DIGITAL PHOTO MONITORING FOR TREE CROWN FOLIAGE CHANGE EVALUATION

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Abstract—Assessing change in the amount of foliage within a tree's crown is the goal of crown transparency estimation, a component in many forest health assessment programs. Many sources of variability limit analysis and interpretation of crown condition data. Increased precision is needed to detect more subtle changes that are important for detection of health problems. Digital photomonitoring can be used to increase the precision of these measures provided exact camera parameter replication is performed and movement of canopy structures is not severe. Two measures of transparency (compactness and DSO, or fractal dimension of silhouettes minus fractal dimension of outlines) show sensitivity to small branches or small canopy gaps, but may offer some unique descriptive information over area ratio measures. Point-wise and region-wise transparency distribution maps provide easy to interpret visual representations of localized transparency.

INTRODUCTION

Visual inspection is often the first step in evaluating the health of an organism. Farmers visually inspect their plant crops on a regular basis to determine when to water, fertilize, or treat an insect or disease outbreak. Likewise, visual inspection is often a key indicator of tree health. National and international forest health monitoring programs (Huettl 1993) such as the Environmental Monitoring and Assessment Program (EMAP) (Tallent-Halsell 1994), which is now Forest Health Monitoring (FHM) (Mangold 1998), and the United Nations Economic Commission for Europe (UN-ECE) (Ferretti 1997) collect tree crown indicators to assess forest health.

Though many variables have been proposed for tree health assessment (Innes 1993), many of these have been dropped from national assessment programs for various reasons-cost, lack of applicability over wide regions, species-specificity, etc. These monitoring programs required cost-effective means of assessing large areas of forest, consisting of many species, over short time intervals. One measure that is common to nearly all programs is the judgment of the amount of foliage present. This ordinal measure has been called crown thinning, defoliation, or transparency and its definition varies slightly among programs (Innes 1993). Foliage amount and condition is a general indicator over all species and serves as an integrative index of current tree condition.

First, challenges of visual foliage measurement are discussed. Then previous applications of photographic methods for tree crown assessment are summarized. This is followed by a brief discussion of the trend toward digital sensors and associated factors. Various crown analysis methods are discussed, and an example of morphological and area-based transparency estimation is given. Finally, ideas for future research are presented and details are provided on ways to increase foliage change estimation precision using digital photographs from monumented viewpoints.

FOLIAGE MEASUREMENT CHALLENGES

Sampling foliage of mature trees involves many challenges with the primary challenge being access (Barker and Pinard 2001). Many creative means are being applied to access tree canopies including climbing with ropes, walkway and crane construction, lift trucks, and scaffolding. Destructive sampling (i.e., cutting a portion or the entire tree) is widely implemented and required for studies where biomass

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must be determined (Montès and others 2000). Litter trap sampling is a standard technique for measuring deciduous foliage over an area, but may have some limitations for individual trees and for forest health assessment as the leaves are then dead.

Visual methods offer an alternative to the physical access problems but face problems due to occlusions caused by overlapping structures as well as other objects in the foreground or background (Ansley and others 1988, Bréda 2003, Dobbertin and others 2004, Lindsey and Bassuk 1992). This issue is identified as a clumping factor in studies of leaf area index (LAI) using visual methods (Chen and others 1997). Observer bias has been a widely documented issue with visual crown condition estimation (Dobbertin and others 2004, Innes 1988, Solberg and Strand 1999). Light conditions are also shown to cause problems (Dobbertin and others 2004).

Though not explicitly set forth in the literature, perspective effects exist caused by viewpoint locations, which are typically constrained by height of observation point and number of observation points considered. Field manuals (USDA Forest Service 2004) typically specify that the viewpoint be located at least tree height distance away from the base of the tree and that two observers create nearly perpendicular sighting angles to the tree. This still leaves a portion of the crown unobserved. Control on azimuthal relocation is rarely specified. The effects of overlooking this control will vary in proportion to the asymmetry of the crown structures within the overall crown space.

USE OF PHOTOGRAPHY FOR VEGETATION ASSESSMENT

Photography is used for detecting (Haering and others 1997), classifying, identifying (Soille 2000), and measuring (Brown and others 2000) vegetation from forest to agriculture and rangeland to wetland. Hemispherical photography is commonly used to evaluate LAI, throughfall, and understory light environment (Hale and Edwards 2002, Rich 1990). Photography also has been used to some extent for evaluating foliage on trees (Curtis and Kelley 1993, Lindsey and Bassuk 1992, Mizoue and Masutani 2003) as well as branch architecture without leaves (Stebbins 1975, Wagar and Heisler 1986).

Photograph collection methods vary among applications, although a few issues are common to all. Perhaps one of the most critical issues in using cameras in outdoor environments is light. As the sun is the dominant light source in outdoor photography, the amount, orientation, and characteristics of radiant input are not fully controllable. Some control can be applied by collecting photographs only under certain atmospheric conditions (i.e., clear or overcast), at a specific time of day, or at specified positions relative to the light source and the object of interest. Lens filters and other light blocking or reflecting media, such as an object to mask the solar disk for hemispherical photos (Peper and McPherson 2003) or a background screen (Ansley and others 1988) may be employed. Penumbral effects need to be evaluated in quantitative applications (Clearwater and others 1999, Wagner 1998). Stebbins (1975) utilized flash photography at night to control lighting and eliminate background effects. Tanaka and others (1998) also used active remote sensing with a scanning laser for 3D modeling.

Cameras and media are also selected based on the frequencies of spectral response they detect. Black and white negative film is typically chosen for applications requiring the most precise quantification of total light as it has a wide dynamic range. Red, green, blue (RGB) color photography is used for applications where classification (i.e., leaves vs. stem) is needed. Infrared wavelengths can be measured to provide higher contrast for vegetation condition.

Scale is another consideration when using photography for evaluation. Scale can be modified by the position relative to the object of interest or by optical magnification. With film photography scale was often ignored provided the object of interest was visible. Scale and output image resolution are critical when using digital imagery for quantitative measurements. As with any spatial sampling, image data must be acquired at a scale at which objects of interest can be resolved. In addition to analytical determinations of image resolution, camera and scene characteristics must also be considered. Frazer and others (2001) indicate that resolution limitations can be quite restrictive with the extreme field of view of hemispherical photography.

Photographic monitoring is the use of cameras to reexamine the same scene over time (Hall 2001). This technique lends itself to qualitative analysis that allows the investigator to visualize change. The quality of the analysis is inherent in the magnitude of change and the ability to perceive the desired elements for analysis. Some examples include examining the abundance of grasses and herbaceous vegetation across a landscape, or the visualization of change as a forest grows or is harvested over the course of decades.

ANALOG TO DIGITAL CONVERSION

Digital cameras are pervasive in the consumer market. These devices have improved tremendously in the last 10 to 20 years, to the point that direct comparisons are being made between digital and film photos (Frazer and others 2001, Hale and Edwards 2002). Digital cameras offer several advantages: there is no expense for film development; output is immediately available for field verification and image processing, transmission, or analysis; there is more flexibility of spectral range; and optics are smaller and cheaper.

Film media have been rigorously vetted within the scientific community, while much is unknown about digital image creation. Film emulsions react predictably, whereas digital results may be subject to electrical corrections and operations that may vary with the change of scene. Depending on the manufacturer of the sensor, these operations may be proprietary and impossible to correct.

Issues of concern that have been identified with some current digital systems are:

- Smaller optics of consumer-level digital cameras limit light capture and widen depth of field for given aperture.
- Imprecise optics not designed for spectral or dimensional measurement can cause color blurring and chromatic aberration (Frazer and others 2001).
- Limited dynamic range, especially for single-chip color formats, causes detail to be lost in either bright or dark regions.
- Single chip color consumer-level cameras usually output RGB data with 8 bits per channel providing limited quantification (256 levels).
- Limited spatial resolution is especially problematic with hemispherical lenses where field of view is fixed (Frazer and others 2001).
- A large number of manipulations can be required, and this can make it difficult to keep track of settings.

2D CROWN ANALYSIS

Analytical procedures depend on the project objectives. The simplest analysis is a qualitative visual comparison revealing obvious changes (i.e., much more sky visible through the crown). Quantitative comparisons are more frequently applied to supply more information and a higher level of precision. Caution must be applied when attempting to be overly precise when using 2D methods to estimate the quantity of objects in a 3D space, as assumptions about their distribution and orientation are important (Chen and others 1997).

Dot grids provide a manageable method of estimating proportions or even the area of a 2D planar region if scale is known. Dot grid techniques have been applied to oblique photographs of tree crowns (Seiler and McBee 1992, Wagar and Heisler 1986). Others have used computers to quantify classified pixels of digital photographs (Curtis and Kelley 1993, Lee and others 1983, Lindsey and Bassuk 1992). With greater access to digital imagery and immense computing power, the trend is toward more advanced image processing for increased information extraction (Dobbertin and others 2005, Lee and others 2003, Montès and others 2000, Paruelo and others 2000, Peper and McPherson 2003).

Regression analysis has been used to estimate total leaf area from silhouette area (SA) measurements. Some have found a linear relationship (Lindsey and Bassuk 1992, Peper and McPherson 2003) while others (Ansley and others 1988, Paruelo and others 2000) noted a curvilinear relationship, which might be expected with increased foliage density. This may be dependent on overall canopy size and architecture as well as species factors.

TRANSPARENCY

Photographic methods are beginning to be applied for the purpose of foliage change evaluation. A substitute might be examining the change of transparency estimates over time. Lee and others (2003) present a method that uses the FHM collection methods and definition of transparency. Transparency is defined as the amount of skylight visible through the live, normally foliated portion of the crown (USDA Forest Service 2004). The authors used image processing techniques to automatically generate a boundary that would be considered the "live, normally foliated portion." Within this boundary they present three methods of transparency estimation: area-ratio, point-wise, and region-wise. Area ratio is simply the count of sky pixels within the boundary divided by the count of plant pixels. Point-wise and region-wise transparency distribution maps use two different sampling strategies to determine localized transparency across the 2D plane (fig. 1). Direct comparisons to human observer estimates were good, provided woody components could be removed for sparsely foliated conditions.

Mizoue (2001) avoided the problem of trying to define the ambiguous region of consideration by using silhouettes(area) and outlines(perimeter). He presented a measure termed DSO calculated by

$$DSO = Ds - Do \qquad (1)$$

where Ds is the fractal dimension of the silhouette and Do is the fractal dimension of the outline. The fractal dimensions tend to converge with increased transparency. Exponential functions relating DSO to crown transparency were created for different species.

Compactness, defined by

$$\text{perimeter}^2 / \text{area} \qquad (2)$$

is often used in computer vision as a shape descriptor. While DSO is more sensitive at low levels of transparency, compactness is most sensitive where transparency is high. It should also be noted that

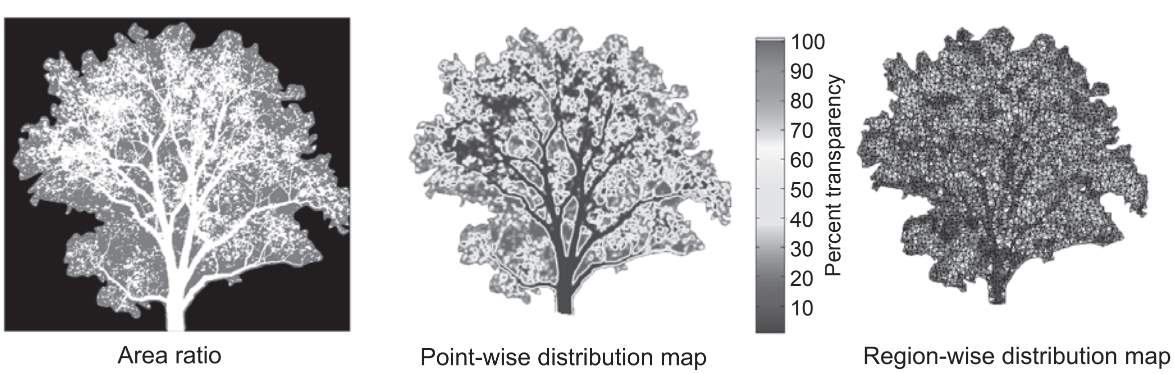

Figure 1—Area ratio (left) is the ratio of sky pixels (gray) to plant pixels (white) within a defined area (gray + white). Point-wise and region-wise transparency maps use different sampling methods to map the distribution of transparency over the projected crown space.

because the perimeters in digital image processing have discrete representations (pixels), these measures are affected by the resolution of the images.

Both of these methods are sensitive to spatial heterogeneity. DSO, compactness, and area-ratio are calculated (table 1) for different texture patterns (fig. 2). In the case of many small twigs (Image B of fig. 2) or small gaps (Image G of fig. 2) the proportion of perimeter to total area increases, causing DSO (value inversely related to transparency) and compactness to demonstrate a greater degree of transparency than area ratio. The analyst must decide which method is the most descriptive. Many small bare twigs represent areas where leaves should be present, while larger gaps are often places where large branches are missing and not part of the "live, normally foliated part of the crown." Much of this also has to do with the scale of the photographs and the severity and pattern of foliage presence or absence.

Table 1—Area ratio, DSO, and compactness measures for sample images

Image	Area ratio	DSO	Compactness
A	0.44	0.25	5206
B	0.44	0.18	9604
C	0.32	0.25	6126
D	0.24	0.31	4440
E	0.18	0.44	1728
F	0.14	0.59	749
G	0.09	0.50	1363

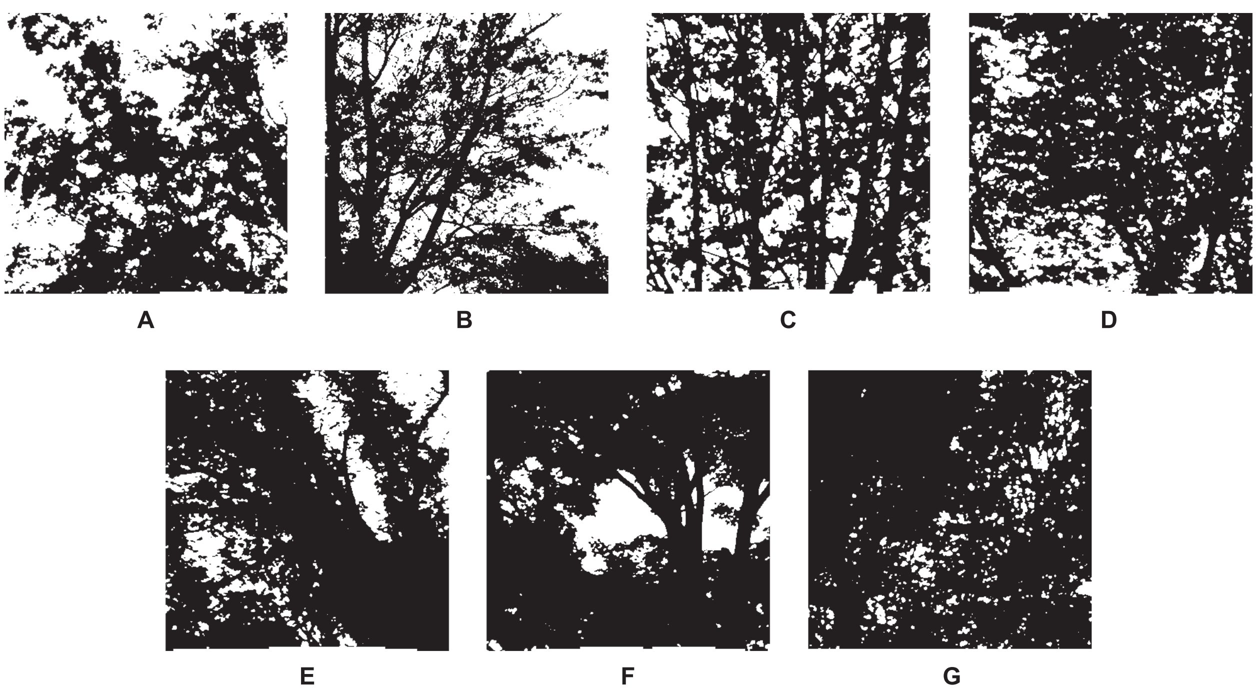

Figure 2—Examples of transparency patterns showing different amounts and distributions of plant structures (black).

TREND ANALYSIS

As previously mentioned there can be substantive variation in the size, shape, number, and spatial arrangement of leaves and branch structures. Therefore, comparisons of transparency measurements between different trees or even between different perspectives of the same tree are not very meaningful. However, one purpose of transparency estimation is to determine the change in the amount of foliage over time. Repeat measures using photo monitoring over short periods of time would limit many sources of extraneous variability and increase precision for this change analysis. For this technique to be successful, camera parameters must be recreated precisely, and tree structures must not have changed positions significantly.

Camera parameters include the optics, exposure and other optional settings, and the location of the camera in relation to the tree. Limiting the amount and nature of change in these parameters between observations is critical. Situations may require the use of a different camera or lens, but testing should be done to ensure the compatibility of the results.

Unfortunately, illumination can not be controlled in the outdoor environment, so exposure settings will need to be adjusted. If plenty of light is available and the crown structures are relatively unaffected by the wind, the recommendation would be to use the smallest aperture setting available. Underexposure by 1 or 2 stops is usually required to preserve sunlight and stray foliage with dominant sky background. It is also helpful to reduce penumbral and image blooming effects.

Relocating the camera can be easy with the proper preparation. If it is possible, permanent markers can be set to reestablish the azimuth. Otherwise, permanent features can be selected and photographed for future reference. These features can be used to triangulate the position for relocation. Find features at different depths that can be aligned relative to one another. The junction of major branches on the tree of interest may be helpful. It is a good idea to have multiple tie points in case a branch breaks or some other change occurs.

Tree structures may be affected by wind and other dynamics (loading caused by foliage, moisture, etc.) It is best to avoid collecting data under windy conditions. Other structural dynamics may be unavoidable, in which case it must be determined what detriment these are to the analysis. There may be small movements of leaves and branch growth. Different leaves (in deciduous trees) virtually guarantee that exact replication of the viewpoint to every structure is not possible. However, if assumptions can be made about the semi-rigid nature of large woody structures and relative consistency of bud locations between years, there is still an advantage in monumented viewpoints. Also, as a tree grows the apical meristems will naturally be dispersed over a broader area. For this reason the length of time between sampling should be reasonably short relative to the growth rate of the tree.

These controls allow more appropriate comparison of transparency estimates to be made. Comparison using area ratio, point-wise and region-wise transparency density maps, compactness, and DSO can be done with some confidence. If replication is performed well, it may be possible to perform localized change detection (fig. 3).

SUMMARY AND CONCLUSION

While contact or destructive sampling provides the best results for foliage measurement, canopy access and associated costs largely prohibit this type of sampling for applications requiring large numbers of trees to be observed. Litter trap sampling of deciduous trees is informative, but challenging at the individual tree level. Visual assessment has been a useful method, particularly for tree health appraisal.

Repeated measures designs are useful for minimizing extraneous variability. Unless a number of assumptions are made regarding the uniform distribution of crown structures within a generalized crown space, perspective control should be maintained over time for maximum precision. Further study is

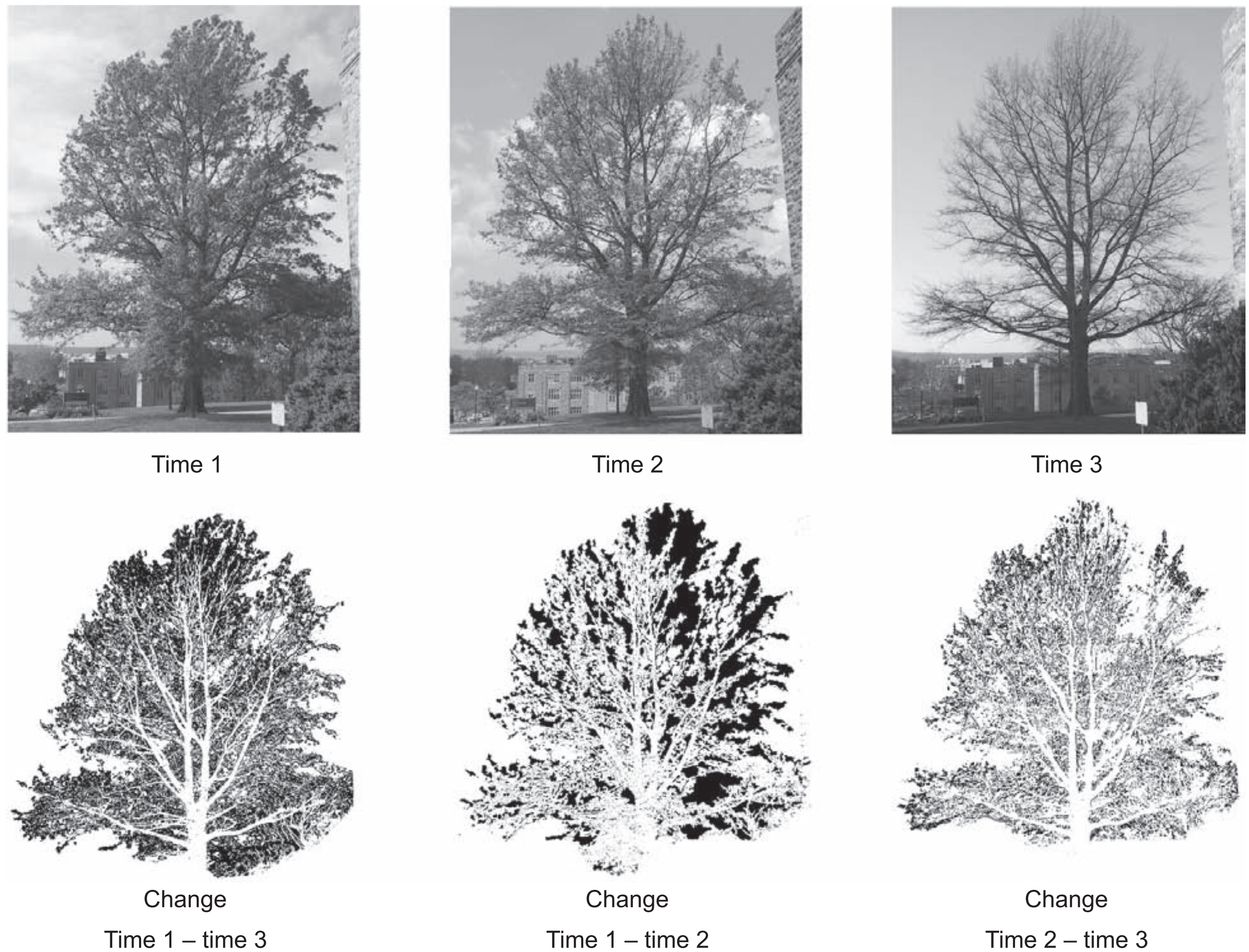

Figure 3—Photos taken at three different times from a monumented viewpoint (top) and visual depiction of localized silhouette area (SA) change (bottom).

needed to examine the tolerances required for perspective control and whether this is possible given the dynamics of the crown structures.

Interpretation of results varies with application. Foliage change can vary as a result of a number of factors and may vary systematically within the crown. Symptomatic characteristics such as discoloration, dead and skeletonized leaves, and wilting may not be detected in underexposed images and would need to be noted before the observer left the plot. Investigation should be made into the creation of transparency coefficients (analogous to LAI, light extinction (Smith 1993), and shading coefficients (Nowak 1996)). These methods also can be used to judge the decline or recovery of trees from various damaging agents. Biological thresholds where defoliation affects tree growth or mortality might be determined by photographic analysis.

Though not explicitly considered with visual methods, scale is a consideration for spatial sampling. This comes to the forefront with digital imaging as the data is sampled and recorded in discrete amounts and over discrete tessellated regions. This should be investigated over a range of transparencies.

These digital photographic methods allow low-cost raw data collection. These data can readily be analyzed by numeric methods, providing consistent estimates over remeasurement cycles. Data are also easily archived and organized without requiring a great amount of physical storage space.

Disadvantages of the proposed method include the need for precise realignment and re-creation or calibration of lighting and camera parameters. This technique is also limited to situations where a large portion, if not all, of the tree crown can be viewed without overlap from other trees or objects in the foreground or background.

Area ratio alone, as a single measure of transparency, lacks specificity of description and does not account for scale explicitly. DSO and compactness provide more information about the complexity of the 2D shape, and thus some indication of porosity. Additionally these methods do not require explicit parameters for creating a crown outline. Transparency distribution maps can allow precise analysis of foliage change over time, provided that spatial changes can be corrected or assumed. Photographic monitoring shows promise for enabling more precise estimates of change in the amount of foliage over time.

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