EVALUATION OF AN AUTOMATED METHOD TO MEASURE WATER POTENTIAL IN CALIFORNIA OAKS (*QUERCUS Spp.*)

A Capstone Project

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To the ESSP faculty:

The purpose of this study was to determine the feasibility of a low cost, automated instrument to measure trunk shrinkage and expansion as an indicator of plant water potential, as a means for monitoring water stress, in oak ecosystem studies. The objective of this study was to develop a strain gage sensor to provide continuous measurements of trunk (stem) diameter changes and correlate this data with xylem water potential by the pressure chamber method. This project will focus on the application of knowledge in the physical and life sciences and the acquisition, display and analysis of quantitative data. My topic primarily covers the biological and physiological principles and theories of water transport in plants. I have also evaluated the development and use of an electronic instrument to acquire data by measurement of trunk shrinkage and expansion; the display of data by utilization of excel formulas and graphs; and analysis by linear regression.

My goal for this project was to provide a low cost, automated method for researchers, resource managers and private landowners to use for the purpose of monitoring water stress in oak woodlands. In particular, a low cost method is needed for continuous measurements of water stress to contribute to ongoing studies on oak regeneration, acorn production, native grass competition, and wildlife management at the Hastings Natural History Reservation, in California. Resource managers would benefit from the use of this method to monitor water availability as needed for management of wildlife resources dependent on oak trees. This method should also be useful for rangeland landowners to make important land use and policy decisions regarding water availability and livestock grazing. A low cost method for determining daily water stress is also important to hardwood growers and orchard growers, for producing cost-effective water irrigation regimens. Finally, an automated method for measuring water potential would be of value to natural resource planners for determining the effects of urban growth and development on oak resources.

Oak habitats provide valuable natural resources for a rich diversity of wildlife, including food and shelter for hundreds of veterbrate species and thousands of invertebrate species. Acorns, leaves, bark, sap and roots are valuable food resources for herbivores, and provide the baseline of the food web for this ecosystem. In addition to providing food and shelter, oaks provide hiding places from predators, corridors for migratory animals, nesting sites for reproduction, perches for predation and nutrients for soil organisms. Water use and availability in the oak ecosystems of California is therefore important to researchers and resource managers for species conservation where many species depend on the oak ecosystem.

A low cost method for measuring water stress in oak trees would be valuable for rangeland managers to examine fluctuations in water availability as needed for the maintenance of a stable understory for livestock grazing. One of the greatest economic values of oak woodlands is for livestock and grazing. Livestock grazing, a multi-billion dollar industry in California, is dependent on annual and perennial grasses of the oak understory, which may be affected by water stress. Grazing and other agricultural practices have been suggested to be a factor in lowered water tables in some fragmented areas (California Oak Foundation, 1998). Maintenance and monitoring of a stable understory may be necessary to ensure adequate water availability between oaks and competing grasses and shrubs. Reduced canopy cover, as a result of water stress, has been correlated with increasing densities of competing annual grasses (Joffre and Rambal, 1993). Increasing grass densities have been suggested as a factor in seedling water stress in blue oak (Momen et al., 1994; Gordon and Rice, 1993). A positive feedback loop also occurs where increasing grass densities decrease soil water availability which in turn causes the oak to drop more leaves and further reduce its' canopy. The decrease in canopy cover in turn allows grass densities to further increase. Therefore, maintenance of balance between native grasses and oaks by grazing ensures livestock sustainability on private rangelands.

Rangeland owners also produce oak hardwood. Oak hardwood growers and fruit tree growers must develop effective irrigation strategies for maximum production efficiency of their crops. Scheduling irrigation based on indicators of water stress is desirable for maximum expansive growth (Fereres et al., 1999). Drip, microsprinkler, or other pressurized irrigation strategies can be used most effectively if autoregulated by plant water status (Selles and Berger, 1990). In the last decade, pressure has increased to regulate oak harvesting due to the lack of regeneration on oak hardwood rangelands (Standiford and Howitt, 1988). Therefore, a low cost, automated method to produce continuous measurements of plant water status would increase cost efficiency and sustainable crop yields.

Current studies utilizing measurements of water potential have provided information about urban disturbances and their affect on water stress, which is useful to natural resource planners. Van Rensburg (1997) found that while seasonal variation in water stress remained similar, decreases in water availability were more pronounced for trees on the edge of town or in town and consequently, trees dropped more leaves to reduce evapotranspiration. Knops et al. (1995), found higher percentages of introduced species (grasses) in disturbed areas, which have been found to reduce soil moisture availability (Callaway, 1992). Therefore, urban planners also require effective methods for measuring water availability in areas slated for development.

For my capstone interview, I have selected and met with Mark Stromberg, Ph.D., manager of the Hastings Natural History Reservation, Research Station for University of California, Berkeley. My preliminary meeting with Dr. Stromberg consisted of going over the needs of researchers at the reserve. Ongoing research at the Hastings Reserve includes oak regeneration, acorn crop size and production, effects of native grass competition, wildlife management and other various individual projects. Researchers conducting these studies need a low cost, automated method to provide such data for their studies. In addition, researchers are also looking for a method to provide continuous data on water potential in order to look at daily trends and patterns specific to differing species. Mark Stromberg has asked us to develop and test the effectiveness of such a method.

I also met with Walter Koenig, a researcher at Hastings Natural History Reservation, who is conducting studies primarily on acorn woodpeckers and acorn crop yields. I discussed with him, his and Jean Knops' recent studies on boom-and-bust acorn crops. Their studies have looked at variation in acorn crop yield and the causes of the variation. Correlation between crop yield and rainfall was examined and Dr. Koenig remarked that their was a need for more feasible, automated recordings of water potential for use in his studies. He also discussed with me an upcoming publication on a six-year study conducted by Johannes Knops and himself on annual variation in xylem water potential. He commented on the large amount of time and people it took to collect samples using the pressure chamber method and that he would be very interested in seeing the results of my study.

I chose this project because I am concerned about human impacts and disturbances to the oak woodlands of California. Growing up in California, since kindergarten, I have heard about protecting oaks, our state's tree, and providing oaks for future generations. My father would tell us how the settlers clear-cut thousands of acres of oak woodland for furniture, buildings, paper and other products, and how little was done to ensure future crops, since the oak was seen as bountiful. At the age of five, I attended Oakland's Arbor Day Annual Tree Planting Day, hosted by our mayor, and was privileged enough to take part in planting one oak tree. Thus, since my youth, I have been concerned about oak regeneration and have watched more and more oaks that have been cut down for development. Places I played as a child no longer contain the oaks I longed to climb on. It has been no surprise to me that oak regeneration is still one of the most thoroughly researched topics, however some questions are yet to be answered, such as why do some species have lower regeneration rates than others? What factors have the greatest role in reduced seedling survival and why haven't we come up with a better way to monitor and reduce these factors? Why is our state's tree not being protected?

The motivation and direction of this study was the concern about oak regeneration as a result of water stress and to provide a method to enable better monitoring of water stress for seedling survival. I have found a substantial amount of evidence relating water stress to poor regeneration as well as the dependency on water availability to seedling survival. In particular, the literature indicates that *Quercus douglasii* seedlings have lower survival rates to due seedling water stress, however little is known about the species' drought avoidance strategies. This is due to the need for more continuous data of overnight recovery for these species (Knops and Koenig, 2000). It may be that the species survival is dependent on other factors not observed yet. I also have found regeneration is highly dependent on acorn productivity (Sork et.al., 1993). There is evidence that lower acorn crop yields correlates with drier years, however acorn germination is also dependent on the number of acorns which sustain from foraging by wildlife (Knops and Koenig, 1995). Increases in ground squirrel and deer populations, as a result of decreasing predators, lead to fewer acorns able to germinate and thus a reduction in oak regeneration.

A second motivation of this study was to provide a method for further research to be used in making policy decisions for the conservation of water use. In examining the literature so far, I have encountered my own biases regarding my interpretation of the causes of water stress. My own bias is that human caused disturbances such as livestock grazing and agricultural use cause greater stress on water availability than do to natural conditions. While I have found this to be true, the effects of water stress as a result of natural conditions may be more harmful than that of grazing and agriculture. The introduction of exotic species from early agricultural practices has been shown to increase water stress; however, it is important to note that some native grasses have an even greater impact on water stress in oaks.

I believe this project holds great value for future studies and management practices affecting the sustainability of oak resources. A low cost, automated method for determining plant water status will be valuable to researchers, resource managers, rangeland owners and growers, and natural resource planners. A working prototype and/or the results of this study will primarily be provided to researchers at the Hastings Natural History Reservation and Field Research Station, UC Berkeley, California, who suggested this project be done. If my results indicate this new method is useful for measuring water stress, efforts will also be made to publish these results. Further dissemination of the results of this study will be provided to undergraduate students interested in conducting studies relevant to this work.

Sincerely,

Dana K. Riggs

Evaluation of an Automated Method to Measure Water Potential In California Oaks (*Quercus Spp.*)

Abstract

The purpose of this study was to determine the feasibility and reliability of a low cost, automated instrument to measure trunk diameter change as an indicator of plant water potential in California oaks (genus: *Quercus*). The measurement of water potential is important for monitoring water stress and its role in oak regeneration, acorn productivity, and disease susceptibility. Several past methods for measuring water potential were examined. A strain gage instrument was developed to measure trunk diameter change in response to the need for an automated method to measure water potential. Values from strain gage measurements were compared with xylem water potential measurements. A dead tree control was used to determine whether the strain gage is affected by daily temperature fluctuations. Results from graphed data sets depict trends that are supported by the cohesion theory of sap ascent; however, results from linear regressions do not show strong correlations between my measurements of trunk diameter change and xylem water potential. Several reasons are suggested, and further testing is recommended to determine if the lack of correlation is due to human error, calibration error, random events, or species-specific water acquisition strategies. These findings suggest, but do not confirm that our strain gage instrument may be a feasible method for providing automated data on plant water potential.

Introduction

The purpose of this study was to determine the feasibility and reliability of a low cost, automated instrument to record trunk diameter changes, which can potentially be used as an indicator of plant water potential in California oaks (genus: *Quercus*).

The stability and sustainability of an ecosystem is dependent on many variables for survival. The following research suggests that water potential is one of the most important variables to be measured in an ecosystem. Measurement of water potential is based on the evaporative demands that occur during photosynthesis, which is dependent on the availability of water to maintain physiological function. Vascular tissues in the plant stem hold the water column that is maintained in a cohesive state by tensile forces acting from the xylem (the water carrying part of the vascular tissues). This process can be explained by the cohesion theory of sap ascent, which states that water must be pulled through the xylem by a tensile force generated by evaporation (Scholander, 1965). After sunrise, stomata (or pores) on the leaf's surface open to acquire carbon dioxide for photosynthesis; this allows water to be diffused out into the atmosphere by evapotranspiration. As the water is released, a negative pressure draws water from the xylem into the leaf cells through osmosis. At midday, when the stomata are completely open, water drawn from the xylem forces the stem to reach its minimum diameter. At this point, the xylem pressure is lowest (most negative). The total water potential, which is the difference between xylem water potential and soil water potential, represents the total amount of potential energy required to move water from the xylem into the cells. At midday it is highest when xylem pressure is lowest and the stomata are completely open. After the sun sets, the leaf's stomata close and the trunk (stem) swells as the xylem pressure increases. At predawn, when the stomata are completely closed, leaf water potential and soil moisture potential are in equilibrium. At this time, the total water potential, as a measure of xylem sap tension (or pressure), reflects the total soil water availability and is therefore a valuable indicator of plant water status (Griffin, 1973).

The measurement of water potential indicates the level of water stress in a given plant species. Water stress occurs when the plant loses more water through its' leaves than it is able to acquire through its roots (Dudley, 1996). Higher water potentials generally indicate a tree is stressed and xylem water potential has been shown to be highly correlated with rainfall, as trees are more stressed during dry years than wet (Knops and Koenig, 2000). In California, oaks are heavily studied due to the concerns regarding the role of water stress in oak regeneration, acorn production and disease susceptibility. The most widely accepted and reliable method currently used in research studies is the pressure chamber method, as described by Scholander et.al. (1965). However, this method is time and labor consuming, as it is only used to measure predawn water potential and requires many samples to be taken from differing heights in the canopy layer. Other methods based on stem diameter changes have been introduced to measure water potential in plants for agricultural needs. In this study, I have looked at these other methods as a guideline for the development of a low-cost, easy-to-use method for measuring water potential in oaks. My goal for this project was to determine the feasibility and reliability of a strain gage sensor to measure trunk (stem) diameter change as an estimate of plant water potential.

Xylem water potential varies with height, location, and canopy cover. Species characteristics, such as root structure and leaf area, also influence xylem water potential. Water stress is generally attributed to seasonal precipitation and soil moisture availability. Water stress is highest from mid April to mid August on the central coast of California (Griffin, 1973), and during drought years (Parker et al., 1982). Early studies conducted by Griffin (1973) and Cline and Campbell (1976), indicated species distribution might be dependent on moisture gradients. Knops and Koenig (1994) found seasonal and diurnal changes in water stress are dependent on the plant's structural ability to take up water and its strategies for drought avoidance and tolerance. They found *Quercus lobata* generally grows on bottomland alluvial terraces, savannas and upland savannas, where it expresses drought avoidance by extending its roots into the water table. *Q. agrifolia* maintains dense stands on north facing slopes and creek beds in riparian and coastal areas to reduce evapotranspiration and limit growth during drier years. *Q. douglasii* is found predominantly on dry, south facing slopes and ridges where it displayed drought tolerant strategies such as dropping leaves to reduce evapotranspiration (Knops and Koenig, 1994). Knops and Koenig (2000) found predawn water potential most accurately reflects individual species access to water availability. However, they also indicated the need for daily patterns of xylem water potential measurements to determine other variables affecting overnight recovery, which is calculated by subtracting predawn measurements from midday (Knops and Koenig, 2000). Therefore, automated, continuous measurements of xylem water potential will be useful for examining individual characteristics for drought tolerance and overnight recovery differences of different oak species.

The Role of Water Stress

Water stress is of great concern due to its effects on regeneration of oaks. Much of the California oak woodland consists of mature oaks with relatively few seedlings and saplings. The lack of regeneration means that fewer trees will replace the mature ones, once they die. Many studies have investigated the implications of water stress and availability and found those implications to be a major limiting factor in growth and development of seedlings and saplings (Klepper et al, 1971; Knops and Koenig, 1994). Growing cells must withdraw some water into the cambium, thus diurnal and annual growth depends on water. Numerous studies have found reduced canopy cover, caused by water stress, to be a factor in poor regeneration (Callaway, 1993; Joffre and Rambal, 1993). These findings show the need to assess site water balance for factors in seedling survival and indicate the need for a water potential measurement in studies that focus on oak regeneration.

Water potential is an important factor in acorn production and crop yield. Some studies have indicated acorn "mast" crop size is linked to reproductive success in some species (Tiejte, 1990), where water stress is suggested to be a limiting factor (Sork et al., 1993). Koenig and Knops (1995) found that water potential correlated well with acorn variability and long-term mean productivity. Germination is also subject to water availability. Water is absorbed through the husk of the acorn causing the embryo root to rupture and permeate into the soil (Pavlik et.al. 1995). Therefore, continuous measurements of water potential as an indicator of water stress are important in monitoring the role of acorn production and germination in oak regeneration.

Measurement of water potential is also useful for determining disease susceptibility. One study on the effect of *Diplodia mutila* inoculations on *Quercus pubescens* and *Q. cerris* seedlings found the fungi had a negative effect on leaf water potential. The authors proposed water stress, measured by leaf water potential, may be an early indicator of infection (Ragazzi, A. et.al., 1999). Water stress from drought also weakens trees natural defenses. Ambrosia beetles, (*Monarthrum scutellare* and *M. dentiger*) depend on oaks with low moisture level which are drought-stressed, and therefore attack dead or weakened trees (Hagen, 1999). Ambrosia beetles are commonly found in cases of the Sudden Oak Death epidemic and other new studies are coming out on the role of water stress as a predisposing factor to these beetles and the fungal species *Phytophthora sp.* and *Hypoxylon thouarsianum*, associated with the epidemic (Frankel, pers. comm., 2001).

Past Methods for Measuring Water Potential

The predominant method used for measuring water potential in oak trees is the pressure chamber method described by Scholander et al. (1965). This method is both accurate and reliable for measuring xylem sap tension, however only predawn water potential is usually measured because of time and labor constraints. With this method, water potential is sampled at the leaf and varies at different levels of the canopy. As a result, many samples must be taken. Hardegree (1989) indicated discrepancies in pressure chamber readings, resulting in lower values of water potential. The author hypothesized that readings result from water movement between the xylem and symplast (cells) which occurs during pressurization in the chamber. Holbrook et.al. (1995) verified measurement of xylem pressure by this method by comparing measurements of xylem tension (or water potential) from the pressure chamber to calculated tensions created by rotational motion, where pressure is derived from a known equation. The results of this analysis also supported the cohesion theory of sap as the primary mechanism for water transport, which indicates the pressure chamber is a reliable, well-established method for obtaining relative water potential.

Xylem sap tensions may also be measured using a sample chamber thermocouple psychrometer as described by Kaufmann (1968) for finding discrete data on leaf osmotic potential. Crown leaves must be sampled to relate to total water potential using pressure-volume curves (Parker et. al., 1982). This method appears to be very time consuming, due to the need to freeze and thaw samples. While present in the literature, the thermocouple psychrometer does not appear to be as widely used in the last decade.

Several recent studies have looked at other methods utilizing stem diameter changes to measure water potential in plants for agricultural needs. These studies have used linear variable displacement transducers (LVDTs) to measure minute changes (on the order of micrometers) in stem diameter on crop plants. Peak values for diameter change was between approximately –1.11 and 7.14 micrometers (Fereres, et.al, 1999). The LVDT method measures water potential (an indicator of water stress) by measuring diurnal trunk shrinkage and expansion without the need for daily calibrations. In a study done by Selles and Berger (1990), maximum daily trunk growth and shrinkage was measured using LVDTs as a measure of water stress for use in auto-regulating irrigation in orchards. Findings indicated the LVDT method showed a response to water stress earlier than leaf water potential. This may be due to a time lag determined in previous studies due to diurnal hysteresis between the xylem and phloem when measuring stem diameter (Klepper et.al., 1971). Hysteresis occurs as a result of translocation, where water flows back through the xylem into the leaf for photosynthesis and causes a two hour delay between corresponding leaf and stem pressures. Greater dependency of the stem diameter on soil water potential has also been suggested to cause the delay in an analysis involving peach trees (Garnier and Berger, 1985). Another study done on peach trees by Fereres et.al. (1999) indicated continuous LVDT recordings with the use of a datalogger provide strong correlation with leaf water potential measurements made with the pressure chamber. These studies indicate that continuous measurements of stem diameter are useful for determining water potential and for use in monitoring water stress in forest ecosystems.

These studies have taken advantage of new technologic improvements in data acquisition, which have been made in the last decade or so. One such improvement is semiconductor-based datalogger instrumentation for the benefit of obtaining automatic and continuous measurements in situ. A benefit is that arrays of such instruments can collect data that can be analyzed for spatial and/or temporal patterns (Moore, 1999). Other benefits are the ability of the datalogger to record unobserved events, or provide explanations for unusual patterns in the data or events that may not have been recorded had the observer been present, such movement from mountain lions climbing up the tree. Until recently, instruments that perform these functions have been too costly for routine use by resource managers, but can now be constructed with relatively little cost (Moore, 1999).

The purpose of this study was to develop and determine the feasibility of a low-cost, automated method for estimating water potential. Working with my advisor, Dr. Steve Moore, I have developed a strain gage sensor and datalogger to measure trunk diameter change as a measure of water potential in California oaks.

Materials and Methods

I developed a strain gage sensor in response to the need of an automated method to provide continuous measurements of trunk diameter change as an estimate of plant water potential. The strain gage was developed in response to several studies that indicated diurnal changes in stem diameter correlates well with xylem water potential. Strain is a measure of deformation from mechanical stress due to mechanical forces acting on or within the trunk. Stress is defined as force per unit area. Strain is measured from movement of the bark, as the tree swells and shrinks against the strain gage sensor. The strain gage sensor is composed of three major components: the strain gage instrument, the signal conditioning circuit, and the datalogger.

A diagram of the strain gage instrument is shown in Figure 1. A protective metal box contains the components and wires to prevent destruction of the wires by rodents, and is secured by two screws attached to the outer bark layer. A flat-head screw (A) is embedded into the heartwood at the bottom of a clearance hole and remains stationary. Two bonded metallic wire resistance strain gages (Omega Y1848, gage factor 2.10) are affixed to the thin brass strip (7.5 x 1 x 0.1cm), which is anchored onto an aluminum block (B). As the water is pulled into the leaf tissues, the xylem tissues shrink (C), so that the bark, which floats above also shrinks (D). As the box drops relative to the flat-headed screw (A), pressure is applied to a small, adjustable screw driven through the brass strip. The pressure forces the brass strip upward (E), relative to the aluminum block. This stretches strain gage SG1, increasing its resistance and compresses strain gage SG2, reducing its resistance (Figure 1). The opposite is true as the trunk expands.

A Wheatstone bridge circuit configuration transforms the tiny changes in resistance (measures in parts per million) into a readable voltage output. The Wheatstone bridge (A) is shown in the circuit diagram in Figure 2. Strain gages SG1 and SG2 make up one side of the bridge. Two resistors on the other side of the bridge maintain a resistance of 348 ohms each. These resistors balance the change in resistance caused by the compression of one gage and the stretching of the other so that the sum of changes between the two gages is passed to the amplifier as negative or positive changes in voltage, which reflect negative or positive strain. Therefore, if each gage had equal force applied, the differential strain would be zero and voltage (V) out would not change. A trimpot resistor (B) was used to adjust bridge balance to set the initial voltage (no strain applied) so that the output would be approximately 2.0 to 2.5 volts. A five-volt regulator (C) is used to maintain a steady flow of current through the bridge. The voltage difference is passed through an amplifier (D) to yield a readable voltage output, which is then passed to the datalogger. The use of two gages doubles the change in resistance resulting in an increase in the sensitivity to the change. A second reason for using two gages is so that a change in temperature would increase or decrease the resistance of both gages equally and is thus canceled out.

The voltage out from the circuit is recorded by the datalogger in increments of 0.0 to 5.0 volts, once every five minutes and stored as an array of 8-bit binary data until it can be later uploaded into a Microsoft Excel program to graph voltage out over time. The datalogger used in this study was designed and developed by Steve Moore, Ph.D., and modified for use with this sensor. Diameter measurements are recorded as changes in voltage output and stored as A/D counts. An increase of 0.5V corresponds with approximately 25 A/D counts. The calibration was determined by bending the brass strip a known distance and measuring the change in voltage output. This revealed a sensitivity of approximately 34.0 um per A/D count.

Based on the study by Holbrook (1995), I have used the pressure chamber technique as a comparison for values obtained by the strain gage sensor. Xylem water potential was measured using the pressure chamber method, as described by Scholander et al (1965). To do this, a twig is cut from the canopy layer of the tree sampled. Once the capillary is cut, the water in the tissues will recede back slightly due to effects from higher atmospheric pressure. The twig is then placed within the sealed pressure chamber and the chamber is slowly pressurized with Nitrogen gas. Eventually, the pressure of the gas forces the sap back to where the capillary was cut. Pressure at this point equals the original negative pressure from the xylem. The pressure was recorded as the tip of the cut twig changes color prior to bubbling over. Twigs were only cut once to avoid error from further recession of the sap. A minimum of two leafy twigs was sampled from both the upper canopy and lower canopy. A third twig was sampled if greater than one bar was measured between the first two, based on earlier studies utilizing the pressure chamber method (Fereres et.al, 1999; Knops and Koenig, 2000). Sampling was conducted at four to six hour intervals over two twenty-four hour periods, composing of one sunny day and one cloudy day. Date, time, temperature, tree diameter and corresponding voltage output were also recorded.

Preliminary data for building this prototype were collected at the Hastings Natural History Reservation, in Carmel Valley, California. Control sampling was conducted on a dead tree specimen at the Santa Lucia Preserve in Carmel Valley, California. Primary testing with the pressure chamber was completed on the former Fort Ord, California in the Coast Live Oak woodland (*Quercus. agrifolia*), south of Inter-Garrison Road, near the intersection with Abrams Road. Based on advice from Dr. Lars Pierce, *Q. agrifolia* was selected for testing because it maintains a water balance in the winter and early spring, when testing was conducted, while other species have stopped transpiring. This study site contains sandy soils that reduce the amount of available water for use by the tree, so that greater diurnal variation is achieved for comparison. The Fort Ord site also provided me close access to the road, which provided greater safety from predators (mountain lions and any odd people wandering around the woods) during night sampling. The site was also surveyed for nests and dens to ensure minimal interaction with other woodland species, such as the striped skunk (*Mephitis mephitis*), whose den was originally missed in our survey. Caution was taken not to upset the animal too much, as it made its presence known whenever we sampled. The strain gage was placed on the north aspect of the tree to reduce temperature effects. A dead tree control was used to measure the amount of variation caused by temperature in the strain gage measurements. The control experiment was accomplished by recording with the strain gage for a twenty-four hour period on the dead tree.

Experimental analysis was designed to test whether the strain gage measures expansion and contraction of the trunk and to note how well trunk diameter change corresponds with leaf water potential. This was done by first converting voltage output to diameter change. Diameter was calculated by converting voltage change to movement, using the calibration number. The initial diameter was estimated by taking the circumference of the tree at the start of the sample set and dividing by pi (3.14). Percentage change in diameter was then calculated by dividing the diameter by the amount of movement. This was graphed using Microsoft Excel, over time to show the amount of change corresponding to predawn and midday. Mean trunk diameter change and xylem water potential measured by the pressure chamber along with temperature changes is graphed in this way also. A graph for the dead tree control shows the A/D counts over time, in delta hours (Figure 6.1). The battery failure that occurred between 1600 and 2300 hours on from the second data set on April 15, 2001 was omitted from the graphs and statistical analysis. Sampling for the pressure chamber began for the first data set at approximately 1500 hours the previous day and ended at 1500 on April 4, 2001. Sampling began for the second data set at approximately 1900 hours on April 14, 2001 and ended at approximately 1500 hours on the April 15, 2001.

For statistical analysis, the mean for xylem water potential measurements for each pressure chamber sample period was calculated and used for regression analysis. The mean for the percentage in trunk diameter change was also calculated according to pressure chamber sampling time and used for regression analysis. On the advice of Dr. Lars Pierce, linear regression was used on all graphed data sets to determine the correlation between the pressure chamber method and the strain gage method for measurement of water potential. If the correlation is strong, we may conclude that an automated strain gage sensor is feasible for measuring water potential as a measure of water stress in oak ecosystems, provided little or no variation is measured from the control.

Results

My initial results indicate the strain gage is detecting movement as shown in Figures 1.1 and 2.1. Results for the first data set occurred on a cloudy day and are shown in Figures 1.1, 1.2 and 1.3. In Figure 1.1, most movement occurred approximately four hours after midday and just after predawn. After midday, percent diameter change appeared to be mostly increasing while after predawn it appeared to be mostly decreasing. This can also be seen in Figure 1.2, where an increase in trunk diameter occurs following midday, and a decrease in trunk diameter occurs following predawn. Figure 1.2 also shows that the smallest trunk diameter occurred around midday, while the largest trunk diameter occurred around predawn. The maximum daily percent change, shown in Figure 1.1 for April 4, 2001 ranged between 0.01% and 0.08%.

Figure 1.3 shows mean xylem water potential measured by the pressure chamber was highest (more negative) during midday and around noon (approximately 20 delta hours) and lowest near predawn. The highest water potential value was –12.0 bars (one bar equals 14 p.s.i) and occurred at approximately noon. The lowest water potential was –5.0 bars and occurred at approximately predawn. Figure 1.3 also shows water potential decreased after midday and began increasing approximately four hours after predawn.

Figure 1.1: 4/4/01 Initial Data on Trunk Diameter Change

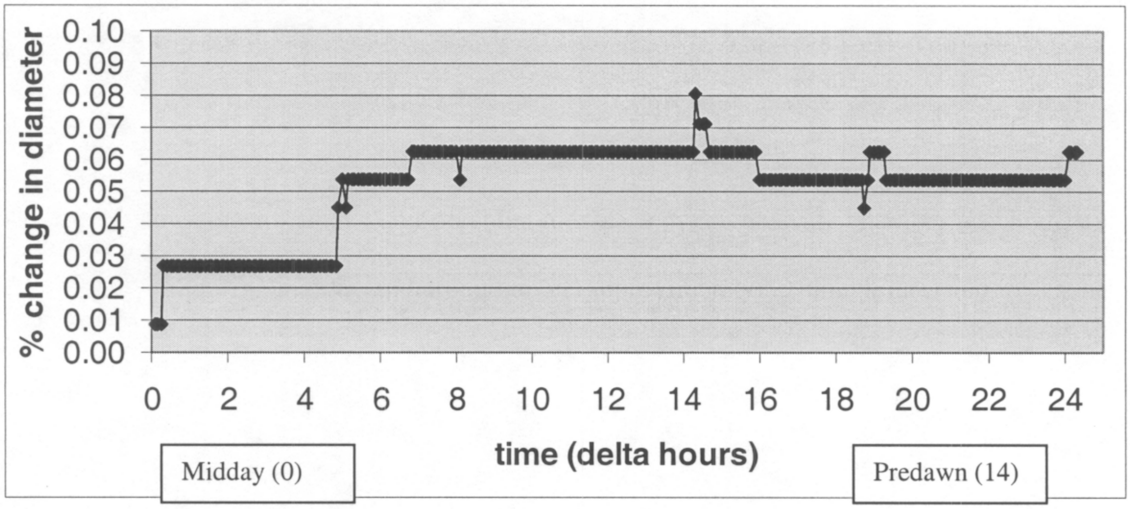


Figure 1.2: 4/4/01 Mean Trunk Diameter Change

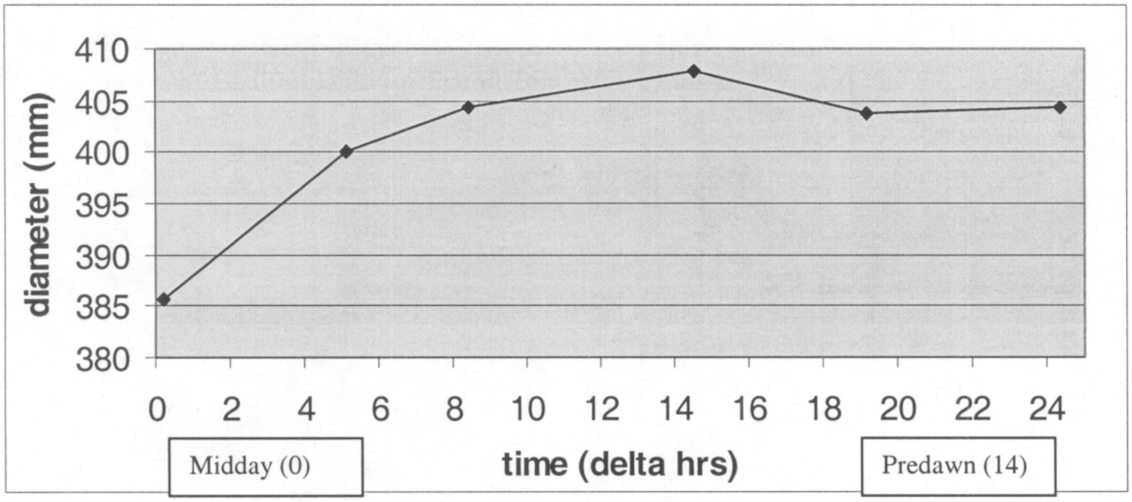
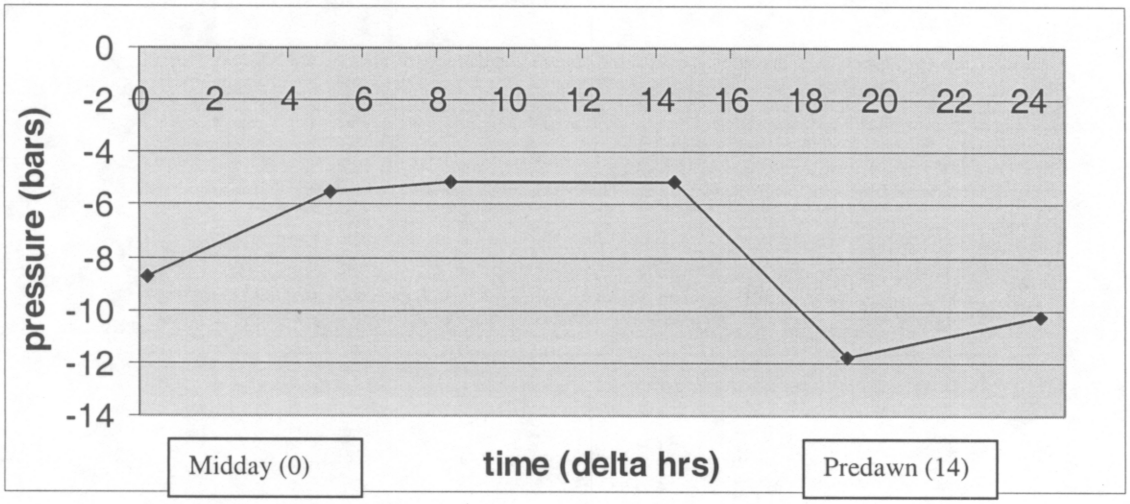


Figure 1.3: 4/4/01 Mean Xylem Water Potential Measured By the Pressure Chamber



Results for the second data set occurred on a sunny day, and are shown in Figures 2.1, 2.2, and 2.3. In Figure 2.1, most movement occurred just after predawn and from approximately noon (16 delta hours) to midday, with little movement prior to predawn. After predawn and prior to midday, percent diameter change appeared to be mostly increasing. The increase between noon and midday can also be seen in Figure 2.2. However, the increase after predawn did not appear during the sampling time represented in Figure 2.2. Figure 2.2 also shows that the smallest trunk diameter occurred approximately one hour prior to noon, though it appears in Figure 2.1 that battery failure or movement of the box may have also occurred at this time. The largest trunk diameter shown in Figure 2.2 occurred at approximately midday. The maximum daily percent change for April 15, 2001 ranged between –0.10% and 1.15%. Figure 2.3 shows mean xylem water potential measured by the pressure chamber was highest (more negative) during midday and around noon (approximately 16 delta hours) and lowest at predawn. The highest water potential value was –9.0 bars and occurred at approximately midday. The lowest water potential was –4.5 bars and occurred at predawn. Figure 2.3 also shows water potential decreased in the early evening until predawn and began increasing just after predawn until midday.

Figure 2.1: 4/15/01 Initial Data on Trunk Diameter Change

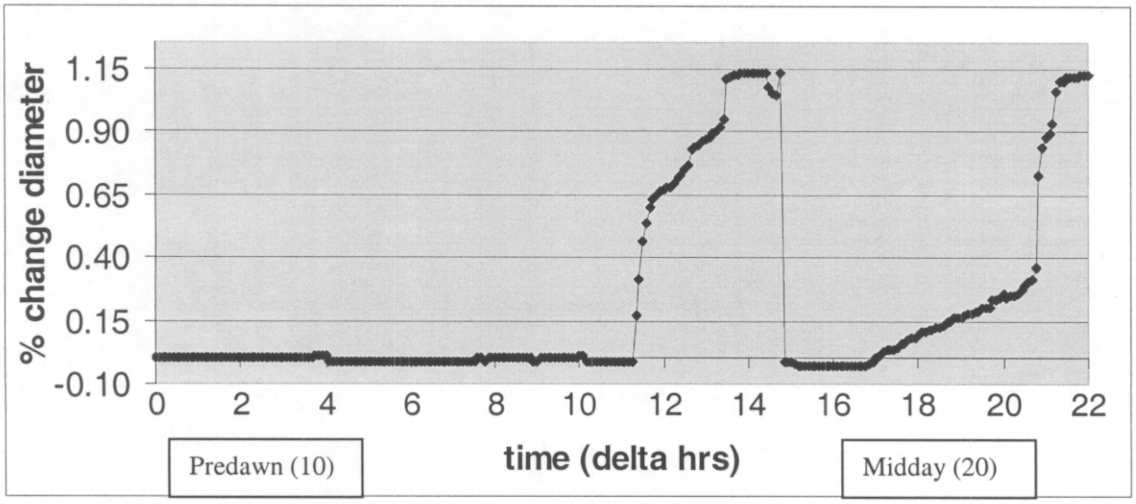


Figure 2.2: 4/15/01 Mean Trunk Diameter Change

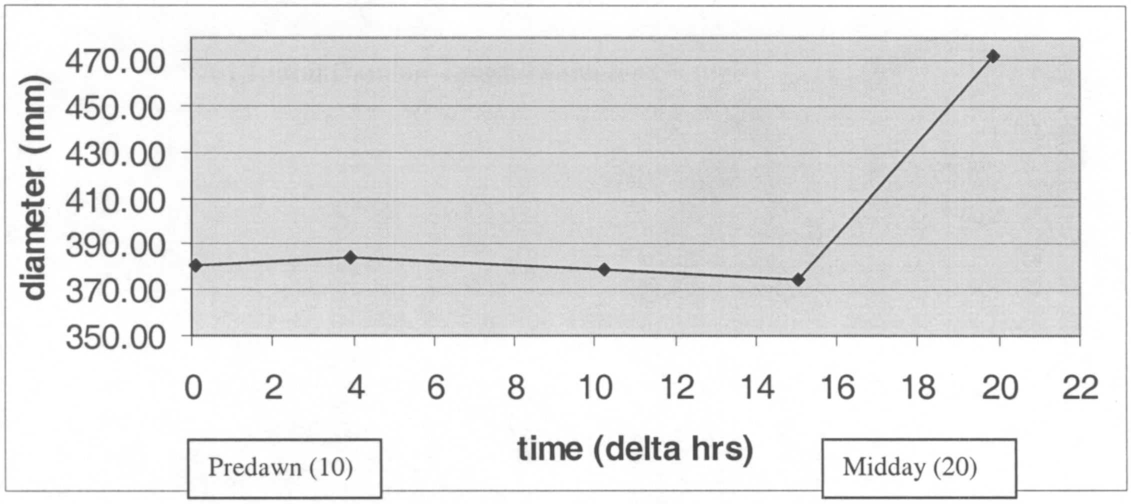
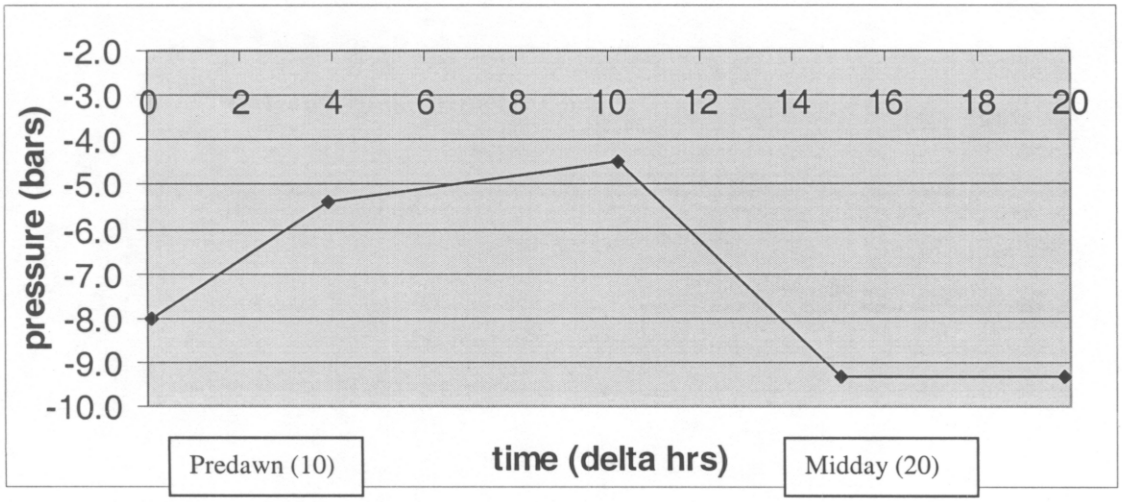


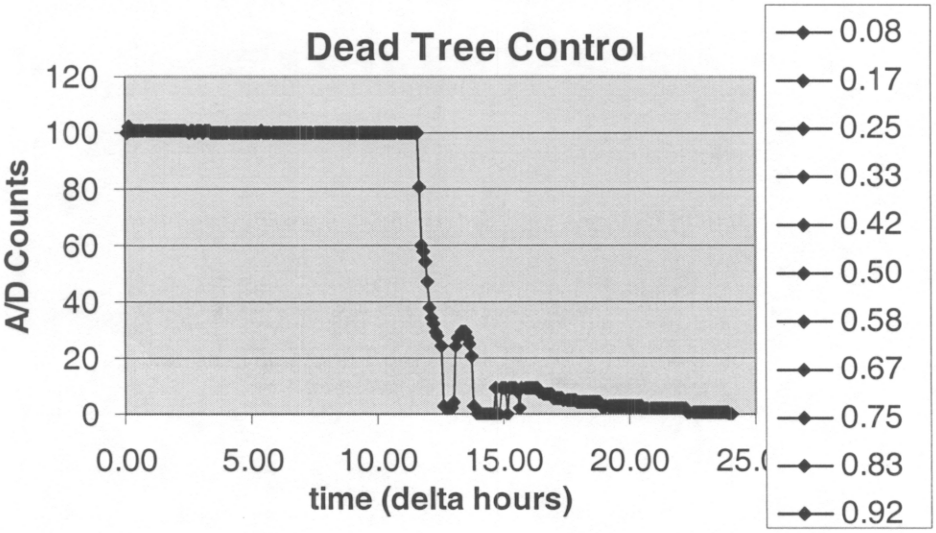
Figure 2.3: 4/15/01 Mean Xylem Water Potential Measured By the Pressure Chamber



My null hypothesis was that the data on xylem water potential measured by the pressure chamber was similar to data obtained by the strain gage instrument. Based on the graphs of the two for the first data set, I expected to see a correlation based on the similarity in patterns, while I did not expect to see a correlation on the second data set. No strong linear correlations between xylem water potential and strain gage diameter change were found for any of the either sampling days. On 4/4/01 R = 0.11, P<0.83; and on 4/15/01 R = 0.47, P<0.42. Therefore, I reject that the data obtained from the two methods are similar.

My second null hypothesis was that if there was no correlation between the pressure chamber method and the strain gage method, then data obtained by the strain gage instrument would be similar to temperature recorded. By looking at graphs of temperature change, I did not expect to see a correlation. The graph from April 24, 2001 for the dead tree control for temperature showed no change for the first 12.00 delta hours at which time it appears the battery failed (see Figure 3). This supports my alternative hypothesis that strain gage data does not reflect temperature change.

Figure 3: 4/24/01 Dead Tree Control for Temperature



Discussion

The earlier discussion on the cohesion theory of sap states that water must be pulled through the xylem by a tensile force generated by evaporation. After sunrise, stomata open to acquire carbon dioxide and draw water from the xylem into the surface of the leaf, which is then transpired into the atmosphere. During the night, the xylem draws water from the soil back into the trunk (Knops and Koenig, 2000). Therefore, we expect to see measurements of xylem water potential higher (more negative) in the day, during evapotranspiration, and predawn measurements to be lower (less negative). We also expect to see similar results with trunk diameter change, where the diameter of the trunk should reach minimum diameter near midday and maximum diameter at predawn.

In the graphs of xylem water potential, we do see that the lower values of water potential occurred at predawn and higher values of water potential occurred at midday on one of the sampling days, April 4, 2001, with most of the movement also occurring during these times. Similarly, we also see that the highest trunk diameter occurred at the point of predawn and the lowest around midday for this day. The same is true for the values obtained by the pressure chamber. These results then suggest that the strain gage is measuring movement in response to time of day and that this method may be feasible for the measurement of water potential. However, Figure 1.1 does not show us very much movement and the percentage change for this day was less than on the second data set. This may result from weather conditions being cloudy and cold on this day, while on April 15th it was sunny and warm.

It does not appear that the strain gage was detecting movement in response to time of day on April 15, 2001. The graphs for this day show that the largest trunk diameter occurred at midday and lower values occurred at predawn. This is the opposite of what I expected. Since the values for water potential obtained by the pressure chamber are what we expected, the values obtained by the strain gage method suggest they are not measuring water potential. However, there is evidence of some error in the percent change in trunk diameter shown in Figure 2.1. The sharp decrease that occurs at approximately 10:00am (14 delta hours) was probably due to a battery change that occurred at that time. My results from data collected indicate the battery probably failed some time shortly after predawn. Therefore, this data was omitted from Figure 2.2 and the linear regression analysis. The results from data collected also indicate the battery failed again only six hours following the first battery change and therefore, may be indicative of a loose wire or some other mechanical malfunction and it may be possible the increase in trunk diameter around midday may be due to error.

The results of the dead tree control showed no change in A/D counts, which supports the alternative hypothesis that trunk diameter change is not based on temperature. These findings indicate that the strain gage is not measuring temperature, however it is possible that it is measuring another variable not controlled, such as movement caused by wildlife, and in some cases movement of the instrument during pressure chamber sampling. Also, the lack of correlation between time of day and trunk diameter change for the second data set indicate more data is needed to rule out malfunction of the strain gage.

No strong linear correlations were found for xylem water potential or trunk diameter change for either of the sampling periods. There may be several explanations for the lack of correlation in the data. First, the strain gage may not be measuring diameter change, but instead may be measuring some other variable or movement, such as rodents climbing on the box. Insufficient data is probable, as greater points are needed for regression analysis. Improper setting of the trimpot value could cut off minimum and/or maximum values. Mechanical malfunction such as loose wires, battery failure, datalogger errors, improper screw adjustment or other technical or operational errors may have also occurred. A final explanation for the lack of correlation is the result of a species-specific physiological trait. For example, lichen present on *Quercus agrifolia* species, which holds water at the leaves for transpiration may affect the results.

Q. agrifolia also may acquire additional water at the leaves from fog moisture particles than absorbed through the soil. Therefore, further testing on alternate species may be necessary.

The results of graphs of diameter change versus xylem water potential for the first data set suggest that the strain gage instrument may be feasible for measuring diameter change as an indicator of xylem water potential. Additional testing is needed for stronger correlations. Results of the dead tree control support this by showing that the strain gage is not measuring temperature, but that some movement is being detected. General increases in diameter around midday and decreases at predawn on at least one data set also support further investigation. Further exploration and/or calibration may need to be done to ensure proper functioning of the instrument and adjustment as needed to prevent frequent battery failure. A final suggestion is to conduct measurements on several different species of oak, if in fact this is a species-specific trait, where correlation may be greater in other species with different water acquisition strategies.

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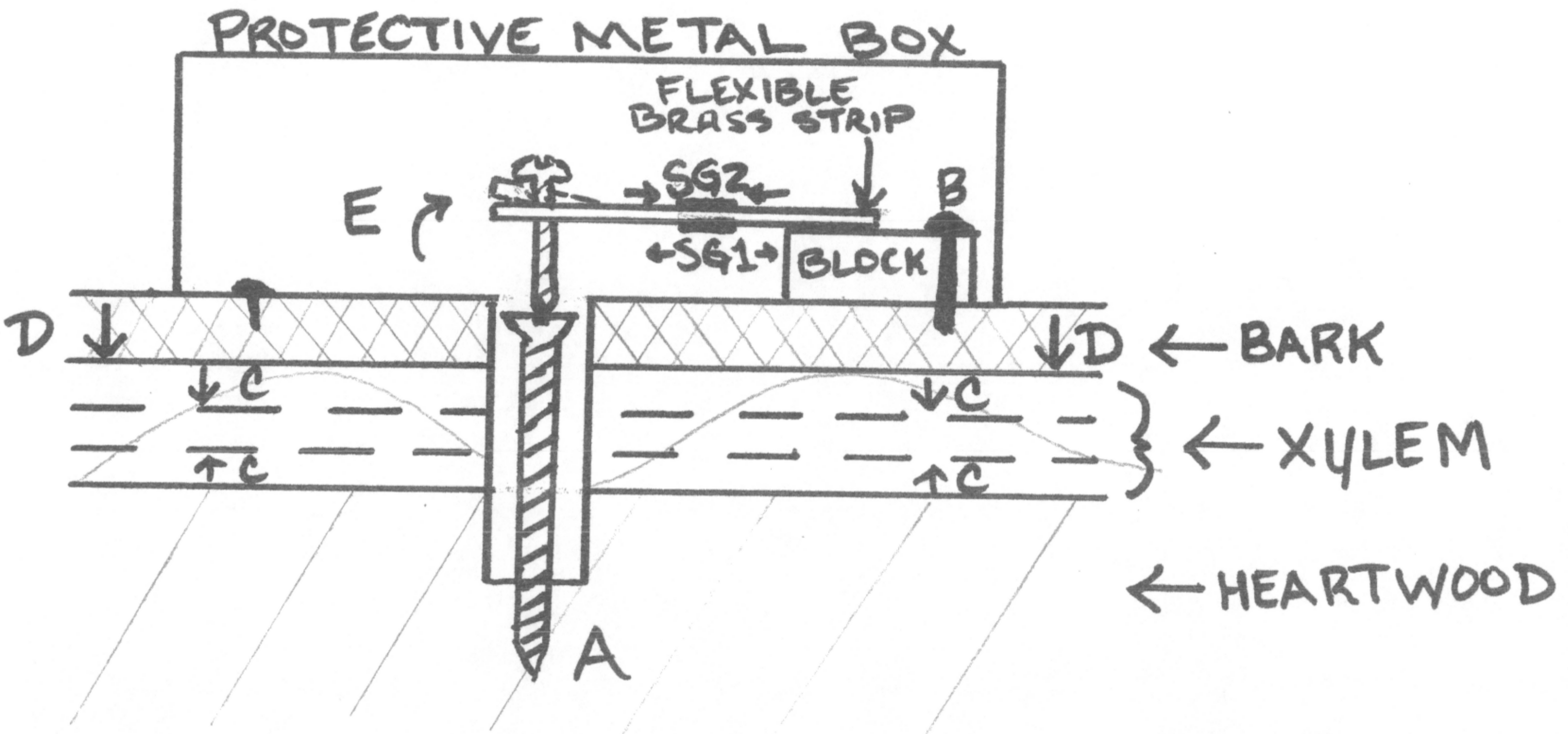
FIGURE 1: DIAGRAM OF INSTRUMENT
(PARTS NOT DRAWN TO SCALE)



A FLAT-HEADED SCREW (A) IS EMBEDDED INTO HEARTWOOD & REMAINS STATIONARY. TWO STRAIN GAGES ARE AFFIXED TO A THIN BRASS STRIP, ANCHORED TO AN ALUMINUM BLOCK (B). AS WATER IS PULLED INTO LEAF, XYLEM TISSUES SHRINK (C), SO THAT BARK ALSO SHRINKS (D). AS BOX DROPS, RELATIVE TO SCREW (A), PRESSURE IS APPLIED TO SMALL, ADJUSTABLE SCREW THROUGH BRASS STRIP. PRESSURE FORCES STRIP UPWARD (E). [redacted]

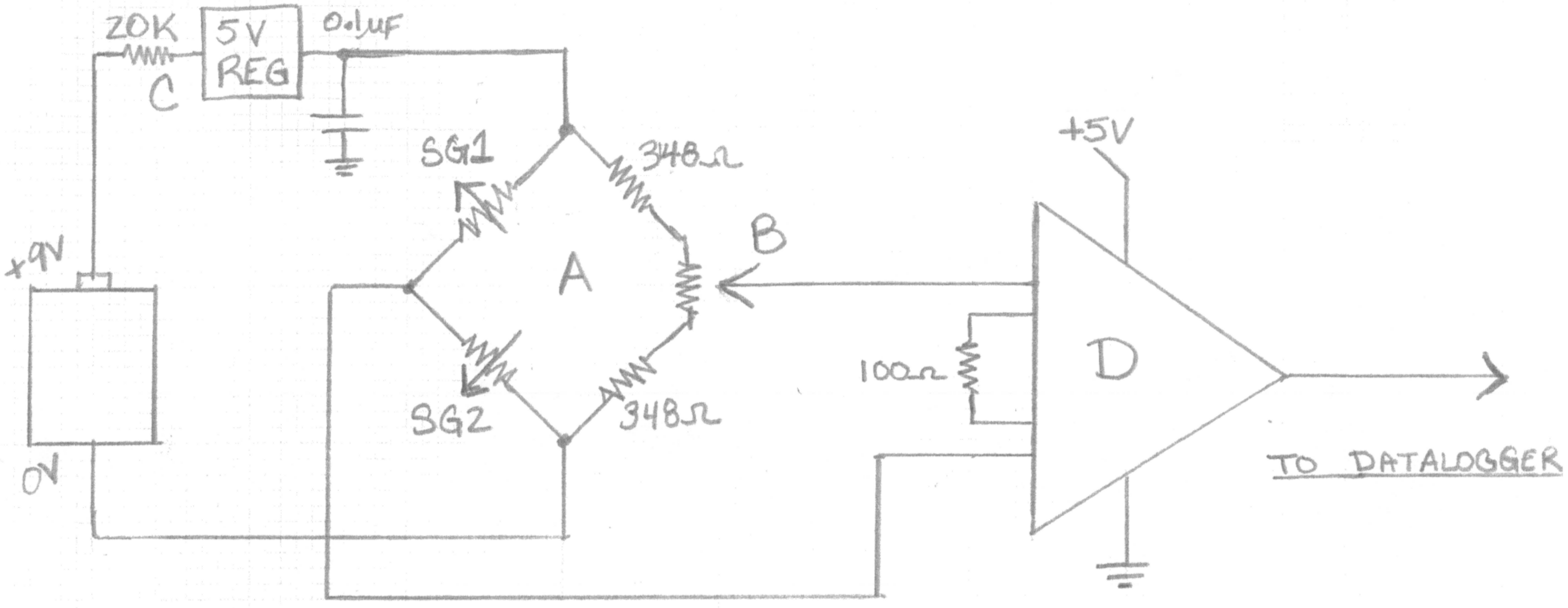


FIGURE 2: STRAIN GAGE CIRCUIT DIAGRAM