STRESS DETECTION IN LOBLOLLY PINE USING RELATIVE APPARENT TEMPERATURES OF FOLIAGE

by

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INTRODUCTION

Temperature differences between normal and stressed loblolly pine prior to the appearance of visual symptoms may relate to initial or subsequent insect problems. The detection of damaging forest insects at the earliest possible time is important to swift and effective remedial action. Perhaps of most importance is the detection of stress conditions predisposing a tree or forest to insect attack. A knowledge of predisposing factors could provide the information necessary to prevent damage by forest insects.

The visual determination of stress in loblolly pine (Pinus taeda L.) is difficult. Brix (1960) states:

> "Natural color changes of leaves have been the most widely used indicator of death of plants and are satisfactory for many species in which browning of the leaves occurs soon after the leaves lose their ability to recover. In other species, including loblolly pine (Pinus taeda L.), this would introduce error into the determination, since the more noticable and drastic color changes may not occur until long after the ability to recover has been lost."

The southern pine beetle (Dendroctonus frontalis Zimm.) is currently believed to be the leading cause of pine mortality in the South (Coulson et al. 1972). The association of this insect with trees under stress is well documented, expecially the stress induced by drought (Craighead 1925) or excessive precipitation (Hetrick 1949).

The prompt detection of souther pine beetle attack on trees is difficult because changes in the foliage color do not occur until two to four weeks after the tree is attacked (Heller et al. 1959). The next generation of bark beetles often develops before control action can be taken. If effective control actions are to be taken, trees susceptible to southern pine beetle attack must be detected prior to the fading of the foliage.

The attraction of bark beetles to stressed trees has been hypothesized by Person (1931) to be a response to volatiles produced by subnormal trees. The possible mechanism by which the trees emit the volatiles has been hypothesized by Heikkenen and Hrutfiord (1965):

> "When the coolant properties of transpiration fail, the absorption of radiant energy may permit rapid volatilization of attractive concentrations of oils (high ratio of alpha- to beta-pinene) from the main stem."

A technique, or instrument, to detect temperatures of stressed trees would contribute to the testing of these hypotheses.

Recent technological developments have resulted in instruments capable of the remote sensing of temperatures. This study used one such instrument, the AGA Thermovision, which detects radiation emitted by objects in the 2-5.6 micron portion of the electro-magnetic spectrum.

This study was conducted to test the ability of the AGA Thermovision to detect temperature differences between normal loblolly pine seedlings and loblolly pine seedlings stressed by drought, flooding, or severing and between normal and severed mature loblolly pine trees. This study also tested if temperature differences could be detected with the AGA Thermovision before stress symptoms were detected either visually or with color or color infrared film.

The previsual detection of stressed loblolly pine would greatly aid the development of the primary host attractant hypotheses. Previsual detection would also aid the understanding of stress factors predisposing pines to bark beetle attack and the detection of bark beetle outbreaks such that control measures could be effective.

LITERATURE REVIEW

Forest entomologists often use the foliage condition of a tree to indicate the susceptability to insect attack or an indication an attack is under way (Baker 1972; Graham and Knight 1965). Visual inspection of a tree includes observing the condition of the foliage in addition to looking for the insect or damage caused by the insect.

Frequently used signs of insect activity are discoloration, wilting, blistering, skeletonizing and rolling of foliage. All of these symptoms may apply to broadleaved trees; however, with conifers, discoloration and some wilting are most often the only clues to insect acitvity.

Foliage Fade

Discoloration of the foliage of conifers may lag weeks or months behind initial bark beetle activity. Changes in foliage color in the southern pines have taken from two to four weeks following attack by the southern pine beetle (Heller et al. 1959), and were further modified by weather, number of beetle attacks, and tree vigor. Virginia pine (*Pinus virginiana*, Mill.) severed by Hines and Heikkenen (1977) were attacked by bark beetles before the crowns began to fade. Belluschi and Johnson (1969) reported that Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) remained green for up to a year following lethal attack by the Douglas-fir beetle (*Dendroctonus pseudotsugue* Hopk.).

Bark Beetle Damage and Photography

The use of color film to evaluate bark beetle damage was reported by Heller et al. (1959) to be cheaper than ground surveys for detecting SPB damage. High correlations between ground and aerial color photography for detecting Douglas-fir beetle damage were found by Wert and Roettgering (1968). According to Heller and Wear (1969), color aerial photography is a reliable method for detecting and evaluating ponderosa pine (*Pinus ponderosa* Laws.) mortality from the mountain pine bark beetle (*Dendroctonus ponderosa* Hopk.).

The foliage of trees infested with the southern pine beetle must fade before color differences can be dectected with infrared film (Ciesla et al. 1967). Other authors (Hanson and Lautz 1969, Murtha and Hamilton 1969, Heller and Wear 1969, Houston 1972, Heller and Bega 1973) agreed that discoloration of the crown must appear before stress or damage can be detected on infrared film. The superiority of infrared film to color film for detecting bark beetles is due to its haze cutting ability and increased color contrast (USDAFS 1970).

Infrared film will not record temperature differences in what we regard as our normal environment, according to Fritz (1967), who cites tests showing an object must be heated to 343°C to be detected by the infrared sensitive layer of the film.

Thermal Imagery

The infrared portion of the electromagnetic spectrum extends from 0.78 microns to 1,000 microns (Holter 1970). This part of the spectrum is not visible to the human eye; therefore, films and infrared scanners must be relied on for its detection. Infrared films are listed by the Eastman Kodak Company (1971) as being sensitive to infrared radiation up to 0.9 microns. Infrared scanners are usually limited to the region below 14 microns. According to Gates (1962), there are transparent "atmospheric windows" through which infrared radiation is transmitted without being absorbed by water, carbon dioxide, or ozone. The largest "windows" occur at 2-5.6 microns and 8-14 microns.

Thermal imagery has been useful for the detection of temperature increases in stressed conifers. Red pine (Pinus resinosa Ait.) trees were poisoned by Weber (1965) to simulate the reduced vigor resulting from bark beetle attack. The treatment raised leaf temperatures 2° to 3°C higher than healthy trees. The increased temperatures were detected on imagery generated from the 8-14 micron band.

Red pine and eastern white pine (Pinus strobus L.) seedlings grown under moisture stress were reported by Weber and Olson (1967) to have higher foliage temperatures than unstressed seedlings. Temperatures were measured with a Stoll-Hardy radiometer in several infrared wave-length bands (greater than 3.5 microns, between 4.5 and 5.5 microns and between 8.1 and 13.2 microns).

Norway spruce (Picea abies L.) seedlings were measured with an AGA Thermovision 680 system by Hagner (1969). Within 6 hours after severing, a severed seedling had a foliage temperature 1°C warmer than a control seedling. The mean foliage temperatures of a group of seedlings left 3 days without water was higher than that of a second group of seedlings one day without water.

Thermal imagery has been also found to be useful for detection of forest pathological problems. According to Murtha (1970), infrared imagery obtained in the 3-5 micron range around midnight permitted identification of trees with Dutch elm disease. Using the 8-14 micron band to detect Douglas-fir with root rot, Wear (1970) found that the foliage temperatures of diseased trees were not consistently higher than that of healthy trees.

Multispectral Sensing

Multispectral sensing involves the simultaneous recording of the visible and infrared regions of the electromagnetic spectrum in discrete bands whether photographically or electronically, Multispectral systems yield data or images in small segments of the electomagnetic spectrum. These segments may be analyzed separately or combined with any other segment or combination of segments to detect changes in a plant.

Forestry applications of multispectral scanning have achieved varying degrees of success. Douglas-fir infected with Poria weirii could not be separated from healthy trees using multispectral imagery in a study by Weber and Wear (1970). Successful detection of

Fomes annosus in red pine was reported by Olson (1972) using multispectral imagery. Ponderosa pine attacked by bark beetles, which had not faded, were not accurately identified by Weber and Polcyn (1972) on multispectral imagery; the number of commission errors (false identifications) was as great as the number of correct identifications.

Leaf Energy Exchange

According to Watson (1933), radiant energy falling on a leaf has three modes of dissipation: reflection from the leaf, absorption by the leaf, and transmission through the leaf.

Reflectance

A plant's reflectance in the visible spectral region (0.4 to 0.7 microns) is reduced to about 10% of the total energy in this region by the high absorbance of leaf pigments, primarily the chlorophylls, although other pigments have an effect (Rabideau et al. 1946, Gates et al. 1965). Little or none of the near-infrared radiation in the wavelength range of 0.7 to 1.3 microns is absorbed internally and about 50% is reflected (Knipling 1970). Due to absorption by water, there is little reflectance by a leaf in the far infrared region beyond 1.3 microns (Allen and Richardson 1968).

An increase in visible reflectance and a decrease in near infrared reflectance as leaves senesce has been reported by several authors) Colwell 1956, Tageeva er al. 1961, Olson and Good 1962). Diseases of plants causing chlorophyll destruction may be detected with films because of an increase in reflectance of the visible spectrum. As water stress increased, leaf reflectance in the visible and infrared increased, according to Dadykin and Bedenko (1961).

Absorption

The sources of radiant energy absorbed by plants are listed by Gates (1965) as: direct sunlight, reflected sunlight, scattered sunlight, and thermal radiation from the atmosphere and surrounding objects. According to Gates and Papian (1971), most plants absorb 50% of the total incident solar radiation and 96% of the infrared thermal radiation.

The absorption by leaves varies with the wavelength of radiation received (Gates et al. 1965). Leaves absorb efficiently in the blue and red wavelengths used by chlorophyll for photosynthesis. Weak absorption in the near-infrared, where the bulk of solar radiation occurs, helps keep leaf temperatures below lethal levels. High absorption in the far-infrared, primarily due to absorption by water, does raise leaf temperature.

Transmission

The Transmission of radiant energy varies with leaf thickness and wavelength of the radiant energy. The amount of energy transmitted through a leaf decreases as leaf thickness increases (Gates et al. 1965). Transmission is low in the visible and the infrared beyond 1.3 microns, but is high in the infrared from 0.7 to 1.3 microns (Knipling 1970).

Energy balance

The exchange of energy between a plant and its environment is given by Gates (1968) as:

$$Q_{abs} = R \pm C \pm LE \pm M$$

The radiant energy absorbed by the leaf is Q_{abs}. Radiation emitted by a leaf is R, this is a loss of energy. Energy may be lost or gained by the convection term C, depending on whether the leaf temperature is above or below air temperature. The LE term is a loss of energy if the leaf is transpiring; it is a gain if moisture condenses on a leaf. Metabolic processes represented by M may be a loss (respiration) or a gain (photosynthesis) in energy.

The radiant energy, R, from a leaf is related to its surface temperature by the Stefan-Boltzmann equation:

$$R = \varepsilon \sigma T^4$$

Where ε is the emissivity constant, σ is the Stefan-Boltzmann constant, and T is the temperature of the leaf in degrees Kelvin. The emissivity is a measure of how well the radiating object mimics a perfect black-body radiator. The emissivity of most plants is reported by Gates and Tantraporn (1952) to be about 0.97. According to Blad and Rosenberg (1976), to account for the total outgoing longwave radiation, the Stefan-Boltzmann equation may be modified as follows:

$$R_{lw} = \varepsilon \sigma T^4 + (1- \varepsilon)B^*$$

where B* is the flux of incoming longwave radiation.

The loss or gain of heat by convection, C, occurs when air temperature and leaf temperature are different. If leaf temperature is higher than air temperature, the leaf will lose heat by convection. If leaf temperature is lower than air temperature, the leaf will gain heat.

Convection, according to Gates and Benedict (1963), has two modes of action, i.e. free convection and forced convection. Free convection occurs due to density gradients in the fluid caused by temperature gradients. In forced convection, the flow of the fluid is caused by an external force or pressure creating a wind. Convection in still air was reported by Gates and Benedict to account for 2 to 11% of heat loss by hardwoods and 2 to 7% for conifers. In a study by Tibbals et al. (1964), forced convection at low wind speeds was found to be very effective in removing heat from conifers. A blue spruce was 8.9 °C above ambient temperature in still air, 2.8 °C at a wind speed of 3.2 km/hr, 1.4 °C at 6.4 km/hr, 0.7 °C at 12.9 km/hr, without any transpirational cooling. Needle and air temperature differences for ponderosa pine were reported by Gates et al. (1965) to be 11.5 °C for still air, 4.5 °C at wind speeds of 3.2 km/hr and 3 °C at 6.4 km/hr.

The effects of transpiration on leaf temperature have been extensively reviewed by Gates (1968). The L of the transpiration term stands for the latent heat of evaporation of water at whatever leaf temperature is being considered. The E term is the rate of transpiration.

The metabolic heat loss or gain is usually a minor component of the leaf energy balance. According to Knoerr and Gay (1965), respiration and photosynthesis represent less than 5% of the combined convection and latent heat losses and can be neglected in most energy balance calculations.

All of the terms of the energy budget equation do not represent equal amounts of heat loss. The re-radiation term is listed in several studies (Gates 1963, Gates and Benedict 1963, Knoerr and Gay 1965) as being the most important term, accounting for 64 to 100% of the heat lost. The convection term accounts for 0 to 30% of the heat lost; transpiration accounts for 0 to 33% of the heat lost (Gates and Benedict 1963, Gates 1964, Knoerr and Gay 1965).

From the discussion of the energy budget of a leaf, it appears that transpiration is the only condition which is directly affected by the condition of the plant; re-radiation is temperature dependent and convection relies on a leaf/air temperature difference and wind.

The importance of transpiration is stated by Gates (1968) as:

> "...there are conditions under which variations of transpiration may make relatively little difference in leaf temperature. However, often the ability to transpire will make a substantial difference in leaf temperature when the heat load on a leaf is large and thermal death is likely to ensue if leaf temperatures rise too high."

Needle moisture content as a measure of stress

Brix (1960) found needle moisture content to be a reliable indication of the water regime of loblolly pine seedlings. The leaf moisture content was highly affected by a decreasing soil moisture; as the soil moisture decreased the leaf moisture content decreased. A needle moisture content of 110% of dry weight was established by Brix as a threshold for survival.

Complete closure of the stomates, which reduces transpiration to zero, was reported to occur at needle moisture contents ranging from 141 to 150% for ponderosa pine (Lopushinsky 1969). Working with loblolly pine seedlings, Bilan et al. (1977) reported nearly complete closure of the stomates and a drastic reduction in transpiration as needle moisture contents of 180-190% were reached. Transpiration rates approaching zero were found in loblolly pine seedlings subjected to drought (Brix 1962).

In a study by Stransky (1963), needle moisture contents of 105 to 65% represented the range within which a loblolly or shortleaf pine (Pinus echinata Mill.) seedling might either live or die. For both species and the two soil types (sand and sandy loam) used, a needle moisture content of 85% was the midpoint at which seedlings had a fifty-fifty chance of survival. As the foliage dried out, it turned from dark greenish-yellow to light greenish-yellow and then to yellowish-red. Needles were light green at 40% needle moisture content, a demonstration that foliage color was not a prompt indicator of seedling viability.

Soil moisture tensions that retard or stop elongation in loblolly and shortleaf pine seedlings were investigated by Stransky and Wilson (1961). Elongation was stopped at a soil moisture tension of 3.5 atmoshperes. The needle moisture content at that time was 195%.

METHODS AND MATERIALS

AGA Thermovision 680 System

An AGA Thermovision 680 system was used to detect the relative apparent temperatures of the seedlings. The AGA Thermovision system senses temperature by measuring the intensity of the infrared energy focused on its detector. The amount of radiation coming from an object is a function of its temperature and emissivity. Since emissivities of plants are less than one, temperatures obtained by measuring infrared energy emitted from them are referred to as apparent temperatures. Temperatures measured with the AGA system are referred to as relative apparent temperatures since the colors of the thermal image are compared relative to each other.

The AGA Thermovision 680 system consists of an optical/mechanical camera, a black and white display/control unit, and a color display unit. The AGA system is sensitive to infrared energy reflected or emitted by an object in the 2 to 5.6 micron spectral range.

The camera unit housed the lens, two rotating prisms, aperture control, filter holder, detector and Dewar flask. The lens has a field of view of 10^{o} X 10^{o} and a range of focus from 0.95 m to infinity. The lens delivered an instantaneous field of 1.3 mrad. The aperture control had 7 f/stops giving the system a detectable temperature range of -30 ^{o}C to +850 ^{o}C. For this study, f/1.8 was used which was sensitive from -30 ^{o}C to +190 ^{o}C. The temperature range could be extended to +2000 ^{o}C by inserting a gray filter in the turret. The detector was an indium antimonide (InSb) photovoltaic type detector sensitive to the spectral range of 2 to 5.6 microns. The detector was made sensitive by cooling it with liquid nitrogen held in a 100 cubic centimeter Dewar flask. The photovoltaic responses of the detector were transported to the display/control unit via a connecting cable.

The display/control unit contained the range and sensitivity controls and the black and white display. The range control determined in which of 10 ranges i.e. 1, 2, 5, 10, 20, 50, 100, 200, 500, or 1000 °C the display operated. The 5 °C range was used for this study, which meant the display represented 5 °C from black to white. The sensitivity control determined where the range of 5 °C was placed in the -30 to +190 °C area. The photovoltaic signal from the detector was amplified and displayed in ten quantified gray levels on the black and white TV-monitor tube. This produced a black and white thermal image of the object being sensed with warmer temperatures represented by the lighter shades of gray to white and cooler temperatures by darker shades of gray to black. The TV-monitor display had a picture field frequency of 16 per second producing real-time thermal images of the object being sensed.

The color monitor of the AGA system assigned a color to each of the gray levels presented on the black and white display. Ten different colors were used, thus each color represented one tenth of the range setting. The 5 °C range was used, therefore each color represented a 0.5 °C difference in apparent temperature. The colors used appeared in a color bar at the bottom of the display giving the position of each color relative to the other colors.

Images produced by the AGA system were recorded photographically. A black and white Polaroid instrument recording camera copied the display of the black and white monitor. The color display was copied with Kodak Ektachrome 5256-MS film in a 35 mm camera mounted in front of the color monitor. The 35 mm camera was set at a shutter speed of one-sixteenth of a second and an aperture of f/3.5.

A front surface mirror was mounted over the seedlings to give the AGA system a vertical view. The camera could not be placed in a vertical position because the Dewar flask which holds the liquid nitrogen can not be sealed and tilting the camera to vertical allows the nitrogen to escape.

Seedling Study 1976

Foliage color

One of the stress symptoms monitored was needle color. Needle color was evaluated by visual examination, and the use of Kodak Ektachrome film 5256-MS and Kodak Ektachrome infrared film with a Wratten 12 filter. Both films were 35 mm.

Culture

One-year-old loblolly pine seedlings were obtained from the Virginia Division of Forestry at Crimora, Virginia, on February 19, 1976. The seedlings were kept moist and cool (4 ^{o}C) until planted in a greenhouse on February 25, 1976. The seedlings were moved out-of-doors on June 1, 1976. The seedlings developed in a normal manner, producing at least one growth flush before treatments were begun.

The seedlings were grown in 18 centimeter plastic pots filled with washed river sand. The seedlings were watered every other day with diluted (10%) Hoagland solution (Hoagland and Arnon 1938) until the solution drained from the bottom of the pot.

Stress treatments of severing, drought, and flooding began on August 6, 1976. Eight seedlings were subjected to severing and drought and four seedlings were flooded at weekly intervals, yielding groups of seedlings stressed for one, two, three, and four weeks on the day measurements were taken.

The severed treatment was initiated by cutting the stems of the seedlings and tying the stems to stakes palced in the pot to keep them upright. The drought treatment was initiated by tying a sheet of clear plastic to the stem of the seedling, allowing the plastic to drape over the side of the pot. This kept rainwater out of the pot. The flood treatment was initiated on four seedlings by maintaining the water level at the surface of the sand.

Needle moisture

After the seedlings were photographed and temperatures scanned, needle samples composed of five current needle fascicles were taken from each of three seedlings of each treatment. The five needle fascicles per seedling were combined, weighed to the nearest milligram, and dried in an oven at 80 °C for 24 hours. The dry sample was weighed and the percentage moisture content computed by:

$$\frac{\text{Fresh weight - Oven dry weight}}{\text{Oven dry weight}} \text{ X } 100$$

Test conditions

Visual inspection, photography, and thermal sensing of the seedlings was done on August 31, 1976. The sky was clear except for a few scattered clouds. Air temperatures ranged from 33 °C to 28 °C during the 2:00 p.m. to 4:46 P.M. EDT time period the work was done. Since winds gusting to 24 km/hr as measured with a Taylor anemometer equalized the apparent temperatures of the needles of both stressed and control seedlings, the seedlings were placed behind plywood windscreens to reduce the effect of the wind.

All photography and thermal imagery of the seedlings was produced from the same arrangement (Fig. 1). The same control seedling was used in position 2 throughout the experiment.

To begin the experiment, eight different control seedlings were selected at random from 22 non-treated seedlings. The control seedlings were scanned in two groups of four and one seedling was randomly chosen to be the reference for comparing the stressed seedlings. For the remainder of the experiment, three seedlings having the same treatment and length of treatment were selected and compared to the control seedling.

Seedling Study 1978

Culture

One-year-old loblolly pine seedlings were obtained from the Virginia Division of Forestry nursery at Crimora, Virginia on June 1, 1978 and planted on June 6, 1978 out-of-doors in 18-centimeter plastic

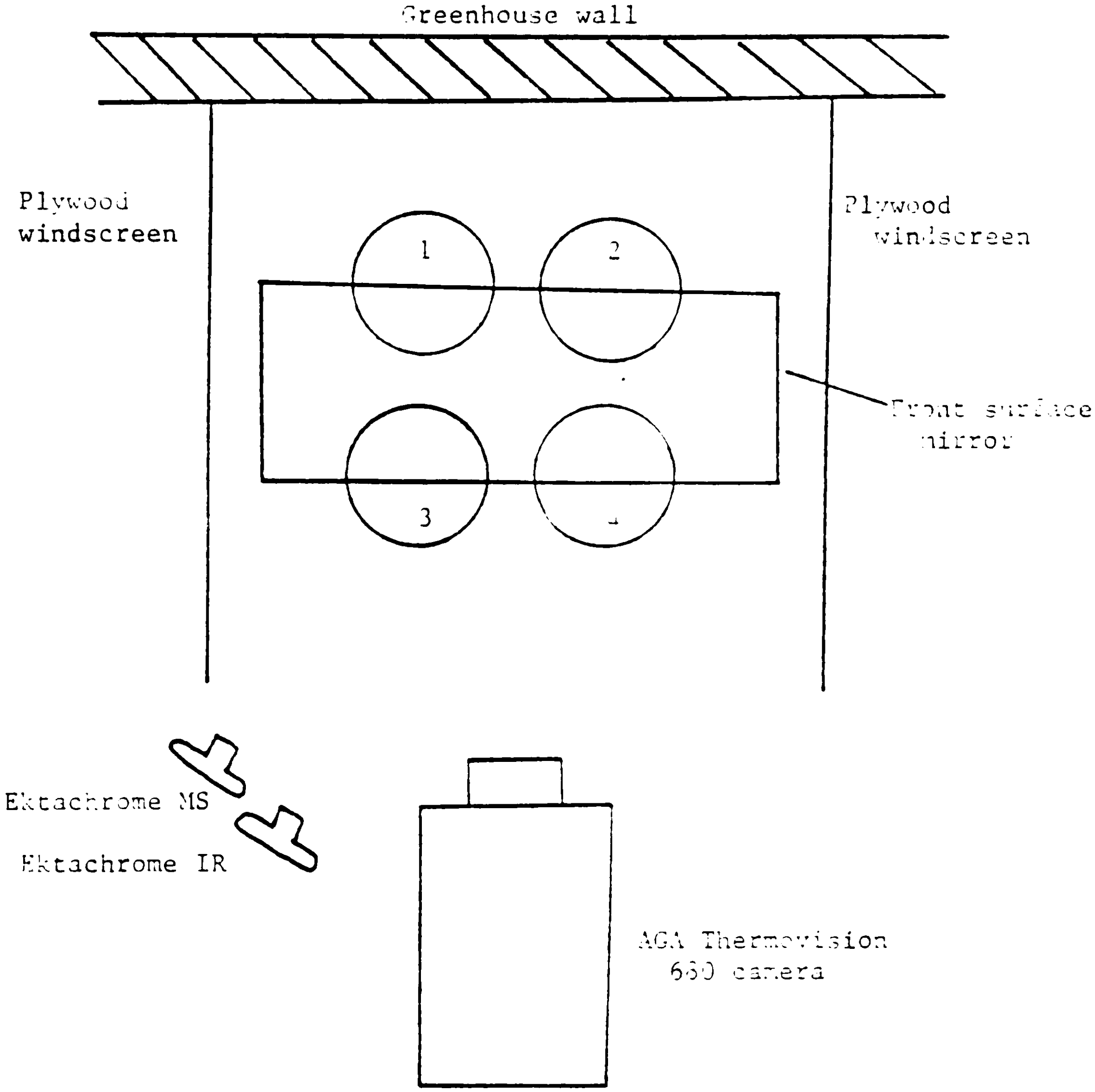

Figure 1. Placement of seedlings, cameras, front surface mirror, and windscreens used in the 1976 seedling study.

pots filled with washed river sand. The seedlings were watered every third day with a trickle irrigation system until water drained from the pots.

On October 6, 1978, forty-two seedlings were selected for possible use in the study. The selection of the seedlings was based on a green healthy appearance, uniform height, and full crowns. The seedlings were assigned numbered tags at random and moved into a greenhouse.

Needle moisture content

The needle moisture content was determined for each seedling from three needle fascicles. One fascicle was taken from the top of the crown, one from the middle, and one from the bottom of the crown. The three needle fascicles were combined, weighed to the nearest tenth of a milligram (fresh weight), and dried in an oven at 80 °C for 24 hours. The dry composite sample was weighed (dry weight) and the percentage needle moisture content computed using the same formula as in the 1976 seedling study.

Final selection of the seedlings to be included in the study was based on three measurements of needle moisture content. Needle moisture contents were determined for all seedlings on October 11, 12, and 16, 1978. The thirty-two seedlings selected had a needle moisture content of 186% or higher for at least one of the three determinations.

Radiometer

A Lambda LI-185 radiometer was used to measure global radiation from both the sun and sky. The pyranometer sensor of the instrument was held slightly above the tips of the seedlings being sensed with the

AGA camera and readings were taken from the meter simultaneously with the copying of the thermal image.

Stress treatments

The types of stress imposed were drought, flooding, and severing. Drought treatments were induced by not watering the seedlings and allowing the sand in the pots to dry. Flooding was induced by maintaining the water level above the surface of the sand in the pot. The severing treatment was induced by cutting the seedling at the surface of the sand and tying the seedling to a stake to keep it upright in the pot.

Four groups of eight seedlings each were randomly drawn from the thirty-two seedlings used in the study. The groups were then designated as controls, drought, flood, or sever.

Treatments were started on four seedlings from each group on October 17, 1978. Four days later, October 20, 1978, the remaining four seedlings of each group were treated. This yielded treatment lengths of eight and four days when the seedlings were scanned on October 24, 1978.

Composite temperature

The imagery produced by the color monitor of the AGA system was quantified by measuring the area each color occupied. The Ektachrome slides were projected onto a horizontal surface and the area of the colors of each seedling were measured with a planimeter. The boundaries of the seedlings were established by comparing the black and white photographs with the color slides. After determining the area occupied by each color, this area was converted to a percentage of the total area represented by the seedling.

A composite temperature was determined for each seedling. The composite temperature was the sum of the products obtained by multiplying the percentage of total area each color occupied by the numerical position of that color. Example:

Control seedling number 41

Color	Percentage of Total Area/100	Position of Color	Position X Percentage of Total Area
Black	.11264	1	.11264
Dark Blue	.40650	2	.81300
Light Blue	.22527	3	.67581
Green	.17833	4	.71332
Pink	.07726	5	.38630
		Composite Temperature =	2.70107

Foliage color

One of the symptoms monitored was needle color. Needle color was evaluated by visual examination and photography using 35 mm Kodak Ektachrome 5256-MS film.

Test conditions

The visual inspection, photography and thermal sensing of the seedlings was done out-of-doors on October 24, 1978. The sky was thinly overcast and the wind was calm. The air temperature was 16 °C and the relative humidity was 40%.

Test procedures

All seedlings were moved out-of-doors two hours prior to sensing with the AGA Thermovision 680 system. The seedlings were placed in groups of four in numerical order by pot number. The treatments were randomly distributed in the groups of four since the treatments were randomly assigned by pot number. The numerical order was broken because one control seedling was included in each group. The four seedlings in each group were sensed simultaneously with the AGA system. The front surface mirror mounted above the seedlings gave the AGA system a vertical view.

Tree Study

Three loblolly pines and one Virginia pine were severed according to the method described by Heikkenen (1976). Four cables were attached just below the crown of the tree to be severed and then anchored to neighboring trees. After four additional cables were attached at approximately one meter above the ground, the bole was completely severed with a chain saw and a plastic sheet placed in the kerf held open with wedges. The wedges were removed and the wound sealed with plaster and plastic. An adjacent tree of the same species and size was designated as a control.

The loblolly pines were located on the VPI & SU Southern Piedmont Research and Continuing Education Center, Blackstone, Virginia. The trees were about 60 year old codominants, 18.3 m in height and 32.5 cm dbh. The fifty-year site index for loblolly pine was 60. The loblolly pines were severed on August 5, 1976, October 8, 1976, and June 8, 1977.

The Virginia pine was located on the Quantico Marine Base, Quantico, Virginia. The severed and control trees were 23 m in height and 30.5 cm dbh. The Virginia pine was severed on September 9, 1977.

Test conditions

The tree severed on August 5, 1976 was scanned at 1615 hours September 1, 1976, four weeks after severing. The sky had a light overcast and wind speeds ranged up to 24 km/hr. The air temperature was 29 °C.

The tree severed on October 8, 1976 was scanned at 1400 hours on October 29, 1976, three weeks after severing. The sky was clear and wind speeds gusted to 32 km/hr. The air temperature was 16 °C.

The tree severed on June 8, 1977 was scanned at 1420 hours on June 15, 1977, one week after severing. Air temperature was 32 °C. The sky had a light overcast and winds were light.

The Virginia pine severed on September 9, 1977 was scanned at 1530 hours on September 23, 1977, two weeks after severing. Air temperature was 20 °C. The sky was partly cloudy and wind speeds ranged up to 28 km/hr.

RESULTS

Seedling Study 1976

Visual appearance of seedlings

Changes in visual appearance of the seedlings appeared only in the severed seedlings. The seedlings subjected to drought, flooding, and the controls were normal in appearance.

The visual appearance of the foliage of the severed loblolly pine seedlings varied with length of treatment. Seedlings severed for only one week retained their green color, however, half of them had wilted foliage. Color changes appeared in the seedlings severed for two weeks, with three of the six seedlings having yellow needles mixed with green needles; wilting occurred in four of the six seedlings. There was no association between green and yellow foliage and wilting. Three weeks after severing, all of the seedlings had wilted foliage with colors of green, yellow and red. Seedlings severed four weeks had red foliage and all seedlings were wilted.

Severed seedlings

Neither color or infrared photography detected stress due to severing until the foliage wilted or turned color. The seedlings which were green and not wilted were not detected as stressed.

The AGA Thermovision system detected relative apparent temperature differences between the severed seedlings and the control seedlings. One week after severing and while the foliage was still green four of six severed seedlings were found to be warmer relative to the control seedlings. Stress continued to be detected as an increase in relative apparent temperature as the length of time since severing increased.

The percentage of needle moisture content of the severed seedlings ranged from 93 to 19 percent based on oven dry weight (Table 1). The percentage of needle moisture content decreased as the length of time for the severed treatment increased.

Drought-stressed seedlings

There was no change in the appearance of the foliage of the drought-treated seedlings during this study. Color and infrared films failed to detect symptoms due to drought.

Relative apparent temperatures of the foliage of some drought-treated seedlings were higher relative to the control seedling one week after the drought treatment was started. Seedlings subjected to drought for two and three weeks had higher relative apparent temperatures; however, none of the seedlings subjected to drought for four weeks had apparent temperatures higher than the control.

The percentage of needle moisture content of the drought-treated seedlings ranged from 153 to 208% (Table 1). The absence of a decline in needle moisture content with length of drought treatment indicated the method of imposing drought was faulty.

Flooded seedlings

There was no change in the appearance of the foliage of the flooded seedlings during this study. Color and infrared films failed to detect stress in the flooded seeldings.

An increase in relative apparent temperature of the foliage of flooded seedlings was found for all treatment intervals. Although the foliage remained green, apparent temperatures of flooded seedlings were higher relative to the control within one week after flooding.

The needle moisture content of the flooded seedlings ranged from 140 to 183% (Table 1).

Seedling Study 1978

Visual appearance of seedlings

There was no change in the visual appearance of the seedlings for any of the treatments at either length of treatment. Differences in foliage color were not detected with Ektachrome film.

Needle moisture content

Needle moisture contents were determined following thermal sensing for all seedlings. Only the needle moisture content of the severed seedlings differed significantly from the needle moisture content of the control seedlings (Table 2).

Radiometer

During the course of the experiment a varying cloud cover produced changes in the amount of solar energy recorded by the radiometer. The readings ranged from 46 to 78 watts/square meter.

Indexed composite temperature

Variation in the thermal images of the seedlings on the AGA color monitor were noted as the amount of solar energy changed. The sensitivity setting of the AGA system was changed for each group of seedlings

TABLE 1. Needle moisture content as influenced by treatment type and length for the 1976 seedling study.

Length of Treatment (Weeks)	Treatment		
	Severed	Drought	Flood
0	200	200	200
0	239	239	239
0	208	208	208
Avg.	216	216	216
1	84	159	167
1	89	178	177
1	93	179	180
Avg.	89	172	175
2	53	176	183
2	36	164	167
2	42	173	140
Avg.	44	171	163
3	34	153	156
3	30	153	158
3	44	208	162
Avg.	36	171	159
4	21	201	174
4	28	163	172
4	12	184	161
Avg.	23	183	169

TABLE 2. Needle moisture contents and indexed composite temperatures as influenced by treatment type and length for the 1978 seedling study.

Treatment		Needle Moisture Content (%)	Indexed Composite Temperature
Type	Length (Days)		
Control		196 a*	1.0 a
Flood	4	194	1.1
	8	195	1.1
	Avg.	194 a	1.1 a
Drought	4	189	1.1
	8	187	1.1
	Avg.	188 a	1.1 a
Severed	4	111	1.4
	8	99	1.4
	Avg.	105 b	1.4 b

*Values within a column which are folowed by a similar letter are not significantly different at 5 percent with Duncan's multiple range test.

to compensate for the changes in solar energy. This resulted in confounding the variation in solar energy with the variation produced by treatment.

To reduce the confounding of changes in solar energy with changes in sensitivity of the AGA system, an indexed composite temperature was derived from the composite temperature. The indexed composite temperature was calculated by dividing the composite temperature of each of the four seedlings in every thermal picture by the composite temperature of the seedling having the lowest composite temperature in that run. Example:

Treatment	Composite Temperature	Division	Indexed Composite Temperature
Flood	4.07005	4.07005/4.07005	1.00000
Sever	5.32332	5.32332/4.07005	1.30792
Control	4.11795	4.11795/4.07005	1.01177
Flood	4.20159	4.20159/4.07005	1.03232

As noted in the example, the seedling having the lowest composite temperature in each run or group of four seedlings was not necessarily the control. The control seedlings in two of the runs had needle moisture contents below 190%, the level at which transpiration may be affected.

The indexed composite temperatures grouped by treatment and treatment length were tested using a Duncan's multiple range test (Table 2).

Indexed composite temperature vs needle moisture content

Indexed composite temperature and needle moisture content have an inverse relationship (Fig. 2). Seedlings having high needle moisture

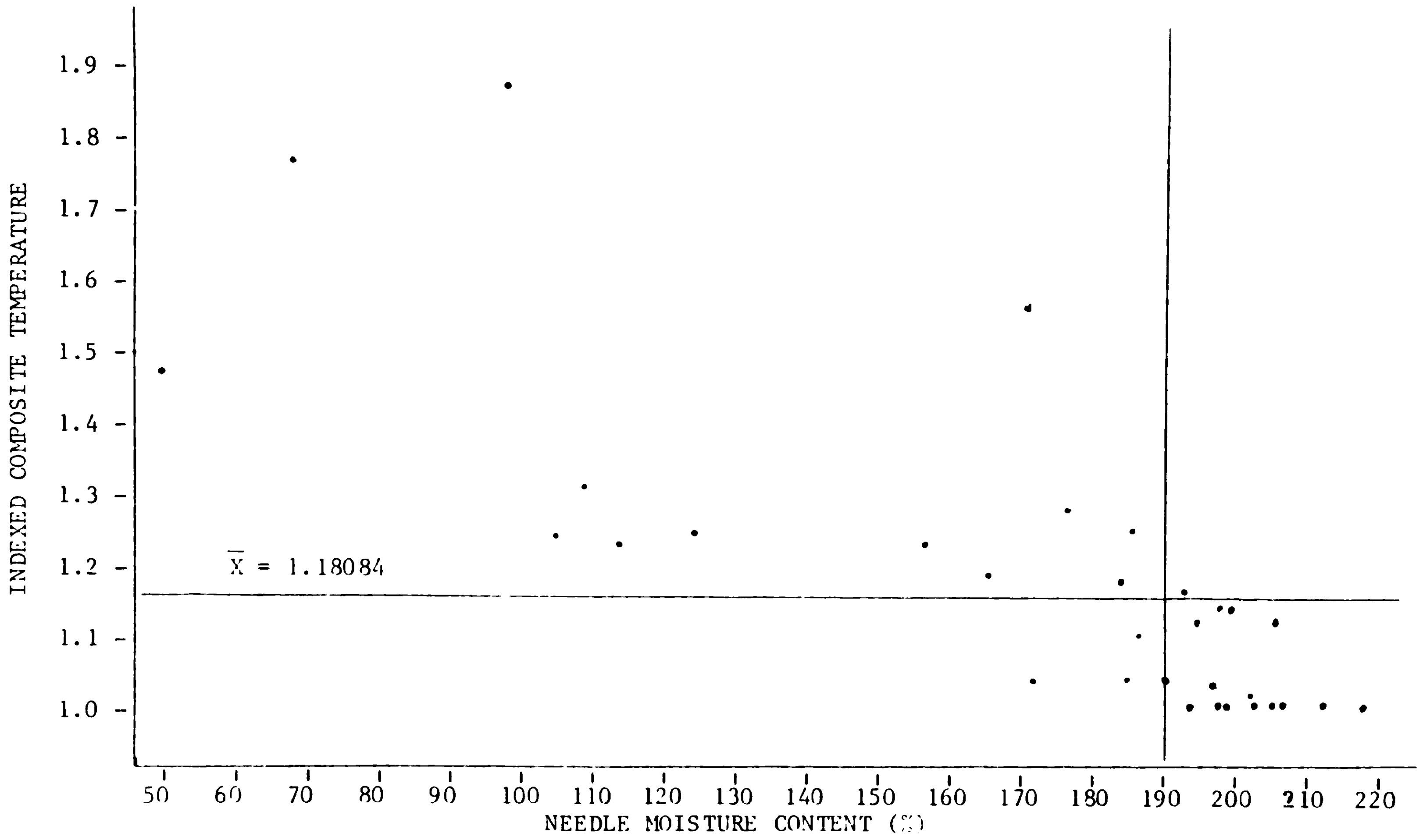

Figure 2. Indexed composite temperature vs needle moisture content for control and stressed seedlings in the 1978 study.

contents had low indexed composite temperatures.

Pearson correlation coefficients calculated for the relationship between needle moisture content and index composite temperature were found to be significant at the 5 percent level. For all seedlings the Pearson correlation coefficient had a r-value of -.79. For seedlings with treatment length of four days and the control seedlings, the r-value was -.72. For seedlings with treatment length of eight days and the control seedlings, the r-value was -.88.

Severed Trees

There was no visual change in the appearance of the severed or adjacent control trees during the period of time the trees were observed. The time intervals between severing and evaluating the trees ranged from one to four weeks. Neither color (Figs. 3, 6, 9, 11) or color infrared films (Figs. 4, 7, 12) provided a distinction between the severed and control trees.

However, relative apparent temperature differences between the healthy and the control trees were detected with the AGA Thermovision system. The loblolly scanned four weeks after severing on August 5, 1976, was 0.5 °C warmer than the control tree (Fig. 5). The second loblolly pine was severed on October 8, 1976 and scanned three weeks later, was 2 °C warmer than the control tree (Fig. 8). A relative apparent temperature difference of 2.0 °C between the third loblolly pine (severed on June 8, 1977) and the control tree was detected one week after severing (Fig. 10). A Virginia pine was severed on

Figure 3. Appearance of the loblolly pine severed on August 5, 1976 (right) and the loblolly pine used as a control (left) on color film September 1, 1976, four weeks after severing.

Figure 4. Appearance of the loblolly pine severed on August 5, 1976 (right) and the loblolly pine used as a control (left) on color infrared film September 1, 1976, four weeks after severing.

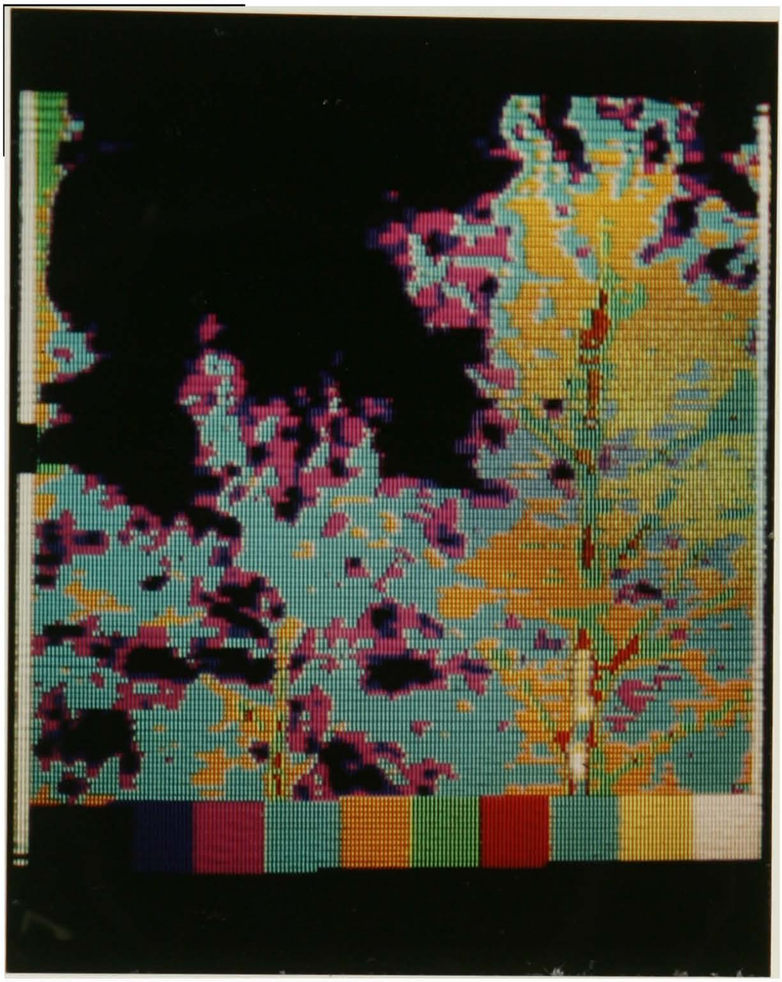

Figure 5. Thermal image of the loblolly pine severed (right) on August 5, 1976 and the loblolly pine used as a control (left) copied from the AGA Thermovision 680 color monitor on September 1, 1976, four weeks after severing. The AGA system was set to scan a 5 °C temperature range, thus each color represents a 0.5 °C change in apparent temperature. The gold color in the severed tree indicates an apparent temperature 0.5 °C warmer relative to the light blue of the control tree.

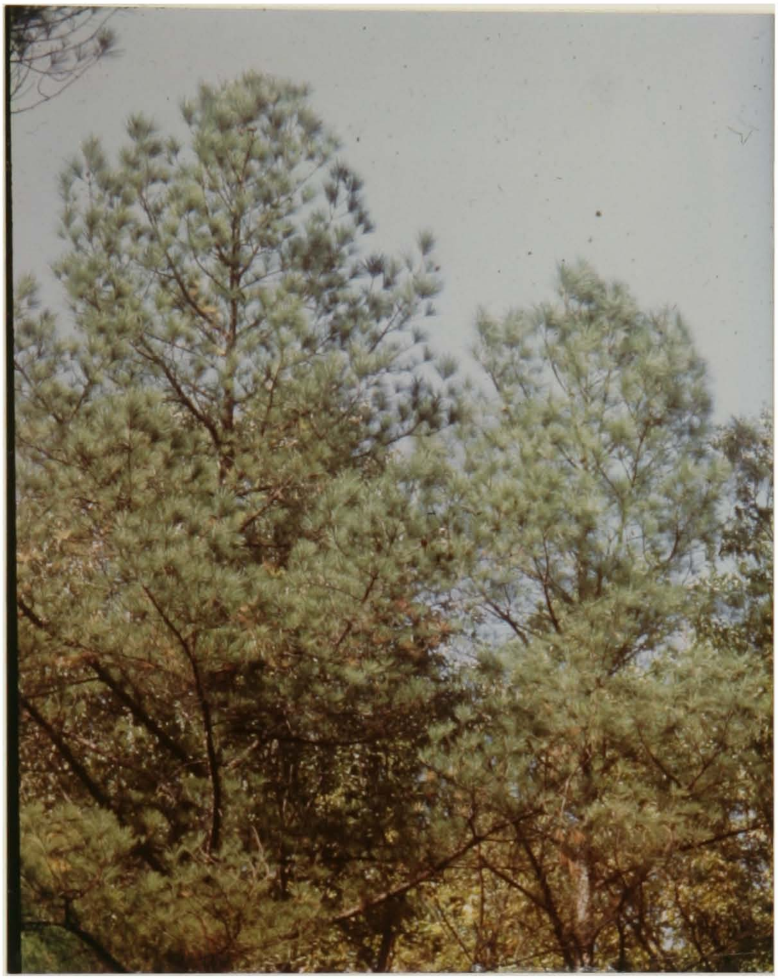

Figure 6. Appearance of the loblolly pine severed on October 8, 1976 (right) and the loblolly pine used as a control (left) on color film October 29, 1976, three weeks after severing.

Figure 7. Appearance of the loblolly pine severed (right) on October 8, 1976 and the loblolly pine used as a control (left) on color infrared film on October 29, 1976, three weeks after severing.

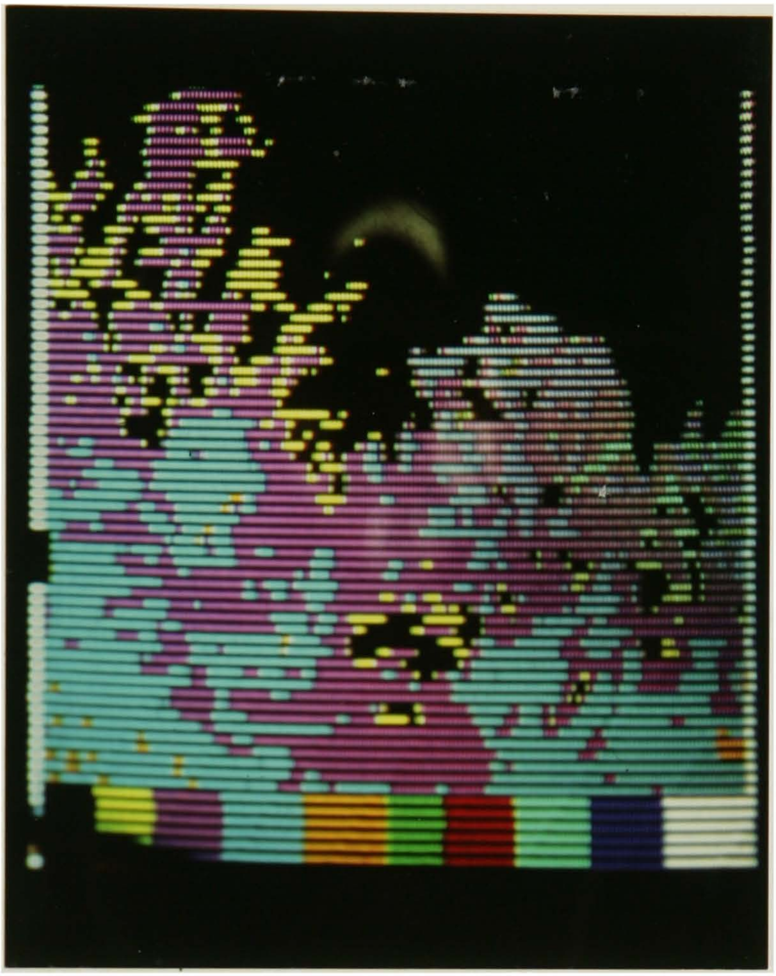

Figure 8. Thermal image of the loblolly pine severed (right) on October 8, 1976 and the loblolly pine used as a control (left) copied from the AGA Thermovision 680 color monitor on October 29, 1976, three weeks after severing. The AGA system was set to scan a 10 °C temperature range, thus each color represents a 1.0 °C change in apparent temperature. The light blue color in the severed tree indicates an apparent temperature 2.0 °C warmer than the yellow of the control tree.

Figure 9. Appearance of the loblolly pine severed (right) on June 8, 1977 and the loblolly pine used as a control (left) on color film on June 15, 1977, one week after severing.

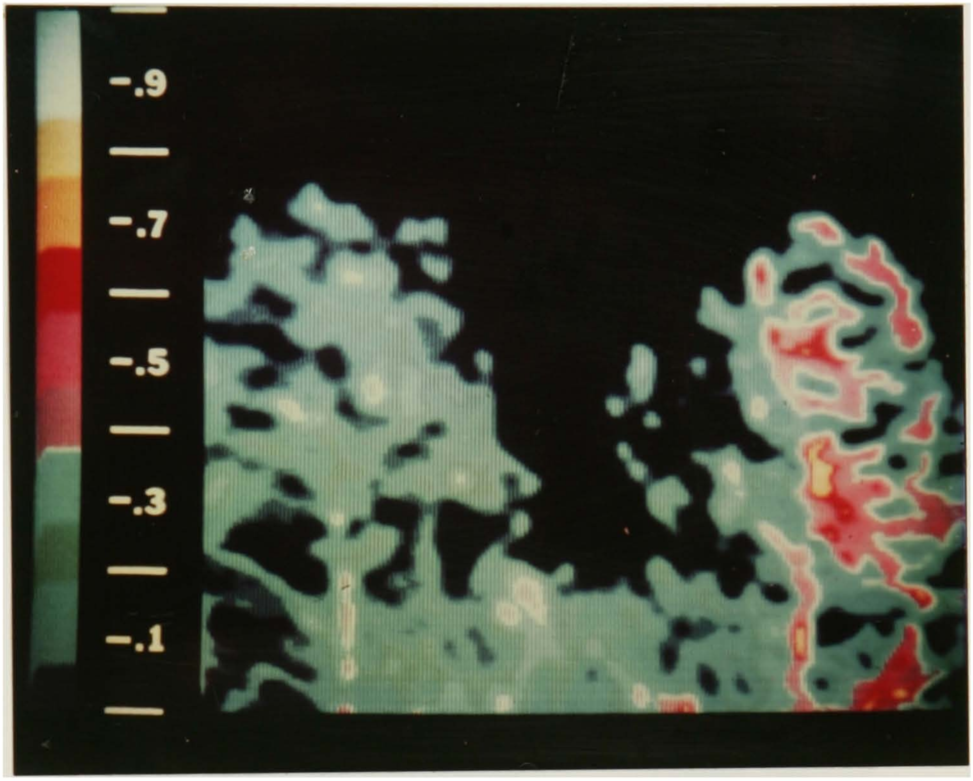

Figure 10. Thermal image of the loblolly pine severed on June 8, 1977 (right) and the loblolly pine used as a control (left) copied from the AGA Thermovision 750 color monitor on June 15, 1977, one week after severing. The AGA system was set to scan a 5 °C temperature range, thus each color represents a 0.5 °C change in apparent temperature. The gold color in the severed tree indicates an apparent temperature 2.0 °C warmer than the light green of the control tree.

Figure 11. Appearance of the Virginia pine severed (right) on September 9, 1977 and the Virginia pine used as a control (left) on color film on September 23, 1977, two weeks after severing.

Figure 12. Appearance of the Virginia pine severed (right) on September 9, 1977 and the Virginia pine used as a control (left) on color infrared film on September 23, 1977, two weeks after severing.

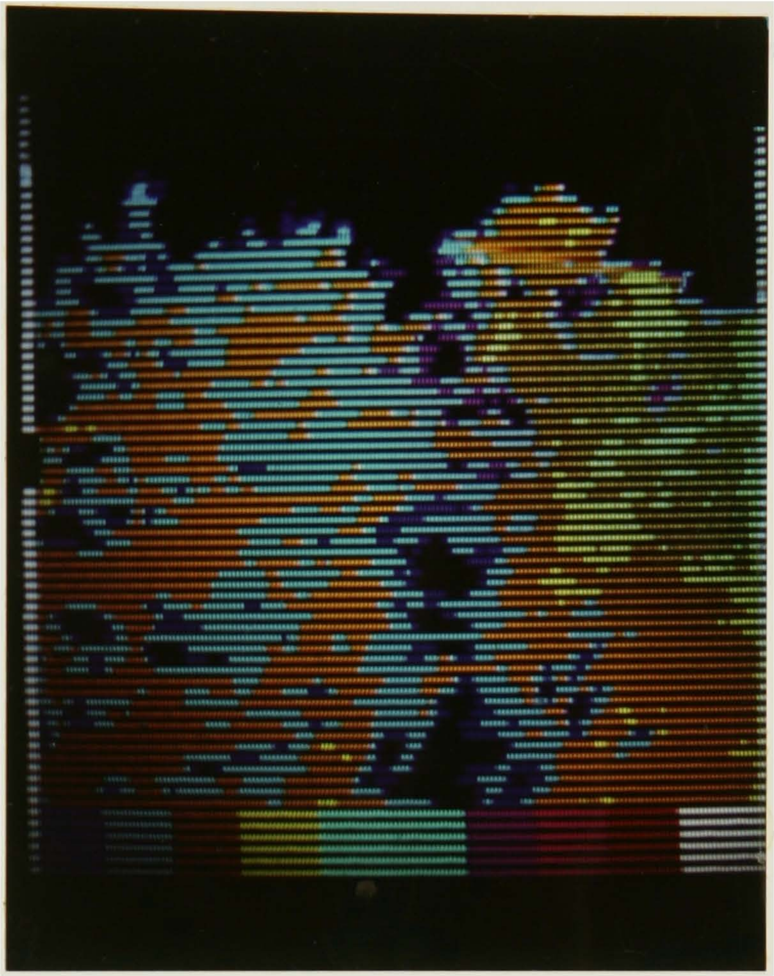

Figure 13. Thermal image of the Virginia pine severed (right) on September 9, 1977 and the Virginia pine used as a control (left) copied from the AGA Thermovision 680 color monitor on September 23, 1977, two weeks after severing. The AGA system was set to scan a 5 °C range, thus each color represents a 0.5 °C change in apparent temperature. The light yellow color in the severed tree indicates an apparent temperature 0.5 °C warmer than the gold color in the control tree.

September 9, 1977 on the Quantico Marine Base, Quantico, Virginia, and scanned two weeks later. The severed tree was 0.5 °C warmer relative to the control tree (Fig. 13).

DISCUSSION

Seedling Study 1976

The drought and flood treated seedlings remained green throughout the experiment, only the severed seedlings changed color. The needle moisture contents of all the seedlings tested except two of the drought-treated seedlings were within or below the range (180-190%) reported by Bilan et al. (1977) where transpiration was drastically reduced. This demonstrated that stress may occur and not be visually detectable in loblolly pine seedlings.

The moisture contents of the needles of the severed seedlings decreased very quickly. The wide variation and no gradual decline in the needle moisture content of the drought-treated seedlings indicated that the technique for withholding water may have been faulty. It was observed that the plastic sheets covering the tops of the pots served as a barrier to evaporation and as a surface for water condensation. This may have contributed to keeping the pots moist. Although the needle moisture contents of the flooded seedlings dropped below that of the control seedlings during the first week of treatment, there was no further decline in needle moisture content as treatment time increased.

Color and infrared films failed to detect stress before visual symptoms occurred in all treatments. Except for their different spatial orientation, even the wilted seedlings appeared the same color as the healthy control seedlings on both films.

Seedling Study 1978

All seedlings remained green throughout this experiment even though the needle moisture content of some seedlings dropped below the threshold for survival (110%) established by Brix (1960). Visual inspection of the Ektachrome slides did not detect differences in foliage color between treated and control seedlings.

The severing treatment was the only treatment which produced needle moisture contents significantly different from the controls. The length of time the drought and flood treatments were imposed may account for the failure to reduce needle moisture content below the 180-190% range. The short days and reduced solar loading of October may also increase the treatment time required to lower needle moisture content.

The correlation between needle moisture content and indexed composite temperature demonstrated the capability of the AGA system to detect stress by increased foliage temperatures. However, it must be noted that the majority of the seedlings tested were in either the lethal or healthy range of needle moisture content. Future work should include seedlings having needle moisture contents in the intermediate range of 110 to 170%.

Large differences in needle temperatures between healthy and stressed foliage are not to be expected as needle temperatures of conifers are very closely coupled to air temperatures (Gates and Benedict

1963). Other factors contributing to the small temperature differences observed during this study may be the amount of foliage scanned and the time of year this study was conducted.

Stressed Trees

Realtive apparent temperature differences between healthy and stressed trees were found for all severed trees prior to a change in foliage color. Ektachrome and Ektachrome infrared films did not detect that the severed trees were under stress.

This technique was used on two different pine species and at three different times of the year. The AGA Thermovision system is a simple, easily transported remote sensing system for detecting relative apparent temperatures of plant foliage without direct contact with the leaves.

Like any camera system, use of the AGA Thermovision system requires conditions which fit the equipment. Schmid (1976) estimated that weather conditions were optimal for detecting temperature differences with thermocouples between bark-beetle infested and healthy Engelmann spruce (*Picea engelmannii* Parry) in Wyoming on 15% of the days of the summer. Weber (1969) working with ponderosa pine in South Dakota, found his thermal imagery from aerial multispectral systems was influenced by a number of environmental and physiological factors, among these transpirational lag and changes in the availability of soil moisture. Future studies should determine the parameters for optimal use of the AGA Thermovision system and the correlations of plant temperatures with the factors influencing plant stress.

This study has shown that temperatures of pine foliage stressed by severing the stem may be higher relative to healthy foliage. This contributes to the primary host attractant hypotheses that bark beetles are attracted to volatiles released from stressed trees due to abnormal respiration (Person 1931), a warming of the tree as transpiration fails (Heikkenen and Hrutfiord 1965), and the subsequent deterioration of plant tissues (Heikkenen 1977).

Previsual detection of stress in loblolly pine and Virginia pine was achieved with the AGA Thermovision system. Apparent temperatures of severed tree crowns were warmer relative to healthy trees within one week of severing. The AGA Thermovision system should prove to be a useful tool for non-destructive sampling of plant stress and for locating stressed trees and potential bark beetle infestations.

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APPENDICES

Appendix Table A. Visual appearance and relative apparent temperature of the foliage of severed loblolly pine seedlings for the 1976 seedling study.

Length of Treatment (Weeks)	Visual Appearance	Relative Apparent Temperature* (^oC)
1	Green-wilted	3
1	Green	1
1	Green	0
1	Green-wilted	1
1	Green-wilted	1
1	Green	0
	Avg.	1.0
2	Yellow green-wilted	3
2	Green-wilted	1
2	Green	0
2	Yellow green	1
2	Yellow green-wilted	0
2	Yellow green-wilted	0
	Avg.	0.8
3	Yellow-wilted	1
3	Yellow-wilted	3
3	Yellow-wilted	0
3	Red-wilted	3
3	Green-wilted	3
3	Green-wilted	1
	Avg.	1.8
4	Red-wilted	2
4	Red-wilted	2
4	Red-wilted	2
	Avg.	2.0

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*Relative apparent temperature refers to the increase in apparent temperature of the stressed seedling compared to the control seedling. A relative apparent temperature of 0 indicates that no temperature dirreremce was detected.

Appendix Table B. Visual appearance and relative apparent temperature of drought-treated loblolly pine seedlings for the 1976 seedling study.

Length of Treatment (Weeks)	Visual Appearance	Relative Apparent Temperature* (°C)
1	Green	1
1	Green	1
1	Green	1
1	Green	2
1	Green	1
1	Green	0
	Avg.	1.0
2	Green	3
2	Green	3
2	Green	3
2	Green	0
2	Green	0
2	Green	0
	Avg.	1.5
3	Green	0
3	Green	0
3	Green	1
3	Green	1
3	Green	1
3	Green	2
	Avg.	0.8
4	Green	0
4	Green	0
4	Green	0
	Avg.	0.0

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*Relative apparent temperature refers to the increase in apparent temperature of the stressed seedling compared to the control seedling. A relative apparent temperature of 0 indicates that no temperature difference was detected.

Appendix Table C. Visual appearance and relative apparent temperature of flooded loblolly pine seedlings for the 1976 seedling study.

Length of Treatment (Weeks)	Visual Appearance	Relative Apparent Temperature* (°C)
1	Green	3
1	Green	1
1	Green	0
	Avg.	1.3
2	Green	3
2	Green	1
2	Green	0
	Avg.	1.3
3	Green	1
3	Green	0
3	Green	0
	Avg.	0.3
4	Green	0
4	Green	0
4	Green	2
	Avg.	0.6

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*Relative apparent temperature refers to the increase in apparent temperature of the stressed seedling compared to the control seedling. A relative apparent temperature of 0 indicates that no temperature difference was detected.

Appendix Table D. Needle moisture contents expressed as a percentage of oven dry weight for 1978 seedling study.

Treat- ment	Pot Number	Date Sample Taken (1978)						
		10/11	10/12	10/16	10/17	10/18	10/20	10/24
Control	41	208	226	231	238	242	219	213
Control	44	196		210	222	226	199	187
Control	45	219		229	220	231	207	198
Control	48	190	169	170	190	239	186	166
Control	52	215	188	226	209	236	212	218
Control	57	173	163	209	212	229	203	202
Control	71	192	216	202	194	214	193	193
Control	75	188	225	210	191	206	206	194
Drought	42	239	195	208	236	262	219	206
Drought	49	189	189	233	192	226	207	178
Drought	63	176	167	184	181	204	192	190
Drought	65	198	182	198	191	210	200	198
Drought	69	156	206	195	187	194	198	199
Drought	76	170	183	197	198	206	181	197
Drought	78	183	200	204	186	172	198	186
Drought	81	146	195	191	176	214	192	192
Flood	51	194	151	195	217	215	209	187
Flood	54	160	122	204	195	221	200	212
Flood	59	182	156	184	187	199	186	171
Flood	66	160	172	176	166	198	198	207
Flood	43	236	207	240	256	246	230	198
Flood	53	127	192	199	197	220	198	185
Flood	70	151	201	180	181	205		194
Flood	79	208		183	195	208	205	206
Severed	47	238	173	203	182	207	200	172
Severed	56		161	186	195	221	180	110
Severed	61	212	174	206	217	221	194	113
Severed	72	123	213	189	142	145	124	50
Severed	46	215	211	237	211	199	143	99
Severed	62	198	156	197	146	151	111	69
Severed	73	144	154	186	162	174	181	123
Severed	77	205	172	201	154	159	139	106

Appendix Table E. Radiometer readings recorded as each group of seedlings was sensed with the AGA System on October 24, 1978.

Radiometer (Watts/Square Meter)	Time (EDT)	Pot Number	Treatment	Treatment Length (Days)
75	1428	41	Control	
		42	Drought	8
		43	Flood	4
		81	Drought	4
72	1432	45	Control	
		46	Severed	8
		47	Severed	4
		62	Severed	8
70	1437	49	Drought	4
		51	Flood	4
		52	Control	
		53	Flood	8
73	1441	54	Flood	4
		56	Severed	4
		57	Control	
		59	Flood	4
78	1444	66	Flood	4
		61	Severed	4
		63	Drought	4
		48	Control	
68	1447	65	Drought	8
		69	Drought	8
		70	Flood	8
		71	Control	
46	1452	72	Severed	4
		73	Severed	8
		75	Control	
		76	Drought	4
66	1457	77	Severed	8
		78	Drought	8
		79	Flood	8
		44	Control	

Appendix Table F. Area and percentage of total area occupied by colors making up the color thermal image of control and stressed seedlings of the 1978 seedling study.

Treatment/ Length (Days)	Pot Number	Area of Color							% of Total Area					
		Black	Dark Blue	Light Blue	Green	Pink	Red	Total	Black	Dark Blue	Light Blue	Green	Pink	Red
Control	41	156	563	312	247	107	0	1385	11.3	40.6	22.5	17.8	7.7	0.0
Drought/8	42	158	422	371	234	352	0	1537	10.3	27.4	24.1	15.2	22.9	0.0
Flood/8	43	153	584	557	378	273	0	1945	7.9	30.0	28.6	19.4	14.0	0.0
Drought/4	81	85	212	278	256	157	0	988	8.6	21.4	28.1	25.9	15.9	0.0
Control	45	769	454	352	0	0	0	1575	48.8	28.8	22.3	0.0	0.0	0.0
Sever/8	46	23	529	774	979	0	0	2305	1.0	23.0	33.6	42.4	0.0	0.0
Sever/4	47	59	219	262	123	0	0	663	0.9	33.0	39.5	18.6	0.0	0.0
Sever/8	62	153	499	485	982	0	0	2119	7.2	23.5	22.9	46.3	0.0	0.0
Drought/4	49	314	746	1092	1278	0	0	3430	9.2	21.7	31.8	37.3	0.0	0.0
Flood/4	51	133	702	983	795	0	0	2613	5.1	26.8	37.6	30.4	0.0	0.0
Control	52	435	830	439	311	0	0	2015	21.6	41.2	21.8	15.4	0.0	0.0
Flood/8	53	144	518	372	446	0	0	1480	9.7	35.0	25.1	30.1	0.0	0.0
Flood/4	54	11	87	245	87	93	205	728	1.5	12.0	33.7	12.0	12.8	28.2
Sever/4	56	7	47	30	77	96	575	832	0.8	5.6	3.6	9.3	11.5	69.1
Control	57	0	140	307	226	237	243	1153	0.0	12.1	26.6	19.6	20.6	21.1
Flood/4	59	210	345	34	293	281	727	1890	11.1	18.3	1.8	15.5	14.9	38.5

Appendix Table F. (Continued)

Treatment/ Length (Days)	Pot Number	Area of Color							% of Total Area					
		Black	Dark Blue	Light Blue	Green	Pink	Red	Total	Black	Dark Blue	Light Blue	Green	Pink	Red
Control	48	4	39	317	95	308	0	763	0.5	0.5	41.5	12.5	40.4	0.0
Sever/4	61	0	60	195	328	313	0	896	0.0	6.7	21.8	36.6	34.9	0.0
Drought/4	63	128	294	346	320	411	0	1499	8.5	19.6	23.1	21.3	27.4	0.0
Flood/4	66	56	402	344	234	292	0	1328	4.2	30.3	25.9	17.6	22.0	0.0
Drought/8	65	24	193	265	409	478	0	1369	1.8	14.1	19.4	29.9	34.9	0.0
Drought/8	69	23	250	146	150	93	0	662	3.5	37.8	22.1	22.7	14.0	0.0
Flood/8	70	31	196	192	195	221	0	835	3.7	23.5	23.0	23.4	26.5	0.0
Control	71	121	425	190	257	299	0	1292	9.4	32.9	14.7	19.9	23.1	0.0
Sever/4	72	16	6	86	529	491	0	1128	1.4	0.5	7.6	46.9	43.5	0.0
Sever/8	73	77	122	314	992	182	0	1687	4.6	7.2	18.6	58.8	10.8	0.0
Control	75	193	926	683	1024	0	0	2826	6.8	32.8	24.2	36.2	0.0	0.0
Drought/4	76	102	331	405	481	0	0	1319	7.7	25.1	30.7	36.5	0.0	0.0
Control	44	136	287	282	585	662	0	1952	7.0	14.7	14.4	30.0	33.9	0.0
Sever/8	77	0	92	351	1810	856	0	3109	0.0	3.0	11.3	58.2	27.5	0.0
Drought/8	78	6	545	661	886	253	0	2351	0.3	23.2	28.1	37.7	10.8	0.0
Flood/8	79	94	326	253	282	274	0	1229	7.6	26.5	20.6	22.9	22.3	0.0

Appendix Table G. Composite temperatures and indexed composite temperatures for control and stressed seedlings of the 1978 seedling study.

Treatment/ Length (Days)	Pot Number	Radiometer (Watts/sq. meter)	Composite Temperature	Indexed Composite Temperature
Control	41	75	2.70108	1.00000
Drought/8	42	75	3.13012	1.15884
Flood/8	43	75	3.01748	1.11714
Drought/4	81	75	3.19028	1.18111
Control	45	72	1.73524	1.00000
Sever/8	46	72	3.17527	1.82987
Sever/4	47	72	2.67722	1.54286
Sever/8	62	72	3.08353	1.77700
Drought/4	49	70	2.97201	1.28621
Flood/4	51	70	2.93379	1.26967
Control	52	70	2.31067	1.00000
Flood/8	53	70	2.75676	1.19305
Flood/4	54	73	4.07005	1.00000
Sever/4	56	73	5.32332	1.30793
Control	57	73	4.11795	1.01177
Flood 4	59	73	4.20159	1.03232
Sever/4	61	78	3.98777	1.23811
Drought/4	63	78	3.39493	1.05141
Flood/4	66	78	3.22892	1.00000
Control	48	78	3.87025	1.19862
Drought/8	65	68	3.82104	1.24853
Drought/8	69	68	3.06042	1.00000
Flood/8	70	68	3.45389	1.12857
Control	71	68	3.14551	1.02780
Sever/4	72	46	4.30585	1.40575
Sever/8	73	46	3.64019	1.25606
Control	75	46	2.89809	1.00000
Drought/4	76	46	2.95906	1.02104
Sever/8	77	66	4.10325	1.25978
Drought/8	78	66	3.35517	1.03010
Flood/8	79	66	3.25712	1.00000
Control	44	66	3.69160	1.13339

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STRESS DETECTION IN LOBLOLLY PINE USING RELATIVE APPARENT TEMPERATURES OF FOLIAGE

by

Larry Allen Alger

(ABSTRACT)

The hypothesis that stressed loblolly pine (*Pinus taeda* L.) could be distinguished from non-stressed loblolly pine by increased foliage temperatures was tested. The foliage temperatures of seedlings and trees were measured with an AGA Thermovision 680 system, imported by the AGA Corporation, Secaucus, New Jersey. The AGA Thermovision 680 system is a simple, easily transported remote sensing system for detecting relative apparent temperatures of plant foliage without direct contact with the leaves. This system is sensitive to infrared wavelengths in the 2-5.6 micron region of the electro-magnetic spectrum.

Foliage temperatures in loblolly pine seedlings increased within one week of stress induced by drought, flooding, or severing. Increased temperatures of stressed seedlings were associated with reduced needle moisture content prior to visual symptoms of stress.

Foliage temperatures of loblolly pine trees stressed by severing the bole were warmer relative to neighboring control trees. Increased temperatures were detected within one week after severing.

Previsual detection of stress can be acheived by measuring foliage temperatures of loblolly pine. The AGA Thermovision should prove to be a useful tool for non-destructive sampling of plant stress, for locating stressed trees, and potential bark beetle infestations.