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Visualization of Computer-Modeled Forests for Forest Management

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Abstract

Forest management is a costly and time-consuming activity. Remote sensing has the potential to improve the process by making it cheaper and more efficient, but only if appropriate characteristics can be determined from computer-models. This paper describes the implementation of a forest visualization system and a corresponding user study that tests the accuracy of parameter estimation and forest characterization. The study uses data obtained from field-surveys to generate a computer-modeled forest. Five different stands were tested. Based on the quantitative results obtained, generally, there is no statistically significant difference in parameter estimation when comparing field-recorded videos and computer-generated videos.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Applications; General Terms: Verification; Additional Keywords and Phrases: Scientific Visualization, Forest Management, Natural Phenomena

1. Introduction

Forestry and the forest products industry represent one of the largest industrial sectors in the United States. In the state of Mississippi, forest managers manage nearly 19 million acres of forest, of which, roughly 6 million acres are pine, with an additional 3 million acres a mixture of pine and hardwood [HL95]. Forest managers are interested in data such as stem density, species type, size and spatial arrangement of trees. Management activities include planning improvements, thinning trees to increase commercial yield, controlled burns to remove excessive undergrowth, and harvesting at peak maturity. Although presence is obviously required for some activities, inventory and planning could possibly be performed remotely. Currently, collecting field measurements is a time-consuming, burdensome task, but is a prerequisite to other management activities. The accuracy and reliability of remote sensing measurement techniques are improving, thereby making data collection cost-effective and more efficient. Likewise, visualization techniques that make use of the increased ability to collect data would likely have a significant, positive impact on the forestry industry. For example, present forest management is dependent on weather conditions and travel. Scientific visualization can potentially allow a manager to work remotely by simulating the forest view on a desktop. This should increase the productivity of the manager. However, this scenario is only effective if visualizations can convey accurate forest characteristics necessary for management. The goal of this research is to investigate the possibility of improving forest management through the visualization of computer-generated tree models.

2. Related Work

The modeling of natural phenomena and interactive computer graphics are at odds with each other. Natural phenomena, such as trees, are visually complex and require thousands of polygons for an accurate representation. On the other hand, only a finite number of polygons can be rendered in a fixed amount of time. This finite number depends on several system-related properties, but is usually far less than the number necessary to render highly detailed, natural scenery interactively. Therefore, most current interactive tree visualization systems are designed to show only a few trees at a time. The interactive methods that do show large groups of trees do not use accurate tree measurements and usually use some form of repetition or simplification to increase speed. Forest visualization can be divided into two main categories: visualization techniques for trees and plants, and forest visualization models and applications. An overview of current visualization techniques can be found in [MAMI*03]. Both geometric (e.g., hierarchical structure description, L-systems, fractals, and point-based rendering) and image-based (e.g., billboarding, bidirectional texture functions, and particle systems) rendering techniques are discussed.

2.1. Forest Visualization Models and Applications

Thus far, most forest visualization models and applications have been developed for assessing aesthetic beauty, for landscape planning purposes, or for simplistic stand evaluation. Systems judge aesthetic beauty since "the appearance of landscapes and individual stands after the harvest is critical to public acceptance of timber harvest practices" [McG98]. The main purpose of most landscape visualizations is to illustrate how terrain features would look at various points in time or under various land alteration schemes [HM91, SJ91]. Stand visualization attempts to convey stand characteristics, which is the purpose of this work. Most current stand visualization applications are limited to displaying general overviews (e.g., flyovers), or they use non-realistic or simplified tree models [All98, Bal00]. While these systems are obviously useful in some circumstances, they are mostly based on statistical data and averages. They do not represent actual characteristics because field measurements have historically been prohibitively expensive to collect over large areas. Monsu and SmartForest are example applications from this category. Systems that do incorporate true tree characteristics only display a few trees at a time [McG98] or address a very specific problem and are not extendable [UO01]. Stand Visualization System (SVS) is an example.

2.2. Validation

Only a few studies have addressed the accuracy of forest visualization systems. Scenic beauty rankings for photographs and corresponding computer-generated images were compared in [BF95]. It was determined that missing objects and the homogenity of trees affected the viewer's perception for the computer-generated images. The accuracy of average stand characterization using Monsu and SmartForest was compared in [RP01]. Mean tree height and diameter were assessed accurately; other characteristics were not.

2.3. Initial Response

Most tree and plant visualization techniques are used mainly for scene enhancement in a virtual world. Most of the forest visualization systems do not use true tree measurements and, instead, use averages. For the models that do depict individual tree measurements, there has been little verification of their ability to convey forest management measurements to an observer. This is due to the fact that collecting field measurements on a large scale is both time-consuming and costly. Therefore, previously, there has not been a clear need for a formal study; rarely would one find it useful to look at a single tree and make the assessment, "This tree has dimension x." However, as remote sensing technologies, such as Light Detection and Ranging (LIDAR), become more widely available, and techniques to extract forest dimensions from LIDAR become more sophisticated and accurate [MRE03, PHS02], virtual forest management becomes more of a possibility. Therefore, a study to determine if computer-generated forest models can accurately depict forest characteristics is now essential.

3. Data

Test stands were chosen based on the fact that they represent various characteristics forest managers face when managing commercial pine stands[Fuj05]. Both well managed and minimally managed stands were chosen, and a total of five different test stands were used. All test stands are located in the Mississippi State University Starr Memorial Forest in east-central Mississippi. The three well managed stands contain a single tree species, loblolly pine (*Pinus taeda, L.*), and are located in an eighteen year old spacing trial research unit. The exact location of every tree is known since the trees were planted in a regular grid pattern. Spacing in the three stands is five feet (1.5 meters), eight feet (2.4 meters), and ten feet (3.0 meters), respectively. The two minimally managed stands consist of one mature stand (40 years old) and one immature stand (8 years old). The mature stand is 73.0 acres. The immature stand is 43.3 acres. Exact tree location for the minimally managed stands is not known. Loblolly pine is the predominate species in each stand. However, the mature stand also contains measurable hardwood trees (understory), which is an important characteristic for management. Data were collected for all measurable pine and hardwood trees.

Data were collected through field inventory, and included tree location, total tree height (HT_TOT), height to the base of the live crown (HT_BLC), diameter at breast height (DBH), and at least four crown radii (one in each of the four cardinal directions). HT_BLC is the distance from the ground to the lowest live whorl, defined as containing at least two branches. DBH is the diameter of the tree, measured at 4.5 feet (1.37 meters) above the ground. Data were collected for every tree in the spacing trial stands. Due to the stand size (73.0 and 43.3. acres, respectively), data were collected in eight randomly selected plots for each of the mature and immature stands. Plots were circular and selected to avoid clearings. Tree location was determined for each tree in the eight selected plots by determining the distance and azimuth

Figure 1: *Screenshot of a computer-generated video (left) next to a field-recorded video (right). Both videos show the trunk-view for the mature stand. Click here to view sample videos.*

from the center of the plot. Data were also collected for the hardwood understory in the eight mature plots.

4. Implementation

To make our comparison in a controlled environment, the subjects estimated forest parameters by viewing either field recorded videos or computer-generated replica videos (Figure 1). Comparing videos removes the necessity for this study to evaluate the effect, if any, of interactivity on parameter estimation. Videos follow a predetermined path, ensuring each subject views identical stand area for an identical amount of time. Videos can also be pre-generated, ensuring that model rendering speed, and thus, frame rate, does not affect the subject's perception.

4.1. Field Videos

For the well managed stands, field videos are analogous to a manager walking through the stand to determine overall stand characteristics. For the minimally managed stands, field videos are analogous to a manager standing in a fixed location (inside a plot) and spinning around to view the stand. Minimally managed stands are viewed in this manner from multiple random positions in the stand since the stand contains thick underbrush and it would be difficult to perform a walk through. A limitation of using videos is the small field of view (FOV) of the camera; it is impossible to see both the tree trunks and the crowns at the same time. However, randomly moving the camera to mimic head motion is not desirable. First, random movement could be jerky and cause nausea. Second, random motion would be very difficult to replicate in the computer-generated videos. Therefore, we chose to capture two videos for each pass or view location. For the first video the camera is held level and a trunk view is captured. For the second video, the camera is held at a constant upward angle and a crown view is captured.

Another limitation of using videos is that two-dimensional images were used to represent a three-dimensional world, resulting in the loss of some depth perception. To alleviate this problem, distance cues in the form of ribbons and flags were placed in the stands before they were filmed. One-inch thick ribbon was placed around tree trunks at breast height (4.5 feet above the ground). Red flags were placed in the ground at regularly spaced intervals, beginning in the center of the stand (or plot) and radiating outwards in each of the four cardinal directions. In the well managed stands, ribbons were placed on every third tree and flags were placed in ten-foot intervals. In the minimally managed stands, ribbons were placed on one tree in each cardinal direction and flags were placed in five-foot intervals. Flags were placed closer together in the minimally managed stands. Since the view location was fixed and there was a large amount of understory and underbrush, the flags quickly became indiscernible as distance from the view location increased. Duplicate videos were recorded for each pass or view location. Later, the videos were individually evaluated for image quality and background noise or disruptions, and the best quality video for each pass was used in the study. A total of 88 videos were recorded; forty-four were used. An example frame from a field-recorded video is shown in Figure 1.

4.2. Virtual Forest

The system needed to create computer-generated videos can be broken into two parts: a forest visualization application and a video generator. As discussed in Section 2, a forest visualization application capable of rendering large stands realistically with accurate forest measurements does not exist. Therefore, an application must be developed. Since loblolly pine is either the sole species or predominate species in all of our test stands, evaluating a model specifically designed for loblolly pine should yield the best comparison between actual and computer-generated stands. Moreover, to remove any estimation error that may occur due to oversimplification, a realistic model is desired. Therefore, we chose to evaluate a model based on the needle model [MAMI*03].

To ensure a fair comparison can be made, it is important for the virtual forest to represent real-life conditions of our test stands as accurately as possible. Therefore, the virtual forest's design is based mainly on the measurement data obtained from the field surveys. This resulted in each of the three stand-types (spacing, mature, and immature) having slightly different end-visualizations. However, each stand-type had the same basic visual components (e.g. tree model, ground, fog). These components and the slight variations, if any, for each stand-type are discussed in the next sections. Additionally, aesthetic modifications based on forestry professionals' advice were included after all the measurement data had been incorporated into the system. These modifications are also discussed below.

4.2.1. Loblolly Pine Trees

The pine tree model developed for this study is a variation of the needle model [MAMI*03]. The stem is centered at the tree location and is composed of two upright, six-sided cylinders (Figure 2). The lower cylinder is the trunk and the upper cylinder is the top trunk. The base of the trunk (at the ground) has a radius of 1/2 DBH. The top of the trunk has a radius of 1/2 DBH times the taper rate. The trunk height is equal to HT_BLC. The top trunk's base is drawn at HT_BLC and aligned and sized to snuggly fit the trunk. The top trunk's upper radius is a constant. The height of the top trunk is equal to HT_TOT - HT_BLC. For this study the taper rate was set at 0.8 and the top trunk's constant was 0.04.

Branches are drawn in whorls emanating from the top trunk, shown in Figure 3. Whorl spacing is determined automatically based on the live crown to height ratio, per our colleagues' recommendations. Whorl spacing is, on average, one whorl per meter, except for immature trees, which have one whorl per foot. Each whorl usually contains four branches, one in each of the four cardinal directions. The number of branches and sub-branches is automatically adjusted based on the size of the live crown. Branch thickness is based on the tree's DBH. The branch-to-stem angle is determined based on branch height and varies from 80 degrees at the base of the top trunk to 35 degrees at the top of the top trunk (top of the tree). Randomness is used to prevent rigid repetitiveness in the model. For example, every tree has a small probability of containing dead branches. When a branch is classified as dead, it is not drawn. The number of dead branches per tree is limited to avoid large gaps. Branch angles and location are also randomly varied to ensure no two trees are identical. Each branch end contains a needle "bunch", which is represented with two orthogonal, textured quads.

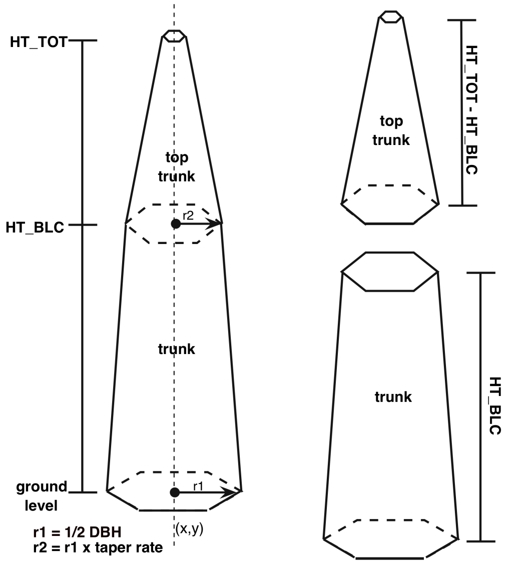

Figure 2: *An illustration of the two-segment trunk.*

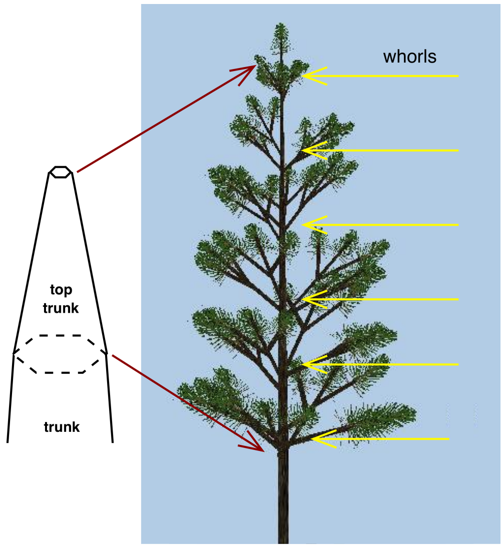

Figure 3: *An illustration of branch whorls.*

4.2.2. Hardwood Trees

Although subjects were not asked to estimate parameters for hardwoods, they were included in the visualization since their omission could potentially lead to false stand impressions. Futhermore, since hardwoods were only included as visual cues to aid in pine tree parameter estimation, a simplistic model was appropriate. The hardwood trees were rendered using billboarding. Traditionally, billboarding uses a single texture affixed to a quadrilateral (quad), which is rotated so that it constantly faces the viewer. However, to ensure both the trunk and crown can be scaled independently, this model utilizes separate textures for each Figure 4. Hardwood trees were only present in the mature stand. Since the viewer's position was constant in the mature stand, it was not necessary to continually rotate the quad. Rather, the billboarded quad was static and drawn three times, each rotated by 60 degrees. Therefore, a total of six quads represent a single hardwood tree (three for the trunk textures and three for the crown textures).

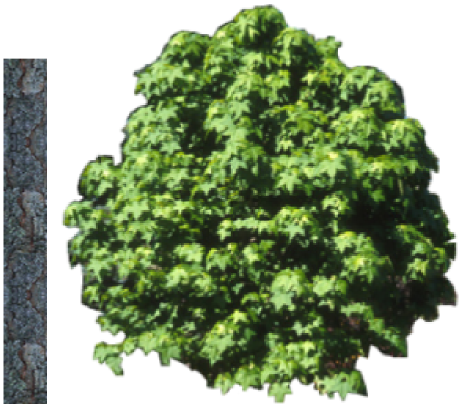

Figure 4: *Screenshots of the hardwood trunk (left) and crown textures (right). The hardwood tree textures were applied separately so they could be scaled independently.*

4.2.3. Ground and Environment

A complete virtual forest must contain ground and a surrounding environment. The omission of ground and surrounding trees destroys the virtual forest illusion. Also, it is imperative the edge of a stand is not discernable or results may be biased. If the observer knows the plot size and is able to visually perceive the edge of the plot, they might more easily estimate parameters such as trees per acre. Due to a lack of terrain data, ground was represented as a repeated texture affixed to a single quad. A surrounding environment was created with a textured bounding box that was situated a static distance away from the user. Fog was added to obscure the transition between the edge of the stand and the bounding box. Fog also added more depth perception [AMH02]. However, even with fog, when the observation point was close to the stand edge, the edge was still discernable. This was especially true for the mature and immature stands since the observer was centered in a small plot (immature plot radius = 5 meters, mature plot radius = 10 meters) within the larger stand. (Recall that data were only available for the small plots, not the entire stand.) Since we had limited available data for these plots, the original plot data were replicated to provide more trees. First, the plot dimensions and average tree spacing were determined. Then, a new plot was formed by randomly rotating the trees in the existing plot. New plots were placed around the existing plot. New plot center locations were based off the original plot's dimensions and tree spacing. In this way, erroneous tree spacing estimation error caused by plot overlap was eliminated. Replication was performed on an individual plot basis.

4.2.4. Visual Distance Cues

Flags and ribbons were placed in the virtual forest in the same manner as the real forest. The only difference was in the placement of ribbon in the minimally managed stands. In the field, ribbons were placed generally one-ribbon in each direction. However, which tree had a ribbon was not recorded. Therefore, our system used the AZI and RADDIST data to chose a tree. For example, our system picked the tree, if any, whose AZI within plus or minus ten degrees from due North. If there were multiple trees in that range, the system chose the tree with the least RADDIST. This ensured the tree was in the general direction desired, and that in the event of multiple trees, the tree closest to the user received a ribbon.

4.2.5. Aesthetic Qualities

The system was implemented and shown to forest professionals who voiced concern that the virtual forest was too clean. It was thought that the lack of underbrush or undergrowth would distract the users. Therefore, random green leaves were drawn. In managed stands, the undergrowth was kept below one foot off the ground. This was due to the movement within the stand. In minimally managed stands, the undergrowth was kept below breast height so as not to obscure distant trees, ribbons, and flags. The resulting virtual forest is shown in Figure 5.

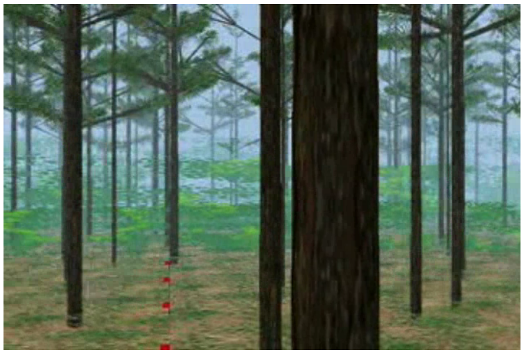

Figure 5: *An example screenshot of a computer-generated video for the immature stand. Distance cues (red flags) and other virtual forest elements are visible.*

4.3. Computer-generated Videos

The application automatically performed a walk-through or spin-through of the stands to mimic the field-recorded videos. Similarly to the field videos, two videos were generated for each plot or path, one trunk view and one crown view. The camera level, camera angle, camera position, and image size (aspect ratio of 4:3) were set to copy the field videos. Videos were generated by capturing successive frames with glReadPixels() and combining them with dmconvert. A total of 44 videos were created.

4.4. User Study

To ensure each subject would have an identical experience, the videos and instructions were combined on a DVD. For a given stand, the subject viewed pre-evaluation instructions, the stand identification number, the plot number (or pass number for the spacing units), and either "trunk" or "crown" depending on the footage to be shown. The plot number and footage type were repeated before each segment for the entire stand. After viewing all videos for a single stand, post-evaluation instructions were displayed. Each subject was assigned to evaluate either the virtual forest videos or the field-recorded videos. Each subject evaluated all five stands for their type. The stands were evaluated on their overall characteristics, not individual passes of plots. That way, a subject had multiple views of the same stand to consider when determining stand characteristics. The questionnaire was designed to evaluate the users' ability to determine stand characteristics necessary for forest management [Fuj05]. Specifically, users were asked to determine overall mean DBH, mean stem density, mean spacing, mean live crown ratio, and mean crown closure. Since there was no initial training and stand order was constant, there is a potential the results may be slightly biased as users became more familiar with the system throughout the session. After all the user studies were completed, the mean and standard deviation for each measure were calculated. The t-test ($\alpha = 0.05$) was used to analyze the statistical significance of the difference between the means [Mot95].

5. Results

Fifty subjects participated in the study. Subjects included forestry professionals and both undergraduate and graduate students from the Department of Forestry. Minimum knowledge of forest field measurements and inventory was verified. Four subjects' data were omitted since they had extensive prior knowledge of the test stands. One subject's data were removed because there was a strong indication they did not have the required background. The following results are based on the remaining 45 subjects. In all the result tables, "FR" indicates the estimates are from the group that viewed field-recorded videos and "CG" indicates the estimates are from the group that viewed computer-generated videos. The table ordering reflects the order the subjects viewed the videos.

5.1. Mean DBH

Subjects were asked to estimate mean DBH for each of the five stands. The mean (μ) and standard deviation (σ) for each group were calculated and are shown in Table 1. Estimations are in inches. The calculated t-value (t) and the corresponding probabilities (p) are also shown. Estimations were not statistically different for four out of the five stands. There was a statistically significant difference between the two groups for the 5x5 plot. In all five plots, on average, mean DBH was estimated higher for the computer-generated videos.

Table 1: *Mean DBH Estimations and Analysis*

STAND TYPE	FR_μ	FR_σ	CG_μ	CG_σ	t	p
8x8	10.02	2.08	10.40	2.54	0.55	0.58
IMM	7.79	2.24	8.27	2.86	0.63	0.53
5x5	8.05	2.82	10.27	3.31	2.43	0.02
MAT	14.71	3.37	15.48	3.06	0.80	0.43
10x10	9.43	2.37	10.25	3.06	1.01	0.32

5.2. Mean Stem Density

Subjects were asked to estimate mean stem density for each of the five stands. This was estimated as the number of trees per acre. The mean (μ), standard deviation (σ), calculated t-value (t), and corresponding probabilities (p) are shown in Table 2. Estimations were not statistically different for four out of the five stands. There was a statistically significant difference for the 5x5 plot. In all five plots, on average, mean stem density was estimated lower for the computer-generated videos.

Table 2: *Mean Stem Density Estimations and Analysis*

STAND TYPE	FR_μ	FR_σ	CG_μ	CG_σ	t	p
8x8	368.5	210.6	323.5	203.4	0.71	0.48
IMM	370.8	220.0	268.3	176.3	1.67	0.10
5x5	573.8	292.3	384.9	150.1	2.61	0.01
MAT	163.4	153.2	151.1	71.5	0.33	0.74
10x10	445.8	232.8	348.3	130.1	1.66	0.10

5.3. Mean Spacing

Subjects were asked to estimate mean spacing for each of the five stands. The mean (μ), standard deviation (σ), calculated t-value (t), and corresponding probabilities (p) are shown in Table 3. Estimations are in feet. Estimations were not statistically different for three out of the five stands. There was a statistically significant difference for the 5x5 plot and the 10x10 plot.

Table 3: *Mean Spacing Estimations and Analysis*

STAND TYPE	FR_μ	FR_σ	CG_μ	CG_σ	t	p
8x8	10.50	3.74	9.67	3.49	0.77	0.45
IMM	10.79	5.59	13.02	4.69	1.44	0.16
5x5	6.71	2.10	8.44	2.49	2.53	0.02
MAT	20.17	7.78	19.98	6.28	0.09	0.93
10x10	8.55	2.37	10.38	2.17	2.69	0.01

5.4. Mean Live Crown Ratio

Subjects were asked to estimate the mean live crown ratio for each of the five stands. This is estimated as the length of live crown versus the total tree height. Estimations are a percentage. The mean (μ), standard deviation (σ), calculated t-value (t), and corresponding probabilities (p) are shown in Table 4. There were no statistically significant differences between the two groups' estimations.

Table 4: *Mean Live Crown Ratio Estimations and Analysis*

STAND TYPE	FR_μ	FR_σ	CG_μ	CG_σ	t	p
8x8	29.25	8.16	32.63	8.45	1.35	0.19
IMM	44.38	14.37	39.21	11.79	1.29	0.21
5x5	24.13	7.40	28.96	11.98	1.64	0.11
MAT	26.33	7.51	24.38	7.85	0.85	0.40
10x10	30.14	10.02	34.58	9.43	1.52	0.13

5.5. Mean Crown Closure

Subjects were asked to estimate mean crown closure for each of the five stands. Estimations are a percentatge. The mean (μ), standard deviation (σ), calculated t-value (t), and corresponding probabilities (p) are shown in Table 5. Estimations were not statistically different for three out of the five stands. There was a statistically significant difference for the 5x5 plot and the immature plot.

Table 5: *Mean Crown Closure Estimations and Analysis*

STAND TYPE	FR_μ	FR_σ	CG_μ	CG_σ	t	p
8x8	62.00	20.38	70.63	16.77	1.54	0.13
IMM	58.43	18.24	38.75	12.09	4.20	0.00
5x5	69.57	18.42	80.42	12.50	2.28	0.03
MAT	35.71	15.43	37.08	16.61	0.29	0.78
10x10	71.19	13.87	73.54	13.39	0.58	0.57

6. Discussion

On average, there were very few statistically significant differences in estimation between the field-recorded videos and the computer-generated videos, as expected. Five estimations were given for five different stands, resulting in a total of 25 comparisons. Table 6 summarizes the calculated p-values. Boldface highlights the cases with a statistically significant difference ($p < \alpha$). Of the 25 comparisons, only six resulted in statistically significant differences, with four of those cases involving the 5x5 spacing trial.

Table 6: *Summary of P-values*

STAND TYPE	DBH	STEM DENSITY	SPACING	LCR	CC
8x8	0.58	0.48	0.45	0.19	0.13
IMM	0.53	0.10	0.16	0.21	**0.00**
5x5	**0.02**	**0.01**	**0.02**	0.11	**0.03**
MAT	0.43	0.74	0.93	0.40	0.78
10x10	0.32	0.10	**0.01**	0.13	0.57

More user studies should be conducted to evaluate why there were so many significant differences with the 5x5 stand. If the 5x5 spacing trial is removed from analysis, we are left with 20 total tests. Of those, two were found to have statistical significance. However, when analyzing random data, on average 1 out of 20 comparisons (at $\alpha = 0.05$) will be statistically significant by chance [Mot95]. Therefore, with further study, it could possibly be shown that those cases also have no statistical difference.

Understory may play a role in parameter estimation. Dead branches and vines, which are present in the field-recorded videos, obscure the view of the sky and may hinder mean crown closure estimation. This is especially true for the immature stand, which has shorter trees; the dead branches and vines are much closer to the observer in this case.

Also, the tree trunks, the distance cues (e.g., flags), and the corresponding spacing are more easily discernable in the computer-generated videos due to lack of understory. This may allow for easier estimation in the computer-generated videos. For example, Table 7 repeats data from Table 3 and shows the mean spacing estimations for the 10x10 stand. The difference for these results was statistically signifiant. However, upon closer inspection, one can see that the mean estimate from the computer-generated videos (i.e., 10.38) is closer to the actual spacing of 10 feet.

Table 7: *Mean Spacing Estimations for 10x10 Stand*

STAND TYPE	μ	σ
10x10 - FR video	8.55	2.37
10x10 - CG video	10.38	2.17

7. Conclusions and Future Work

The overall results of the user study were positive, which suggests that forest management through scientific visualization is likely to be effective. More comprehensive analyses are being conducted, including an analysis of the categorical measures important for forest management, and will be reported in [Fuj05]. It should also be noted that the tree model tested in this study is one of three that was designed to incorporate LIDAR measurement data and create large-scale forest visualizations [MAMI*03]. Now that this model's validity has been verified, tests should be performed to see if interaction improves accuracy. The near-term feasibility of remote forest management depends on the development of LIDAR extraction techniques.

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