the least hit area, still a significant proportion (50 percent) of the trees sustained damage. In figure 8 we see many of the smaller trees have escaped being damaged. There appears to be a reverse J shape to the no damage class. In the two largest d.b.h. classes every tree was damaged. The three largest d.b.h. classes had no uprooting and the five largest d.b.h. classes had no trunk-snapped trees. In the remaining d.b.h. classes there still appears to be a reasonably uniform distribution of uprooted and trunk-snapped trees.

Contingency Table Analyses and Correlations

We constructed two-way tables of damage type against crown class, d.b.h. class, tree topography, slope class (eight degree classes, i.e., 0 to 8, 9 to 16, etc.), and plot topography. Chi-square tests and Spearman correlations were computed. The outcomes are listed in table 1. The general results are that proportions in each damage type

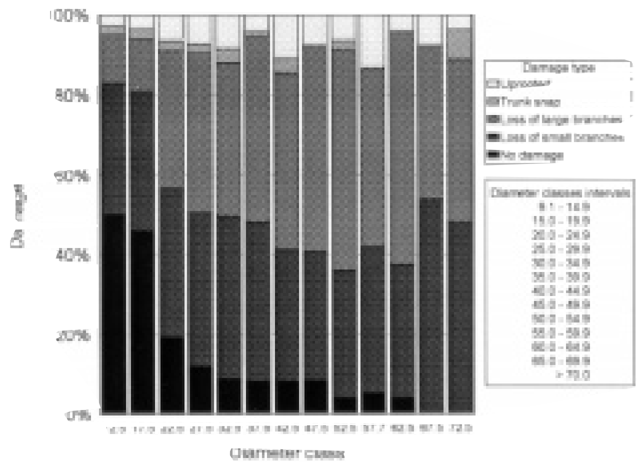

Figure 7—Diameter classes (in centimeters) and percent of damage type for all trees in Río Grande.

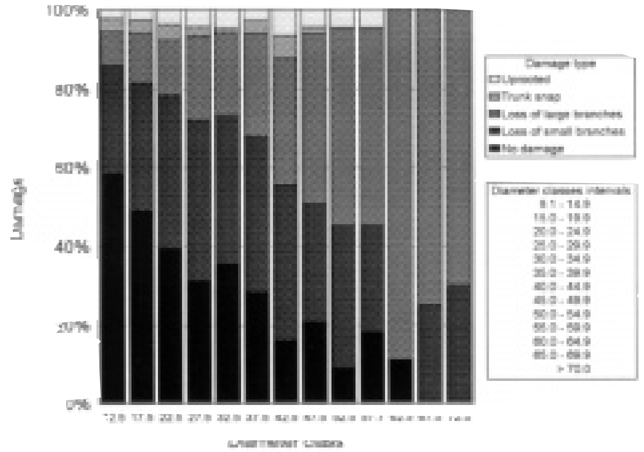

Figure 8—Diameter classes (in centimeters) and percent of damage type for all trees in Cubuy.

are not the same among crown class and d.b.h. class. Chi-square tests were not significant with tree topography, slope class, and plot topography. There appears to be moderate correlation in some of the data, that is, with crown class and d.b.h. class, and low correlation in the rest of the data.

Discriminant Analyses

A discriminant procedure computes various discriminant functions for classifying observations into two or more groups on the basis of one or more quantitative variables. The idea behind discriminant analysis is to see if you can correctly place an individual into its proper group based on certain measurable characteristics of the individual. If you can correctly place most individuals into their respective groups, then you should be able to place future individuals into their proper groups based on the same characteristics, with a known error rate. Based on the contingency table analyses, it is reasonable to conclude that d.b.h. and crown class are good candidate variables for the discriminant

Table 1—Results of two-way contingency table analyses and correlation analyses of damage type against other variables

Location	Variable[a]	X^2 [b]	P-value	Spearman r
Sabana 8	Crown class	234.1	.001	.226
	D.b.h. class	69.8	.022	.252
	Tree topo	25.7	.175	-.043
	Slope class	—	—	—
	Plot topo	10.3	.592	.020
Sabana 4	Crown class	208.7	.001	.173
	D.b.h. class	129.0	.001	.332
	Tree topo	16.8	.669	.004
	Slope class	4.0	.999	-.021
	Plot topo	9.1	.691	-.058
Río Grande	Crown class	155.2	.001	-.217
	D.b.h. class	158.4	.001	.321
	Tree topo	14.1	.823	.081
	Slope class	7.0	.997	-.011
	Plot topo	13.8	.314	-.011
Cubuy	Crown class	202.4	.001	.073
	D.b.h. class	73.4	.011	.216
	Tree topo	7.5	.995	.020
	Slope class	15.5	.745	.028
	Plot topo	7.5	.822	.013

[a] Topo = topography.
[b] Degrees of freedom: crown class—12, d.b.h. class—48, tree topography—20, slope class—20, plot topography—12.

analyses, because they have differing patterns across the damage types and there is a moderate degree of correlation between these variables and damage type. In addition, to bring in the effect of species differences, we computed the importance value (IV) for each species for use in the discriminant analyses. The IV is computed as:

$$IV = (Rel\ BA + Rel\ DEN + Rel\ FRQ)/3$$

where

Rel BA is relative basal area (species BA/total BA × 100),

Rel DEN is relative density (number of trees for species/total number of trees × 100), and

Rel FRQ is relative frequency (number of plots where species occurs/total number of plots × 100).

For the discriminant analyses we reassigned the damage types into three classes. For the two hardest hit areas, Sabana 4 and Sabana 8, we had: (1) none + loss of small branches, (2) loss of large branches, and (3) trunk snapped + uprooted. For Cubuy and Río Grande we had: (1) none, (2) loss of small branches, and (3) loss of large branches + trunk snapped + uprooted. Table 2 gives the error rate by damage class and the overall error rate for each of the four study areas. As is obvious from table 2, there was a high

Table 2—Discriminant analysis error classification summaries for the four study areas in the Caribbean National Forest

Location	Class error rate[a] 1	2	3	Overall error rate
	---------- *Percent* ----------			
Sabana 8	12.8	16.8	14.1	43.7
Sabana 4	14.1	15.3	9.7	39.1
Río Grande	14.8	16.1	12.4	43.3
Cubuy	6.4	27.2	14.2	47.8

[a] Class 1 represents trees with none to slight damage, class 2 represents tree with moderate damage, and class 3 represents trees with severe damage.

rate of error in correctly classifying trees into their proper damage class. Still, about 57 percent of the time we were able to place an individual tree into its correct class out of the three damage classes defined for the analyses.

DISCUSSION

Several trends are readily apparent. As Francis and Gillespie (1993) observed, if you are a large tree you will sustain damage. In areas close to the hurricane track (Sabana 4 and 8), which experienced heavy gusts, winds were such that all trees experienced some damage, save a few of the very smallest. In areas farther from the hurricane track (Río Grande and Cubuy), the greater the d.b.h. the greater the probability of being damaged. It was interesting to discover a somewhat uniform distribution of trunk-snapped and uprooted trees over diameter class at each site. Why this is probably relates to the gross tree and plot factors affecting the type and amount of wind damage sustained by trees. These factors were expounded by Mitchell (1995) and Ruel (1995) and reviewed in the section on **WIND RESEARCH.**

Not all trees are created equal with respect to hurricane resistance. The main adaptation to survival in hurricanes is quick reduction of wind resistance through defoliation. As examples, let us consider balsa (*Ochroma lagopus*) and yagrumo (*Cecropia schreberiana*). Both species have relatively weak wood, but quickly lost all of their few, large leaves, and consequently experienced very little damage. Large, strong trees of the forest like *Buchenavia tetraphyla* and tabonuco (*Dacroydes excelsa*), suffered extensive branch breakage because they have large spreading crowns which do not readily defoliate.

The forests of Puerto Rico have amazing resiliency. Many species, like *Shefflera morototonii*, readily sprout new branches. Gaps created by uprooted and trunk-snapped trees fill in quickly. Damage can be highly variable and is determined by many interacting factors such as species characteristics, soil properties, stand structure, and topography. Trying to predict individual tree outcomes at each area with discriminant functions was only moderately successful. Still, it gives us a tool for assessing potential damage and mortality from future storms.

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PREDICTING THE MOVEMENT OF IMIDACLOPRID IN A COASTAL PLAIN SETTING USING VS2DT

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Abstract—Imidacloprid has been shown to control pine tip moths (*Rhyacionia* spp.) in loblolly pine seedlings (*Pinus taeda* L.). Field data for an imidacloprid dissipation study were used to calibrate the computer model VS2DT (Variably Saturated 2-Dimensional Transport). VS2DT uses a finite-difference approximation of the advection-dispersion equation to simulate contaminant transport through variably saturated porous media. The site was simulated in a vertical cross section (X-Z plane) of a treated watershed from the soil surface to the water table (approximately 60 ft) spanning 260 ft horizontally. The cross section was centered on an ephemeral stream which drains the watershed, but for symmetry reasons, only half (130 ft horizontal distance) of the cross section was modeled. Modeling results showed that imidacloprid moved more rapidly through sandy soils than sandy clay loam soil material. No imidacloprid concentrations above the detection limit of 0.6 ppb were predicted in groundwater or in lysimeters in the unsaturated zone through 6 months post-application.

INTRODUCTION

Infestation by pine tip moths (*Rhyacionia* spp.) is one of the limiting factors in early growth and development of pine stands in the Southeastern United States. Imidacloprid (1-[(6-chloro-3-pyridinyl)-methyl]-4,5-dihydro-*N*-nitro-1H-imidazol-2-amine) is a systemic insecticide which has shown efficacy in controlling sucking insects, some beetles, and leafminers on various crops. Applied in a Florida field study, imidacloprid controlled tip moths on loblolly pine seedlings (*Pinus taeda* L.) for 1 to 3 years.[2]

An imidacloprid soil dissipation study was initiated in January, 1996 on a coastal plain site near Downs, GA. Imidacloprid residues in runoff-water, soil solution, and groundwater were monitored after significant rainfall events. These residue data were used to assess the VS2DT hydrologic model.

The fate and transport of pesticides depend, in part, on the flow path within the soil. There are three major flow paths: overland flow, subsurface lateral flow, and vertical percolation through the unsaturated zone to the water table. Overland flow rarely occurs within forested watersheds. Solute transport through the subsurface is controlled by various mechanisms including advective transport (Solutes move with the flowing water.), hydrodynamic dispersion (variability of fluid velocity causes a spreading of solutes toward the average direction of water flow.), and solute sorption. Solute transport is also dependent on the soil structure because interconnected macropores induce preferential flow paths which accelerate the movement of solutes.

Computer models were developed to simulate the fate of pesticides because environmental fate studies are expensive and time consuming. Hydrologic computer models for water and solute movement within variably saturated porous media are useful tools for gaining insight into processes that occur within the unsaturated zone. A hydrologic environmental model, VS2DT (Variably Saturated 2-Dimensional Transport) was developed by the U.S. Geological Survey. This model uses a finite-difference approximation to the advection-dispersion equation to simulate water movement through variably saturated porous media. VS2DT can simulate problems in one-dimensional columns, two-dimensional vertical cross sections (X-Z plane), or three-dimensional, axially symmetric cylinders (Healy 1990, Healy and others 1993). Boundary conditions used for flow include fixed pressure heads, infiltration with ponding, evaporation from the soil surface, plant transpiration, or seepage faces.

OBJECTIVES

The objectives of this study were to:

(1) Evaluate VS2DT's simulation of imidacloprid movement in a coastal plain watershed by comparing field data to the predicted values from VS2DT.

(2) Determine VS2DT limitations in predicting pesticide movement.

MATERIALS AND METHODS

Study Site

The imidacloprid study area is located in the Georgia Coastal Plain near the town of Downs, GA, in Washington County, approximately 90 miles south of Athens, GA. Historically, the area was a natural forest and pesticides have not been applied to the study area for at least 40 years. The imidacloprid site is surrounded by mature, mixed hardwood and loblolly pine forests. A stream borders the site on the southwestern side. The stream flows from the

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[2] Personal communication. 1994. J.L. Foltz, The University of Florida, Gainesville, FL.

northwest to the southeast and has a width of approximately 15 ft and depth of 2 to 4 ft. An ephemeral stream forms and drains the bottom of the watershed during large rainfall events. Within this study area, a 5.4-acre watershed was chosen to monitor the movement of imidacloprid.

The soil is predominately Orangeburg series with small areas of Ochlocknee series in the draws. Coastal plain soils of the Orangeburg series are generally well drained, permeable soils of sedimentary origin. The upland flats are characterized by three distinct soil layers based on split spoon samples taken during well installation onsite. The upper layer is an approximate 3- to 4-ft sand to loamy sand. The middle layer is clay-enriched and consists of red, dense, sandy clay to sandy clay loam that is approximately 15 to 17 ft thick. Visual observations of a nearby road cut showed rainfall-related saturation on top of the sandy clay loam layer. The final layer extends from the bottom of the red clay-enriched layer to the water table and has the same characteristics as the first horizon with a distinct bedding of sand. The watershed was created by massive erosion that exposed the red clay-enriched layer at certain areas within the site. Three-dimensional pictures of the red layer within the watershed were constructed using observations taken during the installation of lysimeters. The clay layers slope toward the center of the watershed and have erosional features hidden by overlying sand. These irregularities could aid in concentrating the insecticide within the site.

Site Preparation

Trees onsite were harvested during August 1994. Site and regeneration activities included spot raking (June 2, 1995), chopping using a drum roller (June 30, 1995), burning (July 14, 1995) and harrowing (September 12, 1995). On November 7, 1995, loblolly pine seedlings were planted with a mechanical planter along the contour of the watershed in a 6 ft- by 12 ft-spacing (600 trees/acre).

Instrumentation of the Treated Watershed

The watershed was instrumented with the following (fig. 1):

(1) a weather station equipped with a pyranometer, ananemometer, weather vane, relative humidity gauge, internal and external temperature gauges, barometer, tipping rain gauge, standard rain gauge, and an evaporation pan;

(2) 42 porous cup lysimeters for sampling soil water in the unsaturated zone;

(3) five 2-in diameter PVC wells for monitoring and sampling groundwater; and

(4) a 1.5-ft H-flume equipped with an FW-1 stage-height recorder for determining runoff volume and duration.

Pesticide Application

On February 26, 1996, approximately 1 gram of active ingredient imidacloprid was applied in a dibble hole at a point that was approximately 4 in deep and 4 to 6 in from the base of each pine seedling. As part of the vegetation management program for the pine plantation, herbicides were applied on April 1, 1996 (hexazinone and sulfometuron methyl) and September 24, 1996 (imazapyr).

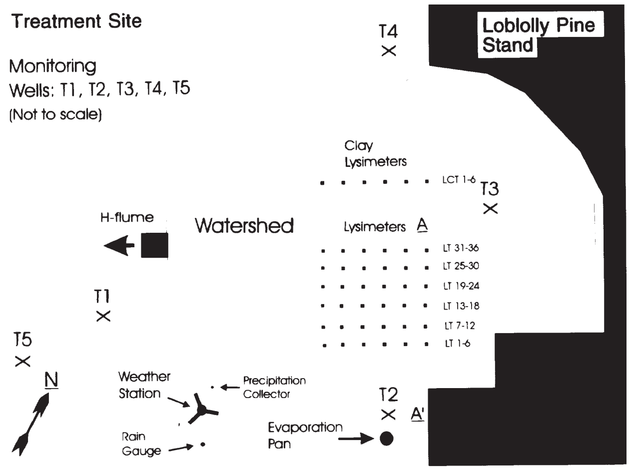

Figure 1—X-Y view of the treated watershed and the position of the monitoring devices.

FIELD DATA

Field data collection began prior to the imidacloprid application and will continue through 3 years post-application. Rainfall input-runoff ratios were calculated from rainfall data and data from surface flow duration and runoff volume through H-flumes that were measured from March 1996 through September 1996. These data showed that an average of 3 percent of the total rainfall volume on the watershed flows through the H-flumes. Based on these results, the major pathway that imidacloprid travels is through the vadose zone to the water table. This assumes that the insecticide does not biodegrade, adsorb strongly to organic matter or clay, or is totally absorbed systemically by vegetation.

Lysimeters and monitoring wells were used to collect water as it traveled through the unsaturated zone to the water table. Water in the lysimeters accounted for horizontal movement and preferential flow paths above the clay-enriched layer. Thirty-six lysimeters were installed approximately 24 ft apart in a 6 x 6 array in the treatment watershed. Water samples were collected from lysimeters after each significant rainfall event (>0.5 in rainfall) and analyzed for imidacloprid residues. The five monitoring wells were sampled monthly to detect groundwater contamination. Imidacloprid was not detected (method detection limit of 0.6 ppb) in groundwater.

CONCENTRATION CALCULATIONS

Imidacloprid concentrations in the application scoop (71 cm^3) and in the top 15 cm of soil (304 cm^3) were calculated to calibrate the model output. The total concentration in the soil is the aqueous phase concentration plus the concentration adsorbed to the soil. The imidacloprid concentration (active ingredient) in the formulation material is 25,000 ppm. The theoretical concentration in the top 15-cm soil core is 1,890 ppm (assuming the whole application area is sampled). The initial total imidacloprid concentration in the 0 to15 cm range from the model should be consistent with the value calculated for the total concentration in a 15-cm core.

MODEL DESCRIPTION

VS2DT was used to simulate the movement of imidacloprid in the treated watershed. This model is governed by the advection-dispersion and conservation of mass equations. The values for the model are approximated by a two-dimensional, block-centered, finite-difference scheme.

VS2DT utilizes rainfall events to introduce water into the problem. Rainfall events are considered recharge events, and the times between them are considered evaporation events. Data from a tipping-bucket rain gauge were used to calculate the duration and intensity of the precipitation periods. The concentrations of imidacloprid during the rainfall events were introduced into the model.

VS2DT uses aqueous phase concentrations. In this study, only the initial total application concentration was known. The initial aqueous phase concentration was adjusted to meet the calculated initial total concentration in a 15-cm core. Site specific parameters such as meteorological data, soil parameters, and imidacloprid characteristics were used in the model. VS2DT simulated 191 days using meteorological data from the treated watershed starting on February 19, 1996 and ending on August 28, 1996.

As with any model, VS2DT has problems which must be considered:

(1) Aqueous phase concentrations are used as inputs for the model.

(2) The evaporation boundary condition is treated differently from other boundaries where water leaves the domain; evaporating water is assumed to be solute free (no solute leaves the domain through evaporation.). Therefore, evaporation nodes may become concentrated as evaporation proceeds (Healy 1990).

(3) VS2DT does not account for losses due to uptake by plants (transpiration).

(4) Preferential flow can not be simulated in VS2DT. Systems which exhibit preferential flow characteristics can not be accurately modeled.

(5) VS2DT can only use a domain (grid) which has ≤ 36,000 nodes.

(6) VS2DT assumes homogeneous and isotropic conditions within the defined soil textures.

(7) Large nodal models with small discretization require fast computers with ample hard drive space and a great deal of memory.

Two conceptual models of different scales were used to simulate flow through the vadose zone. VS2DT has a tilt factor built into the code (Healy 1990). At the top of the grid, the left side is A, while the right side is A’. When the tilt is used, A’ is raised to create a downward slope from A’ to A (A is the pivot point). Models 1 and 2 have a 6 percent tilt.

Model 1

Model 1 was used to simulate the movement of imidacloprid from a single imidacloprid application through the top 15 cm and down to a single lysimeter (fig. 2). This model is a fragment of Model 2 and used a finer grid (112 rows by 132 columns). The rows had a vertical height of 1 cm and the columns were 2.54 cm wide. The total height was 122 cm (4 ft) and the total horizontal distance was 335.3 cm (11 ft). Only two soil textures were used: loamy sand and sandy clay loam.

The imidacloprid aqueous concentration inputs occurred in three nodes representing a total volume of 45.7 cm^3 (6 cm x 7.62 cm x 1 cm). The observation nodes in Model 1 were used to record the initial concentrations in order to compare these results with the calculated values, and the lysimeter nodes were compared with the field data. To calibrate the model, the concentration of the observation nodes in the top 15 cm will be averaged and compared to the calculated total concentration in the upper 15 cm.

Model 2

Model 2 was used to simulate the movement of imidacloprid from the ground surface to the water table (fig. 2). The nodal grid used in the model was 220 rows by 132 columns. The nodes for the first 111 rows had a vertical height of 1 cm. The next 68 rows had a vertical height of 7.62 cm (3 in), and the remaining 40 rows had a vertical height of 30.48 cm (1 ft). Horizontally, the 132 columns had a length of 30.48 cm (1 ft) per block. The total vertical distance was 60 ft to the water table and the total horizontal distance was 132 ft.

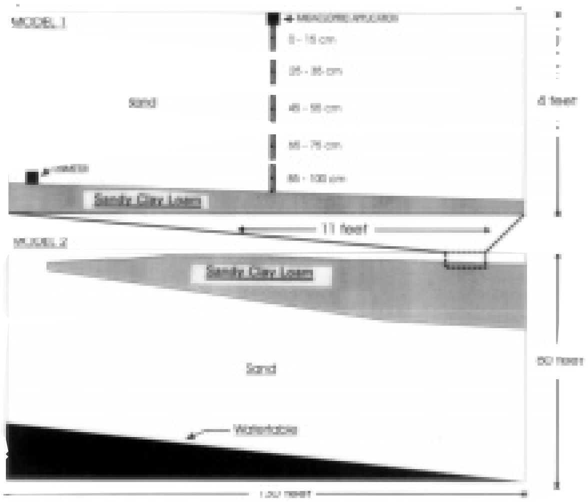

Figure 2—Conceptual Models 1 and 2 used in VS2DT to simulate the movement of imidacloprid in a coastal plain setting. Both models are tilted 6 percent in VS2DT (A’ is raised 6 degrees.).

Three soil layers simulated were: loamy sand, sandy clay loam, and sand. At A', the loamy sand is 4 ft thick, the sandy clay loam layer is 17 ft thick, and the sand is 40 ft thick. At A, the loamy sand is 4 ft thick, and the sand is 57 ft thick.

Eight observation nodes were used to track the concentration of imidacloprid over time. The nodes were positioned in two columns: nodes consisting of all sand and nodes of sand-clay-sand down to the water table. This strategy allowed the comparison of how imidacloprid behaves in the sand and in the sandy clay loam layers. The nodes closest to the water table for each column were used to estimate the concentration entering the groundwater.

Model 1 and 2 Correlation

Model 1 was used to calibrate the predictions of VS2DT to the field data (both groundwater and lysimeter data) and the top 15-cm calculation. Once they agreed, Model 2 was run using the same parameters as Model 1. However, Model 2 had an initial concentration six times higher than Model 1 due to the difference in height of the application nodes.

VS2DT RESULTS

Calibration with Calculated Concentration

To accurately predict the movement of imidacloprid through the two models, the models must be calibrated to the calculated total concentration. The concentration that both models predicted was 2020 ppm in the top 15 cm. This value is consistent with the range from the calculations. After these calculations were verified for both models, the simulation was run for 191 days (approximately 6 months), and the observation points at the lysimeter, water table, and various points between were analyzed.

Lysimeters

The lysimeter concentrations predicted by VS2DT were below the detection limit (< 0.6 ppb). Based on these predictions, no imidacloprid reaches the lysimeters, and the concentration by day 191 averaged 10^{-28} ppb.

In the field, however, lysimeter row LT13-18 was the only row of lysimeters to show measurable concentrations of imidacloprid. The lysimeters in this row are located in a distinctively different area from the other lysimeters. Lysimeters LT13-18 are positioned between large remnant stumps with extensive root systems which could cause preferential flow and aid in the movement of solutes. The inputs for VS2DT do not account for this type of movement.

Discounting the model's predictions for row LT13-18, due to its inability to account for preferential flow, the model fits the field data by predicting that levels of imidacloprid in the lysimeters are far below detection limits.

Movement in a Sand Column versus Sand-Clay-Sand Column

Imidacloprid moved more quickly through the sand column than the sand-clay-sand (S-C-S) column. Detectable concentrations were predicted down to 220 cm (7.2 ft) in the sand column on the 191st day, but concentrations were below detection limits below that point. The S-C-S column shows that the concentration of the solute was severely retarded by the clay-enriched layer. Measurable concentrations were predicted within the upper 7.2 ft, but the nodes within the clay-enriched layer and below showed concentrations far below detection limits. The solute traveled approximately twice as fast and as far vertically in the sand column as in the S-C-S column.

Groundwater

The nodes at a depth of 57.1 ft (just above the water table) for both the sand and S-C-S columns, showed concentrations of imidacloprid below detection limits. This prediction agreed with the field data that showed that concentrations of imidacloprid in the groundwater were below detection limits.

CONCLUSIONS

Infiltration is the main agent of transport for imidacloprid. During rainfall events, imidacloprid desorbs from the application clay and increases the aqueous concentration in the soil-pore water. This relationship depends on the soil water content and amount of rainfall.

After rainfall events, evaporation dominates and the upper soil horizon dries. The aqueous concentration within the loamy sand nodes decreases during this period as the imidacloprid adsorbs to the soil.

Imidacloprid transport is different within the loamy sand and sandy clay loam layers. The insecticide travels more slowly through the clay-enriched layer than in the sandy layers. Computer simulations predicted that imidacloprid will not reach the water table or lysimeters within 191 days following application.

ACKNOWLEDGMENT

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INITIAL INVESTIGATION OF HEIGHT-DIAMETER RELATIONSHIPS OF DOMINANT TREES IN THE MIXED HARDWOOD BOTTOMLAND FORESTS OF EAST TEXAS

Brian P. Oswald, Gordon Holley, Leslie Dale, and Gary D. Kronrad[1]

Abstract—Three to five dominant trees from each of 445 ten-factor variable radius inventory points were utilized to evaluate the height- diameter relationships of 13 species or genera found on bottomland hardwood sites throughout east Texas. Regression analysis was performed using the linear model such that height = $\beta_0 + \beta_1$ x (d.b.h.). The species were placed into six groups: (1) pines (*Pinus taeda* and *P. enchinata*); (2) water oak/willow oak/white oak/swamp chestnut oak (*Quercus nigra*)/(*Q. phellos)/(Q. alba)/(Q. michauxii*); (3) blackgum/laurel oak/overcup oak *(Nyssa sylvatica)/(Q. laurifolia)/(Q. lyrata*); (4) ash/maple (*Fraxinus* spp.*)/(Acer* spp.); (5) hickories *(Carya* spp.), and (6) elms (*Ulmus* spp.), or were analyzed as individual species: (7) cherrybark oak (*Q. pagoda*) and (8) sweetgum (*Liquidambar styraciflua*) based on similar intercepts and slopes of the regression lines. The coefficients of the model were estimated and residual analysis conducted for each species group.

INTRODUCTION

There are about 180 million acres of commercial forest land in the Southern United States, 50 percent of which can be classified as being composed of hardwoods. Bottomland hardwood forests, growing on the flood plains of rivers and streams, comprise 14 percent (1.6 million acres) of the total commercial forest land in east Texas. These forests provide quality timber along with wildlife habitat. In east Texas, the area classified as bottomland hardwood has decreased by about 12 percent in the last 15 years, due primarily to the logging of accessible mature stands, shifts to croplands, and the development of man-made lakes (McWilliams and Lord 1988).

The demand for hardwood products, both within the United States and for export, is increasing (McWilliams 1988, Hair 1980). The pulp and paper industry is utilizing more hardwoods in an effort to increase the quality of their product. In addition, the demand for high-quality logs for lumber, plywood, and veneer is increasing. Since 1975, the world demand for U.S. hardwood logs, veneer, and lumber has quadrupled (Araman 1989). Hardwood harvesting rates are increasing while the supply is decreasing (Tansey 1988, Birdsey 1983).

Adequate information on bottomland hardwood growth and management has not kept pace with the knowledge we have on southern pines. (Porterfied 1972). Most of the research performed on bottomland hardwoods in the South to determine growth and yield information and management strategies of these species (Barrett 1995, Burns and Honkala 1990, Baker and Broadfoot 1979) often did not involve stands located in east Texas. The best management practices for the species found in these ecosystems in east Texas have not been determined, and growth equations, volume and yield tables, and site index curves for many southern hardwood species are lacking. This information gap is of such high priority to the National Hardwood Lumber Association, that resolution of this gap is one of their priorities for 1996. Since many of these questions can not be resolved in a single year, there will be a priority over the next decade to obtain the necessary information from which proper management decisions can be made.

There is a need to obtain information on what species are found in the bottomlands of east Texas as well as the stand structure of these bottomlands. Basic height and diameter relationship information on the dominant trees in these stands will provide some of this information. The objective of this study was to evaluate the dominant tree height-diameter relationships of the major species in the mixed bottomland hardwood forests of east Texas.

METHODS

The study areas were chosen to represent bottomland hardwood stands common to the region and data was collected from numerous sites within Angelina, Nacogdoches, Newton, Sabine, San Augustine, and Shelby Counties in the summers of 1993, 1994, and 1995. Sample points were systematically located within the study areas. Distance between points was three chains, and distance between transect lines was five chains. Initially the tallest five trees sampled with a 10-factor prism were utilized in this study, and the species, total height (to nearest foot) breast height (d.b.h. to nearest tenth of a foot) were recorded for each of these sampled trees. Species included cherrybark oak (*Quercus pagoda*), willow oak (*Q. phellos*), water oak (*Q. nigra*), laurel oak (*Q. laurifolia*), white oak (*Q. alba*), overcup oak (*Q. lyrata*), swamp chestnut oak (*Q. michauxii*), sweetgum (*Liquidambar styraciflua*), blackgum (*Nyssa sylvatica*), and pines (*Pinus taeda* and *P. enchinata*). A variety of hickories (*Carya* spp.), elms (*Ulmus* spp.), ash (*Fraxinus* spp.), and maples (*Acer* spp.) were also recorded. Additional species were initially included in the sample, but since they each totaled less than 10 individuals across all of the sample points, they were excluded from the analysis.

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Statistical analysis followed Oswald and others (1994). Preliminary analysis indicated that the relationship between tree height and d.b.h. of the dominant trees was linear. Therefore, the following equation was used for each of the above species:

$$\text{Height} = \beta_o + \beta_1 \text{ x (d.b.h.).} \qquad (1)$$

Based on the similarity of the intercepts and slopes of the regression lines for each species, some of the species were placed into species groups. The equation (1) was then fitted to each species group. Otherwise, the species were evaluated individually. Residual analysis was also conducted for each model.

RESULTS AND DISCUSSION

Among the 2,165 dominant trees sampled, 73.7 percent were oaks (*Q*. spp.) with willow oak (26.1 percent), cherrybark oak (15.5 percent), and water oak (14.0 percent) being the dominant species (table 1). Only sweetgum (15.2 percent) approached these oaks in frequency. The tallest species tended to be cherrybark, white, willow and water oaks, while those with the largest d.b.h. were swamp chestnut oak and cherrybark oak. As is usually found on these sites, the maples, ash, and blackgum had the smallest mean diameters, while maple was the shortest in mean height.

The equation (1) was fitted to each species with more than 10 individuals over all of the plots. Based on similarity of the intercepts and slopes of the regression lines for each species, the species were placed into six species groups : Pines, water oak/willow oak/white oak/swamp chestnut , blackgum/laurel oak/overcup oak, ash/maple, hickories, and elms, or were analyzed as individual species: cherrybark oak and sweetgum. Then the equation (1) was refitted to the groups and the resulting models obtained:

(1) Ash/maple: HT = 54.40 + 1.82(d.b.h.) with N = 42, R^2 = 0.39, and C.V. = 18.1 percent
(2) Blackgum/laurel oak/overcup oak: HT = 63.05 + 1.30(d.b.h.) with N = 327, R^2 = 0.35, and C.V. = 13.7 percent
(3) White oak/swamp chestnut oak/willow oak/water oak: HT = 76.27 + 1.10(d.b.h.) with N = 990, R^2 = 0.26, and C.V. = 12.1 percent
(4) Cherrybark oak: HT = 82.59 + 1.08(d.b.h.) with N = 334 , R^2 = 0.26, and C.V. = 13.7 percent
(5) Pine spp: HT = 67.46 + 1.45(d.b.h.) with N = 81, R^2 = 0.39, and C.V. = 9.7 percent
(6) Sweetgum: HT = 60.02 + 1.95(d.b.h.) with N = 328, R^2 = 0.47, and C.V. = 12.6 percent
(7) Hickory spp.: HT = 69.87 + 1.23(d.b.h.) with N = 43, R^2 = 0.16, and C.V. = 16.5 percent
(8) Elm: HT = 19.50 + 3.07(d.b.h.) with N = 12, R^2 = 0.57, and C.V. = 18.9 percent

Equation (1) was also fitted to the total number of trees (2,165) to provide an overall equation for the relationship between height and diameter of all of the dominant trees:

HT = 69.78 + 1.36(d.b.h.) with R^2 = 0.33, and C.V. = 13.67

Table 1—Total number of trees, averages, and ranges of tree diameter and height of the dominant trees

Species	No. trees	Mean d.b.h.	Range	Mean height	Range
			Inches		*Feet*
Fraxinus spp.	33	18.9	7.1-35.4	92.9	45-150
Nyssa sylvatica	59	18.1	6.6-39.1	85.8	58-135
Ulmus spp.	13	20.7	11.8-28.3	83.2	45-125
Carya spp.	44	21.7	9.3-38.8	95.7	53-127
Pinus spp.	82	22.1	9.6-34.4	99.5	76-133
Acer spp.	10	18.8	12.4-26.7	75	55-92
Liquidambar styraciflua	329	19.7	4.0-40.2	98.6	16-141
Quercus pagoda	335	25.2	2.5-70.5	109.9	20-163
Q. lyrata	116	22.9	10.4-38.9	93.5	60-124
Q. michauxii	70	25.9	12.5-55.3	98.3	67-128
Q. nigra	303	22.4	7.7-43.4	101.4	46-153
Q. alba	52	22.4	10.9-37.3	101	70-130
Q. phellos	566	22.9	7.5-60.0	102	51-144
Q. laurifolia	153	19.8	4.8-48.6	88.7	58-136
Total	2165	21.6	2.5-70.5	94.7	20-163

Although the $R^{2'}$s of the models appear low, the primary purpose of the study was to evaluate the relationship between height and diameter of the dominant trees, not for prediction. The simulations using the above models for the groups are illustrated in figure 1.

The dominant oak species (cherrybark, willow, and water) all have good-to-excellent growth rates, are intolerant to shade, and are intermediate to very intolerant to periodic flooding. Cherrybark is the best of the red oaks in the region, while water and willow oaks can be favored through management on the flats (Barrett 1995). The other highly frequent species, sweetgum, needs release for best growth and form, but shows medium growth rates when compared to the above oaks. Some of the other species found in this study, specifically the hickories and ashes, can be managed for, as they can provide good-quality products for a variety of uses when found on better sites. The two pine species will most likely become even less of a component of these stands with harvesting and succession. Even-aged management in the form of clearcuts or modified shelterwood (Loftis 1990), or with uneven management through group-selection, are common management tools used in other bottomland hardwoods in the South (Barrett 1995), and should be effective in producing a high-quality product while maintaining the stand structure found on these sites.

CONCLUSIONS

Stands similar to those utilized in this study are found throughout east Texas. Many of these stands have been mis-managed, poorly managed, or not managed for a number of years. These same stands had been high-graded in the past, and are now made up of a variety of species,

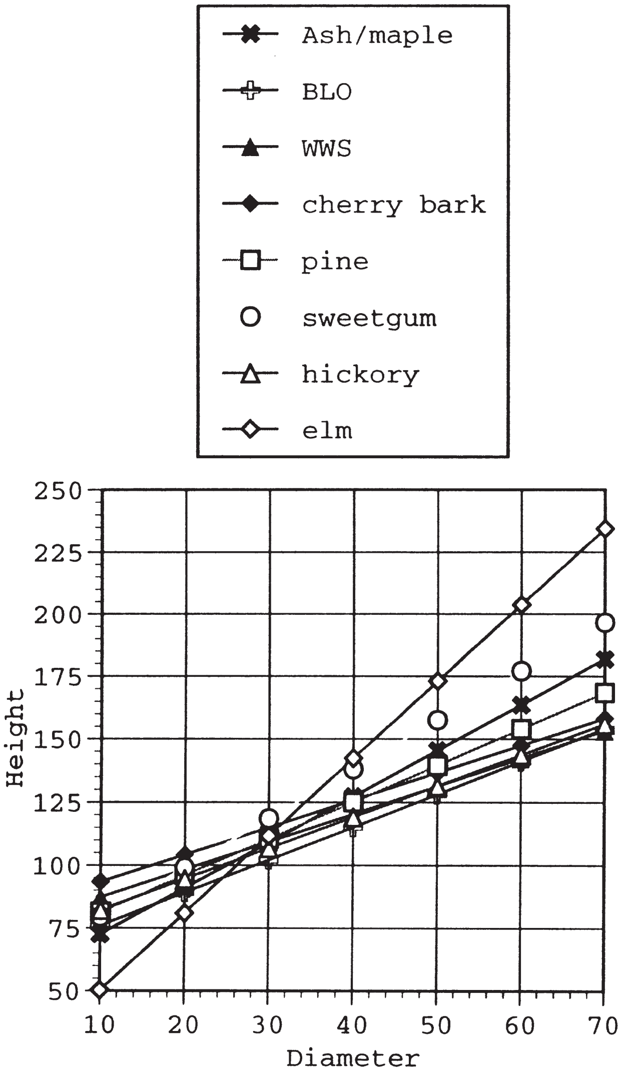

Figure 1—Simulation models of eight species groups.

many of which do not have traditional market value. With the increase in demand for hardwood by the pulp and paper industry, these species—traditionally an impediment to harvesting, regeneration, and management—make these stands more attractive for management. As can be seen from this study, these stands can and do produce good individual stems of high-quality species such as cherrybark and some of the other oaks, as well as sweetgum and occasionally loblolly pine. More information is needed on stand structure, age/height/diameter relationships and site productivity before the necessary management guidelines can be developed.

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COMPARISON OF OPTICAL DENDROMETERS FOR PREDICTION OF STANDING TREE VOLUME

Robert C. Parker and Thomas G. Matney[1]

Abstract—Enhanced sets of compatible stem profile equations were used with data collected from felled and standing pine trees to calculate tree volumes to various top merchantability limits. Standing trees were measured with the Criterion 400 Laser, Tele-Relaskop, and Wheeler Penta prism. These measurements were used to compare accuracies of the optical dendrometers for the measurement of tree d.b.h. and height and the prediction of tree volume from stem profile equations. The Criterion 400 Laser was more accurate for d.b.h. and total height measurement than was the Tele-Relaskop or the Wheeler Penta prism. Mean percent differences in d.b.h. measurement translated, in absolute units, to -0.05, +0.20, and -0.34 inches of the mean tree d.b.h. for the Criterion 400, Tele-Relaskop, and Wheeler Penta prism instruments, respectively. Mean percent differences in total height measurement translated, in absolute units, to 0.5, 1.6, and 1.7 ft, respectively, of the average tree height. The combined measurement data for d.b.h. and dob_{16} , indicated the Tele-Relaskop would produce more reliable volume results than the other instruments if the dendrometer measurements were used with form class volumes. Profile equations developed with felled-tree data produced the most consistent estimates of merchantable height and cubic foot volume to specified merchantable top limits. In general, the Criterion 400 produced the smallest mean differences in standing-tree measurements and profile equation predictions of merchantable height and cubic foot volume. However, the Tele-Relaskop produced the most consistent tree measurement and profile prediction trends. The Wheeler Penta prism was the least accurate of the three dendrometers.

INTRODUCTION

The prediction of standing tree volume has traditionally involved destructive measurement methods, but these methods cannot be used in fragile forest ecosystems. Recent developments in telescopic and laser dendrometer instruments make it feasible to obtain upper-stem measurements of standing trees in a nondestructive manner. However, the measurement accuracy and application technology of these instruments have not been evaluated.

The Tele-Relaskop (Bitterlich 1978) is a precision, telescopic dendrometer that has been used, in limited industrial and research applications, to develop taper and volume functions for standing trees (Parker 1996, Bitterlich 1984, Heske and Parker 1983, Parker 1983). Parker (1983, 1995) expanded the theoretical conoid concepts for tree volume computations proposed by Bitterlich with polynomial taper functions, developed application software for the microcomputer, and compared volume and taper applications with conventional inventory procedures.

Laser dendrometers and distance measuring instruments are being developed and some have been tested by the USDA Forest Service (Jasumback and Carr 1991). According to Carr (1992), laser technology of the Criterion model 400, manufactured by Laser Technology, Inc. (1992), has advanced to a point where accurate short- and long-range measurements are possible on nonreflective objects such as trees. In forestry applications, the Criterion 400 has been used for measuring tree heights and diameters, locating a specific height or diameter, selecting sample trees in variable plot inventories, measuring horizontal and slope distances, and determining coordinate azimuths and distances to defined targets (LaBau 1991, Liu and others 1995).

The Wheeler Penta prism (Wheeler 1962) has been used in forestry applications for obtaining upper stem diameters for many years. Although it does not have the telescopic optics of the Tele-Relaskop or sophisticated electronic circuitry of the Criterion 400, it can provide consistent estimates of upper stem diameters at heights determined by an attached clinometer.

Stem profile equations provide the most flexible methods of calculating tree volumes to specified merchantable top diameters from standing tree measurements. The technology of stem profile systems used by Burkhart (1977), Clutter (1980), Matney and Sullivan (1982), and Van Deusen and others (1982) did not allow the use of upper stem diameters. Newer technology has produced compatible sets of stem profile equations (Matney and Parker 1992) that allow the prediction of tree volume to user-defined top merchantability limits.

This paper compares d.b.h. and height measurements taken on standing trees with the Criterion 400 Laser, Tele-Relaskop, and Wheeler Penta prism with direct measurements after felling. It also compares predicted volumes and heights from an enhanced set of compatible stem profile equations using the optical measurements on standing trees and the direct measurements on felled trees.

DATA COLLECTION

One hundred sample trees (*Pinus taeda* L.) were selected from a stand on the John Starr Memorial Forest that had been previously thinned from below to remove intermediate and suppressed trees. The sample trees ranged in size from 5.7 to 24.2 inches in d.b.h. and 53 to 109 ft in height. On each sample tree, breast height (4.5 ft above average ground level) and the top of the first 16.0-ft log (16.5 ft,

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assuming a 0.5-ft stump) were marked with a horizontal orange line and measured with a caliper.

Since operational inventories in fragile ecosystems would preclude the use of destructive measurement of felled trees (at 4.0-ft intervals) and would possibly be limited by time and/or economics, stem measurement data obtained with optical or laser dendrometers would most likely be taken at stem intervals exceeding 4.0 ft. Therefore, dendrometer measurements of stem diameter [outside bark (o.b.)] and height were taken at breast height, at the top of the first 16.0-ft log, at two intermediate points spaced approximately equal between the top of the first 16.0-ft log and an estimated 3.0 inch top (o.b.), at an estimated 3.0 inch top (o.b.), and at total tree height. These stem measurement locations correspond to the d.b.h., four intermediate, and total height points described by Parker (1995) in previous applications of the Tele-Relaskop.

Sample trees were felled with a 0.5-ft stump. Diameters (o.b.) and bark thickness measurements were taken at the stump, 3.0 ft (2.5 ft above stump height), breast height (4.0 ft above stump height), and 4.0-ft intervals along the stem to the terminal bud. Diameters were measured to the nearest 0.1 in. with a steel caliper, and two bark thicknesses were obtained (one under each caliper arm) with a bark gauge to the nearest 0.1 in. Total tree height was computed as the sum of the measurement intervals and the distance from the last diameter measurement to the tip.

DATA ANALYSIS

Although the primary objective of this study was to compare volume prediction accuracy of stem profile equations developed from optical dendrometer and felled-tree data, estimates of “point” measurement accuracy could be obtained for common measurements taken at breast height, 16.5 ft, and total height. The data sets were reduced to 96 trees because 4 trees in the felled-tree data set had at least one missing (inaccessible) measurement at or below breast height caused during the felling operation. Mean percent difference and standard error of the mean percent difference between the dendrometer measurements and felled-tree values were computed (table 1). The observed differences between felled-tree values and dendrometer measurements are expressed as a percentage of felled-tree value. Felled tree diameters at breast height and 16.5 ft were measured with a caliper in the same plane as viewed with the optical dendrometers.

To simulate measurement practices during operational forest inventories and to obtain sample tree volumes to variable top diameters, a compatible set of stem profile equations was developed to allow the prediction of outside- and inside-bark stem diameters at desired merchantability points from standing tree measurements of d.b.h. and total tree height. The profile prediction system models used in this study are enhanced versions of the nonsegmented, third-degree polynomial conditioned through the top (i.e. at $h_i=h_{total}$ or $X=h_i/h_{total}=1$, $dob_{hi}= 0$) used by Parker (1983, 1996) and the fifth-order polynomial constrained through

Table 1—Comparisons of optical dendrometers for diameter and height measurement of standing trees where is mean percent difference (observed difference as a percentage of felled-tree value) and is the standard error of the mean percentage difference (Basis: 96 trees)

Measurement		Criterion 400	Tele-Relaskop	Wheeler Penta prism
		- - - - - - - - - -	*Percent*	- - - - - - - - - -
D.b.h.	$\bar{d}$	-0.39	+1.41	-2.40
($\overline{dbh}$=14.1 in.)	$s_{\bar{d}}$	+0.53	+0.40	+0.57
Dob_{16}	$\bar{d}$	+1.92	+1.54	-4.16
($\overline{dob}_{16}$=12.6 in.)	$s_{\bar{d}}$	+0.60	+0.66	+0.56
Total height	$\bar{d}$	+0.59	+1.68	+1.87
($\overline{H}_t$=92.8 ft)	$s_{\bar{d}}$	+0.45	+0.78	+0.33

d.b.h. and the top merchantability limit (i.e., dob_{hi}/d.b.h.=1 when h_i=4.5 ft and dob_{hi} = merchantable top dob when $h_i=h_m$) used by Matney and Parker (1992).

The set of profile prediction system models applied to the felled and optical dendrometer tree data where b_i and b'_i are regression coefficients for outside and inside bark, respectively, are:

At stump height of 0.5 feet (i.e. h_i= 0.5 ft)

$$\frac{dob_{0.5}}{dbh_{ob}} = b_1\left(\frac{1}{dbh_{ob}}\right) + b_2 \qquad (1)$$

$$\frac{dib_{0.5}}{dbh_{ob}} = b'_1\left(\frac{1}{dbh_{ob}}\right) + b'_2$$

At d.b.h.: $d.b.h._{ob}$ to $d.b.h._{ib}$ conversions (i.e. h_i = 4.5 ft)

$$\frac{dbh_{ib}}{dbh_{ob}} = b_3\left(\frac{1}{dbh_{ob}}\right) + b_4 \qquad (2)$$

Variables for below/above breast height profile equations:

$$\text{Dependent: } y_i = \frac{dob_{h_i}}{dbh_{ob}} \quad z_i = \frac{dib_{h_i}}{dbh_{ib}}$$

$$\text{Independent: } x_i = \frac{h_i}{h_t} \quad w_i = \frac{4.5}{h_t}$$

Below breast height (i.e. h_i < 4.5 ft)

$$y_i = 1 + b_5\,(x_i - w_i) + b_6\,(x_i^2 - w_i^2) \qquad (3)$$

$$z_i = 1 + b'_5(x_i - w_i) + b'_6(x_i^2 - w_i^2)$$

Above breast height (i.e. $h_i > 4.5$ ft)

$$y_i = \frac{x_i - 1}{w_i - 1} + b_7\left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)}\right] + b_8\left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)}\right]$$
$$z_i = \frac{x_i - 1}{w_i - 1} + b'_7\left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)}\right] + b'_8\left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)}\right] \quad (4)$$

Bark relationship above breast height (i.e. $h_i > 4.5$ ft)

$$\left(\frac{dib_{h_i}}{dob_{h_i}}\right) = \left(\frac{dbh_{ib}}{dbh_{ob}}\right) e^{b'_9\left[\frac{dbh_{ob}}{dob_{h_i}} - 1\right]^{0.25}} \quad (5)$$

Equation (1) predicts stump diameter (o.b. and i.b.) at 0.5 ft aboveground from d.b.h.$_{ob}$. Equation (2) predicts d.b.h.$_{ib}$ from d.b.h.$_{ob}$. Equation (3) is a constrained, second-degree polynomial, profile model to predict stem diameter (o.b. and i.b.) between stump height and breast height. Equation (3) is constrained through breast height such that at h_i=4.5 ft, dob$_{hi}$/d.b.h.$_{ob}$ =1. Equation (4) is a constrained, third-degree polynomial, profile model to predict stem diameter (o.b. and i.b.) between breast height and total tree height. Equation (4) is constrained through both breast and total height such that at h_i=h_{total} , dob$_{hi}$ = 0 and dib$_{hi}$ = 0. Thus, equation (4) is constrained through ratio estimate points 1 and 0. Equation (5) predicts the dib/dob (i.e. bark) relationship along the upper stem above breast height. The exponent in equation (5) was fixed at 0.25 because attempts to fit that parameter often causes convergence problems with some nonlinear procedures. Equation (5) was developed from the felled-tree data for use with the dendrometer data sets when an inside bark diameter is needed. Computing the bark relationship with equation (5) is more efficient than computing the o.b. and i.b. values in two steps with equation (4).

PROFILE EQUATION RESULTS

The resulting profile equations to predict dob/diob diameters below breast height and the bark relationship above breast height for the felled-tree data set, where $s_{y.x}$ is the standard error of prediction and I^2 is the index of fit for 96 trees, are:

At stump height of 0.5 feet (i.e. $h_i = 0.5$ ft)

$$\frac{dob_{0.5}}{dbh_{ob}} = 0.9364\left(\frac{1}{dbh_{ob}}\right) + 1.1294 \quad (6)$$

with n=96, $s_{y.x=0.0708}$ and $I^2 = 0.1165$

$$\frac{dib_{0.5}}{dbh_{ob}} = -0.0149\left(\frac{1}{dbh_{ob}}\right) + 1.0342$$

with n=96, $s_{y.x=0.0697}$ and $I^2 = 0.0000$

At d.b.h.: d.b.h.$_{ob}$ to d.b.h.$_{ib}$ conversions (i.e. $h_i = 4.5$ ft)

$$\frac{dbh_{ib}}{dbh_{ob}} = -0.3815\left(\frac{1}{dbh_{ob}}\right) + 0.8896 \quad (7)$$

with n=96, $s_{y.x=0.0295}$ and $I^2 = 0.1124$

Below breast height (i.e. $h_i < 4.5$ ft)

$$y_i = 1 + -7.1727(x_i - w_i) + 45.3420(x_i^2 - w_i^2) \quad (8)$$

with n=192, $s_{y.x=0.0567}$ and $I^2 = 0.6691$

$$z_i = 1 + -8.0688(x_i - w_i) + 62.1590(x_i^2 - w_i^2)$$

with n=192, $s_{y.x=0.0572}$ and $I^2 = 0.6778$

Bark relationship above breast height (i.e. $h_i > 4.5$ ft)

$$\left(\frac{dib_{h_i}}{dob_{h_i}}\right) = \left(\frac{dbh_{ib}}{dbh_{ob}}\right) e^{0.0642\left[\frac{dbh_{ob}}{dob_{h_i}} - 1\right]^{0.25}} \quad (9)$$

with n=1,600, $s_{y.x=0.0368}$ and $I^2 = -0.5791$

The parameter estimates and statistics of fit for equation (4), developed from the felled-tree and dendrometer data taken above breast height, are shown in table 2. Since optical and laser dendrometers are most commonly used to obtain outside bark diameters for above-breast height stem locations because of stump visibility limitations, only the coefficients for equation (4) were obtained for the dendrometers.

Each data set equation was judged significantly different from zero and each data set equation was judged significantly different from other equations at the 0.01 level. Profile equations were fitted to the felled-tree data set and to the three sets of optical dendrometer data. Heights to various diameters and cubic foot volumes were predicted with the profile equations and compared to the computed, felled-tree volumes. Table 3 shows the mean percent differences between heights and volumes computed with the profile system equations and measured felled-tree

Table 2—Tree profile prediction system parameter estimates* and statistics of fit for felled-tree and optical dendrometer (above breast height) data for loblolly pine where O.B. and I.B. are outside and inside bark, n is number of observations, $s_{y.x}$ is the standard error of prediction, and I^2 is the index of fit

Parameter	Felled-tree O.B.	I.B.	Criterion 400 O.B.	Tele-Relaskop O.B.	Wheeler Penta prism O.B.
b7	+1.7496	+1.1616	+1.8016	+1.6914	+1.9809
b_8	-1.5837	-1.3391	-1.5607	-1.5266	-1.6567
n	1699	1699	477	476	470
$s_{y.x}$	0.0457	0.0484	0.0642	0.0623	0.0508
I^2	0.9665	0.9651	0.9589	0.9624	0.9737

Table 3—Comparisons of profile equation predictions of tree height and cubic foot volume from felled tree and optical dendrometer data where $\bar{d}$ is mean percent difference (observed difference as a percent of measured felled tree value) and is standard error of the mean percent difference (Basis: 96 trees)

Profile value	Felled-tree		Criterion 400		Tele-Relaskop		Wheeler Penta prism	
(Mean of actual value)	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$
Height to 0 in. top (92.3 ft)	-0.002	0.002	+0.583	0.456	+ 1.684	0.781	+1.874	0.330
Height to 3 in. top (80.4 ft)	+1.873	0.355	+1.695	0.589	+ 3.401	0.794	+2.484	0.476
Height to 6 in. top (64.7 ft)	+3.400	1.410	-0.385	1.744	+ 5.318	1.463	-3.606	1.725
Height to 8 in. top (49.6 ft)	+4.805	1.800	+2.031	3.678	+ 9.439	2.158	-4.999	2.804
Height to 10 in. top (34.5 ft)	+6.212	2.848	-0.039	3.036	+11.236	3.025	-4.735	3.209
Cu. ft to 0 in. top (49.4 ft^3)	+0.483	0.938	-3.027	1.305	+ 3.658	1.278	-7.031	1.252
Cu. ft to 3 in. top (49.2 ft^3)	+0.496	0.966	-3.117	1.323	+ 3.663	1.295	-7.226	1.273
Cu. ft to 6 in. top (47.3 ft^3)	+1.891	1.552	-3.594	2.101	+ 5.635	1.699	-10.379	1.956
Cu. ft to 8 in. top (43.1 ft^3)	+2.315	1.734	-1.089	3.817	+ 8.728	2.211	-10.549	2.878
Cu. ft to 10 in. top (36.4 ft^3)	+3.277	2.631	-3.217	3.225	+10.085	3.112	-9.782	3.249

values. Cubic foot volumes and merchantable heights of the felled trees were computed to 0, 3, 6, 8, and 10-inch top diameters (o.b.) using Smalian's formula and linear interpolation of intermediate bolt diameters. Percent difference is the arithmetic difference between the computed value from the profile system equation(s) and the measured felled-tree value expressed as a percentage of felled-tree value. Equation (4) coefficients for each of the felled-tree and dendrometer data sets (table 2) were used to compute upper stem diameters at 4.0-ft intervals above breast height. Diameters below breast height (0.5 and 3.0 ft) were computed for all data sets with felled-tree equations (6) and (8). Bolt length to a specified top merchantability limit that was contained within a bolt was obtained by linear interpolation of computed endpoint bolt diameters.

DENDROMETER COMPARISONS

Point Estimates

The Criterion 400 was more accurate for d.b.h. and total height measurement than the Tele-Relaskop or the Wheeler Penta prism. While the mean percent differences in table 1 were significantly different statistically, they were most likely not significantly different in a practical sense. The mean percent differences for the d.b.h. measurement in table 1 translated in absolute units to -0.05, +0.20, and -0.34 inches of the mean tree d.b.h. for the Criterion 400, Tele-Relaskop, and Wheeler Penta prism instruments, respectively. None of these mean differences would result in a change in tree diameter for a 1-inch d.b.h. class interval.

The mean percent differences for a quadratic mean dob_{16} of 12.6 inches would translate, in absolute units, to -0.24, +0.19, and -0.52 inches for the Criterion 400, Tele-Relaskop, and Wheeler Penta prism, respectively. While these differences might appear to be insignificant from a practical standpoint, they could translate into significant volume differences if the d.b.h. and dob_{16} dendrometer measurements were used to obtain Mesavage and Girard form class volumes. For example, using the average tree values of dob_{16} = 12.6 in. and d.b.h.$_{ob}$ = 14.1, equation (7) for d.b.h.$_{ib}$, and equation (9) for dib_{16}; the computed form class for the "average tree" would be:

$$\text{d.b.h.}_{ib} = -0.3815 + 0.8896(14.1 \text{ in. d.b.h.}_{ob})$$
$$= 12.16 \text{ in} \qquad \text{from equation (7)}$$

$$dib_{16} = 12.6(12.16/14.10)\exp[0.0642(14.1/12.6 - 1)^{0.25}]$$
$$= 11.29 \text{ in} \qquad \text{from equation (9)}$$

$$FC = (11.29/14.10)100\%$$
$$= 80.04\% = 80\% \qquad \text{from definition of form class}$$

Likewise, using the resulting average dob_{16} values for the dendrometers (i.e. 12.6-0.24, 12.6+0.19, 12.6-0.52), the resulting d.b.h.$_{ob}$ values (i.e. 14.1-0.05, 14.1+0.20, 14.1-

0.34), equation (7) for d.b.h.$_{ib}$, and equation (9) for dib$_{16}$; the computed form classes for the "average" Criterion 400, Tele-Relskop, and Wheeler Penta prism tree would be 79 percent, 80 percent, and 79 percent, respectively. If the assumption of 3 percent (board foot) volume change per form class point is used, the volume differences would be -3 percent, 0 percent, and -3 percent, respectively. Cubic foot volume changes approximately 2 percent per form class point. Thus, the combined measurement data for d.b.h. and dob$_{16,}$ indicate that the Tele-Relaskop would produce more reliable volume results than would the other instruments if the dendrometer measurements were used with form class volumes.

The Criterion 400 was more accurate for total height measurement than was the Tele-Relaskop or the Wheeler Penta prism. Again, the mean percent differences are not different from a practical standpoint because they translate to absolute height differences of 0.5, 1.6, and 1.7 ft from the average tree height of 92.8 ft The height difference associated with the Wheeler Penta prism are attributable to the accuracy of the attached clinometer, not the optics of the dendrometer.

Profile Equation Estimates

All upper-stem profile equations [from equation (4)] were judged to be statistically significant and all possible pair-wise comparisons showed that each equation was significantly different from the others at a significance probability of less than 0.0001.

Since the primary objective of this study was to compare volume prediction accuracy of stem profile equations developed from optical dendrometer and felled-tree data, estimates of merchantable height (i.e., stem length) and cubic foot volume to various top merchantability limits were computed with the profile equations for each data set and compared to the felled-tree values (table 3). The o.b. upper-stem profile equation coefficients for each data set (b_7 and b_8 in table 2) were used to compute estimates of merchantable height and volume above breast height. Cubic foot volume below breast height was computed for all data sets with predicted diameters at 0.5 and 3.0 ft from felled-tree equations (6) and (8), respectively. Profile equations for predicting diameters below breast height were not developed for the dendrometers because in field applications, visibility of the stump and most stem locations below breast height is severely limited by forest vegetation. This is not a serious limiting factor in dendrometer use because the stem section below breast height can be treated as a cylinder or other appropriate geometric solid.

The accuracy of computed height (stem length) and volume values to a specified merchantability limit from a felled-tree profile equation diminishes as the merchantability limit moves down the stem from the top toward breast height (table 3). This decline in prediction accuracy is attributable in part to changes in taper caused by inflection points of the stem profile. The upper-stem profile equations used in this study are constrained through the top and breast height, but as the rate of stem taper decreases in the midportion of the tree bole above breast height, relatively small changes in predicted diameter result in large changes in stem length (height). For example, the mean measured felled-tree heights in table 3, reflect a taper rate of 0.252 in./ft between the tree top and a 3 in. top dob, 0.191 in./ft between 3 in. and 6 in., 0.132 in./ft between 6 in. and 8 in., 0.132 in./ft between 8 in. and 10 in., and 0.134 in./ft between 10 in. and the average d.b.h. of 14.1 in. These "average tree" taper rates show that the stem profile is "relatively flat" (actually, the taper rate is relatively constant) between a 6 in. top and d.b.h. Thus, a +4.8 percent error in height to an 8 in. top translates to +2.4 ft which equates to a error of +0.295 inches in diameter prediction if the taper rate is 0.132 in./ft. From a practical standpoint, a 4 to 6 percent error in merchantable height prediction in the midbole region of a standing tree should have little impact on volume prediction.

The error associated with profile equation prediction of merchantable height (table 3) increases in a consistent manner as the top merchantability limit increases (i.e., moves down the stem toward d.b.h.) for the felled-tree and Tele-Relaskop data sets, appears to be random for the Criterion 400 data, and has a segmented trend for the Wheeler data.

Errors in profile prediction of cubic volume should be attributable to the combined effects of errors in merchantable height and stem diameter prediction. For example in table 3, the average height prediction error (expressed as mean percent difference) for the felled-tree data profile equation is +4.805 percent or 2.38 ft for the 8 in. top. Using the previously established taper rate of 0.132 in./ft, the end diameter of this +2.38 ft "error bolt" would be approximately 8.3 inches and its cubic volume would be approximately +0.86 ft^3. The actual volume difference for the 8 in. top in table 4 is +2.315 percent or 0.99 ft^3.

Overestimation of height and/or stem diameter should result in overestimation of cubic volume. The computed values for felled-tree and Tele-Relaskop equations produced consistent error patterns in diameter, height, and cubic foot volume. The Tele-Relaskop overestimated d.b.h., dob$_{16}$, and total tree height (table 1) and the resulting profile equations overestimated merchantable height and therefore cubic foot volume (table 3). The Criterion 400 underestimated standing tree diameters, overestimated total height, and had both positive and negative estimation errors in profile height prediction. Yet, the profile equation volume prediction was consistently low. Since cubic foot volume varies with the square of bolt diameter, it must be concluded that the Criterion 400's underestimation of stem diameter has a stronger influence on volume prediction than does its inconsistent estimation of height. Likewise, the Wheeler Penta prism underestimated standing tree diameters and the resulting profile equations consistently underestimated cubic volume by 7.0 - 10.5 percent.

The profile equations developed with felled-tree data produce the most consistent estimates of merchantable height and cubic foot volume to various merchantable top limits. It is difficult, however, to make definitive conclusions about the accuracy ranking of the Criterion 400, Tele-Relaskop, and Wheeler Penta prism. In general, the Criterion 400 produced the smallest mean differences in standing tree measurements and profile equation predictions of merchantable height and cubic foot volume. On the other hand, the Tele-Relaskop produced the most consistent tree measurement and profile prediction trends. There is no doubt that the Wheeler Penta prism was the least accurate of the three dendrometers in a statistical sense, but these inaccuracies may not be relevant in a practical sense.

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BENEFITS OF LONG-TERM SILVICULTURE RESEARCH TO ACCOMPLISHING TOTAL MANAGEMENT OBJECTIVES

M. Boyd Edwards[1]

Abstract—In 1982, a study on the benefits of six site preparation treatments to survival and growth of loblolly pine was initiated in the Piedmont of Georgia. That original study is still active and a study summary will be presented. However, in addition to research information obtained from the original study about survival and growth of young loblolly pine stands, nine additional studies have resulted on the site that deal with subjects such as wildlife benefits, floristics/succession, economics, stand development, soil relationships, and vegetation/environmental relationships. Highlights from individual studies will be presented that serve to demonstrate the benefits of long-term silviculture research to accomplishing the science needed to sustain and enhance southern pine productivity.

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CANOPY LIGHT TRANSMITTANCE IN NATURAL STANDS ON UPLAND SITES IN ARKANSAS

Yanfei Guo and Michael G. Shelton[1]

Abstract—The relationship between overstory basal areas and understory light intensity was modeled from measurements of photosynthetically active radiation from a series of ongoing research studies, demonstration areas, and operational-level stands that represented a wide range in conditions (age, density, structure, and species composition) and sites (poor and good). Light intensity was sampled with a ceptometer during clear sky conditions at 4.5 ft in height between 1030 and 1330 solar time in the summer. There was a total of 93 observations, representing the following stand compositions: 35 pine, 54 pine-hardwood, and 4 hardwood. The developed model is: $I=100/(1 + T\ exp(-5.401 + 0.01446\ T + 1786\ H/T)$, where I is percent light intensity, and T and H are the total stand and hardwood basal areas, respectively (ft^2/acre). All regression coefficients were significant at $P \geq 0.001$, and the fit index was 0.94. Hardwoods appear to intercept more light per unit of basal area than pines. This difference can be attributed to crown size and foliar characteristics. The relationship between overstory basal area and understory light intensity has implications for stand regeneration, competing vegetation, and wildlife habitat.

INTRODUCTION

The transmittance of light through the canopy is an important stand characteristic that has a pronounced effect on the understory environment (Valigura and Messina 1994), and its measurement can be used to estimate the canopy's energy capturing ability and leaf area index (Pierce and Running 1988). Silviculturists manipulate light transmittance by controlling the density, structure, and species composition of the trees making up the canopy. Such manipulations of light transmittance are usually incidental to some other management goal, but they become crucial when stands are being naturally regenerated using either even- or uneven-aged techniques. Because most natural reproduction cutting methods retain some overstory trees on the site during stand regeneration, seedlings developing in natural stands typically grow in the partial shade of overstory trees. For even-aged methods, seed-tree stands of southern pines typically retain 5 to 10 ft^2/acre of overstory pines, while retention in shelterwood stands is 20 to 40 ft^2/acre (Willett and Baker 1993). In contrast, acceptable stocking levels in uneven-aged pine stands range from 45 to 75 ft^2/acre (Baker and others 1996). In addition, some nonindustrial private landowners and public land managers want to retain a component of overstory hardwoods during stand regeneration to enhance the nontimber resources of their stands (Waldrop 1989).

Successful natural regeneration depends on creating an acceptable understory environment for seedling establishment and development. A key feature of the understory environment is light intensity and quality. Regrettably, these overstory-understory relationships are still poorly known for loblolly (*Pinus taeda* L.) and shortleaf (*P. echinata* Mill.) pines and their hardwood associates. To develop a model for canopy light transmittance in natural stands, we compiled data from a number of ongoing research studies where both light intensity and overstory basal areas were measured. These data were supplemented by measurements from several demonstration areas and operational-level stands.

METHODS

Study areas

Sampling utilized an existing series of research areas, demonstration areas, and operational-level stands, which were all natural in origin. These studies and stands are summarized in table 1.

Study 1 is testing the initial application of uneven-aged silviculture using single-tree selection in an irregularly structured shortleaf pine-oak stand (Shelton and Murphy 1991). The study is located in Perry County, AR and consists of 20 square 0.5-acre plots surrounded by a 58-foot isolation strip treated in an identical manner. The study plots were arranged in a randomized complete block design with four replicates. One plot per block was designated as an untreated control that was not harvested. The pine component of the treated plots was reduced to a target basal area of 60 ft^2/acre using uneven-aged marking guidelines, and plots were harvested during the winter of 1988/89. Treatments were three levels of retained hardwoods (0, 15, and 30 ft^2/acre in trees with d.b.h. of 3.6 inches and greater). Hardwoods were uniformly scattered across the plot; in addition, the treatment retaining 15 ft^2/acre of hardwoods was repeated with a clustered distribution of hardwoods. Hardwoods (≥1 inch d.b.h.) that were not designated for retention were controlled with stem-injected herbicide.

Study 2 is testing the shelterwood reproduction method in a shortleaf pine-oak stand in Perry County, AR (Shelton and Baker 1992). Eight rectangular 3-acre plots were established and surrounded by a 66-foot isolation strip that was treated in an identical manner. Plots were arranged in a randomized complete block design with four replicates.

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Table 1—Summary of the stand and site conditions sampled for light intensity

Designation	Management system and intensity[a]	Dominant tree Species[b]	Age	Pine basal area	Hardwood basal area
			Years	*Ft²/acre*	*Ft²/acre*
Study 1	UEA/high	SLP	50-80	57-68	0-35
Study 1[c]	EA/low	SLP	50-80	71-116	18-55
Study 2	SW/high	SLP	55-75	27-32	0-18
Study 3	EA/high	LOB	36	72-113	0-39
Study 4	None	LOB	50-120	61-183	21-78
Stand 1	EA/high	LOB	50	62-70	0
Stand 2	UEA/high	LOB/SLP	50-80	56-73	0
Stand 3	UEA/high	LOB/SLP	50-80	44-50	0
Stand 4	ST/high	LOB	50	8-22	0
Stand 5	EA/low	OAKS	60-80	2-6	84-100

[a] Management systems are: UEA=uneven-aged using single-tree selection, EA=established even-aged stands managed with periodic thinnings, SW=shelterwood reproduction cutting method, ST=seedtree reproduction cutting method. High intensity stands are harvested frequently and have some type of understory control imposed. Low intensity stands are infrequently thinned and have no understory control. Study 4 has had no significant disturbance for over 60 years.
[b] LOB=loblolly pine, SLP=shortleaf pine, OAKS=mixed upland oaks. Stands dominated by SLP are on poor sites (50 to 60 ft for shortleaf pine at 50 years); all other stands are on good sites (85 to 95 ft for loblolly pine at 50 years).
[c] Unharvested control plots.

The pine component on all plots was reduced to a target basal area of 30 ft^2/acre in trees selected principally for their potential as seed trees. Two levels of overstory hardwoods were retained (0 and 15 ft^2/acre in trees 3.6 inches d.b.h. and larger). All merchantable pines were harvested during the winter of 1989/90, and merchantable hardwoods not designated for retention were harvested during the spring and summer of 1990. After harvesting was completed in 1989, plots were split into two 0.70-acre measurement plots, and two control methods for submerchantable hardwoods (≥1 inch d.b.h.) were imposed (chainsaw felling with and without stump-applied herbicides).

Study 3 is a thinning study in a 35-year-old loblolly pine-hardwood stand in Drew County, AR (Tappe and others 1993). Twenty-seven circular 0.2-acre plots were established and surrounded by a 33-foot isolation strip that was treated in an identical manner. Plots were arranged in a completely randomized design with three replicates. The pine component was reduced to three basal areas (70, 85, and 100 ft^2/acre). Three levels of hardwoods were retained (0, 15, and 30 ft^2/acre in trees 3.6 inches d.b.h. and larger). Merchantable pines and hardwoods that were not designated for retention were harvested during 1988/89. Submerchantable hardwoods (≥ 1 inch d.b.h.) were controlled with stem-injected herbicide.

Study 4 is located in the R.R. Reynolds Research Natural Area in Ashley County, AR (Cain and Shelton 1995). This 80-acre area is a mature pine-hardwood stand, where many of the dominant trees are more than 100 years old. The stand developed after harvest of the virgin forest in the 1910's, and there have been no significant stand disturbances over the last 60 years. Twelve 0.25-acre plots were located systematically within the stand.

Stand 1 is a 5-acre demonstration area in the Crossett Experimental Forest in Ashley County, AR that was regenerated to loblolly pine using clearcutting with seeding from the adjoining stand in 1942 (Baker and Murphy 1982). The stand has been thinned from below on a 5-year interval. Understory vegetation was periodically controlled by prescribed burning.

Stands 2 and 3 are the Good and Poor Farm Forestry Forties, two 40-acre demonstration areas in the Crossett Experimental Forest. No study treatments were imposed in these stands, which have been under uneven-aged silviculture for more than 50 years (Reynolds and others 1984). Herbicide control of nonpine understory vegetation was applied during the late summer of 1989. The most recent harvest within the stands was during the winter of 1990/91.

Stand 4 is an operational-level loblolly pine seed-tree stand located in Ashley County, AR. The stand was about 40 acres and was cut about 2 years earlier. Competing vegetation was controlled with an area-applied herbicide.

Stand 5 is an upland oak stand located in Drew County, AR. There was no recent evidence of cutting or stand treatments.

Measurements and Data Analysis

The d.b.h. of each tree ≥ 3.6 inches d.b.h. in the research plots was obtained from the most recent inventory, which was either annually or biennially. For the other stands, pines and hardwoods ≥ 3.6 inches d.b.h. were tallied using a 10-BAF prism at 10 points in Stand 1 and 20 in the others. Sampling in Stands 2, 3, and 4 was restricted to an area of about 10 acres.

Photosynthetically active radiation (PAR) was determined at 4.5 feet aboveground during clear sky conditions using an 80-sensor Sunfleck Ceptometer (Decagon Devices, Inc., Pullman, WA). Sampling was conducted on the following dates: August 2, 1991 (Study 1); August 1, 1991 (Study 2); July 31, 1991 (Study 3); August 8, 1991 (Study 4); August 20, 1991 (Stands 1, 2, 3, 4); and July 23, 1991 (Stand 5). All measurements were taken between 1030 and 1330 solar time. Measurements were also made several times during each date in full sunlight, which permitted calculating relative light intensity. For Studies 1 and 2, PAR was determined at 10 and 18 permanent 0.001-acre subplots, respectively, that were used for regeneration inventories in each plot, taking 10 readings across each subplot. For Study 3, a total of 30 readings was systematically taken across each 0.20-acre plot. For Study 4, five temporary 0.001-acre subplots were located and PAR was determined as described before. For all of the other stands, three temporary 0.001-acre subplots were located within 10 feet of the prism point, taking 10 readings across each subplot.

For the research studies, PAR was averaged for each plot, and the basal area in pine and hardwood components was calculated. For the other stands, PAR and basal areas were averaged for groupings of five adjacent prism points; we felt that this would provide an observation fairly comparable to those from the research plots. There was a total of 75 observations of basal area and light from the research studies and 18 from the other stands for a total of 93, representing stand compositions of 35 pine, 54 pine-hardwood, and 4 hardwood.

The Beer-Lambert law is generally used to describe the relationship between light transmittance and leaf area index (LAI):

$$I = I_0 \exp(-k \,\mathrm{LAI}) \qquad (1)$$

where

I is the amount of incident PAR penetrating the canopy,

I_0 is the incident PAR, and

k is a coefficient (Kera and others 1969).

By replacing LAI with total basal area and adding a term for hardwood/total basal area ratio in the model, several modified models were tested. After evaluating the potential models, the following one was selected because it had the lowest root mean square error and highest fit index (analogous to R^2 for linear equations):

$$I=100/(1 + T \exp(b_0 + b_1 T + b_2 H/T) \qquad (2)$$

where

I is the relative light intensity (PAR at 4.5 ft expressed as a percentage of PAR in full sunlight), and

T and *H* are the total stand and hardwood basal areas, respectively (ft^2/acre), and the b_i's are the coefficients to be determined by nonlinear least squares regression using the SAS MODEL procedure (SAS Institute 1988).

RESULTS AND DISCUSSION

The developed equation for canopy light transmission is:

$$I = 100/[1 + T \exp(-5.401 + 0.01446\, T + 1.786\, H/T)] \quad (3)$$

All regression coefficients were significantly different from zero (P≤0.001). The fit index was 0.94, and the root mean square error was 6.7 percent. The equation uses a modification of the logistic function and thus is constrained to yield a value of 100 percent for a total basal area of 0 ft^2/acre. The significance of the regression coefficient for the ratio of hardwood basal area to total basal area [H/T in equation (1)] indicates that pines and hardwoods have different effects on canopy light transmittance.

The equation was solved for a reasonable range of total and hardwood basal areas that were represented in the data and results are shown in figure 1. Predicted light transmittance ranges from 98 percent for a pine-only basal area of 5 ft^2/acre to 6 percent for a total basal area of 180 ft^2/acre, which is made up of 135 ft^2/acre for pines and 45 ft^2/acre for hardwoods.

Hardwoods appear to intercept more light per unit basal area than pines. This is apparent in figure 1 because the light intensity progressively decreases as hardwoods make up a higher proportion of total basal area. The reduction in light intensity from retained hardwood is most evident at the

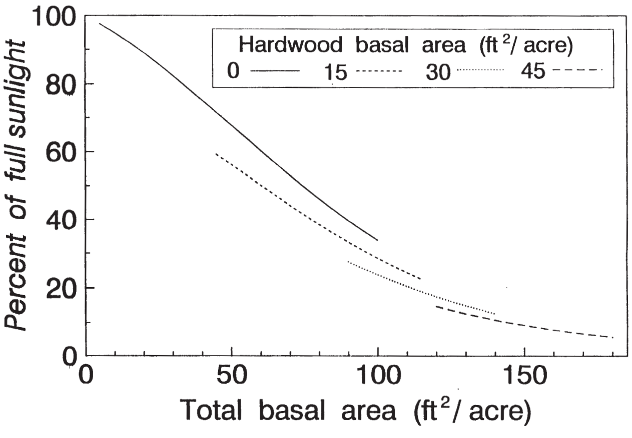

Figure 1—Relationship between basal area and light intensity.

lower values of total basal area. When total basal area is held constant at 45 ft^2/acre, for example, increasing the hardwood component from 0 to 15 ft^2/acre reduces light intensity from 72 to 59 percent, a difference of 13 percentage points. Increasing the hardwood component from 0 to 15 ft^2/acre when the total basal area is 100 ft^2/acre will reduce light intensity from 34 to 29 percent, a difference of 5 percentage points. The greater light interception of hardwoods probably reflects their large crowns, short heights, and broad leaves.

In studying the effect of shortleaf pine basal area on light intensity, Jackson and Harper (1955) reported an inverse relationship between the logarithm of stand basal area and the logarithm of light intensity. This relationship is close to the one found in this study. For instance, with a shortleaf pine basal area of 40 ft^2/acre, the light intensity was about 60 percent of full sunlight, and the light intensity decreased to about 20 percent at a basal area of 120 ft^2/acre. For the same basal areas, the predicted light intensity in this study was 70 and 25 percent, respectively. For a shelterwood stand with 40 ft^2/acre of loblolly pine basal area, Valigura and Messina (1994) reported that the daily total PAR was 64 percent of that in an open area. The minor difference in transmittance of Valigura and Messina's study and ours (64 versus 70 percent) may be due to the difference in the methods of data collection. Our data were collected between 1030 and 1330 hours when shadow length was minimum. In contrast, Valigura and Messina (1994) used daily total PAR. Shade length was found to affect light intensity in the understory in a tropical forest (Longman and Jenik 1974).

The light relationships of mixed pine-hardwood stands have not been intensively studied. However, hardwoods have generally been observed to intercept more light than pines. Under temperate hardwoods, light intensities from 1 to 5 percent are common, while the common ranges for even-aged pine stands are from 10 to 15 percent (Spurr and Barnes 1980). In addition, Garrett and others (1977) reported that shortleaf pine stands transmitted more than twice as much light as white oak (*Quercus alba* L.) stands with the same basal area. Species composition also influences light quality with more green light being reflected by hardwoods (Spurr 1960).

Our model for canopy light transmission is limited because it is heavily weighted toward sawtimber-sized pine stands with and without a significant component of midcanopy hardwoods. However, additional sampling is planned in the future to include younger stands and managed hardwood stands.

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A SYSTEM FOR DRAWING SYNTHETIC IMAGES OF FORESTED LANDSCAPES

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Abstract—A software package for drawing images of forested landscapes was developed. Programs included in the system convert topographic and stand polygon information output from a GIS into a form that can be read by a general-purpose ray-tracing renderer. Other programs generate definitions for surface features, mainly trees but ground surface textural properties as well. The package can be used to design logging cut unit boundaries that are less visible from a given viewpoint. Images created using the system may also be suitable for showing the public how a given prescription might appear if implemented. The package was used to make images showing the potential for using strip clearcutting as a means of mitigating the visual impact of harvests on steeply sloping ground. An analysis of the package indicated that there was a potential to improve its data handling and user interface components.

INTRODUCTION

Appearance is the most convincing source of information available to the public in evaluating the status of a landscape (Nassauer 1992). Silvicultural treatments on a landscape can leave unintended visual impacts that persist for a number of years. These impacts can often be avoided or reduced by careful planning but it is difficult to incorporate consideration of the visual effects of a prescription into the planning process. This has led to the development of software tools that give feedback to treatment designers on how decisions might affect the appearance of a landscape. Pictures derived from these tools have been found to be useful in both planning prescriptions, and in gauging the public's reaction to a proposed treatment before it is implemented (Bergen and others 1992).

Perhaps the most succesful computer terrain visualization tool developed to date has been Vantage Point (Fridley and others 1991), developed at the University of Washington Cooperative for Forest-Systems Engineering. Vantage Point is a highly integrated environment for creating visual simulations of forested landscapes. It has the capability to incorporate topographic and stand-related information into a rendering system to produce high-quality images showing landform, trees, roads, and cut areas. The software also has domain-specific knowledge of how trees grow and can use this to generate time-sequenced images of a series of treatments.

Although Vantage Point is a powerful design tool, it is currently available only for a specific workstation-class platform. Other tools are more widely available. SmartForest, for example, developed at the University of Illinois Landscape Architecture Department's Imaging Lab, runs on a variety of Unix-based workstations. UVIEW is PC-based and is a geographic analysis software package developed by the USDA Forest Service that includes some landscape rendering capabilities. At present, however, these alternatives are designed primarily for purposes other than landscape visualization and their output quality cannot duplicate that of Vantage Point.

The need exists for a visualization tool that provides output renderings of acceptable quality, and that is available for use on a variety of hardware/operating system platforms. Such a system should be inexpensive, be flexible enough to interface with any number of data sources, particularly GIS, and should be relatively simple to operate. This paper reports on the development of such a system that, although it does not duplicate the full functionality of Vantage Point, it does produce high-quality renderings of forested landscapes.

DESIGN OBJECTIVES

The visualization system was conceived as a means of achieving two related functions: (1) to provide feedback to logging engineers on the visual impacts of cutblock boundary changes when designing treatments, and (2) to create images that could accurately convey to the public the results of the engineer's design decisions. As a design tool, producing images should be fast and simple enough so that a sufficient number of alternatives can be evaluated within a treatment design cycle. The system should also interface smoothly with a GIS to easily access topographic, unit boundary, and stand data. As a tool for informing the public on treatment decisions, output images should be realistic with respect to boundary placement, residual stand density, landform, and other visual cues an observer might use in judging the scenic beauty of a landscape.

The primary development objective for the system was that it should be reasonably simple to use and available for as wide an array of computer platforms as possible. This required designing to a "least common denominator" and development efforts therefore concentrated mainly on functional aspects as opposed to user interface concerns. Although the user interface was not considered a primary feature of the system, the various components were kept fairly consistent in their usage. Finally, because there was a great deal of previously developed software freely available, it was decided to use public domain programs to as great an extent as possible.

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SYSTEM DEVELOPMENT

From a software development standpoint, the most difficult part of creating a landscape viewing system is building the rendering engine, the program that calculates the interaction between “lights” and “objects” in a virtual “world,” and creates a depiction of the scene based on its results. Fortunately, several rendering systems have been developed and are in the public domain. Of those available, the POVRAY ray tracer is available for nearly every computer platform that exists, is actively used by thousands worldwide, and is under continuous development by a group of very talented people. POVRAY is a powerful ray tracer that uses a very general scripting language as its input, includes many standard and prebuilt objects and textures, can model a large set of graphics primitives and do constructive solid geometry with most (for example, do intersections or unions between two objects), and can model atmospheric attenuation and particle-induced scattering (haze, smoke, or fog). Because of its flexibility, power, and availability, POVRAY was chosen as the rendering engine of our landscape visualization system. The remaining components of the system were designed to provide the data necessary to drive the rendering engine and included tools for terrain and object (for this application, tree) modeling.

Terrain data is available in many digital forms, most commonly as U.S. Geological Survey Digital Elevation Models (DEM’s). A DEM is a matrix of elevations arranged in row echelon, and is sometimes referred to as a heightfield. Heightfields are discrete in nature, but for locating objects on its surface we need a method of interpolating between the grid points. There are, again, multiple means of interpolating heightfields, but we chose the triangulated irregular network (or TIN) as our preferred method. TIN’s can significantly reduce the amount of data required to represent smooth surfaces, they are continuous (except along triangle intersection lines) and use planar facets, making it simple to calculate surface object locations. Since most topography data exists as DEM’s, however, a method was needed to convert this type of data to a TIN. Again this problem has been solved and the tools placed in the public domain. A package known as scape, developed by Paul Heckbert and Michael Garland at Carnegie Mellon University, was chosen to fulfill this task in our system (Garland and Heckbert 1995).

Rendering trees requires some notion of where on the landscape trees should and should not be, and what they should look like. Our contributions to the visualization package were in developing tools to integrate the various components, and in developing methods for efficiently drawing and placing trees on the landscape. Two assumptions were made concerning tree locations in developing the methods: (1) trees were assumed to be objects uniformly distributed within any given polygon, and (2) locations of individual trees were assumed to be independent of all others regardless of species or age. With this model, only a density and polygon boundary are necessary to generate object locations. Assigning an object type (tree, for example) and object characteristics (species and age) to locations is done separately and can make use of positional information in classifying them. Species may vary with elevation, for example, and methods are provided to assign characteristics based on height above a reference plane.

SYSTEM USAGE

Table 1 lists a sequence of steps necessary to create a rendered image of a landscape, and the programs used in each step. The system is intended to be used in conjunction with a GIS for maintaining stand, DEM, and polygon data. We are currently using the GRASS GIS for data storage, and translation utilities have been developed to convert output data into intermediate formats understood by the system programs. Using another GIS would require development of a similar set of utilities.

DISCUSSION

The visualization package was designed to meet two particular goals: that it provide a design tool for logging engineers to evaluate prescriptions for their visual impacts; and that it produce images that accurately convey a sense of how a given prescription would look if implemented. Testing of the system by outside users has not been

Table 1—Steps and tools used in creating a rendered landscape image

Step	Software	Input requirements	Output
1. Data assembly	GIS		DEM, view points, stand polygons, tree species and age info
2. Create TIN	scape	raster DEM	List of triangle vertices
3. Add vertex normals	normcalc	TIN	TIN with vertex normals, in intermediate format
4. Add trees	lt cutpoly	TIN, stand polygons, # of trees	List of x, y, z coordinates tree locations
5. Convert TIN to POV-Ray	gs2pov	TIN, surface texture Info	POV-Ray object with textures assigned to triangles
6. Assign species, age to trees	trees2pov	Tree types, sizes	A list of “tree” objects for inclusion in POV-RAY
7. Render	POV-Ray	Control script, tree definitions	24-bit color image of landscape

conducted so it is difficult to draw conclusions on how well the system meets these goals. Some preliminary observations based on a trial study by our research unit, however, indicate that it can potentially do both given that the user is aware of specific problems.

Data from a study on alternative silvicultural prescriptions in upland hardwood management were used as a test case. An objective of the study was to measure the difference in visual impact due to prescription based on viewer preferences. Because of space constraints, the prescriptions could not be implemented on a large scale. It was felt that viewer response to the actual treatment plots would not accurately reflect their feelings about large-scale implementation of the prescriptions, so the visualization system was used to produce images showing the treatments applied across a large hillside.

The study site was in northern Alabama near the Bankhead National Forest. A sequence of images was created to duplicate the view from an observation point across a narrow valley looking toward the hillslope where the treatments were installed. Figures 1 through 3 are a series of images created using the visualization system and show the hillslope in an uncut state, with a 72-acre clearcut, and with 43 acres removed as three 150 ft-wide strips following the terrain contour.

Suitability as a Design Tool

Based on experience in developing the images in figures 1 through 3, problem areas were identified that might limit the utility of the visualization system. One was the lack of true integration between the system components. Although this was not generally a problem, lack of integration forces the user to be familiar with the workings of several independent programs and the data formats, and idiosyncracies, of each. An example of this type of problem was the inconsistency in how scaling of data was handled by the various system programs. For example, the TIN generation tool takes as input a DEM that is a form of raster. A raster format is assumed to be on a uniform grid and, therefore, no x,y coordinate data are included. This means, however, that scaling information is lost—the output TIN covers an mXn grid, where m and n are the number of rows and columns of the input DEM. This shortcoming is easily fixed by simply multiplying the output TIN x and y coordinates by the DEM scale. It does illustrate, however, the degree of familiarity with the system that is required, and the need for the user to direct the flow of correct information between the system components.

Generating images using the system was a data-intensive process. For the 4 alternatives evaluated in our study, a total of 11 data files were needed: a control script to drive the renderer (~0.6K bytes in size), a file defining how trees were to be drawn (1.2K), plus images of trees (in our case, 6, each about 12K), the topography TIN (600K plus foreground and cut area texture image files, each about 15K), and lists of tree locations (unique to each image, ranging from 3970K to 4540K in size—49,759 to 56,850 trees). Although the system required about 5000K of data

Figure 1—Example application of the visualization system. Rendered view of a hillside in an uncut state.

Figure 2—Identical view as in figure 1, but with a 72-acre clearcut imposed.

Figure 3—Identical view as in figure 1, but with a 43-acre strip clearcut imposed.

to create a single image, no integrated tools were provided to manage it. Again, this was not a limiting problem, but required methodical documentation of the steps taken to keep track of file locations.

The use of a general-purpose rendering engine meant that there was a significant amount of time spent in learning to use it. A degree of familiarity with the syntax and capabilities of POVRAY is needed to create the script file defining viewpoints, camera direction, lighting, and other object characteristics. This can only be gained from reading the large amount of documentation supplied with POVRAY, and by actually using it.

Creating realistic trees was the most difficult part of using POVRAY. Trees themselves are complex 3D objects, and it was difficult to capture that complexity in such a way that enough trees could be included in the scenes without exceeding the memory constraints of the computer system. Initially, trees were modeled as cylindrical trunks with a 3D polygonal canopy. It was found, however, that only about 3,000 of these trees could be placed in the scene before the virtual memory capacity of our workstation was exceeded. The circumstances in our test case required about 50,000 trees be included, so another type of tree had to be used. Our solution to this problem was a transparent, zero-thickness box with a picture of a tree painted on it. POVRAY had no problem handling 57,000 of these "flat" trees (~47M bytes virtual memory peak usage), and they appeared as visually complex as a real tree as long as they were viewed from an adequate distance. Images with trees in the foreground, however, might require a different approach.

As a design tool, application of the visualization system was constrained primarily by the familiarity of the user with POVRAY. Once the details of the rendering process were worked out, time on the part of the user to create an image was on the order of a few hours from start to finish. If the design goal is selecting among alternative cut unit boundaries, the image creation process is greatly simplified after the first, and the time per picture is reduced to essentially the time to render. Rendering times for an image like those in the figures averaged a little over 60 minutes on a SUN workstation at 600 x 400 resolution. Increasing resolution had the most dramatic effect on rendering times—a 2048 x 1536 image took 9 hours 36 minutes to complete. Adding atmospheric scattering effects increased rendering times by a factor of 3.

Quality of the Images

Bergen and others (1993) compared observer response to computer-generated and photographic images of a particular viewshed. Their results indicated that, as long as elements that are important in forming an opinion about a scene are preserved, computer-generated images are suitable as a basis for gauging public opinion about a silvicultural treatment. The most important visual cue in these images was topography. Examination of the rendered images and several photos taken from observation points showed that there were some small differences between the generated terrain and the actual. The differences were mainly visible along the ridge top, with the rendered scene showing more relief than was truly present. This was likely due to inaccuracies in the input DEM, but this has not been verified. Accuracy of the trees in the rendered images could also be improved. As stated before, trees were "painted" on transparent boxes to create the scenes. The tree images used in the process were more like clip-art, and greater realism in the final renderings would be possible if scanned photos of canopy-grown hardwoods were used.

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