Multitemporal Analysis Using Landsat Thematic Mapper (TM) Bands for Forest Cover Classification in East Texas

Jason C. Raines, Jason Grogan, I-Kuai Hung, and James Kroll

ABSTRACT

Land cover maps have been produced using satellite imagery to monitor forest resources since the launch of Landsat 1. Research has shown that stacking leaf-on and leaf-off imagery (combining two separate images into one image for processing) may improve classification accuracy. It is assumed that the combination of data will aid in differentiation between forest types. In this study we explored potential benefits of using multidate imagery versus single-date imagery for operational forest cover classification as part of an annual remote sensing forest inventory system. Landsat Thematic Mapper (TM) imagery was used to classify land cover into four classes. Six band combinations were tested to determine differences in classification accuracy and if any were significant enough to justify the extra cost and increased difficulty of image acquisition. The effects of inclusion/exclusion of the moisture band (TM band 5) also were examined. Results show overall accuracy ranged from 72 to 79% with no significant difference between single and multidate classifications. We feel the minimal increase (3.06%) in overall accuracy, coupled with the operational difficulties of obtaining multiple (two), useable images per year, does not support the use of multidate stacked imagery. Additional research should focus on fully utilizing data from a single scene by improving classification methodologies.

Keywords: remote sensing, unsupervised classification, pixel-based classification, land cover mapping

Satellite imagery has been used to monitor land resources and land cover/land-use change since the launch of Landsat 1 in 1972. Medium resolution imagery such as Landsat and Systeme pour l'Observation de la Terre covers a large geographic footprint, permitting (1) production of land cover maps at considerably less cost than traditional field methods and (2) producing maps in a repeatable manner on a much more regular cycle (Rack 2000, Bauer et al. 2004). Typically, land cover maps are produced using image classification procedures. The product of these classifications—the cover type map—can be used to monitor landscape change from total harvest operations, fires, or outbreaks of insects or disease, as well as to determine the distribution of various cover types (Bonn and Howarth 1983, Beaubien 1994, Jensen 2005). Additional analysis of land cover maps can aid in obtaining biometric measurements (when used alongside other data sources) and forest age class assessments and monitoring change in the landscape over time (Unger et al. 2003). Results from these analyses depend greatly on the accuracy of the initial classification and can be improved on by improving the accuracy of initial classification.

Unsupervised classification is a method used commonly by analysts when prior knowledge of the area is limited. This method allows the computer to assign each pixel of the input image into an output cluster using natural breaks in the data without interference from the analyst. The analyst then must assign each cluster into a meaningful class using reference data, generally high-resolution aerial photography, or high-resolution satellite imagery, to produce a cover type map (Campbell 2002). This study focuses specifically on producing a forest cover type map.

Several advantages and disadvantages have been identified when using unsupervised classification methods (Campbell 2002). The analyst does not need any prior knowledge of the region to perform the classification. However, the analyst must have enough knowledge of the region to classify the output clusters into meaningful classes. The analyst also limits the amount of human error introduced into the classification procedure due to the lack of input into the classification procedure besides specifying the number of output clusters. Unsupervised classification also allows for recognition of unique classes that may be missed or lumped into other classes when other classification methods are used. One limitation of unsupervised classification is that this methodology identifies spectrally homogenous classes that may not correspond to meaningful classes of interest to the analyst. The analyst has little control over the identity of each class, which can be very important when trying to match classifications for adjacent regions or similar dates. The spectral properties of an area can and will change over time, affecting the difference between spectrally similar classes as well as classes of interest to the end user.

Often, cover type maps are created from multidate composite images, which are needed to separate the spectral signatures of classes of interest to the user (Rack 2000, Campbell 2002). Although cover type classifications have been created using multidate and leaf-on only imagery, it may be possible to get statistically similar accuracies for a more detailed classification using leaf-off

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Jason C. Raines (rainesjason@titan.sfasu.edu) and Jason Grogan (jgrogan@sfasu.edu), Columbia Regional Geospatial Service Center, Stephen F. Austin State University, PO Box 13074, SFA Station, Nacogdoches, TX 75961. I-Kuai Hung (hungi@sfasu.edu), Arthur Temple College of Forestry, Stephen F. Austin State University, PO Box 6109 SFA Station, Nacogdoches, TX 75962. James Kroll (jkroll@sfasu.edu), Columbia Regional Geospatial Service Center, Stephen F. Austin State University, PO Box 13074, SFA Station, Nacogdoches, TX 75962. *This project was funded in part by the Columbia Regional Geospatial Service Center, Arthur Temple College of Forestry and Agriculture and an appropriation from the State of Texas. We would like to thank the three anonymous reviewers for their comments, which improved the quality of this manuscript.*

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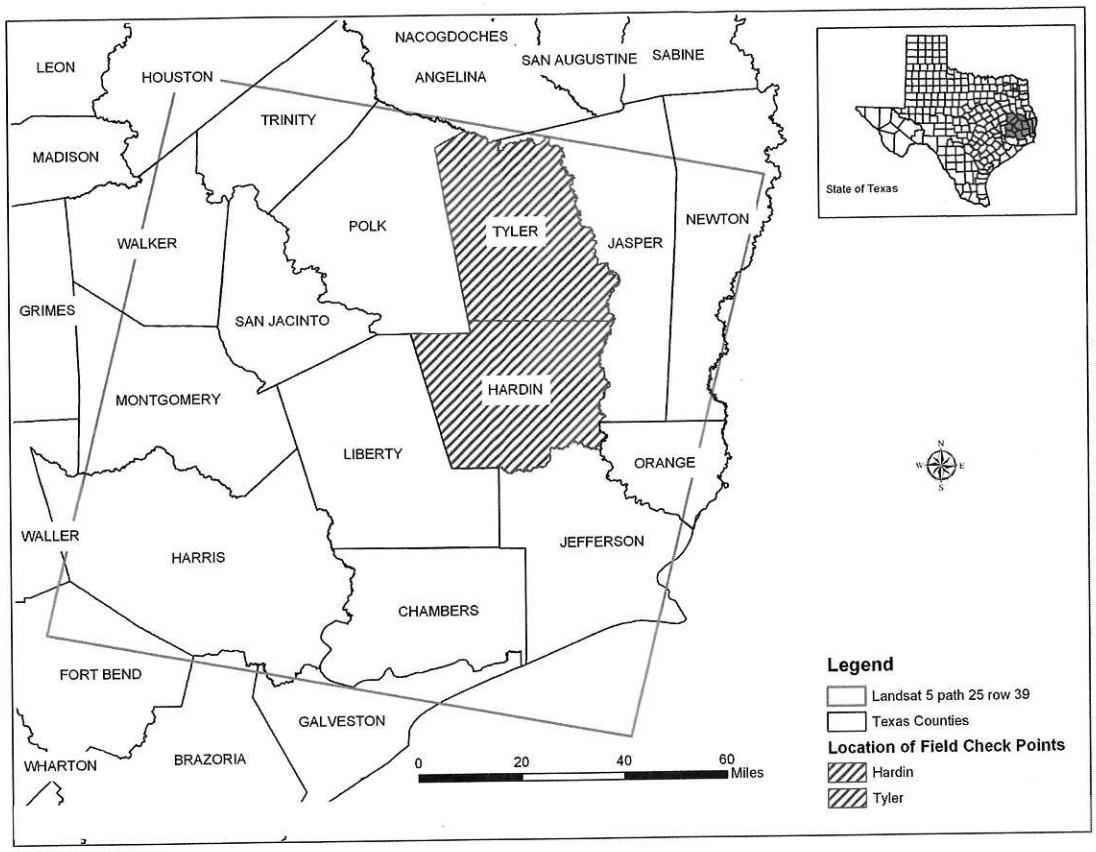


Figure 1. Study area for the ETFI—South Project.

imagery only (Dodge and Bryant 1976, Fox et al. 1983, Bauer et al. 1994, Sivanpillai et al. 2005). Six east Texas counties were successfully stratified into forest and nonforest areas in 2005 using Landsat 7 Enhanced Thematic Mapper (ETM) imagery and unsupervised classification methodologies (Sivanpillai et al. 2005). The results from this study compared favorably with Forest Inventory and Analysis phase 1 methods currently in use.

One of the initial goals of the East Texas Forest Inventory (ETFI) Project was to classify current forest composition by cover types (Unger et al. 2003). The same methodology used in the initial ETFI Project was expanded into the "flatwoods" area of southeast Texas. During our attempts to produce forest cover type maps for this area, concerns over high water table/excessive soil moisture confounding the classification were noted. Because of large amounts of flooded timber and saturated soils, Landsat TM band 5 (mid-infrared (MIR)—the moisture band) may be introducing a "normalizing" effect on the data when classified, resulting in a decrease in accuracy for the resulting cover type map. Therefore, it may be possible to achieve better accuracy of a forest cover type map by excluding the moisture band(s). Furthermore, stacking multiple scenes may exacerbate the normalizing effect by "doubling" the moisture band.

Objectives

The main goal of this study was to find the most efficient methodology of producing an accurate land cover map of southeast Texas in an applied, operational setting, which consisted of three primary objectives. The first objective was to determine whether a leaf-off only or a stacked leaf-off–leaf-on Landsat TM image will result in greater accuracy when classifying forest cover types. The second was to determine if including or excluding the moisture layer (band 5) from stacked or leaf-off only TM imagery will result in greater overall accuracy. The third objective was to find any differences in classification accuracy between the six band combinations tested, to determine the most effective methodology for creating forest cover type maps of east Texas on an annual basis. The key issue here was determining a classification methodology that is highly accurate and can be consistently applied annually to the best available data. Past studies have examined the use of multidate stacks based on "ideal" circumstances, rather than the reality of difficulties of annually obtaining multiple, usable images.

Study Area

The study area was based in a single Landsat TM scene (path 25, row 39). This scene contains, partially or completely, the following Texas counties in the study area: Angelina, Hardin, Houston, Jasper, Liberty, Montgomery, Newton, Orange, Polk, San Jacinto, Trinity, Tyler, and Walker counties—referred to as southeast Texas (Figure 1). Southeast Texas is dominated by industrial and nonindustrial pine plantations (*Pinus* spp.), upland pine-hardwood communities (*Pinus* spp., *Quercus* spp., *Carya, Sassafras*, and *Ulmus*), and bottomland hardwood forests (*Quercus* spp., *Acer*, *Betula*, *Magnolia*, *Ilex*, and *Fraxinus*) along creeks, rivers, and swamps (Nixon and Cunningham 1985). Farmland and prairies also comprise a small portion of the landscape. Elevation ranges from 30 to 400 ft (9–122 m) above mean sea level with average summer temperatures around 94°F (34°C) and average winter temperatures around 40°F (4°C). Precipitation averages between 40 and 50 in. (102–127 cm) per year with a growing season lasting 241–246 days (University of Texas at Austin/Texas State Historical Association 2007).

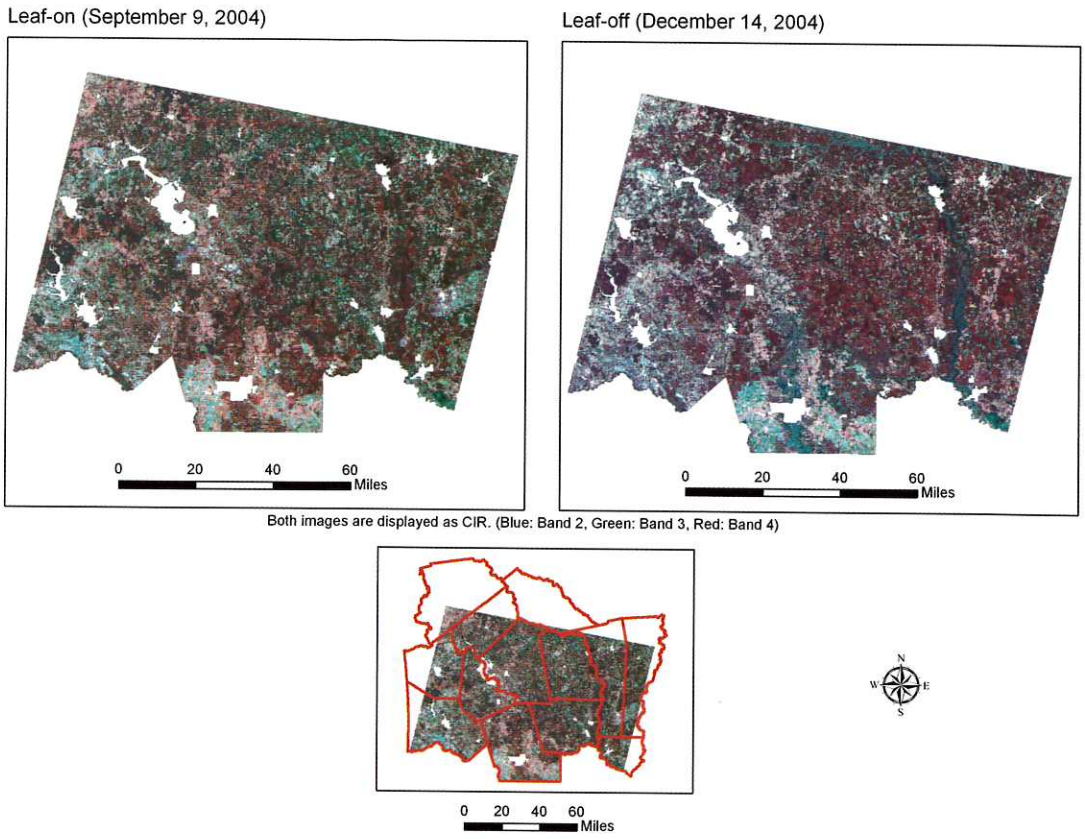


Figure 2. Landsat imagery used to perform forest cover classification analysis after preprocessing.

Methods

Landsat TM imagery from two acquisition dates was used in this study (Sept. 9, 2004 as leaf-on and Dec. 14, 2004 as leaf-off), which were acquired from the USGS Earth Resources Observation and Science Data Center. ERDAS Imagine 8.7 (Leica Geosystems AG, St. Gallen, Switzerland) and ArcGIS 9.1 (Environmental Systems Research Institute, Inc., [ESRI] Redlands, CA) software were used for image processing purposes. Radiometric correction was performed via dark object subtraction to remove atmospheric haze and environmental noise from both scenes (Campbell 2002, Jensen 2005). Some clouds present in the leaf-on image were removed by manual digitization. These areas were replaced using another leaf-on Landsat TM image acquired on Nov. 11, 2003. The Gulf Coastal Prairie and Houston metropolitan areas were removed from both scenes because these areas are not of interest in this study and could introduce bias and confusion into the classification. Other urban areas inside the study area were removed as well using a vector layer from the Texas Natural Resources Information System created by the Strategic Mapping Program (StratMap). Water bodies were removed using a vector layer from the National Hydrography Dataset. Figure 2 shows both Landsat TM scenes after preprocessing.

Once preprocessing was completed, six band combinations were created (Table 1), tested, and analyzed using ERDAS Imagine 8.7 software. Band combinations were selected based on combinations of leaf-on and leaf-off imagery that included and excluded the moisture layer—TM band 5 (Campbell 2002). Previous studies have delineated forest cover types with TM band 7 (second MIR band) excluded, and also with leaf-off only Landsat imagery; therefore, TM band 7 was not included in any combination, and no leaf-on only combinations were tested (Londo et al. 2000, Collins et al. 2005). Each band combination went through an unsupervised classification using the Iterative Self-Organizing Data Analysis algorithm to obtain 100 unknown clusters of pixels (ERDAS 2006). Then, each cluster was recoded into one of four cover type classes (pine forest, hardwood forest, mixed pine-hardwood forest, and nonforest) using nine 2004, leaf-off, high-resolution aerial photographs purchased from the Texas Forest Service as a visual reference. All band combinations were classified and recoded by the same analyst to eliminate skill level differences between multiple analysts. Class description was determined using an 80% majority coverage rule. That is, if hardwood or pine canopy covered 80% or greater of a pixel area, the pixel was coded as pure hardwood or pure pine, respectively. A forested pixel was classified as mixed pine-hardwood if neither pine nor hardwood canopy occupied more than 80% of the pixel area (Collins et al. 2005).

To determine accuracy of the classified images, field check points were selected based on a stratified random sample with a minimum

Table 1. Landsat TM band combinations tested on southeast Texas for forest cover type classification.

Band combination	Bands		Total number of bands
	Leaf-off	Leaf-on	
A	1–4		4
B	1–5		5
C	1–4	1–4	8
D	1–4	1–5	9
E	1–5	1–4	9
F	1–5	1–5	10

Band 1: blue-green, 0.45–0.52 μm; band 2: green, 0.52–0.60 μm; band 3: red, 0.63–0.69 μm; band 4: near infrared, 0.76–0.90 μm; band 5: midinfrared, 1.55–1.75 μm (Campbell 2002)

Table 2. Accuracy assessment for band combination A (bands 1–4 leaf-off).

Classified Data Class	Reference data				Total	User's (%)		Kappa (%)
	Nonforest	Pine	Hardwood	Mixed				
Nonforest	39	3	1	0	43	90.70		89.07
Pine	0	114	6	13	133	85.71		70.99
Hardwood	0	5	33	7	45	73.33		65.92
Mixed	0	11	17	13	41	31.71		21.87
Total	39	133	57	33	262		Overall	
Producer's (%)	100.00	85.71	57.89	39.39		75.95		63.61

Table 3. Accuracy assessment for band combination B (bands 1–5 leaf-off).

Classified Data Class	Reference data				Total	User's (%)		Kappa (%)
	Nonforest	Pine	Hardwood	Mixed				
Non-forest	39	4	1	2	46	84.78		82.12
Pine	0	118	10	14	142	83.10		65.67
Hardwood	0	2	25	4	31	80.65		75.26
Mixed	0	9	21	13	43	30.23		20.18
Total	39	133	57	33	262		Overall	
Producer's (%)	100.00	88.72	43.86	39.39		74.43		60.80

Table 4. Accuracy assessment for band combination C (bands 1–4 leaf-off and bands 1–4 leaf-on).

Classified Data Class	Reference data				Total	User's (%)		Kappa (%)
	Nonforest	Pine	Hardwood	Mixed				
Nonforest	39	6	1	1	47	82.98		80.00
Pine	0	116	2	10	128	90.63		80.96
Hardwood	0	2	46	16	64	71.88		64.05
Mixed	0	9	8	6	23	26.09		15.44
Total	39	133	57	33	262		Overall	
Producer's (%)	100.00	87.22	80.70	18.18		79.01		68.25

Table 5. Accuracy assessment for band combination D (bands 1–4 leaf-off and bands 1–5 leaf-on).

Classified Data Class	Reference data				Total	User's (%)		Kappa (%)
	Nonforest	Pine	Hardwood	Mixed				
Nonforest	39	14	1	0	54	72.22		67.36
Pine	0	107	3	9	119	89.92		79.52
Hardwood	0	1	38	11	50	76.00		69.33
Mixed	0	11	15	13	39	33.33		23.73
Total	39	133	57	33	262		Overall	
Producer's (%)	100.00	80.45	66.67	39.39		75.19		63.43

of 30 points in each class (Congalton and Green 1999). A total of 262 points were created in Tyler and Hardin counties. Field check plots were located using an Archer field computer by Juniper Systems (Juniper Systems, Inc., Logan, UT) with ArcPad software (ESRI) and a Geneq SXBlue global positioning systems receiver (Geneq, Inc., Montreal, QB, Canada). Cover type of each plot was determined in the field during the summer of 2006. Normally, very little change in cover type occurs over a short time period (1–2 years); however, in areas where obvious change had occurred, attempts were made to reconstruct 2004 conditions. Accuracy assessment was performed using the accuracy assessment tool present in ERDAS Imagine 8.7.

Kappa-analysis was performed to determine statistically if error matrices were different from one another (Congalton and Green 1999). Additional statistical testing, focusing on the binary distinction between correct and incorrect reference point classification was performed using the McNemar test (Foody 2004, Leeuw et al. 2006). This test has been used in remote sensing to determine significant differences between two thematic maps when the same set of reference points was used to determine accuracy. All statistical calculations were performed at the 90% confidence level ($\alpha = 0.1$).

Results

Accuracy assessment showed each band combination had an overall accuracy of between 72 and 80% and overall kappa-values between 59 and 69%, indicating moderate agreement between the classified data and the reference data (Congalton and Green 1999). Tables 2–7 show the error matrices for each band combination. These tables also show where many of the misclassification errors occurred. The most common source of misclassification was in the mixed class, which had by far the lowest average accuracy. Pine accuracy generally was over 80%, indicating good separation of pine pixels from others by the unsupervised classification. *Z*-scores were calculated for each individual band combination to determine whether or not results of the classification were better than random chance. *Z*-scores ranged from 15.4 to 18.97, and when compared

Table 6. Accuracy assessment for band combination E (bands 1–5 leaf-off and bands 1–4 leaf-on).

Classified Data Class	Reference data						
	Nonforest	Pine	Hardwood	Mixed	Total	User's (%)	Kappa (%)
Nonforest	39	4	1	1	45	86.67	84.33
Pine	0	108	4	11	123	87.80	75.23
Hardwood	0	2	45	10	57	78.95	73.09
Mixed	0	19	7	11	37	29.73	19.60
Total	39	133	57	33	262	Overall	
Producer's (%)	100.00	81.20	78.95	33.33		77.48	66.44

Table 7. Accuracy assessment for band combination F (bands 1–5 leaf-off and bands 1–5 leaf-on).

Classified Data Class	Reference data						
	Nonforest	Pine	Hardwood	Mixed	Total	User's (%)	Kappa (%)
Nonforest	39	6	1	1	47	82.98	80.00
Pine	0	102	3	8	113	90.27	80.23
Hardwood	0	1	35	11	47	74.47	67.37
Mixed	0	24	18	13	55	23.64	12.63
Total	39	133	57	33	262	Overall	
Producer's (%)	100.00	76.69	61.40	39.39		72.14	59.55

Table 8. Results of kappa-analysis for the comparison of six band combinations using the delta-method (tested at $\alpha = 0.10$).

	Band combinations				
	B	C	D	E	F
A	0.5147 (0.6068)	0.8835 (0.3770)	0.0347 (0.9723)	0.5284 (0.5972)	0.7493 (0.4537)
B		1.4066 (0.1595)	0.4849 (0.6277)	1.0455 (0.2958)	0.2304 (0.8177)
C			0.9279 (0.3534)	0.3504 (0.7261)	1.6531 (0.0983)
D				0.5686 (0.5696)	0.7216 (0.4706)
E					1.2857 (0.1985)

Z-value (*P*-value).

Table 9. Results of McNemar test for the comparison of six band combinations (tested at $\alpha = 0.10$).

	Band combinations				
	B	C	D	E	F
A	0.5000 (0.4795)	1.5238 (0.2170)	0.1667 (0.6830)	0.5000 (0.4795)	2.7778 (0.0956)
B		2.7692 (0.0961)	0.0909 (0.7630)	1.6000 (0.2059)	0.9000 (0.3428)
C			2.9412 (0.0863)	0.4000 (0.5271)	8.1000 (0.0044)
D				1.3846 (0.2393)	2.1333 (0.1441)
E					6.5333 (0.0106)

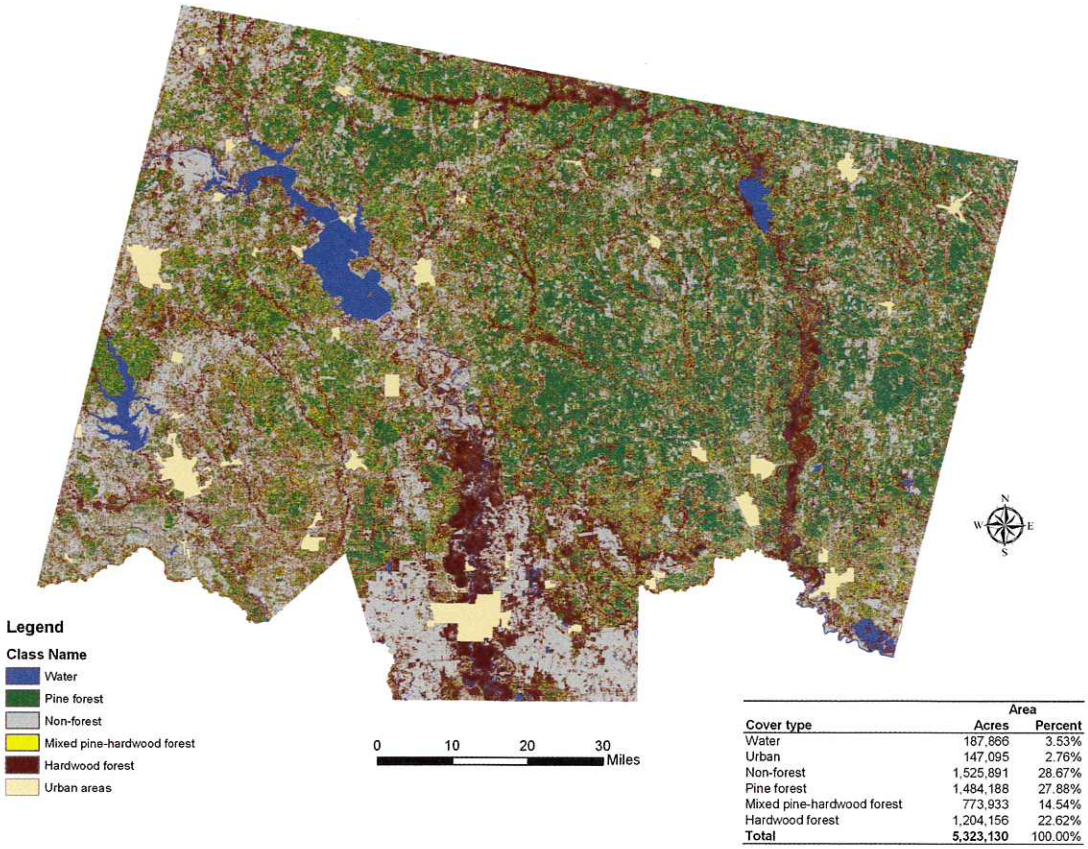
Chi-square value (*P*-value).

with a critical *Z*-value of 1.6449, indicate all the classified images were classified better than random.

Statistical analysis performed using pairwise comparison methodologies is shown in Tables 8 and 9. Band combinations were compared two at a time for a total of 15 statistical comparisons. A statistically significant difference is present if the *Z*-value is greater than 1.6449 ($P < 0.1$) for the kappa-analysis or a chi-square value of 2.706 ($P < 0.1$) for the McNemar test. The only band combinations that showed any statistically significant difference using kappa-analysis was between combination F (bands 1–5 leaf-off with bands 1–5 leaf-on) and combination C (bands 1–4 leaf-off with bands 1–4 leaf-on). In this case, combination C produced a significantly better forest cover type classification than combination F. Figure 3 shows the forest cover type classification produced by band combination C, which had an overall classification accuracy of 79.01%. Using the McNemar test, a total of six band combination comparisons were found to have significant differences (Table 9). Based on this test, combinations A, E, and F produced statistically superior results (overall accuracies of 75.95, 77.48, and 79.01%, respectively) to other combinations. Combinations B, C, and D all produced statistically inferior results to at least one of the aforementioned band combinations.

Discussion

The large majority of misclassification occurred within the mixed pine-hardwood cover type class. This could be for several reasons. One reason could be not enough initial clusters were created to discriminate between over 80% majority coverage and under 80% majority coverage. Misclassification in the mixed forest category could be caused by a lack of enough aerial photographs acquired for reference data to provide an accurate representation of the entire study area for recoding the original clusters. All mixed forest classification errors were split almost evenly between pine and hardwood classes, which indicate neither pure cover type was biased over the other.



Cover type	Area Acres	Percent
Water	187,866	3.53%
Urban	147,095	2.76%
Non-forest	1,525,891	28.67%
Pine forest	1,484,188	27.88%
Mixed pine-hardwood forest	773,933	14.54%
Hardwood forest	1,204,156	22.62%
Total	**5,323,130**	100.00%

Figure 3. Forest cover type map resulting from band combination C (79.01% overall accuracy).

The moisture band (TM band 5—MIR) did tend to have a normalizing effect on pixels representing forested areas when unsupervised classification was conducted. Initially, a total of 100 clusters were generated. When moisture bands were included, the first 20–25 clusters represented pine pixels, the middle 40–50 clusters represented hardwood and mixed forest pixels, and the last 25–30 clusters represented nonforest pixels. In comparison, when the moisture bands were removed, as in combinations C and A, the first 65–75 clusters represented all three types of forest cover pixels and the last 20–30 clusters represented nonforest pixels. This indicates a normalizing effect on the unsupervised classification occurred when the moisture bands were included in the analysis. However, excluding the moisture bands only significantly increased accuracy when using a multidate composite image, where both moisture bands were excluded, but not when using a single-date image.

The multidate composite combinations failed to increase accuracy significantly when compared with the leaf-off only combination with the moisture band (band 5) removed. Therefore, increased cost in terms of imagery needed and processing time by the analyst may not be justified (Table 10). Using only a single leaf-off image to produce a forest cover type map of southeast Texas eliminates the need to find multiple cloud-free images for the same year, which in some years can be very difficult, if not impossible. Also, it eliminates the need for the preprocessing of an extra image, or in the case of this study, two extra images. The use of a single-date image of four bands (combination A) also decreases time required by the analyst for preprocessing procedures, storage space, and processing requirements of the computer used to complete the task. Besides reduced cost and preprocessing requirements, another main advantage of using only a single image is the ability to capture the conditions of an area at a single point in time. This can be a major advantage for change detection studies in areas that are rapidly changing, where a multidate image could potentially introduce significant error.

Table 10. Budget comparison of 2004 forest cover type classifications in southeast Texas using Landsat TM imagery.

Costs	Date	Price
Leaf-off only		
5025039000434910	Dec. 14, 2004	$500.00
Analyst costs (55 hr)[a]		$1,084.05
Total		$1,584.05
Stacked		
5025039000434910	Dec. 14, 2004	$500.00
5025039000425310	Sept. 9, 2004	$500.00
5025039000331410[b]	Nov. 11, 2003	$500.00
Analyst costs (70 hr)[a]		$1,379.70
Total		$2,879.70
Total saved using leaf-off only versus stacked		$1,295.65
Percent savings using leaf-off versus stacked		55.01%

[a] Rate based on $41,000/yr salary (salary.com, Inc. 2007).
[b] Used to replace cloud areas in 5025039000425310.

Conclusions

Landsat TM data using various band combinations can be used successfully to discriminate between forest cover types in southeast Texas. However, a single leaf-off Landsat TM scene can produce statistically similar results as multidate composite Landsat TM images when classifying forest cover type. This translates into tremendous savings in image acquisition, analysis, and analyst time and effort required for processing. These savings, when considered as a

single instance, may seem insignificant. However, in an operational, annual inventory system, savings could be tremendous over just a few years. Also, often times, it is difficult to obtain a single useable Landsat scene annually, and in many years multiple cloud-free scenes simply are not available. The success of an operational truly annual system only can be achieved when necessary imagery is available annually. With statistically similar accuracies between single and multidate classifications, truly annual updates seem more likely to be a reality with single-date imagery. The methodology used here could allow analysts to produce a forest cover type map on an annual or biannual basis, which could help natural resource managers and policymakers make decisions based on current information. In fact, data from the ETFI project already have been used to monitor annual change (harvesting and reforestation) from 2002 to 2006 for a different study area. In addition, results show that the moisture band (Landsat TM band 5) can be excluded in areas with saturated and/or flooded soils without significant change in accuracy.

Additional studies should focus on several areas that are currently and continue to be researched. An objective methodology of determining cover type in the field should be standardized so it does not depend solely on the experience of the analyst. Other areas of research should and currently do focus on using elevation data (digital elevation model) and/or indices such as Normalized Difference Vegetation Index, Tasseled Cap transformation or other vegetation indices in combination with the Landsat TM data to enhance information already present in the satellite imagery. New object-oriented classifiers and supervised classification also should be researched to determine if there is any increase in accuracy when classifying forest cover type from Landsat data. Finally, we propose methods using data from a single TM image should be researched before adding additional bands (images), which potentially could confound the classification.

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The Southern US Forest Bioenergy Encyclopedia: Making Scientific Knowledge More Accessible

Jianbang Gan, H. Michael Rauscher, C.T. Smith, Sarah Ashton, Larry Biles, Daniel Cassidy, Darwin Foster, Matthew R. Howell, William G. Hubbard, Ben Jackson, Chyrel Mayfield, Donald J. Mead, Semida Silveira, and Eric Taylor

ABSTRACT

Production of forest biomass in sustainably managed forests in the southern United States has great potential to improve forest health, make energy supplies more secure, and increase the social and economic welfare of rural communities. The awareness and access of landowners and forestry and natural resource professionals to new knowledge and market development opportunities must be increased, and new technological advances in knowledge dissemination systems can be very useful in this connection. The *Encyclopedia of Southern Bioenergy* was developed within *The Forest Encyclopedia Network* (www.forestencyclopedia.net/) to facilitate the transfer of useable knowledge from scientific experts in bioenergy and bio-based products to natural resource professionals, landowners, and the general public. Using the encyclopedia as a base, a team of bioenergy and extension education experts has developed several new educational products. These materials are designed as components of an overall biomass training program for the South that is being disseminated through the Southern Regional Extension Forest network.

Keywords: forest biomass and bioenergy, Forest Encyclopedia Network, knowledge management, Southern United States, technology transfer

The United States has the opportunity to use biomass from sustainable, domestic plant resources to meet a significant portion of its fuel, power, and chemical needs (Perlack et al. 2005). The Biomass Research and Development Act of 2000, the Healthy Forests Restoration Act of 2003, and the Energy Policy Act of 2005 call for using domestic biomass resources to (1) improve our national strategic energy security, (2) create new jobs and new higher-valued products and technology, (3) significantly decrease the annual trade deficit, and (4) maintain the health and productivity of our forests. To accomplish these objectives, it will be necessary both to create new knowledge and to make the best possible use of what we already know.

We developed the Internet-based *Encyclopedia of Southern Bioenergy* (ESB) (www.forestencyclopedia.net/p/p2) to synthesize the best available published scientific knowledge about bioenergy in the southern United States. This article (1) introduces the ESB as a scientific knowledge management (KM) tool, (2) explains how the ESB was developed and peer reviewed, (3) summarizes what we learned about the status of bioenergy resources in the southern United States, and (4) discusses the strengths and weaknesses of the ESB approach and its future directions.

Using Hypertext Encyclopedias to Manage Scientific Knowledge

Delivering scientific knowledge to a diverse audience always has been a challenge. Typically, new knowledge is reported in peer-reviewed scientific journals intended primarily for other scientists to digest. This primary scientific knowledge is interpreted and synthesized for use by nonscientist audiences by a large and vibrant technology transfer/science delivery community. The process of science delivery aims to (1) synthesize scientific knowledge into larger, more meaningful units; (2) translate this knowledge into the language and style that appeals to a nonscientist audience; and (3) timely connect scientific conclusions and forecasts with the needs and issues of a nonscientist audience. Currently, the forest science community relies largely on conventional, print-based vehicles such as manager's handbooks, technology transfer bulletins, how-to leaflets, and journal articles written for natural resource managers and the lay public. Nonprint-based science delivery methods that also have been successfully used include lectures, workshops, videos, and field trips. With the recent widespread availability of extremely capable computer hardware and software and the Internet, electronic methods to supplement the conventional methods of science delivery have become practical.

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Jianban Gan (j-gan@tamu.edu), Department of Ecosystem Science and Management, Texas A&M University, College Station, TX 77843-2138. Michael Rauscher (mrauscher@fs.fed.us), US Forest Service, Southern Research Station, Asheville, NC. C.T. Smith (tat.smith@utoronto.ca), Faculty of Forestry, University of Toronto, Toronto, ON M5S 3B3, Canada. Sarah Ashton (sashton@warnell.uga.edu), Southern Regional Extension Forestry, Forestry Building 4-433, University of Georgia, Athens, GA 30602. Larry Biles (lbiles@warnell.uga.edu), Southern Forest Research Partnership, Inc., PO Box 6938, Athens, GA 30604-6938. Daniel Cassidy (dcassidy@csrees.usda.gov), Cooperative State Research, Education, and Extension Service, 1400 Independence Ave., SW, Stop 2210, Washington, D.C. 20250-2210. Darwin Foster (cdfoster@tamu.edu), Department of Ecosystem Science and Management, Texas A&M University, College Station, TX 77843-2138. Matthew R. Howell (mhowell@sref.info) and William G. Hubbard (hubbard@warnell.uga.edu), Southern Regional Extension Forestry, Forestry Building 4-433, University of Georgia, Athens, GA 30602. Ben Jackson (bjackson@warnell.uga.edu), Warnell School of Forestry and Natural Resources, The University of Georgia 30602-2152. Chyrel Mayfield (c-mayfield@tamu.edu), Department of Ecosystem Science and Management, Texas A&M University, College Station, TX 77843-2138. Donald J. Mead (don.mead@xtra.co.nz), PO Box 6, Collingwood, Golden Bay, New Zealand. Semida Silveira (semida.silveira@energy.kth.se), Energy and Climate Studies, School of Industrial Engineering and Management, KTH, Brinellvägen 68, 100 44 Stockholm, Sweden. Eric Taylor (eric-taylor@tamu.edu), Department of Ecosystem Science and Management, Texas A&M University, College Station, TX 77843-2138. *The authors are grateful to the USDA and DOE Biomass Development and Research Initiatives Program for funding this project (Grant 68–3A75-4-143).*

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Until fairly recently, many people did not think in terms of systematically "managing knowledge." They felt that knowledge was a personal asset accumulated from experiences, education, and trusted colleagues (Plunkett 2001). As computer technology improved and became cheaper in the early 1990s, researchers began to explore the gains that could be made by organizing knowledge, codifying it, and sharing it more widely. The field of KM slowly emerged. KM can be defined as a systematic strategy of creating, conserving, and sharing knowledge to increase performance (Plunkett 2001, Heinrichs et al. 2003). As the Internet became more popular, it was obvious to some that KM systems using web-based hypertext had an enormous competitive advantage over other science delivery methods. Universally available access and inexpensive updating make web-based KM an attractive alternative to traditional, paper-based methods. This realization led to a proliferation of web-based KM services for science delivery to the natural resource field (Rauscher et al. 2007).

One type of web-based KM site identified by Rauscher et al. (2007) is "the scientific content management site." Scientific content management sites attempt to improve the communication of research results to user audiences (Kennard et al. 2005). The cornerstone for high-quality scientific content management is the scientific literature, which contains published, peer-reviewed, primary research results. Sites that provide access to this literature in electronic format are called Library Service sites. A good example is the US Forest Service's TreeSearch system (www.treesearch.fs.fed.us).

Another scientific content management system (CMS) offers audience-specific versions of published scientific articles. For example, the Waldwissen project, a consortium of forest research institutes from Germany, Austria, and Switzerland, offers a collection of scientific research articles grouped by themes (www.waldwissen.net). Each of these articles has a summary written for a nonscientist audience by a professional science editor to make the article more interesting and more understandable. These summaries often are available in five languages: German, English, French, Italian, and Slovenian. In Waldwissen (2008), the granularity of the basic science article is maintained, meaning that several articles on the same topic such as "forest fire" are not synthesized by the site.

Finally, there are the encyclopedia sites that provide a seamless synthesis of the fragmented scientific literature. There are two versions of encyclopedia sites: those that are not peer reviewed and open to anyone to author new material such as the Bioenergy Wiki (www.bioenergywiki.net) and those that are peer reviewed and open only to accredited and vetted authors such as the ESB (biomass.forestencyclopedia.net). The advantages and disadvantages of each of these two approaches will be discussed in the Conclusion section of this article.

Developing the ESB

The ESB is one of six encyclopedia projects contained within the *Forest Encyclopedia Network* (FEN; www.forestencyclopedia.net). The FEN began in 2000 with funding from the USDA National Research Initiative Competitive Grant program to facilitate the transfer of useable knowledge from scientific experts to natural resource professionals, landowners, and the general public. The FEN was created as a collaboration of the US Forest Service Southern Research Station and the Southern Region Extension Forestry System. Each of these two originating organizations provides one member of an FEN Steering Committee. Each encyclopedia has a senior managing editor who is also a member of the FEN Steering Committee. It is the FEN Steering Committee, backed by the credibility of the Southern Research Station and the Southern Region Extension Forestry Office, which guarantees the effectiveness of the blind-peer-review system that provides the standard quality control mechanism for the published synthesized knowledge.

Each encyclopedia project that is a part of the FEN uses a customized CMS based on Zope, an open source web development environment (Learner 2002, Jordin et al. 2003). This customized CMS software simplifies web authorship and citation management, standardizes page design and display, enforces role-based security, and manages the flow of work from content creation through peer review, editing, and publishing. The FEN uses web technology and the Internet not only for distributing its content but also for managing it. Editors and authors can perform their tasks from anywhere on the Internet using commonly available browsers in a true multi-authoring system.

The ESB project began with the development of an overall conceptual outline that defined the bioenergy topic (Table 1). Well-qualified authors were then identified and engaged to write the various sections of the ESB. The topic outline became the navigational structure for the ESB as the content pages were written and posted in the FEN. During this initial writing stage, the pages were not published and thus were only visible to project members, not the general Internet user.

Once the initial version of each ESB section was written, the peer-review process began. The first level of review consisted of an internal review by the managing editors and a round of revisions. Next, blind reviews were obtained from referees who were completely outside the ESB project. Two or three reviewers were engaged to critically analyze a section from a scientific synthesis point of view with attention to completeness, coverage, soundness, clarity, efficiency, fairness, and utility. Reviews were collected and results were communicated to the authors, who made further revisions. Once this round of revisions was completed satisfactorily, the section was published as peer reviewed in the FEN.

Each page of the ESB displays the author/contributor, the date of last revision, and a unique encyclopedia identification (EID) at the bottom right corner (see biomass.encyclopedia.net). The EID is like a page number in a book. It can be used to cite an exact FEN page (Smith and Rauscher 2007). The EID also can be used to quickly locate a particular page in the ESB. For example, in the ESB there is an EID search field in the lower left corner of each screen. If you enter p1176 into this box and press the GO button, you will be transported to the Carbon Displacement page. Additional tips on how to use the FEN system can be found under the HELP button at the top of each page or by going to EID h0, the Help Home Page.

In May 2006, the ESB of the FEN received a formal program review from the US Department of Agriculture, the funding agency for developing this encyclopedia. The review team assessed the potential contributions and applications of the ESB to science delivery and technology transfer outreach and suggested further improvements as follows:

> The potential contributions of this extension and outreach development activity may extend far beyond the immediate goal of biomass utilization. The Internet based modules represent the future direction of outreach education in general. The discussions among the group to develop "templates" to allow for "on demand" construction and printing of fact sheets by cooperating field agents represents, in our opinion, the next generation of extension activity. Further discussions to add links to detailed scientific papers would potentially

Table 1. Structure, content, and senior authors of the ESB.

Section	Content
Understanding Bioenergy Resources Dr. Darwin Foster Dr. Semida Silveira	Global utilization of forest biomass (availability of biomass worldwide, utilization of forest biomass, organization for economic cooperation and development countries, European union, and future scenarios) Current status of forest biomass in the United States Environmental benefits of forest biomass Economic benefits of forest biomass Energy benefits of forest biomass Promoting bioenergy (market formation, bioenergy systems, biofuels, and challenges in bioenergy)
The Southern Bioenergy Resource Dr. Darwin Foster	The southern United States and potential for bioenergy The southern forest (forest types and geographic characteristics)
Forest Management Dr. Donald Mead	Favorable stand attributes for bioenergy production Forest management and silviculture for bioenergy production (sustainable forest ecosystem management, forest management issues for bioenergy production by NIPFs, biomass harvesting and its silvicultural implications, biomass production by forest type, integrating bioenergy harvesting with silviculture—a California example, and designing low-impact operations)
Harvesting and Transportation Dr. Ben Jackson	Defining biomass feedstock forms (unconsolidated materials, comminuted materials, and composite residue logs) Review of harvesting systems (basic steps of timber harvesting, state-of-the-art biomass harvesting systems, and small-scale biomass harvesting systems) Preprocessing and drying Transportation and delivery (trucks, trailers, and vans) Storage (how and where to store biomass and wood quality) Cost factors affecting harvesting biomass (factors affecting harvesting costs, and factors affecting transportation and delivery costs)
Utilization Dr. Daniel Cassidy	Woody biomass (wood composition, properties of wood, forest residues, and wood-processing residues) Bioenergy (ethanol, methanol, and biodiesel) Biomass industrial products (intermediate and specialty chemicals and bio-based materials) Production methods (biochemical processes, thermochemical processes, and fiber composite manufacturing) Worldwide utilization (Europe, India, China, Russia, Mali, Italy, and Ukraine) Energy units (energy converter)
Economics Dr. Jianbang Gan	Supply of forest biomass (factors affecting supply, sources and quantity of supply, location, uncertainty, and long-term supply) Cost competitiveness (feedstock production, electricity production, and carbon displacement) Community impacts (type and importance of community impacts; case studies of East Texas, Georgia, Oregon, and South Carolina) Policy factors and incentives (existing incentive programs, incentives needed, and experience in other countries)
Environmental Sustainability Dr. C.T. Smith	Framework for achieving sustainable forest management (adaptive forest management, international agreements and protocols, and certification systems) Soil values (composition, function, productivity, and forest practices that can affect soils) Hydrologic values (hydrologic processes affected by harvesting and water quantity and quality) Biodiversity values (understanding biodiversity and forest biodiversity conservation tools) Designing low-impact operations

offer a technical depth to the website, not typically available to the public in conventional outreach programs and activities.

Using the material synthesized in the ESB as a base has allowed us to develop several educational products. These include the Sustainable Forestry for Bioenergy and Bio-based Products Training Notebook, the Sustainable Forestry for Bioenergy and Bio-based Products web-based learning modules hosted by the National Learning Center for Private Forest and Range Landowners (forestandrange.org), and the Forest Bioenergy Web Portal (forestbioenergy.net). These products are designed as components of an overall bioenergy training program for the South that is being disseminated through the Southern Regional Extension Forest network. By using the ESB we are able to provide natural resource professionals with an outreach program that is based on scientifically accurate and peer-reviewed materials. Using the ESB also allows us to give our audience an evolving, up-to-date reference synthesized from material from various sources. The ESB has enabled us to integrate new and innovative forms of KM with traditional extension programming efforts.

The Status of Bioenergy in the Southern United States

The potential for using forest biomass as a source of feedstocks for renewable bioenergy has not been achieved in the United States in general or in the South in particular. Progress has been limited by many market, energy, and natural resource management policy barriers. These barriers include the benefit/cost balance, market formation, creating synergies with agriculture and the energy sector, and managing competition in terms of resource uses and markets (Silveira 2005, Silveira and Foster 2007). However, climate change, forest health, wildfires, rural development, and energy security are emerging as new driving forces that may move our nation to urgently consider increased use of renewable forest biomass resources to meet our energy needs. Understanding the current situation clearly enough to correctly interpret the impact of future change on the production and marketing of woody biomass in the South is likely to lead to important advantages.

It is clear that the forestlands of the United States and, in particular, the 214 million ac of forestland in the South, have the potential to provide a large quantity of biomass to support the development of a viable bioenergy and bio-based products industry (Mayfield and Foster 2007). Much of this biomass resource could be supplied from standard silvicultural operations. Precommercial thinnings, stand improvement, residue removal, brush control, and stand rehabilitation are some of the ways in which biomass for bioenergy production can be achieved as part of normal commercial forestry operations (Mead et al. 2007). For the nation as a whole, recovering

unused residues from such conventional timber harvesting operations has the potential for providing 40 million dry tons annually for biomass for energy or bio-based products (Mayfield and Gan 2007). Additional biomass is available from urban wood waste (28 million dry tons annually), short-rotation woody crop plantations (5 million dry tons annually), natural disaster recovery cleanup operations (1–2 billion dry tons periodically), and fuel reduction treatments to mitigate wildfire hazard (60 million dry tons annually; Mayfield and Gan [2007]). Over 100 million dry tons of mill residues are produced annually in the United States, although 97% of this residue is already being used by the forest industry. We can conclude that the physical availability of biomass to support a substantial bioenergy industry in the United States is not a problem.

Harvesting biomass is a challenge because it is very inefficient to handle small-diameter woody stems over large areas of forestland (Jackson and Schroeder 2007). There are a variety of harvesting configurations in use in the South but currently the most cost-effective harvesting method is a one-pass system that harvests roundwood and/or sawlogs and biomass simultaneously. This occurs when common timber harvesting equipment such as feller-bunchers, grapple skidders, and knuckleboom loaders are combined with an in-woods chipper to recover the residue. This method is popular because, other than adding a small to medium size chipper, there are few, if any, modifications to current configurations. Other methods that have promise are the harvester-forwarder system and the composite residue log system that uses a specialized bundler machine.

Transportation from the forest to the processing facility is a significant challenge to economically using biomass as a product (Schroeder and Jackson 2007). Transportation of woody biomass accounts for about 25–50% of the total delivered costs and this is likely to increase as fuel prices escalate. Transport becomes limiting as its costs increase with changes in topography and increases in haul distance. Making bioenergy profitable requires biomass to be supplied from within a limited distance of a bioenergy plant for a given type and scale of bioenergy conversion technology. Improved technologies or larger-scale plants may allow somewhat greater hauling distances.

If bioenergy is to be considered a renewable natural energy source, it must be produced in a manner that is consistent with environmental, social, and economic criteria of sustainable forest management. Special care should be taken to ensure that biomass removal from the site is done in a way to retain nutrient availability, ensure adequate watershed function, and maintain biodiversity by providing habitat for plant and animal species. Certification systems involving third-party audit procedures, such as those being applied to production, manufacture, and trade of traditional forest products, can be used to develop sustainable biomass production systems (Mayfield and Smith 2007).

Currently, the most practical, economical, and environmentally sustainable use of wood biomass is the production of power and energy through combustion and cofiring (Cassidy 2007). In addition to heat and power, the production of ethanol as a transportation fuel from wood is technically possible but is not currently economic. Continued research, such as that supported by the recent $325 million granted by the US Department of Energy to new bioenergy research centers across the nation, may lead to reduced production costs of cellulosic ethanol. Although new and cheaper enzymes and catalysts show particular promise, a national ethanol industry is not expected to completely remove our dependence on fossil fuels.

In conclusion, forest bioenergy, in general (except for some special cases such as mill residues), is typically not cost competitive with fossil fuels under current technologies and market conditions in the United States. However, it offers a variety of cobenefits ranging from cost savings in forest regeneration or restoration to CO_2 emissions offsetting and to the creation of jobs and income. Greater efficiencies in biomass production and energy conversion technologies, integration of forest biomass production with conventional forest management, coordination of forest bioenergy production with manufacturing of mainstream wood and fiber products, and development of bioenergy incentive programs can help improve the competitiveness of forest bioenergy production systems and products (Mayfield and Gan 2007).

Conclusions

The potential for using forest biomass as a source of feedstocks for renewable bioenergy has not been achieved in the United States. Progress has been limited by many market and energy and natural resource management policy barriers. However, climate change, forest health, wildfires, rural development, and energy security are emerging as new driving forces that move our nation to urgently consider increased use of renewable forest biomass resources to meet our energy needs. The ESB provides a synthesis of our scientific knowledge about the ways in which the forests of the southern United States might provide bioenergy feedstocks. This comprehensive summary and synthesis of knowledge uses the knowledge transfer efficiencies associated with the Internet and, specifically, the FEN to reach a broad audience of forest landowners, natural resource professionals, and educators to increase their awareness of the opportunities and challenges associated with forest biomass production.

Learning how best to use new Internet-based capabilities to support the management of scientific knowledge is going to take time and experimentation. It should be recalled that the transition from hand-written and copied manuscripts to printed manuscripts began with the attempt to use the printing press to duplicate the look and feel of the best handwritten documents. It took time and experience for publishers and the reading public to realize that different media require different approaches. For example, the printing process encouraged authors to move away from ornately artistic text with colorful but expensive graphics to a more utilitarian presentation that reduced the price of books by orders of magnitude. Something was lost in this transition but much more was gained. Similar changes are likely to occur as we move from print-based, paper documents to documents that exist only in electronic form.

We believe that the transition in KM technology from static, paper-based methods to dynamic, Internet-based methods will most likely involve making adjustments in the degree of multiauthor and multireader participation in the content development and updating. Some level of central control needs to be in place to ensure adequate quality control. Too little editorial control leads to problems such as the ones Wikipedia has experienced recently. Because the Wikipedia approach is a user-written, open-edited CMS, several professors from Yale University and Middlebury College have concluded that the Wikipedia cannot be regarded as being a legitimate scholarly source (Middlebury College 2007, Torbati 2007). In contrast, we also believe that the absolute editorial control currently practiced by the FEN, where authors are first vetted and then their contributions are subjected to the standard, blind-peer-review process and where users have little direct input, may not be the best approach either.

The strengths of the FEN approach are that authors of content are generally scientists and professionals with expertise in the field about which they are writing and that there is a peer-review–based quality control system that all published content must pass. The weaknesses of this approach are that it (1) reduces content accretion rates, (2) reduces the number of qualified authors available to contribute, (3) involves substantial administrative expense associated with management of the editorial process, and (4) provides limited user feedback and user interaction with authors about content. The strengths and weaknesses of the Wikipedia approach are a mirror image of those of FEN. We anticipate that some compromise solution will emerge over time.

The editors and authors of FEN are expanding the content continuously. The *Encyclopedia of Southern Pine Beetle* was funded for development in 2006 (Coulson and Klepzig 2007). Other encyclopedia editors also are engaging new authors, adding new content, or updating existing content. Keeping scientific knowledge in the FEN current is a continuing challenge. However, it must be kept in mind that the pace of scientific advances is uneven and that the best available knowledge for field use often is decades old but still valid today. Knowledge content currency must not be thought of in terms of the latest 5 years, but rather assessed on a subject-by-subject basis. The right question is, Has this content been superseded? As FEN reaches more users, we hope that we will get more feedback about inaccuracies and gaps in the content that we cover.

The next major technical improvement will be to link the citations in the FEN to the abstracts and full text articles found in the US Forest Service's TreeSearch system (www.treesearch.fs.fed.us). Initially, only those full text articles that are published in the public domain will be available. However, we hope to reach agreements with major scientific journals under which their copyrighted content might be accessed by users who are using FEN content. FEN editors and developers also are working on providing a broad range of graphical navigation methods to readers. These methods will make it easier and more enjoyable for readers to understand what content is held within the FEN, how pages relate to each other, and how best to use the FEN to support self-directed learning. Finally, we are exploring the use of different mechanisms for making readers a more active part of the FEN. For example, we are experimenting with a comment system attached to a page of content so readers can discuss the knowledge and its implications among themselves. We also want readers to be able to freely e-mail authors with questions, suggestions, or critiques.

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Dual-Cropping Loblolly Pine for Biomass Energy and Conventional Wood Products

D. Andrew Scott and Allan Tiarks

ABSTRACT

Southern pine stands have the potential to provide significant feedstocks for the growing biomass energy and biofuel markets. Although initial feedstocks likely will come from low-value small-diameter trees, understory vegetation, and slash, a sustainable and continuous supply of biomass is necessary to support and grow a wood bioenergy market. As long as solidwood products are more valuable, bioenergy production will not be the primary market for southern pine. A study exploring a dual-cropping system for southern pine bioenergy and solidwood products was begun in 1982 in Louisiana to determine the phosphorus (P) nutritional requirements of the system. Fertilization of 60 kg ha^{-1} of P was required to produce 90% of the maximum volume at the age of 22 years. Direct-seeding pine in the interrows of a traditional pine plantation produced about 10.2 Mg ha^{-1} of biomass for energy at the age of 5 years but had no lasting effect on the planted pine height, diameter, or standing volume. The system is a viable method to produce both bioenergy and solidwood products. Herbaceous competition control and nitrogen (N) fertilization likely would make the system even more productive and profitable.

Keywords: fertilization, phosphorus, competition, stand development

Interest in alternative energy sources, especially bioenergy, has increased recently in the United States. Market-based strategies for biomass energy and biofuels have been developed and will increase in part because of the Energy Policy Act of 2005, which established the Renewable Fuels Standard that will reduce crude oil imports by 2 billion barrels by 2012. The most successful biobased energy market to date in the United States is that of corn (*Zea mays* L.)-based ethanol. Ethanol has become the third largest market for corn (Renewable Fuels Association 2006), which has, in turn, altered corn agribusiness dynamics and land-management decisions and likely will continue to do so in the future (World Agricultural Outlook Board 2006). Similar markets are being developed for other agricultural crops, such as switchgrass (*Panicum virgatum* L.).

Wood-based biofuel technology, including wood biomass gasification to ethanol, also is being developed, and this new technology will create additional wood biomass markets. These markets may create a strong demand for previously low-value small-diameter trees, woody understory, and slash. However, wood biomass plants likely will be located near other wood-demanding industries because of logistics, and competition for wood may result. In these cases, landowners may wish to maximize total economic value by producing wood biomass for energy in addition to higher-value solidwood products.

The concept of growing trees with an additional crop usually is considered in the context of the agroforestry practice of alley cropping. Alley cropping consists of an agricultural crop grown between widely spaced tree rows. The trees selected usually provide multiple economic products, such as nut and wood production, and have different root system architectures from the crop plant. This system has been adopted successfully in developing countries and by some landowners in the United States as a way to diversify economic returns. Within the United States, the most successful example is that of cropping corn or other agricultural crops with black walnut (*Juglans nigra* L.) plantations in the Midwest. These systems generally work well only where the soil is conducive to row crop production with or without trees.

In contrast to high-quality agricultural lands of the Midwest, dual-cropping pine is more compatible in the southern states where forest soils are too dry, wet, or infertile for the annual row crop component of an alley-cropping system. Grasses can be productive on some of these lands, and research has shown some success with growing grasses as cattle forage amid widely spaced southern pine trees in silvopastoral systems (Clason 1999). However, in practice, silvopastoral systems require a high degree of skill with both range and forest management and frequent management activities.

In pine plantations, control of both herbaceous and interspecific woody competitors is vital for maximum pine plantation productivity (Miller et al. 2003, Borders et al. 2004). Conversely, maximum biomass growth of pure pine plantations per unit area occurs in dense stands because of maximum photosynthetic light interception (Zeide 2004). In these systems, therefore, intraspecific competition is not as deleterious to total production as interspecific competition. Therefore, dual cropping a conventional pine stand with additional pine seedlings for biomass production may provide a viable alternative to row crops or grasses and require only forestry expertise and occasional stand management activities.

This basic proposal was developed originally in the late 1970s after the oil crisis, when interest in alternative energy increased. Koch (1980) developed the components of a combined biomass and solidwood products forest system that would use direct seeding to establish a very dense stand of pine that would be progressively

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D. Andrew Scott (andyscott@fs.fed.us) and Allan Tiarks (aetiarks@worldnet.att.net), US Forest Service, Southern Research Station, 2500 Shreveport Highway, Pineville, LA 71360. *Rick Stagg and Morris Smith Jr. performed the field measurements at age 22 years. Jeff Goelz provided helpful suggestions toward data analysis and provided constructive comments on an earlier draft. Christine Bliss and Michael Blazier provided constructive comments on an earlier draft.*

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thinned to provide biomass energy wood and, later, sawtimber-suitable trees. Alternatively, he proposed incorporating direct-seeded trees in the interrows of planted pines. Tiarks (1985) adapted this second concept by incorporating the direct-seeded biomass cropping concept within a standard plantation system. Early results from this study focused on initial phosphorus (P) fertilizer responses and on the production and energetic value of the direct-seeded biomass crop, which was about 10.2 Mg ha^{-1} at age the of 5 years (Tiarks 1993).

While this concept was developed as a way to use direct seeding as an economical way to establish dense stands for energy biomass, the concept of creating a dense understory of pine under a more conventional pine plantation also could be used to increase water or nutrient uptake. For example, direct-seeding pine within a young pine plantation could provide greater sediment control near riparian areas while the plantation was developing. Additionally, the concept potentially could be used to reduce hydrologic inputs to streams to help control stream degradation.

As long as the market value of solidwood products greatly exceeds that of biomass energy crops or other small-diameter wood products, this system should not restrict growth of the planted trees, either in terms of volume production or of higher-value product classes for maximum economic efficiency to be realized. Accordingly, our objectives were to determine (1) planted tree growth responses to fertilizer and biomass energy cropping systems after 22 growing seasons and (2) temporal stand dynamics related to biomass energy cropping systems.

Materials and Methods

Study Location and Establishment

The study was performed on the Longleaf Tract of the Palustris Experimental Forest in central Louisiana (31.008°N, 92.616°W). Before harvest, it had been in native grasses with scattered small hardwoods. The site was plowed in 1980 and disked three times in 1981 to reduce grass competition. The soil is a Beauregard silt loam (fine-silty, siliceous, superactive, thermic Plinthaquic Paleudults), which is very common to central Louisiana (USDA Soil Conservation Service 1980).

The study was double-planted in January–February of 1982 with 1–0 bareroot loblolly pine from a single half-sib family on a 2 × 3 m spacing with 15 rows of 11 planting spots per 0.1 ha (22 × 45 m) main plot (Figure 1). The seedlings were reduced to one live seedling per planting spot during the winter of 1982–1983. Nitrogen (N) was applied as urea to all plots (40 kg ha^{-1}) in April 1982. The study was established as a split-plot design with four P fertilizer rates (0, 81, 162, and 324 kg ha^{-1}) applied as triple superphosphate (TSP 0-46-0) in April 1982 to the main plots. The split-plot treatments consisted of three interrow, direct-seeded biomass production treatments: no seeding (NS), seeded and harvested at the age of 5 years (SH), and seeded but not harvested (SNH). The NS treatment served as the operational control treatment, and the SH treatment tested Koch's (1980) concept. The two seeded treatments were designed originally to be harvested at two different ages (ages 4 and 5 years) to determine the optimal age of biomass harvesting. In practice, the SNH plots, which originally were designed to be harvested at the age of 4 years, were never harvested. This treatment provided a comparison of stand dynamics of a system in which the biomass energy crop was not able to be harvested for some reason, or of a system with high levels of early intraspecific competition but little interspecific competition. The biomass production split plots were seeded with unimproved, woods-run loblolly pine seed in February 1982 by placing 3–10 seeds in spots 0.25–0.5 m apart in a 1.5-m swath in the middle of the planted tree rows (Figure 1). In 1984, the direct-seeded trees were hand thinned to the tallest seedling per planting spot. Measurement plots consisted of five rows of three trees each with a border row between each split plot (Figure 1). Each treatment was replicated three times.



Figure 1. Photo depicting half-sib, 1–0 planted seedlings on a 2 × 3 m spacing with unimproved pine seedlings direct seeded in the interrow area for biomass energy after one full growing season..

Total heights and diameters (rootcollar diameter at the age of 1 and 2 years, dbh [1.3 m] thereafter) were measured at ages 1, 2, 3, 4, 5, 6, 7, 9, and 22 years after planting and fertilizer application. Stem volume outside bark from a 0.15-m stump to the stem tip was calculated using equations developed for unthinned loblolly pine in Louisiana (Baldwin and Feducca 1987) and scaled to the areal level.

Analysis

We analyzed the 22-year growth responses (height, diameter, stand density, and volume) to treatments with analysis of variance (SAS Institute, Inc., 1994). We determined the fertilizer requirement by fitting individual subplot biomass at the age of 22 years to the P fertilizer applied to a modified Mitscherlich function (Mitscherlich 1909; Equation 1) and calculating the fertilizer required to produce 90% of the maximum biomass. We chose 90% as a yield goal because 90% of maximum yield is commonly used to determine nutrient critical levels (Epstein 1972). In practice, the appropriate fertilizer rate should be determined by the marginal revenue gained by the increase in yield and the marginal cost associated with the additional fertilizer,

$$Y = b_0 + b_1 * (1 - e^{-b_2 * P}) \quad (1)$$

where b_i are parameters to be estimated, P is kilograms of phosphorus, and Y is volume (m^3 ha^{-1}).

We compared temporal growth patterns by determining the difference among treatments with highlight short-term responses in height and diameter to the biomass treatments. Finally, we determined the frequency of trees from each treatment in 2-cm diameter classes and performed a chi square test of distribution equality.

Results

Planted Tree Responses to P Fertilizer and Cropping System

Fertilization had significant effects on mean height, diameter, and stand volume at the age of 22 years and did not interact with

Table 1. Probabilities of a greater *F*-value for mean tree and stand characteristics of 22-yr-old loblolly pine stands subjected to four P fertilization rates and three direct-seeded interrow biomass energy cropping systems.

Effect	df	Height	Diameter	Density	Volume
F	3	0.0015	0.0030	0.6456	0.0012
CS	2	0.0503	0.3515	0.7277	0.0219
F × CS	6	0.9638	0.7059	0.1957	0.1087

CS, cropping system; F, fertilization.

Table 2. Mean height, diameter, stand density, and stand volume of 22-yr-old loblolly pine stands subjected to four P fertilization rates and three direct-seeded interrow biomass energy cropping systems.

Treatment	Height (m)	dbh (m)	Density (trees ha^{-1})	Volume (m^3 ha^{-1})
Fertilization				
0 kg ha^{-1} P	19.5b	0.191b	1531a	448b
81 kg ha^{-1} P	21.8a	0.212a	1469a	587a
162 kg ha^{-1} P	22.4a	0.216a	1420a	607a
324 kg ha^{-1} P	22.6a	0.216a	1469a	633a
Biomass				
NS	21.7a	0.211a	1491a	587a
SH	21.8a	0.210a	1472a	579a
SNH	21.2b	0.206a	1454a	541b

Main-effect means within a column and treatment type followed by the same letter are not significantly different at $P < 0.05$.

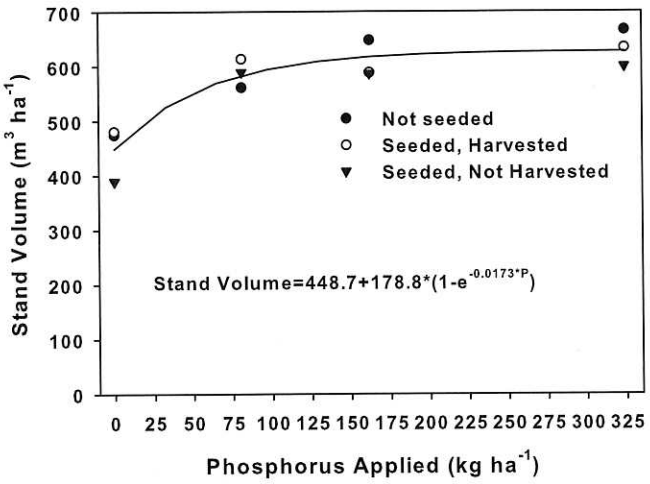


Figure 2. Unthinned loblolly pine stand biomass at the age of 22 years in relation to P fertilizer rate applied at stand establishment.

cropping system (Table 1). P fertilization increased the mean height, diameter, and stand volume by 14, 12, and 36%, respectively, over the plots receiving no P fertilizer (Table 2). Regression analysis indicated the expected yields for this site were 449 and 627 m^3 ha^{-1}, for 0 and 324 kg ha^{-1} added P, respectively (Figure 2). Based on Equation 1, 60 kg ha^{-1} of P was needed to produce 90% of the maximum expected yield (564 m^3 ha^{-1}).

The inter-row direct-seeding system in which the trees were harvested as planned at the age of 5 years (SH) had no impact on height, diameter, or stand volume at the age of 22 years compared with the NS treatment, but when the direct-seeded trees were allowed to remain on the site (SNH), height and stand volume were reduced by 3 and 7%, respectively, compared with the SH treatment plots (Table 2). Stand density was not affected by any of the seeding treatments (Table 2).

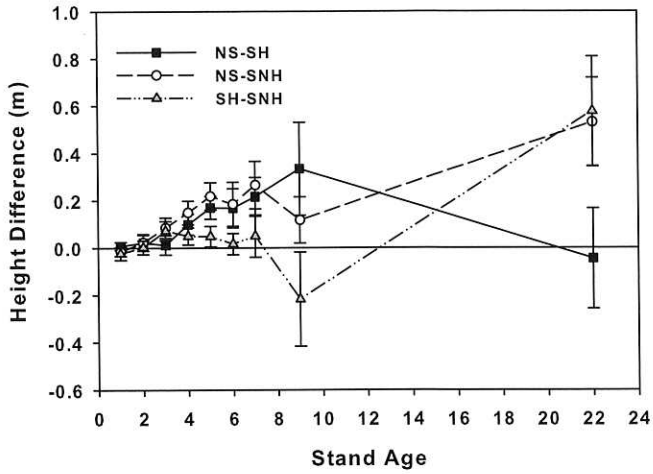


Figure 3. Mean height difference between interrow biomass production systems (NS = nonseeded; SH = seeded, harvested at the age of 5 years; SNH = seeded, not harvested) through 22 growing seasons. Example: NS-SH indicates the mean relative height difference between the NS plots and the SH plots. A positive value indicates trees on the NS plots were taller than the trees on the SH plots. Error bars represent one standard error.

Temporal Stand Dynamics of the Planted Trees in Three Cropping Systems

The difference in mean height between the NS and SH plots increased through the age of 9 years, when the trees on the NS treatment plots were about 0.3 m taller (Figure 3). The height difference of the NS treatment trees compared with the SNH trees also steadily increased through the age of 7 years to a maximum of 0.27 m. Given that until the age of 5 years the SH and SNH treatments were the same treatment (both were direct seeded but neither was harvested), the lack of height growth difference between these plots through the age of 7 years is not surprising. At the age of 9 years, however, the SH treatment trees were 0.33 and 0.22 m shorter than the NS and SNH treatment trees, respectively. At the age of 22 years, the impact of the direct seeding was clear; the NS and SH treatment trees were almost 0.75 m taller than the SNH treatment trees but were not different between each other.

Difference in diameter of the planted trees among the three direct-seeded treatments followed similar patterns (Figure 4). Through the age of 5 years, trees planted in the NS treatment had 0.5-cm larger diameters than the planted trees in the SH or SNH treatments, respectively. Diameter growth of the planted trees responded quickly to harvesting the direct-seeded trees on the SH plots. Within a year after the direct-seeded trees were harvested, the planted trees on the SH plots had 0.27-cm larger diameters than the planted trees on the SNH treatment. By the age of 9 years, the trees on the NS and SH treatment plots had similar diameters and were about 0.5 cm larger than the planted trees on the SNH plots. The diameter growth was unchanged after the age of 9 years, although the diameter differences among the NS, SH, and SNH treatments were not significant at $\alpha = 0.05$ at the age of 22 years because of an increase in variation (Table 1; Figure 4).

At the age of 22 years, not only were the diameters similar among the biomass harvest treatments, but the diameter distributions were similar as well (Figure 5). The SNH treatment resulted in fewer trees in the 19-23-cm diameter range than the other treatments and more trees in the 17-cm diameter class, but the distributions were not statistically different based on the chi-square test of distribution equality ($P > 0.3389$).

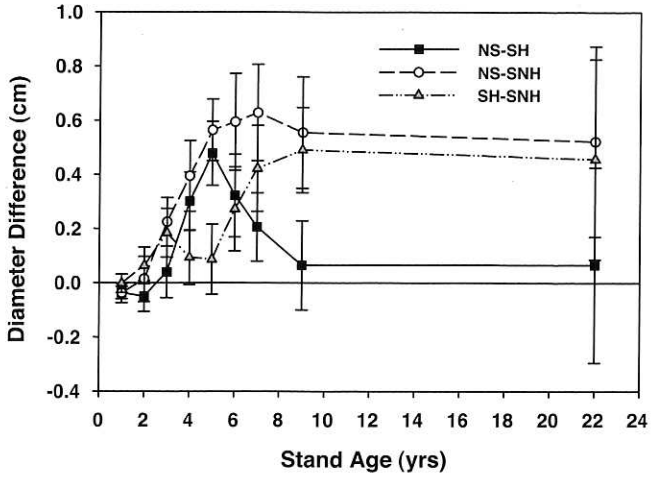


Figure 4. Mean diameter difference at breast height (dbh) difference between interrow biomass production systems (NS = nonseeded; SH = seeded, harvested at the age of 5 years; SNH = seeded, not harvested) through 22 growing seasons. Example: NS-SH indicates the mean relative dbh difference between the NS plots and the SH plots. A positive value indicates that trees on the NS plots had greater diameters than trees on the SH plots. Error bars represent one standard error.

Discussion

Plantation growth was excellent across all treatments through age 22. The mean annual increment averaged 20.4 and 27.7 $m^3\ ha^{-1}\ yr^{-1}$ for the unfertilized and fertilized treatments, respectively. These growth rates are comparable to the average of 26.6 $m^3\ ha^{-1}\ yr^{-1}$ reported for six 10 to 12-yr-old, intensively managed plantations in Georgia (Borders and Balley 2001) and the 24.6 $m^3\ ha^{-1}\ yr^{-1}$ reported for 25-yr-old stands in Hawaii (DeBell et al. 1989). These stands were about 40% more productive than the best plots of four 10-yr-old sites in the Louisiana Long-Term Soil Productivity study (Sanchez et al. 2006).

The response to P fertilization was highly positive and sustained. This indicates that P fertilization increases productivity on soils similar to the Beauregard soil. This finding is supported by previous studies in this region and across the South that have found substantial growth responses to P fertilizer (Pritchett and Comerford 1982, Haywood et al. 1997). Similarly, evidence from studies of intensive harvesting in coastal plain pine stands has indicated the potential for growth reductions because of a reduction in nutrient availability (Tiarks and Haywood 1996, Johnson et al. 2002, Scott and Dean 2006). Although much of the recent research on intensive forest management and forest nutrition is focused on N fertilization, this research assumes that P limitations have been avoided through site selection or fertilization, as has been accomplished on many industrial forestlands. This assumption is not valid across all lands, where fertilization may not have been a common component of management. In addition, the optimal P rate found in this study (60 $kg\ ha^{-1}$ P) is essentially the same as the common establishment rate of 56 $kg\ ha^{-1}$ of P. However, the estimated 60 $kg\ ha^{-1}$ P rate is substantially less than the 162 $kg\ ha^{-1}$ of P estimated by the P sorption isotherm procedure used to determine the fertilizer rates before study establishment and the 117 $kg\ ha^{-1}$ of P rate estimated rate after 1 year of growth on this site (Tiarks 1983). These P fertilization rates were determined early in the rotation, when N availability was likely higher because of the recent soil disturbance at harvesting (assart effect). Had N demand been met throughout the rotation with midrotation N applications, as many intensively managed loblolly pine plantations are, the relative P demand likely would have been greater throughout the rotation.

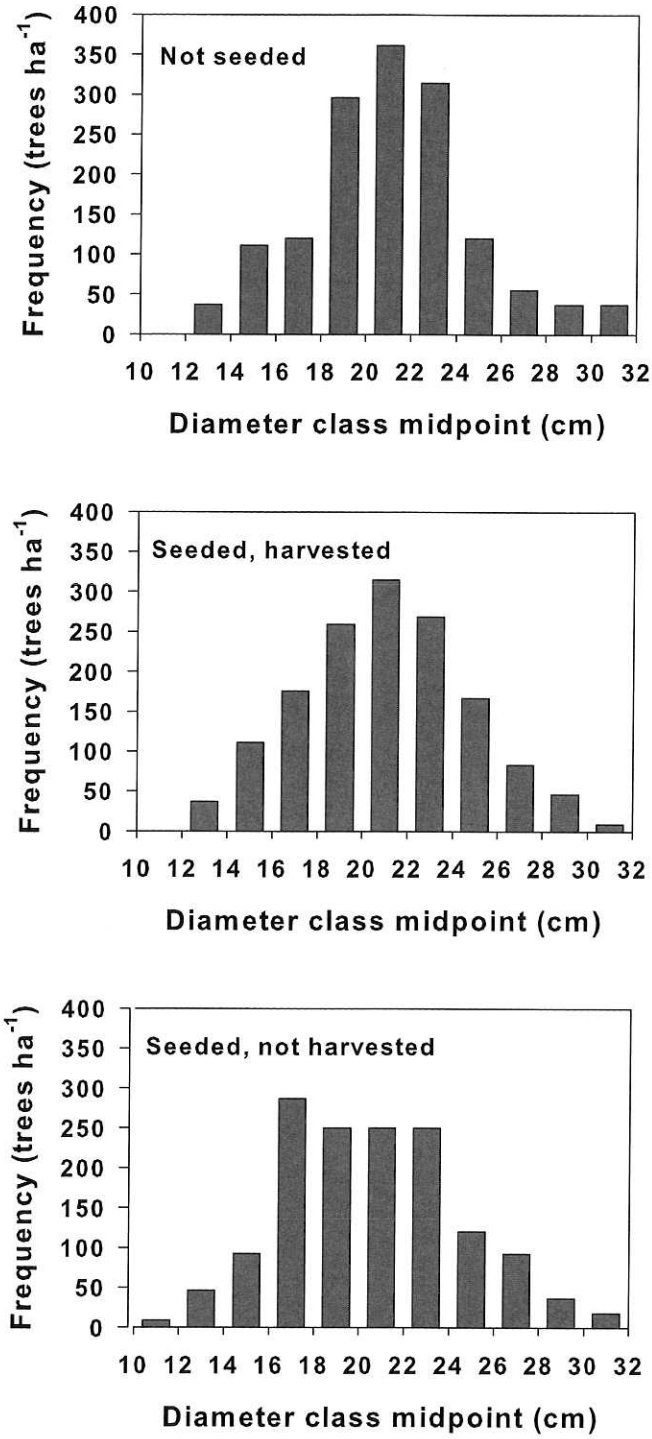


Figure 5. Planted pine diameter frequencies in 2-cm classes by inter-row biomass production system (NS = nonseeded; SH = seeded, harvested at age 5; SNH = seeded, not harvested) at the age of 22 years.

Second, growing pines in the interrows of a relatively commonly spaced pine plantation had no significant impact on the standing volume of the planted pines at the age of 22 years when the biomass crop was harvested. Conceivably, a landowner might initiate a similar dual-crop system but be unable to harvest the biomass crop for various reasons. This might happen if the market value for biomass changed or if the system was installed for another reason, such as soil stabilization in a riparian area. In this case, which was tested with the

other split plot, the planted tree volume was reduced by about 18.5 m^3 ha^{-1} compared with the single-crop system.

The competitive effect of the direct-seeded trees occurred early in the stand development, but the stand recovered when the direct-seeded trees were removed. The mean planted tree diameter and height were increasingly reduced by the presence of direct-seeded trees through the age of 9 and 22 years, respectively (Figures 4 and 3, respectively). After the direct-seeded trees were harvested at the age of 5 years on the SH plots, the planted tree heights and diameters recovered relative to the trees on the NS plots. The tree diameters were similar after only 4 years after the biomass crop harvest (Figure 4), and trees planted on the SH plots remained shorter until 15 years after the biomass crop harvest (Figure 3) at the age of 20 years. Because the direct-seeded trees were substantially shorter than the planted trees (Tiarks 1993), they competed with the planted trees primarily more for nutrients and water than for light. By the age of 22 years, no direct-seeded trees survived. Additional N fertilization likely would have precluded the early reduction in height and diameter growth and improved both direct-seeded and planted tree growth.

Conclusions

This study has shown that Koch's (1980) concept for southern pine bioenergy plantations is biologically viable, and over 22 years produced over 10 Mg ha^{-1} of pine biomass for energy and up to an additional 633 m^3 ha^{-1} of wood that could be used for either biomass energy or for various solidwood products. Thinning likely would have increased solidwood product value in the stands through increasing diameter growth. The inclusion of the direct-seeded trees for biomass had no long-term impact on stand biomass production, although early height and diameter growth was impeded by the biomass planting. Forest managers interested in managing southern pine stands for productivity, especially if they plan on intensive harvesting of either a biomass crop or of entire planted trees, should ensure their stands have adequate P. Although this study did not incorporate repeated N fertilization and herbaceous competition control, these treatments would improve the overall system production.

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TECHNICAL NOTE

An Improved Tree Height Measurement Technique Tested on Mature Southern Pines

Don C. Bragg

ABSTRACT

Virtually all techniques for tree height determination follow one of two principles: similar triangles or the tangent method. Most people apply the latter approach, which uses the tangents of the angles to the top and bottom and a true horizontal distance to the subject tree. However, few adjust this method for ground slope, tree lean, crown shape, and crown configuration, making errors commonplace. Given documented discrepancies exceeding 30% with current methods, a reevaluation of height measurement is in order. The sine method is an alternative that measures a real point in the crown. Hence, it is not subject to the same assumptions as the similar triangle and tangent approaches. In addition, the sine method is insensitive to distance from tree or observer position and can not overestimate tree height. The advantages of the sine approach are shown with mature southern pines from Arkansas.

Keywords: hypsometer, sine method, tangent method

Foresters have measured height in many ways since the earliest years of the profession (e.g., Schlich 1911). One technique, direct measurement, is commonly done using a height pole for small- to medium-sized trees, and rarely with a tape dropped from the top of tall trees. Direct measurement, however, typically requires the observer to carry a bulky height pole or be skilled in the hazardous art of tree climbing. Most other height measurement techniques use mathematics as their basis. For example, some have used a pole or rod of known length as the basis for comparison with a standing tree (e.g., Curtis and Bruce 1968, Bell and Gourley 1980). This proportionality approach reduces the size of the pole needed to determine height but provides only an approximation of height. Hypsometers also have been developed with more sophisticated optically based mathematics or digital image processing using other proportional formulations for height determination (Anuchin 1971, Clark et al. 2000).

None of these approaches, however, have supplanted the most popular height measuring techniques. One of the oldest applies the geometry of similar triangles, which operates on the principle that triangles of the exact same configuration are direct scalars of each other. The most common height determination approach can be called the "tangent method" and multiplies the tangent of the angles to the top and bottom of the crown with a true horizontal baseline distance from the observer to the tree. Under idealized circumstances, both similar triangles and the tangent method will yield the exact height of a tree. However, rarely are the assumptions of either satisfied, and the resultant measurement errors can be significant. For instance, the Eastern Native Tree Society (ENTS) has documented numerous cases of national champion-sized trees measured with these techniques being overestimated by 5–20 m (ENTS 2006).

Fortunately, the increasing availability of inexpensive and accurate distance measuring devices has provided a unique solution for most measurement problems. A "new" trigonometric approach to height determination uses the product of the sine of the angles to the top and bottom of a tree and their respective slope distances to determine height. The "sine method" was developed originally to improve height estimates of very large individual trees and has been repeatedly validated using direct measurements with tapes lowered from very tall (>50 m) specimens (Blozan 2006). In this article, advantages of the sine method with three mature pines from southern Arkansas are shown.

Methods and Materials

The Tangent and Sine Height Determination Methods

Any height computation technique assumes that all angles and distances are measured without error and that the observer can identify the highest part of the crown. The best means to differentiate between the sine and tangent methods of height determination is to display the techniques graphically. The tangent method must either meet some very precise assumptions or be correctly adjusted to produce the exact height of a tree. Specifically, these assumptions are the tree must be truly vertical (i.e., perpendicular to a level horizontal plane), the diameter of a tree can be ignored, and the highest point of the live crown is located directly over the base of the stem. The tangent method shown in Figure 1a can be expressed as

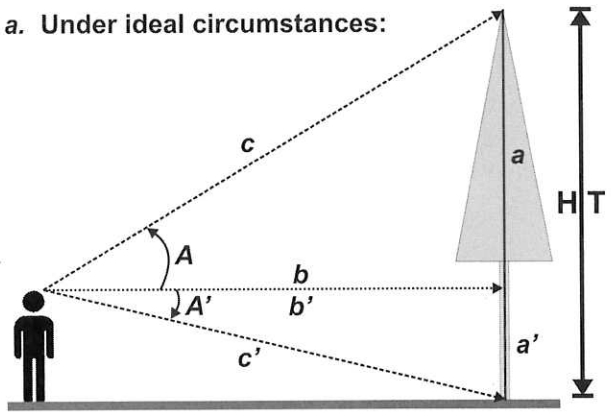
$$HT = b \times \tan(A) + b' \times \tan(A'), \quad (1)$$

where the baseline lengths (b and b', identical in this case) are true horizontal distances and the angles A and A' are of the true top and bottom of the tree, respectively. Note that under these same circum-

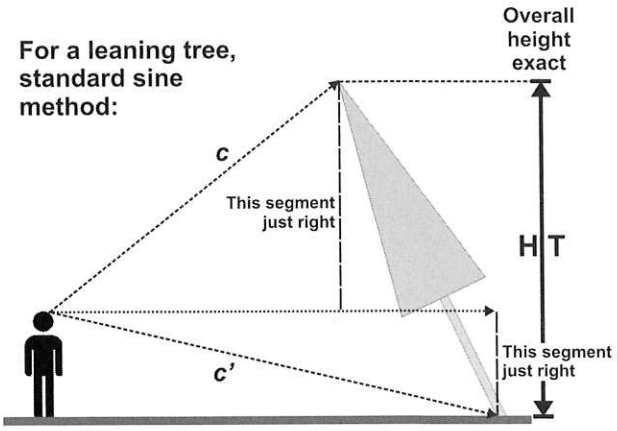
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Don Bragg (dbragg@fs.fed.us), US Forest Service, Southern Research Station, PO Box 3516, University of Arkansas at Monticello, Monticello, AR 71656. *The author thanks Will Blozan (Eastern Native Tree Society), Mike Chain (US Forest Service), Jim Guldin (US Forest Service), Nancy Koerth (US Forest Service), Robert Leverett (Eastern Native Tree Society), Mike Shelton (US Forest Service), and Kirby Sneed (US Forest Service) for their contributions to this effort. This article was written by a US Government employee on official time and is therefore in the public domain.*

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For tangent method, baseline length (*b*) controls height



For sine method, slope distances (*c* and *c'*) control height

Figure 2. The sine method addresses leaning trees or offset crowns by directly measuring the slope distance to the top (*c*) and bottom (*c'*) of the tree.

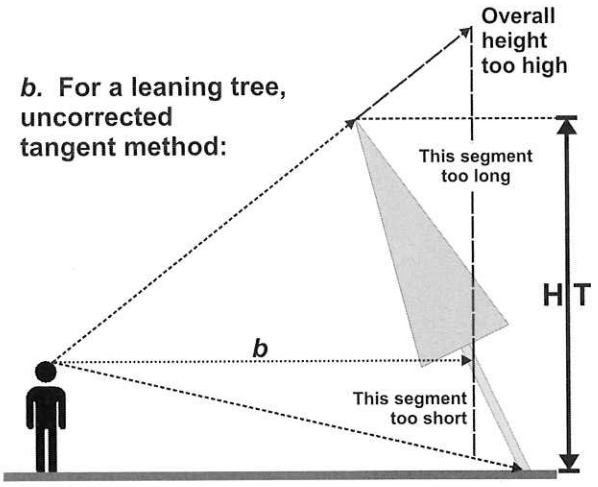


Figure 1. The tangent method of tree height determination, under (a) ideal and (b) less-than-ideal circumstances.

stances, the following is also true:

$$HT = c \times \sin(A) + c' \times \sin(A'), \quad (2)$$

where c and c' are the slope distances corresponding to A and A', respectively. Equation 2 is the standard form of the sine method and would exactly equal the tangent-determined height under the conditions shown in Figure 1a.

However, for the tangent method to yield the actual height of a leaning tree or one with an offset crown, corrections are needed to ensure that the proper baseline distances are used (Figure 1b). Under less-than-ideal conditions, the tangent method can overestimate height if the lean or offset is toward the observer or underestimate height if the lean/offset trends away (see also Husch et al. 2003). Typically, adjustments to baseline length or perspective are made to reduce this error—either the observer measures horizontal distance to a spot assumed to be directly under the highest point or the observer moves to a position perpendicular to the lean or crown offset tree to ensure that any departure from the true base is minimized. Although both corrections can help, rarely are they precise enough to eliminate estimation problems, and either can prove time-consuming or even impossible.

The sine method is free of virtually every assumption of the other techniques because it directly measures a point on the tree crown, not a projection based on a potentially erroneous baseline distance. Measuring the requisite slope length (Figure 2) has been made possible only recently by the advent of accurate technology (e.g., laser rangefinders). To be effective, the slope measuring device must be able to strike the correct part of the tree, which can be challenging on windy days or in thick vegetation. Because it does not need to be performed from any specific location providing the true top and bottom of the tree are visible, the sine method permits the observer to move around the tree until the best vantage point is found. Hence, there is no need to be perpendicular to a leaning or offset crown top, as required by the most common tangent method correction applied in the field, or to spend time identifying the crown nadir.

Test Subjects and Study Area

Three mature pines were selected for this study. One was an 89-cm dbh loblolly pine (*Pinus taeda* L.) from the Crossett Experimental Forest (CEF) in Ashley County, Arkansas. Second was a 91-cm dbh shortleaf pine (*Pinus echinata* Mill.) from the Levi Wilcoxon Demonstration Forest (LWDF), also in Ashley County. Both of these were on level sites and possessed a slight (4–5°) lean that has been suggested as inconsequential enough to be ignored when determining height (e.g., Avery and Burkhart 1994). The third tree, a 49-cm dbh shortleaf pine located on the University of Arkansas–Monticello (UAM) campus in Drew County, was chosen to highlight the relative insensitivity of the sine method to violations of the assumptions of the tangent method. This shortleaf pine grows on a moderate (approximately 10%) slope, has a spiraling 5–10% lean, and is found in a relatively closed canopy, limiting the number of clear observation points. The close proximity of its crown to its neighbors, coupled with its tilt and the slope of the ground, therefore makes determining the best measuring location difficult.

Measurement Tools

An Impulse 200LR laser rangefinder was used to measure the height of all trees. According to the manufacturer, the Impulse 200LR has a maximum distance measurement error of 15 cm up to

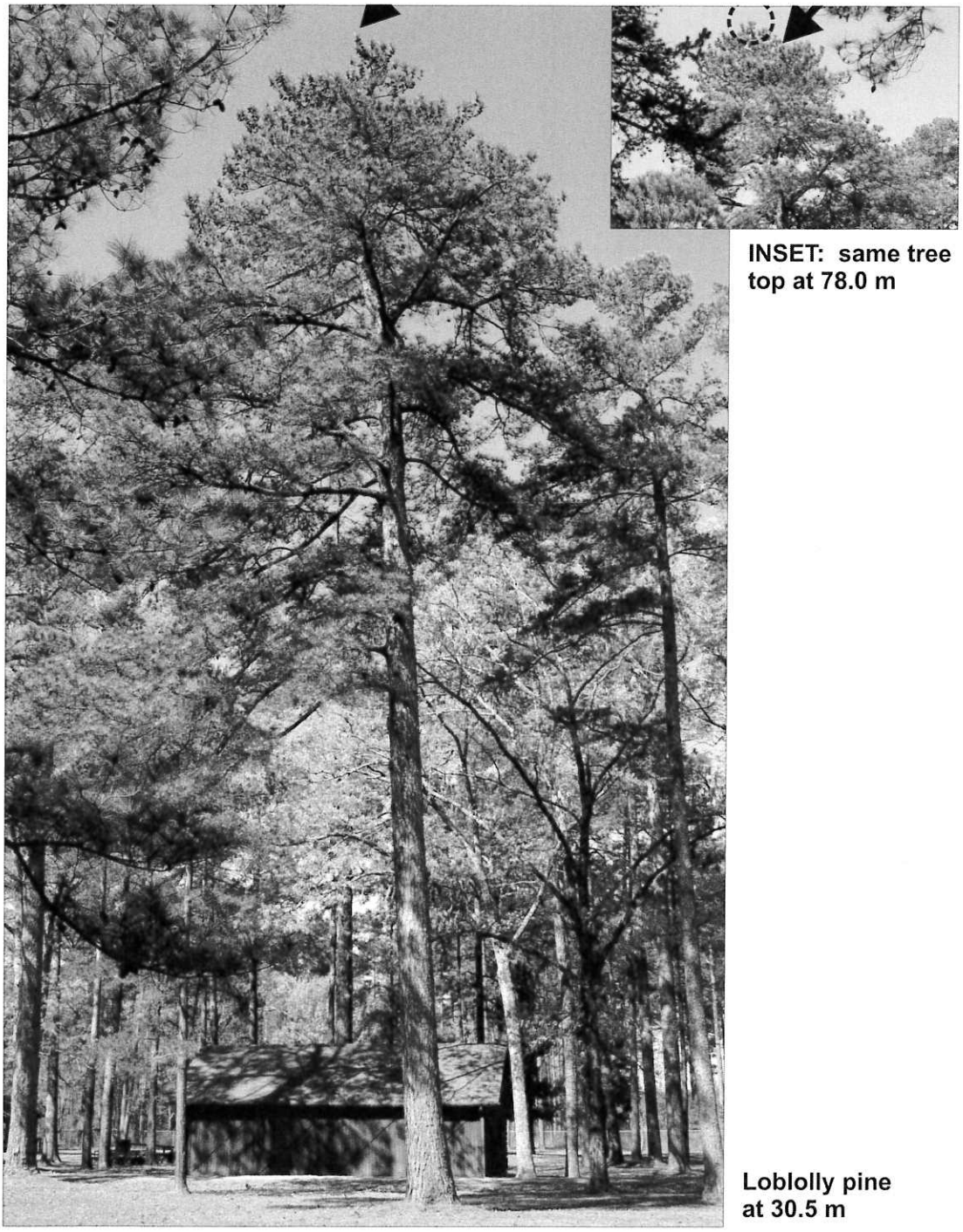


Figure 3. The mistaken identification (arrows) of a subordinate branch as the top of the loblolly pine on the CEF at a distance of 30.5 m was only recognized with the sine method. At 78.0 m, the true top (circled in inset) was visible and clearly taller than the "obvious" top.

575 m (with "typical" accuracy of 3–5 cm), and an angle measurement accuracy of ±0.1° (Laser Technology, Inc. 2006). Because it has an electronic inclinometer and can produce both horizontal and slope distances, this device is capable of both the tangent (the default program) and the sine height techniques.

However, most foresters use more affordable devices such as handheld clinometers and cloth or steel measuring tapes. Even though less accurate, these tools are more compact and can quickly yield a height. For the CEF and LWDF pines, the Impulse provided the exact horizontal distance for the tangent method using both the clinometer and the laser rangefinder. The UAM shortleaf pine was approached somewhat differently—to highlight the potential for multiple errors on the estimation of height, distance from the observer was determined exclusively with a cloth tape for all tangent-based measurements.

Study Design and Analysis

For the Ashley County pines, three to four transects with three observation points each were extended from each tree. Transects corresponded to cardinal directions based on tree lean, so each pine had one transect that followed, one that went against, and at least one perpendicular to the lean. The first observation point along each

Table 1. Height measurements on the CEF loblolly pine taken from three different perspectives (a building blocked the view from the west) using a laser rangefinder (tangent and sine methods) and a tape and clinometer (tangent method only).

	North distance			East distance			South distance					
Measure	30.5	47.0	67.9	30.5	48.2	78.1	30.5	51.6	85.3	Min.	Max.	SD
	(m)											
Tangent	29.4	29.8	29.7	31.2	30.0	30.4	32.9	31.8	31.2	29.4	32.9	1.16
Sine	29.6	29.8	29.9	27.6	30.3	**30.7**	30.0	30.0	30.3	27.6	30.7	0.87
Observer 1	29.3	29.6	29.9	30.2	29.9	30.4	32.0	32.0	32.4	29.3	32.4	1.18
Observer 2	29.3	29.2	28.5	29.9	29.4	29.7	32.6	33.5	31.6	28.5	33.5	1.74
Observer 3	29.6	29.2	29.2	29.9	29.4	29.7	32.6	30.9	32.4	29.2	32.6	1.35

Bold font indicates the greatest sine height.

Table 2. Height measurements for the LWDF shortleaf pine taken from four different perspectives using a laser rangefinder (tangent and sine methods) and a tape and clinometer (tangent method only).

	North distance			East distance			South distance			West distance					
	30.5	47.3	58.8	30.5	46.8	65.3	30.5	53.2	67.0	30.5	45.6	51.7	Min.	Max.	SD
	(m)														
Tangent	42.2	41.9	41.3	40.2	40.5	41.0	43.5	42.1	41.9	46.9	44.0	43.5	40.2	46.9	1.86
Sine	41.1	**41.4**	41.1	39.4	41.2	41.3	38.2	40.3	41.3	39.7	40.5	40.5	38.2	41.4	0.98
Observer 1	41.5	42.1	41.7	39.6	40.7	41.1	43.0	40.5	41.5	46.6	43.8	41.9	39.6	46.6	1.82
Observer 2	40.8	40.7	41.7	40.8	39.8	41.1	43.3	42.1	40.8	46.3	44.3	43.5	39.8	46.3	1.88
Observer 3	41.8	41.6	42.3	39.9	40.3	40.5	42.7	41.5	40.8	46.3	43.8	43.5	39.9	46.3	1.81

Bold font indicates the greatest sine height.

transect was placed at a convenient standard of 30.5 m, and the others were located at good viewpoints from 45 to 85 m along the transects.

Because the UAM pine was included to show the insensitivity of the sine method to poorly chosen locations, a different design was used. Six observation points were chosen where the top and bottom of the pine were clearly visible, regardless of position relative to tree lean, distance from the stem, or ground slope. Because this shortleaf, although noticeably leaning, was not drastically off center, these point locations should emulate a measurer opting for viewing convenience rather than the spot capable of the greatest height accuracy. Each of these locations where chosen because they provided reasonable views of what appeared from each spot to be the top. These points also were relatively close to the subject tree (between 20 and 60 m).

Two to three observers with 5–30 years of forestry experience used a percent-baseline distance clinometer to estimate tree height following conventional techniques at every observation point. Observers were instructed to regard the top of the crown as the highest apparent point from the viewing location. At each of the 6–12 observation points per tree, observers also made tangent and sine height estimates using the laser rangefinder to the exact same point of the crown. To avoid biasing the results of the clinometer measurements, each observer silently and independently recorded their estimated heights.

True height was then needed to compare measured heights. Because we could not drop a tape vertically to directly measure height, the next best option was chosen. The sine method, when applied to the appropriate top and bottom of a tree, can not overestimate tree height. It is possible for the sine height of a subordinate part of the crown to be less than the actual height, especially when the true top of the tree is hidden. Hence, the maximum sine height taken from multiple distances and angles provides a robust estimate of total height. However, the same can not be said for the tangent method, because there is no way to account for how much (or even why) the heights depart from the true value.

Results and Discussion

Both techniques are considerably easier and quicker on open-grown trees. In a forest, the tangent method generally is faster, because one only needs to approximate the top of the crown. However, this convenience lends itself to potentially significant errors in height determination.

Height Accuracy and Variation between the Techniques

If the corresponding angles and distances are measured correctly, the sine method is the most consistent and accurate means to remotely measure tree height because it always measures a physical object rather than a projection of the top of the crown. For the loblolly pine on the CEF, the maximum sine method height estimate is 30.7 m, the shortleaf pine at the LWDF reached 41.4 m, and the shortleaf pine on the UAM campus was 32.0 m tall—these numbers were used as the truest available estimates of their respective total tree heights. To accurately determine total tree height with the tangent method, corrections for leaning stems or offset crown tops must be used. Otherwise, the horizontal baseline difference (Figure 1b) does not reflect either the top or the bottom of the tree as projected. Hilly topography can further exacerbate this problem, especially when using equipment that does not automatically compensate for slope.

Slope was not an issue for the loblolly pine on the CEF. For this south-leaning example, the east-based measurements corresponded best to the true height of the tree. This set of measurements showed very little difference as a group, with one noticeable exception. From the east at a distance of 30.5 m, the tangent method produced height estimates ranging from 29.9 to 31.2 m. This range turns out to be a reasonable approximation of the tree's best height estimate (30.7 m), but for the wrong reason—at this distance, a stray branch projecting toward the observers appeared as the highest point. In reality, this was subordinate to the actual crown top (Figure 3). Only the sine method showed that the elevation of this point (27.6 m) was substantially less than the true height of the loblolly. Note that the quasi-agreement of some of the errant tangent readings in Table 1

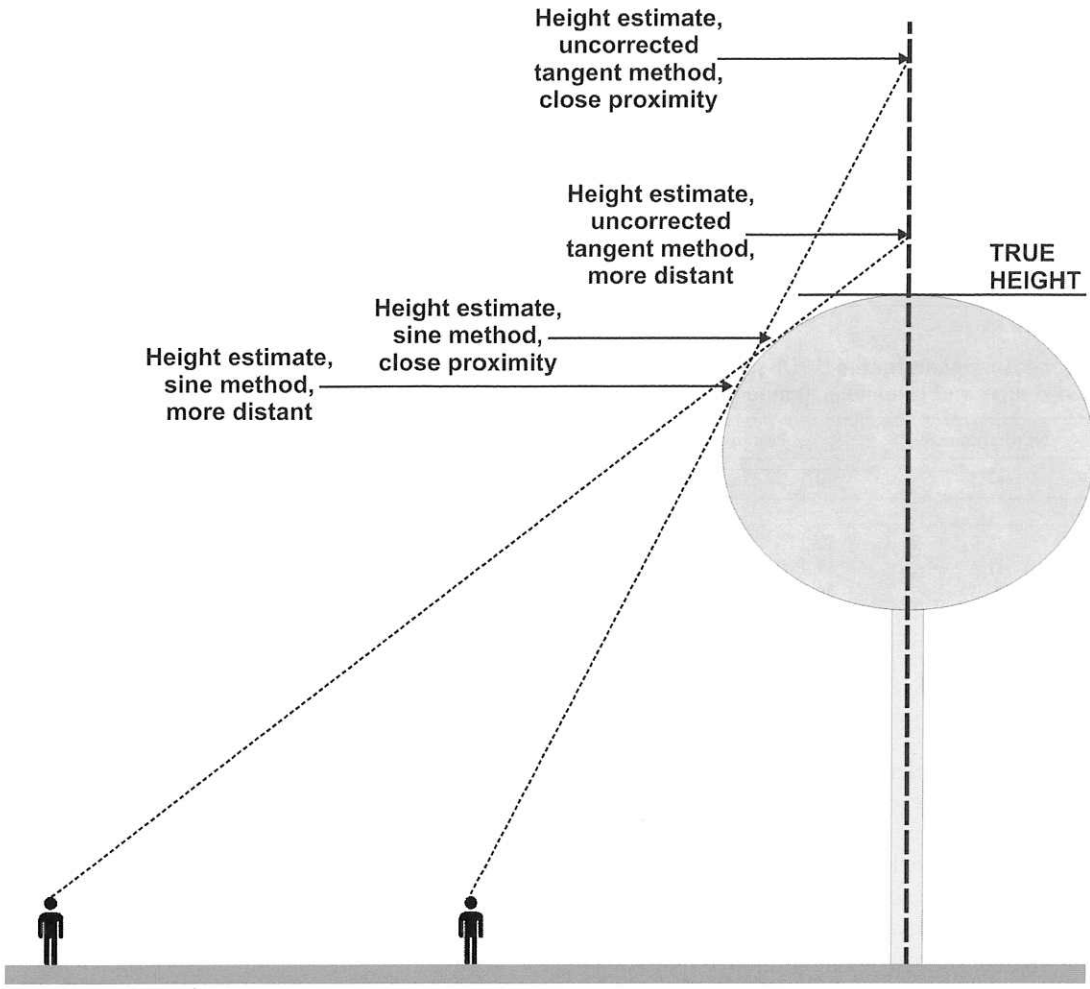


Figure 4. Proximity effects on misread crown heights for the sine and tangent methods.

and true tree height are no guarantee that this pattern will be consistent, given their sensitivity to the assumptions inherent in the technique.

Not surprisingly, the sine method, being insensitive to the primary sources of measurement error using the tangent method (especially tree lean and offset crowns), had noticeably less variation in the estimated heights of the CEF and LWDF pines (Tables 1 and 2). Both trees had a particular direction for which the tangent error was greatest, with departures of 2.5–5.5 m from true height. This may not seem like much, except that neither tree had a dramatic lean or highly offset crown.

The sine method yields a significantly lower degree of variation (standard deviation [SD] = 0.87 m) than any of the tangent-based observations (SD between 1.16 and 1.74 m) of the loblolly pine on the CEF (Table 1). If we ignore the observation of the subordinate branch at 30.5 m, variation is even lower for the sine method (only 0.33 m), and the tangent-based observation SD actually increased slightly (now 1.23–1.84 m). The trends are similar for the shortleaf pine on the LWDF (Table 1), with the sine method yielding almost one-half the SD of the tangent-based observations (0.98 m versus 1.81–1.88 m). Assuming the inherent error of the equipment is negligible, the source of this variation is easily explained for the sine-based observations—the target struck by the laser as the presumed top of the tree was actually a somewhat subordinate position. For the tangent observations, the variation could have resulted from a number of factors, including the lean of the tree or offsets in the top of the crown.

The magnitude of the tangent-based errors also depends on the proximity to the stem—the more distant the observer, the lower the impact of errors in crown position and angle projections. In mature forests of tall stature, proximity becomes increasingly important for tangent-based measures of tree height. As stand density and structural complexity increases, there are more obstructions affecting the view of any given tree top. It becomes virtually impossible to distinguish one from another, especially in monospecific stands. Under these circumstances, it is common for the observer to guess where the tops and/or bottoms of the subject tree are, which can lead to serious misapplications and substantial measurement errors.

Alternatively, observers sometimes adjust for poor visibility by measuring height from very close to the tree, which can result in an additional problem—systematic overestimation (e.g., Husch et al. 2003, Bragg 2007). For instance, many species (especially open-grown hardwoods) produce spreading, dense crowns. If an observer takes the side of the crown as the true top, then errors in height may arise because of an inappropriate baseline distance (Figure 4). The closer the observer is to the subject tree, the greater the error when using the tangent method. The sine method is relatively insensitive to distance from the tree because it measures slope distance of an actual point and accurately yields its height—which, obviously, is still in error, because it is not the intended total tree height (Figure 4).

Table 3. Height measurements of the University of Arkansas–Monticello shortleaf pine taken from six different points surrounding the tree using a laser rangefinder (tangent and sine methods) and a tape and clinometer (tangent method only).

Measure	Point number						Min.	Max.	Ave.	SD
	1	2	3	4	5	6				
Azimuth (°)	53	179	262	290	354	5	.....	(m)	.....	
Horizontal distance (m)	20.9	34.4	21.9	56.0	22.0	42.1				
Tangent	35.8	31.0	33.3	32.7	37.8	34.9	31.0	37.8	34.3	2.42
Sine	**32.0**	**32.0**	27.8	30.2	31.8	31.9	27.8	32.0	31.0	1.69
Observer 1	33.5	31.4	32.4	34.2	34.6	34.7	31.4	34.7	33.5	1.32
Observer 2	33.7	30.8	32.8	32.0	36.0	34.7	30.8	36.0	33.3	1.88

Bold font indicates the greatest sine height.

The tangent method can be as reliable as the sine method if proper steps are taken to correct for these influential factors. However, most observers are not likely to perform them in the field, especially if their correction would prove time-consuming. For the third tree in this study, the UAM shortleaf pine (Table 3), four of the six sine observations fell within 0.2 m of the maximum sine height estimate of 32.0 m, with the other two noticeably less (4.2 and 1.8 m, respectively). The tangent-based observations varied more, ranging from just under 31 m to almost 38 m, and mostly overestimated height. Two of the three points with the lowest tangent heights also produced the lowest sine heights, suggesting a subordinate crown position.

Cost Effectiveness

Because of the differences in how the technology is applied, it is hard to compare the sine and tangent methodologies under most field conditions. A clinometer ($100–200) and a logger's tape ($50) are the most affordable, and laser measuring devices can run from basic units ($200–400, without inclinometers and relatively low accuracy of ±1 m) to thousands of dollars. Devices capable of both fairly accurate distance and angle measurements can be purchased for $600 to 1,200. Although this amount may seem high, the greatest cost involved is the total time it takes to get an accurate measurement.

In most forested settings, the tangent method usually is quicker, if less accurate. The need for accurate height estimates must be balanced with the expenses of obtaining that accuracy. If the cost of having some degree of unpredictable errors in the height data does not exceed the expediency of using the tangent method, then few users are likely to switch to the slower but more accurate sine method. However, it should not be assumed that tangent height measurement errors are randomly distributed and unbiased, even over the course of a large inventory (i.e., as equally likely to overpredict and underpredict, with the total errors then "averaging" out) because technique biases and crown irregularities tend to overestimate height.

Conclusions

Height accuracy depends heavily on the assumptions violated when measuring a particular tree. Without the proper adjustments and identification of the true top of the tree, the similar triangle- or tangent-based methods will produce significant errors. The sine method, which directly measures the slope distance to a given part of the tree, automatically adjusts for tree lean, crown top offset, or sloping ground, assuming (as is the case with the tangent method) that all angles and distances are accurately measured.

With the sine method, having multiple height measurements for a single tree from different perspectives makes it easy to predict maximum height, because the highest value is the best estimate. However, there is no general rule that can be applied when using the tangent method. One thought has been to assume that estimation errors (both positive and negative) are equally distributed, and that an average of multiple readings would produce a relatively unbiased estimate of height. Table 3 shows that this is not necessarily so and that observer biases (e.g., most people would not measure toward or away from the lean of a tree) and the complexity of crown architecture tends to favor overestimates. Averaging may reduce the departure from actual height, but this is only true if no other systematic biases exist.

There are some challenges to using the sine method, not the least of which is that because it is not the default program of laser hypsometers, it often must be calculated manually. Some people will be reluctant to change how heights are measured, especially when they have many years of data using more conventional approaches. To them, the accuracy improvement would have to be dramatic for them to even consider the sine method. However, there are many circumstances where highly precise and accurate tree height measurements are required. For these, the sine method is superior to the tangent method. In the end, the user must balance their need for consistency and expedience with the desire for the best possible measure of tree height.

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TECHNICAL NOTE

Survival of Longleaf and Loblolly Pines Planted at Two Spacings in an East Texas Bahiagrass Silvopasture

Brian P. Oswald, Kenneth W. Farrish, and Micah-John Beierle

ABSTRACT

The practice of combining intensive timber and forage production on the same site, a silvopasture system, offers landowners the potential for diversification of income. The establishment of such a system in a pasture setting offers unique challenges compared with traditional timber or forage systems. In 2003, a silvopasture demonstration was established south of Carthage, Texas, in a pasture dominated by bahiagrass (*Paspalum notatum*). Four replications of treatments composed of open pasture, longleaf (*Pinus palustris*) and loblolly (*Pinus taeda*) pine planted at a traditional spacing, and longleaf and loblolly pine planted at a silvopasture spacing were established. Due to high mortality rates, replanting of trees occurred in 2004 and 2005. Third-year seedling survival was highest for loblolly pine in both planting systems, and forage production levels did not significantly differ among treatments. Wild hog damage contributed to the low longleaf pine seedling survival rates.

Keywords: *Pinus palustris, Pinus taeda,* plantations, agroforestry

Silvopasture is an intensive, multiple resource management practice that integrates forest and forage production. This integration allows landowners to have management and economic diversity across the same land unit. Livestock, timber, and even recreational opportunities may offer cash flow opportunities for an operational silvopastoral system (Harwell and Dangerfield 1991). Overall increases in financial return and economic diversity have been noted from silvopasture systems compared with either pine plantations or forage systems alone (Clason 1988, Dangerfield and Harwell 1990, Harwell and Dangerfield 1991, Lawrence and Hardesty 1992, Zinkhan 1996).

A silvopasture system may be established in either an existing plantation or, more commonly, an existing pasture (Clason 1999). The variety of options (i.e., tree spacing, tree species, and forage species) provides landowners tremendous flexibility for management. East Texas traditions of forage, livestock, and timber production and an established infrastructure of watering systems, fencing, and livestock handling facilities make the region an ideal setting for their integration. A common question is the ability of tree seedlings to successfully establish within a well-established pasture without unacceptable mortality caused by competition from the forage crop. Another common issue for those managing pastures is the impact of tree establishment on forage production. In addition, data are lacking on what forage or tree species to use, what spacing to be used, and what possible pitfalls may hinder the establishment of a silvopasture system in East Texas. The objective of this case study was to explore the establishment success of a silvopasture system in a bahiagrass pasture using loblolly pine (*Pinus taeda*) and longleaf pine (*Pinus palustris*) and two tree spacings (traditional plantation and a common silvopasture spacing).

Site Description

The study site is located south of the city of Carthage in Panola County, Texas, approximately 80 km southwest of Shreveport, Louisiana, and 241 km west of Dallas, Texas. The regional climate is classified as subtropical, permanently humid climate with mean rainfall of 112 cm and an average growing season of 240 days (USDA Natural Resources Conservation Service 2004). The site contains several soil types: Bowie fine sandy loam, Sacul fine sandy loam, Nahatche complex, Cart-Erno complex, and Wrightsville-Cart complex (USDA Natural Resources Conservation Service 2004).

Methods

In 2003, four replicates were laid out in a bahiagrass pasture. Within each replicate, 5 planting arrangements were randomly assigned: bahiagrass open pasture, no trees; longleaf pine or loblolly pine on traditional plantation spacing (2.1 × 3.7 m spacing for 1,282 trees ha^{-1}); and longleaf pine or loblolly pine on silvopasture spacing (1.8 × 9.1 m for 598 trees ha^{-1}), each within a 4.1-ha treatment block. A banded application of Arsenal (glyphosate) at 4 oz A^{-1} was applied in the fall of 2003, and the rows were ripped prior to container-grown seedlings being planted in the winter. Oust Extra (56.25% sulfometuron methyl and 15% metsulfuron methyl) at 3 oz A^{-1} was applied the following spring to further control herbaceous competition. A fertilizer application of 20-8-15 at 68 kg ha^{-1} (375 lbs A^{-1}) was applied in the summer of 2004.

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Brian P. Oswald (boswald@sfasu.edu), Arthur Temple College of Forestry and Agriculture, Stephen F. Austin State University, Box 6109 SFA Stn, Nacogdoches, TX 75962-6109. Kenneth W. Farrish and Micah-John Beierle, Arthur Temple College of Forestry and Agriculture, Stephen F. Austin State University, Nacogdoches, TX 75962-6109. *Funding was provided by USDA Natural Resources Conservation Service Agroforestry Center and McIntire-Stennis Cooperative Research Program. The authors gratefully acknowledge the access to a bahiagrass pasture provided by Sid and Kim Fowler, owners of the K-S Ranch in Carthage, Texas.*

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Table 1. Mean bahiagrass dry forage production by treatment for the Carthage silvopasture study site for May 2006.

Treatment	Tons ac^{-1}	Mg ha^{-1}
Bahiagrass	0.83	2.64
Loblolly silvopasture	0.81	2.66
Longleaf silvopasture	0.77	1.91
Loblolly plantation	0.76	1.74
Longleaf plantation	0.71	1.76

Mean square error = 0.2561.

Over the next 2 years, forage production and seedlings survival were monitored. Forage production was measured by clipping 4 randomly located plots per treatment plot, oven dried, and weighed. Expansion to the per-hectare level was determined by estimating the plot area producing forage within each treatment plot and then calculating the equivalent forage production on a per-hectare basis. In the winters of 2005 and 2006, seedlings lost to mortality were replaced so that the area could also be used as a demonstration area, but overall survival numbers were recorded. A second application of Oust Extra (3 oz ac^{-1}) was applied in the spring of 2006. Hay cutting was performed multiple times each year during the period of this study. Using 2006 data for seedling survival at the end of a 2-year establishment period, analysis of variance (SAS Institute 1999) was used to determine whether significant differences in forage production and seedling survival occurred, and Tukey's Student range (honestly significant difference) test was applied when significance was found at the $\alpha = 0.05$ level.

Results and Discussion

No significant difference was found in 2006 for forage production regardless of treatment (Table 1). Although this represented a single sampling period comparison, the results were consistent with those found in earlier sampling periods. Forage production was already at a high level prior to plot establishment, and the fertilizer treatments used in this study maintained the overall capacity of the area to produce forage, even when a proportion of the area was not producing trees.

Seedling survival was significantly greater for loblolly pines than longleaf pines in both silvopasture and traditional spacing arrangements (Table 2). Negligible mortality was attributed to the hay cutting activities. Machine operators were careful to avoid rows of seedlings, which were easy to locate with the residual effect of the herbicide treatment. Herbaceous vegetation encroachment into the sprayed rows was minimal, so little mortality can be attributed to herbaceous competition. A majority of the mortality was attributed to wild hog (*Sus scrofa*) activity. Hogs came from adjacent forested landownership, much of which is low-lying hardwood-pine mix, a perfect habitat for wild hogs. The hogs did not appear to eat many of the longleaf pine seedling root systems. Mortality was caused instead by the longleaf pine seedlings in the grass stage being buried when

Table 2. Percentage of seedling survival after replanting in 2004 and 2005 for the Carthage silvopasture study site sampled in May 2006.

	Silvopasture		Plantation	
	Loblolly	Longleaf	Loblolly	Longleaf
Mean	94.9%(A)	56.1%(B)	89.9%(A)	45.3%(B)

Percentages in a row with same letter are nonsignificantly different at the $\alpha = 0.05$ level. Mean square error = 120.8430.

the hogs burrowed along the rows where herbicide had been applied. The herbicide may have actually made it easier for the hogs to root within the rows, since the dead herbaceous vegetation was not producing viable, growing roots. The decaying roots may also have been a better habitat for grubs, although this was not documented in this study. For whatever reason, the majority of the hogs' rooting activity was along and within these areas, burying the longleaf seedlings, causing mortality. Although rooting activity was also recorded in loblolly pine rows, the height of the seedlings limited burial- caused mortality.

Conclusions

It does appear that a silvopasture system in a bahiagrass pasture is possible in East Texas when using loblolly pine. Forage production in the form of hay and good seedling survival can occur, with fiber production and grazing occurring on the same site. The use of longleaf pine appears to be more problematic. Although there does not appear to be any difference in the ability of longleaf pine and loblolly pine seedlings to establish based on factors that influence seedling establishment, there is a greater risk in losing a large portion of planted seedlings to indirect hog damage through burial of the seedlings. On the basis of these results, it is recommended that anyone considering a silvopasture management option for East Texas pastures should use loblolly pine containerized seedlings or be prepared for active hog control.

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