FINAL REPORT

DENDROMETER, DENDROGRAPH AND PHYTOGRAM CHARACTERISTICS OF DOUGLAS FIR AND SOUTHWESTERN WHITE PINE IN THE RINCON MOUNTAINS

submitted to

THE FRANKE FOUNDATION
AARBURG, SWITZERLAND

by

W. Gensler
AGRICULTURAL ELECTRONICS CORPORATION
TUCSON, ARIZONA, USA

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TABLE OF CONTENTS

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The genesis and purpose of the project are the work of Walter Franke. He recognized the strength of interdisciplinary scientific analysis and constantly kept sight of the objective. He supplied the funding but also entered into a detailed understanding of the measurement systems

EXECUTIVE SUMMARY

INTRODUCTION In a previous study, the PHYTOGRAM technique has been shown to supply a quantitative scale of health, the anthropogenic impact of sulfur and the pathogenic impact of root rot. The scale can also be used to determine the magntitude of drought stress. The question has arisen as to the relation of the electropotential and PHYTOGRAM indices to other measurement techniques used in forest science. One such technique is the short and long term analysis of tree radius. Changes in tree radius arise on a daily and seasonal time scale due to the hydration/rehydration cycle. An annual biomass increment is measured by the size of the "tree ring." There are daily, seasonal and multi year patterns in the PHYTOGRAMs. This leads to the specific question of the correlation of the PHYTOGRAM patterns with the tree radius patterns.

OBJECTIVE The determination of the correlation between the PHYTOGRAM patterns and the tree radius patterns on a daily, seasonal and annual time scale. A secondary objective is the determination of the presence and extent of anthropogenic and natural impacts at the site under investigation.

SITE SELECTION AND METHOD The site of the investigation was an interwoven stand of Douglas fir and southwestern white pine on the north slope of the Rincon Mountains in Southern Arizona. The method was to install manual dendrometers, automatic dendrographs and PHYTOGRAM electrodes on an interwoven stand of Douglas fir and southwestern white pine. The automatic dendrographs and the potential of the electrodes were measured every fifteen minutes. The manual dendrometers were measured when personnel were at the site. This combination of chemical and physical measurements permits the correlation between potential and radius to be made on both a short and long term basis.

Forty three manual dendrometer readings were installed in August and measured in October, 1989, February and June, 1990. Twenty-four automatic dendrographs became operational in October, 1989. Forty-three PHYTOGRAM electrodes were installed in October, 1989 but became operational in February, 1990.

RESULTS All trees at the site contracted in radius between October and February. Between February and June, seventeen out of forty-three trees expanded. Between October and June, four out of forty-three trees showed a net expansion. The magnitude of the seasonal radius change due to the hydration/rehydration cycle is

dominant in any measurement of tree radius at this site. Tree contraction for only a part of the cycle can be as high as 1100 micrometers. The radius change is not correlated with tree age and tree radius.

The potential change and radius change showed an excellent correlation in the matter of "when" the response occurred. The response of radius and potential was virtually simultaneous.

The magnitude and direction of the potential response was not uniform with regard to the magnitude and direction of the radius response. There were two groupings of responses corresponding to the two extreme phase patterns of the potential diurnal cycle. This indicates a wide variation in the water status of the trees at the site. It also necessitates an analysis of the trees on an individual basis before further generalizations can be made.

DISCUSSION AND CONCLUSIONS The dominant mechanism in the determination of changes in radius is the seasonal hydration/dehydration cycle. The trees at the site are under a drought stress which was not relieved by the snowmelt in the spring of 1990. Weather disturbances have a strong influence in changes in radius. Diurnal changes, while intrinsically interesting, are not significant in relation to weather disturbances and seasonal variations.

There is an excellent correlation between radius change and potential change with regard to the timing of the change. But the question of "how much" and "in what direction" requires further analysis of the present data set and additional data from this site. This problem is to be expected because of the age and species differences and the variable drought stress intrinsic in the present data set.

It is not possible to determine the impact of airborne pollutant within the present data set because of the dominance of the drought stress effects.

INTRODUCTION AND STATEMENT OF OBJECTIVE

INTRODUCTION

In recent years a substantial decline has occurred in the forests of western Europe. The cause of this decline has been the subject of intense investigation. It has become evident as a result of these and concomitant studies in North America that the problem is very complex and involves the interaction of chemical, physical and biological factors in the soil-atmosphere continuum.

In a previous study, the PHYTOGRAM technique has been tested to determine if it can be used as a quantitative scale of health and the anthropogenic impacts which are believed to be the cause of this decline. The technique is based on the use of invasive electrochemical sensors placed in the tree tissue for indefinite periods. The potential patterns derived from these sensing electrodes, termed PHYTOGRAMS, are distilled into daily indices of tree status. The study indicated that the PG11 and PG12 indices will yield a quantitative measure of the anthropogenic impact of sulfur, the pathogenic impact of root rot and naturally occurring drought stress.

The use of electrochemical sensors is quite new. The question has arisen as to the relation of the PHYTOGRAM characteristics and the electropotential to other techniques presently used in forest science. Although the potential and the indices can be empirically determined from field measurements without recourse to physiological interpretation, the physical and chemical chain of causality associated with the electropotential would enhance the use of the indices in quantifying forest health.

This brings into focus two questions: what is the relation of the PHYTOGRAM to other measurements made in forest science and what is the physical and chemical basis of the electropotential patterns.

One technique widely employed in forest science is the analysis of tree rings. While the emphasis in many cases of tree ring analysis is to determine long term patterns of climate, the tree rings can be analyzed to determine short term growth of particular sites. A second physical technique is the measurement of circumference by manual means with dendrometers or automatically with dendrographs. Circumference measurements are employed because they provide an integrated measurement of the change in the radius of the tree main stem without the necessity of extrapolating from a measurement at a single point on the perimeter.

There are three variations in time scale that must be considered in the measurement of circumference: diurnal, seasonal and annual. During the diurnal time period the main stem will expand and contract due to the inherent intake and extake of water from the tissue of the sapwood, cambial zone and phloem. At the seasonal time scale the tree will decrease in circumference in response to periods of drought. Rehydration comes with rains in particular seasons. The annual time scale is in the order of one year or more. In this time scale there is a net biomass increase customarily referred to as the size of the tree ring. Any change in circumference is the superposition of the diurnal cycle, the seasonal cycle and the biomass increment.

In like manner, the PHYTOGRAM can be viewed in terms of three times scales. There is a diurnal potential pattern, a seasonal potential pattern and a multi year potential pattern.

From the viewpoint of time scales, the question becomes the relation of the electrochemical patterns of the PHYTOGRAM to the physical patterns of the tree circumference.

STATEMENT OF OBJECTIVE

The objective of this project is to determine the correlation between the PHYTOGRAM electropotential patterns and the main stem circumference patterns on a daily, seasonal and annual time scale.

The second objective is the examination of the patterns to determine the magnitude and type of impact and/or stres which may be present at the test site.

II. SITE SELECTION AND METHODS

The Rincon Mountains in Southern Arizona were selected because of their proximity to Tucson and the presence of mixed native stands of species believed to be sensitive and insensitive to airborne pollutants. On the north slope of the Rincon Mountains sensitive Douglas fir and relatively insensitive southwestern white pine exist side by side in a location which overlooks Redington Pass. Visual observation attests to the presence of airborne sulfur emissions from the San Pedro Valley coming through the pass about 800 meters below the site. In addition, tree ring data from the site suggests an influence of airborne pollutants in the area.

Trees of widely different age were present at the site. This permitted simultaneous analysis of species and age differences. The site is quite remote and has no human encroachment. The site has good drainage and normal soil and moisture conditions for a site of this aspect.

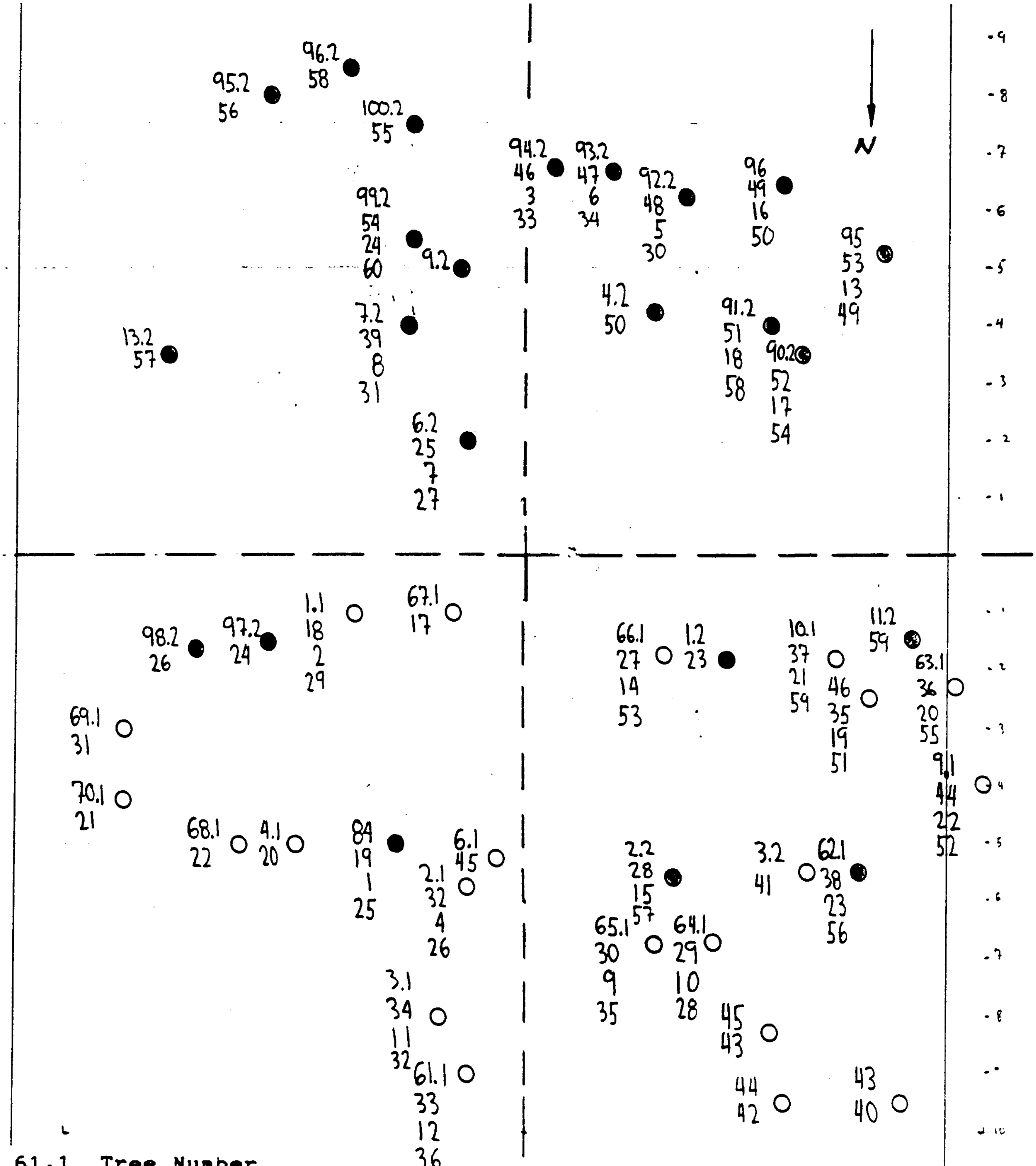
The site, shown schematically in figure 1, is divided into four quadrants with the data acquisition PODs at the center. The basic approach was to install manual dendrometers and PHYTOGRAM electrodes on twenty-one Douglas fir and twenty-one southwestern white pine. In addition, twelve automatic dendrographs would be installed on each species. This permits the simultaneous measurement of the two species by the three techniques under the same ecological conditions. Tree selection within the site was guided by an attempt to obtain a wide variety of ages from each species.

Each particular measurement approach will now be considered in detail.

CIRCUMFERENTIAL DENDROMETERS

The dendrometer consisted of a 3.17 mm wide 0.051 mm thick band made of Hastalloy C276 (Teledyne-Rodney, Pico Rivera, CA) wrapped around the main stem at breast height and attached at the two ends to a well type readout. The latter consisted of two spring loaded concentric brass tubes which slid within each other as the tree expanded or contracted. The readout of the movement of the inside tube was by means of a Brown and Sharpe Digit-Cal plus Universal Digital Caliper, Model #599-571-3. Intrinsic caliper accuracy was plus and minus five micrometers in circumference. Each dendrometer was read three times and the results averaged. The results of this averaging was a reading good to within plus or minus twenty

Figure 1. Schematic Layout of the Site. The Dendrograph and PHYTOGRAM PODs are located at the center of the diagram. The slope of the hill is from the south down to the north. A shallow wash is located just east of the POD. The scale of distance is approximately forty meters to the outermost tree from the PODs. Circles which are filled in are Douglas fir, circles which are open are southwestern white pine.



61.1 Tree Number
33 Electrode Wire Number
12 LVDT Channel Number
36 LVDT Wire Number

micrometers of the average reading. The coefficient of linear expansion of the Hastalloy C276 was 12.42 micrometers /meter/degree centigrade. The band was held by three stainless steel compression springs in series. The spring rate of each spring was 0.394 N/mm (Associated Spring C0240-024-2000-S). Typical tension on the spring was approximately 10N. The circumference itself was measured with a conventional manual tape in June of 1990.

Relations between differential volume, circumference and radius are

$$\frac{dV}{V} = \frac{2\,dC}{C} = \frac{2*dR}{R} \qquad (1)$$

$$\frac{dV}{L} = \frac{C\,dC}{2*3.14} \qquad (2)$$

$$\frac{dV}{C*L} = \frac{dC}{2*3.14} = dR \qquad (3)$$

where V is the volume, C is the circumference, R is the radius and L is the vertical length, all in metric units. Equation 1 is a measure of the percent biomass change relative to the existing biomass. Equation 2 is a measure of absolute biomass change. This relation yields the incremental value used in the forestry community on an annual basis. Equation 3 is a measure of the biomass change per unit surface area.

AUTOMATIC DENDROGRAPHS

The automatic dendrographs employed linear variable differential transformers (LVDT) as the displacement sensor. The LVDT's were mounted on a brass housing which permitted attachment of the invar band both to the housing and the core of the LVDT. Resolution of the sensor was 4 micrometers with an unadjusted range of 16000 micrometers and an adjusted range of 45000 micrometers.

The band on the automatic dendrographs was located no more than 25 centimeters from the manual dendrometer band. The sensors themselves were widely spaced on the perimeter of the trunk to minimize any interaction during data readout and maintenance.

The band was spring loaded with a compression spring (Associated Spring #C0300-032-2500-S) with a spring rate of 0.642 N/mm. The tension of the spring was approximately ten to fifteen newtons. Band dimensions were the same as the manual dendrometers. The only difference in the two bands was the material. The invar has a coefficient of linear expansion of 1.44 micrometers per meter per degree centigrade between -1 and 100 degrees centigrade.

There are three sources of variation of the tree radius: biomass increment, diurnal hydration/dehydration cycle and seasonal hydration/dehydration cycle. The biomass increment is the increase in tree size over the long term. It is essentially wood production. The diurnal hydration/dehyration cycle is the short term twenty-four hour changes in tree radius due to movement of water into and out of the band region. The seasonal cycle is the same type of phenomenon, that is, a water related process. In this case the time scale of the change is months. The magnitude of each of these changes is not well documented in the literature and must be determined for the particular site under analysis.

PHYTOGRAM

The placement of the electrodes began with a removal of a square of bark a maximum of 25 mm by 25 millimeters in area. This area varied with the thickness of the bark. The thinner the bark, the smaller the area. The bark was removed down to the cambium. The location of the cambium was easily discerned because of the hard more radial woody tissue just past the cambium. The electrode was slid horizontally a distance of at least one to two centimeters along the cambium.

If the insertion was proper, there was virtually no resistance to the movement of the electrode. This length of contact insured that the electrode was located in normal tissue as opposed to any scar tissue that would build up at the bark removal perimeter. The electrode and exposed cambium was then covered with tar right up to the insulation of the metal. This yielded an sealed surface and at the same time strain relieved the electrode lead wire.

The electrode was soldered to the lead wire just before insertion in the field. Moisture resistant (tefzel) lead wire, #24 gauge was used throughout.

Two reference electrodes were buried within no more than one half meter of the POD and at least fifty centimeters deep. These electrodes were connected to pins 16 and 60.

Pin 15 was used for a light sensor A thermistor temperature sensor was connected to pin 16. The thermistor was mounted in a tree approximately two meters off the ground.

The forty-three measuring electrodes, the temperature sensor, the two reference electrodes and the POD battery were monitored every fifteen minutes. The measurements were made, for example, at 1400, 1415, 1430 and 1445 hours. At 1446 the four acquisition values were averaged and the one hour average stored in the POD memory as the potential at 1400 hours. Mountain standard time was used throughout at all times and at all sites. There were 4608 measurements made at each site on each day.

Data was stored in the POD memory and transferred periodically (at least every 108 days) to a portable computer. The data was then transferred to a desktop computer for processing.

The manner in which the particular electrodes were tested for proper insertion and wire continuity evolved during the testing period. The method arrived at consisted of the transfer of charge from the capacitor at the electrode-tissue interface to an external capacitor of known size. The magnitude of this charge transfer gave a very reliable indication of the continuity of the electrochemical circuit.

There are three ranges of potential. The normal range is from 300 to 700 millivolts relative to the standard hydrogen electrode. The potential exhibits a diurnal periodicity consisting of a rise in the morning hours to an afternoon plateau, then a decline in the late afternoon and early evening. This decline in potential ensues until dawn at which time the potential rises once again. The hypo-potential range extends from about zero to 400 millivolts. This range is entered when the plant is subjected to very wet conditions. Residence in this range is usually transitory, but under sustained wet soil, the potential will remain at these low levels. The hyper-potential range is characterized by very high potentials. Movement into and out of this range is very rapid and gives rise to the term "spiking." This range is entered only under special conditions which consist of a relatively specific combination of temperature and light. The potential characteristics in each zone have been related to environmental changes on a purely empirical basis without recourse to a knowledge of the underlying electrochemical reactants.

Empirical observations and in vitro experiments have given rise to the "Oxygen Hypothesis." Under this hypothesis, the potential is a measure of the oxygen concentration in the extracellular fluid. An increase in oxygen consumption in the mitochondria within the cell cause a movement of oxygen into the cell and a subsequent decrease of oxygen in the extracellular region. This causes a decrease in measured potential. Conversely, an increase in the potential is an indication of an increase in the oxygen concentration. The observed diurnal periodicity in potential is a manifestation of an oxygen replenishment/usage cycle. Under the oxygen hypothesis, the lower the potential, the lower the oxygen concentration. This implies that it is possible to reach a state wherein the oxygen is for the most part depleted. This corresponds to entry into the hypo-potential zone or anaerobic zone. The hypothetical dominant reactant in this zone is the ethanol-acetaldehyde couple. In other words, the plant shifts into a respiration mode dominated by this reaction. Empirically, one observes entry and subsequent residence in this zone under very wet soil conditions.

While movement within the normal and anaerobic zones can extend over indefinite periods, residence in the hyper-potential zone is almost always a daytime phenomenon and only occurs under the specific conditions of relatively low predawn and early morning temperatures concomitant with a high light level. This empirical observation plus the very high measured values in the scale of biological reactants has led to one possible hypothesis, namely, the causative reactant is hydrogen peroxide. The proposed mechanism is as follows: under sunny conditions, the photosynthesis reaction produces a stream of electrons. This stream is normally consumed by the NADP-NADPH reaction. But under low temperature, this energy sinking reaction is inhibited. The electron stream is channeled into the formation of super oxide radicals which are immediately converted into peroxide. This peroxide diffuses out of the cell and is measured by the electrode. The potential spike normally begins several hours after dawn. This is presumably the time required for the peroxide to diffuse from the generation regions to the surface of the electrode. The dissipation and conversion of peroxide is completed by late afternoon. This hypothesis will be examined in the data sets taken during this study.

INDEX FORMATION

The characteristics of the PHYTOGRAM has led to the formation of distillation algorithms whereby the hourly data taken from each channel each day is converted into a single daily index. In the case of the respiratory activity index, empirical results from various parts of the North American Continent and on different plant types has led to the following algorithm:

PG11 Index = (725 - Minimum Daily Potential)

High values of the PG11 index are indicative of high utilization levels, low values are indicative of low utilization levels. The 725 millivolt value is considered a zero utilization potential, that is, the potential at which the oxygen utilization level is an "absolute" minimum. The units of this index are millivolts. For example, if the minimum potential of a particular electrode during a twenty-four hour period is three hundred millivolts, the PG11 index is 725-300 or 425mV for that particular electrode for that particular day. The index can then be extended to multiple electrodes and over longer periods of time.

A second index was formed from the data set. The autotoxicity index is based on the following algorithm:

PG12 Index = (Potential-725)*(Time above 725 mv, hours)*0.1

As the excursion above 725 millivolts is greater and of longer duration, the index is greater. If the potential does not rise above 725 millivolts, the index is zero. This index is duration and magnitude sensitive. The units of this index are millivolt-hours. For example, if the potential of a given electrode was below 725 millivolts for a twenty four hour period with the exception of two hours during which the potential was 1000 millivolts, the PG12 index is (1000-725)*2*0.1 or 55 mVh. This index addresses the question of "how high was the potential above 725 millivolts and for how long". Both indices can be applied to the individual electrode or to the site as a whole. Both indices are determined each day over the twenty-four hour period beginning at midnight. Fortunately, the two indices are independent since the minimum in potential occurs almost always during the early morning hours while the hyper-potentials are present only during the daylight hours.

The data will be analyzed at three time scales: monthly, daily and hourly. In a monthly time scale the average value of the PG11 and PG12 indices are determined for thirty day intervals during the year. In the daily time scale, the average values of the two indices are graphed for each day in selected months. In the hourly time scale, the hourly potentials from individual electrodes are graphed.

Table I gives a summary of the tree characteristics, the PHYTOGRAM electrode number and the dendrograph number. Table II gives the dendrograph POD terminal number and function. Table II gives the PHYTOGRAM POD terminal number and function.

TABLE I

SENSOR DESIGNATIONS, TREE TYPE, AGE AND SIZE

PHYTOGRAM POD PIN#	LVDT CHNL #	TREE#	SWP-1 DF-2 SPECIES	INNER-MOST YEAR	AGE YEARS	RAD CHGE OCT89-JUN90,MM	MEASURED BY NPS RAD,CM
17		67.1	1	1931	59	-0.39	10.05
18	2	1.1	1	1920	70	-0.33	14.25
19	1	84.0	2	1791	199	-0.47	49.04
20		4.1	1	1944	46	0.09	7.61
21		70.1	1	1896	94	-0.20	23.89
22		68.1	1	1909	81	-0.21	16.88
23		1.2	2	1924	66	-0.62	16.88
24		97.2	2	1808	182	-0.53	53.68
25	7	6.2	2	1959	31	0.20	7.01
26		98.2	2	1843	147	-0.48	42.99
27	14	66.1	1	1856	134	-1.37	19.90
28	15	2.2	2	1955	35	0.32	7.20
29	10	64.1	1	1926	64	-0.59	14.46
30	9	65.1	1	1913	77	-1.12	21.97
31		69.1	1	1899	91	-0.50	15.30
32	4	2.1	1	1945	45	-0.22	6.70
33	12	61.1	1	1931	59	-0.35	19.59
34	11	3.1	1	1944	46	-1.03	8.06
35	19	46.0	1	1889	101	-0.76	26.43
36	20	63.1	1	1892	98	-0.56	21.34
37	21	10.1	1	1948	42	-0.39	5.05
38	23	62.1	1	1860	130	-0.02	21.97
39	8	7.2	2	1969	21	-0.03	3.98
40		43.0	1	1853	137	-1.25	28.82
41		3.2	2	1954	36	0.17	10.00
42		44.0	1	1873	117	-1.08	24.68
43		45.0	1	1805	185	-1.44	29.94
44	22	9.1	1	1950	40	-0.69	6.56
45		6.1	1	1920	70	-0.90	5.35
46	3	94.2	2	1911	79	-0.13	28.66
47	6	93.2	2	1909	81	-0.14	20.86
48	5	92.2	2	1922	68	-0.62	23.57
49	16	96.0	2	1766	224	-0.35	58.98
50		4.2	2	1943	47	-0.44	11.00
51	18	91.2	2	1896	94	-0.73	32.17
52	17	90.2	2	1871	119	-0.56	34.87
53	13	95.0	2	1849	141	-0.20	39.65
54	24	99.2	2	1942	48	-0.19	15.46
55		100.2	2	1935	55	-0.18	17.52
56		95.2	2	1909	81	-0.57	33.44
57		13.2	2			-0.24	9.06
58		96.2	2	1916	74	-0.70	28.98
59		11.2	2			-0.37	29.30

Table II

Terminal Designations for the LVDT POD

Terminal Number	Function
1	RS 232
2	RS 232
3	Power Grd
4	Power Grd (Solar Low)
5	Reset
6	Temperature Sensor Input
7	Light Sensor Input
8	Solar High
9	Spare
10	Spare
11	Light Sensor Grd
12	Light Sensor High
13	LVDT Primary (Red/Yel)
14	LVDT Primary (Red/Yel)
15	LVDT Primary (Red/Yel)
16	LVDT Primary (Red/Yel)
17	LVDT Primary (Red/Blk)
18	LVDT Primary (Red/Blk)
19	LVDT Primary (Red/Blk)
20	LVDT Primary (Red/Blk)
21	Common (Blk)
22	Common (Blk)
23	Common (Blk)
24	Common (Blk)
25	LVDT Secondary, Relates to 13 and 17, (Red)
26	LVDT Secondary, Relates to 14 and 18
27	LVDT Secondary, Relates to 15 and 19
28	LVDT Secondary, Relates to 16 and 20
29	LVDT Secondary, Relates to 13 and 17
30	LVDT Secondary, Relates to 14 and 18
31	LVDT Secondary, Relates to 15 and 19
32	LVDT Secondary, Relates to 16 and 20
33	LVDT Secondary, Relates to 13 and 17
34	LVDT Secondary, Relates to 14 and 18
35	LVDT Secondary, Relates to 15 and 19
36	LVDT Secondary, Relates to 16 and 20

37	LVDT Primary (Red/Yel)
38	LVDT Primary (Red/Yel)
39	LVDT Primary (Red/Yel)
40	LVDT Primary (Red/Yel)
41	LVDT Primary (Red/Blk)
42	LVDT Primary (Red/Blk)
43	LVDT Primary (Red/Blk)
44	LVDT Primary (Red/Blk)
45	Common (Blk)
46	Common (Blk)
47	Common (Blk)
48	Common (Blk)
49	LVDT Secondary, Relates to 37 and 41, (Red)
50	LVDT Secondary, Relates to 38 and 42
51	LVDT Secondary, Relates to 39 and 43
52	LVDT Secondary, Relates to 40 and 44
53	LVDT Secondary, Relates to 37 and 41
54	LVDT Secondary, Relates to 38 and 42
55	LVDT Secondary, Relates to 39 and 43
56	LVDT Secondary, Relates to 40 and 44
57	LVDT Secondary, Relates to 37 and 41
58	LVDT Secondary, Relates to 38 and 42
59	LVDT Secondary, Relates to 39 and 43
60	LVDT Secondary, Relates to 40 and 44

Table III

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ile: Pinlist2.doc
.************************************************************************-
'**       COMPONENT CROSS REFERENCE: 1989 SYSTEM
'
'
'     POD TERMINAL                                         SPECIAL FUNCTION
'      *                                                         *
'      *       ANALOG BOARD EDGE CONNECTOR                       *
'      *                                                         *
'      *       *                                   ADC TEST      *
'      *       *      DATA CHANNEL                 VOLTAGE (mv)  *
'      *       *      *                                 *        *
'      *       *      *      SOFTWARE ADDRESS           *        *
'      *       *      *      *                          *        *
'      *       *      *      *      RELAY NUMBER        *        *
'      *       *      *      *      *                   *        *
'      *       *      *      *      *     RELAY BANK    *        *
'      *       *      *      *      *      *            *        *
'      *       *      *      *      *      *            *        *
'      *       *      *      *      *      *            *        *
'      *       *      *      *      *      *            *        *
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POD TERMINAL	ANALOG BOARD EDGE CONNECTOR	DATA CHANNEL	SOFTWARE ADDRESS	RELAY NUMBER	RELAY BANK	ADC TEST VOLTAGE (mv)	SPECIAL FUNCTION
3&4	1&2						PWR GROUND
8	3&4						SOLAR INPUT
9,10, 11,12	11						INSTR GRD
6	12						SPARE
2	7&8						RS-232-IN
1	9&10						RS-232-OUT
5	5						*RESET
7	6						SPARE
17	19	31	9F	15	1	- 70	
18	20	15	8F	15	0	+ 160	
19	17	30	9E	14	1	- 60	
20	18	14	8E	14	0	+ 150	
15	15	29	9D	13	1	- 50	
16	16	13	8D	13	0	+ 140	
13	13	28	9C	12	1	+ ??	BAT. VOLTAGE
14	14	12	8C	12	0	+ 400	EXT. TEMP.
25	27	24	98	8	1	- 10	
26	28	8	88	8	0	+ 90	
27	25	25	99	9	1	- 20	
28	26	9	89	9	0	+ 100	
21	23	26	9A	10	1	- 30	
22	24	10	8A	10	0	+ 110	
23	21	27	9B	11	1	- 40	
24	22	11	8B	11	0	+ 120	
36	35	17	91	1	1	+ 180	
35	36	1	81	1	0	+ 20	
34	33	16	90	0	1	+ 170	
33	34	0	80	0	0	+ 10	
29	31	22	96	6	1	+ 230	
30	32	6	86	6	0	+ 70	
31	29	23	97	7	1	+ 240	
32	30	7	87	7	0	+ 80	

RESULTS

Before any presentation of the results is made it is important to understand just when the various measurement systems became operational and the duration of each data set. The manual dendrometers and automatic dendrographs were installed on the trees in August of 1989. The first measurement of the manual dendrometers was made on 12 October, 1989. Two further measurements of the manual units were made on 11 February and 7 June, 1990. There have been three measurements of the manual dendrometers up to 25 June 1990. Although the automatic dendrographs were installed in August, the units were not set at a base point until October 1989. Data from this instrument is valid from this point onward. Unfortunately, the settings of the automatic units were based on the assumption of a positive change (biomass increment) in circumference. The trees however, contracted from this initial setting, thereby moving the dendrographs past the negative limit to their range. For this reason much of the data from the automatic units is off-scale.

The PHYTOGRAM electrodes were inserted in October of 1989. Loss of electrical energy in the POD curtailed data collection until February of 1990. At this time acquisition began and continued until June of 1990.

This sequence of events has led to a relatively limited data set on which to base the correlation analysis. Concurrent data for the automatic dendrographs and the PHYTOGRAMs exist for particular electrodes from day 60 to day 122. The correlation analysis in this report is based on this time interval.

There have been several animal interactions at the site. A bear caused extensive damage to the dendrograph POD prior to the October trip. The site was repaired during the October trip to the site. Rodents cut the wires in several places since October. The broken wires were repaired during the June 89 trip.

The data in the graphs which will be presented have not been adjusted for temperature variations in the band and terminal materials. The influence of temperature is not significant except circumference shifts under about twenty micrometers. All potentials described in this report are with respect to standard hydrogen. The bias level used in this report to convert from the measured potentials to the standard scale is 240 mV.

In the following presentation, the phrase "50 years old" or "104 years old" refers to the inner date as determined by tree ring analysis. The actual birth of the tree is probably about twenty years before this date.

MANUAL DENDROMETERS

Table IV gives the radius changes using the radius on 12 October as a base. Figure 2 gives the location of the trees that elicited a positive increase in circumference in the period from October, 1989 to June, 1990. Figure 3-8 gives the summary of the October to February change and the February to June change and finally the October to June change. Figure 3-5 are radius change against age and figures 6-8 are radius change against radius. The distribution indicates that all the trees experienced a decrease in radius between October and February. From February to June, seventeen out of forty-three trees expanded. Overall, from October to June, only four trees had a positive change in radius. These were all young trees. The plot of radius change against radius indicates trees of widely different size experienced a contraction.

Figure 2 indicates that fourteen of the seventeen trees eliciting a positive increase in stem diameter during the period from February to June of 1990 were Douglas fir. This would indicate that some combination of the hydration\dehydration cycle and biomass increment caused the positive change during this time interval. It may be possible to determine the proportion of each of these contributions with an examination of the automatic dendrographs.

AUTOMATIC DENDROGRAPHS

Figure 9 and 10 illustrate an example of the radius of a young tree over a period of six months. The values from day 220 to day 285 are considered random and should be disregarded. The sharp change in value to a radius of -1000 micrometers on day 285 is the setting of the base point during the October trip. From this day onward, the data is valid. The young tree moved gradually in the negative direction through the fall with a sharp drop in size around day 331. This response corresponded to a very cold period. The tree expanded on day 337 and then remained the same size until day 342 when a second contraction occurred. There was a brief recovery from this response.

Figure 10 shows the tree at a level of contraction that yielded an off scale reading until day 104 when the tree was in the midst of a steady expansion. The expansion continued at a steady rate until day 113 when a sudden cold front moved into the area and cause a temporary decrease in size. On day 117 the tree returned to its previous size and continued to expand at an even greater rate.

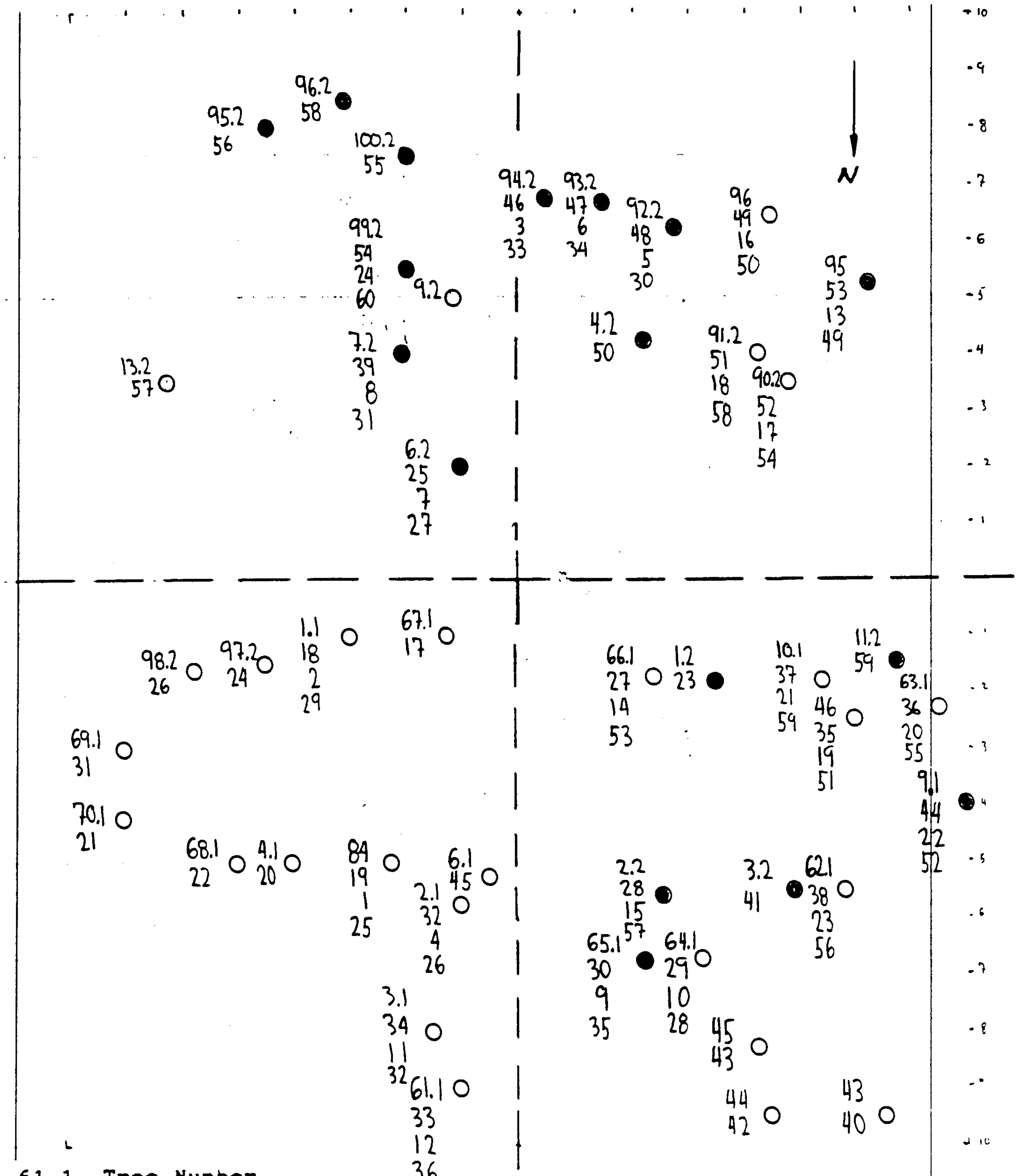
The radius of the oldest tree monitored is shown in figure 11 and 12. The decline in radius is very steady with only two periods of rapid decline and recovery on days 292 and 322.

Table IV

TABULATION OF RADIUS CHANGE, MM

PIN#	RAD CHGE OCT-FEB	RAD CHGE FEB-JUN	RAD CHGE OCT-JUN
17	-0.07	-0.32	-0.39
18	-0.19	-0.14	-0.33
19	-0.22	-0.25	-0.47
20	-0.21	0.30	0.09
21	-0.08	-0.12	-0.20
22	-0.23	0.02	-0.21
23	-1.09	0.47	-0.62
24	-0.24	-0.28	-0.53
25	-0.57	0.77	0.20
26	-0.46	-0.02	-0.48
27	-0.72	-0.65	-1.37
28	-0.37	0.68	0.32
29	-0.31	-0.28	-0.59
30	-0.70	-0.42	-1.12
31	-0.40	-0.10	-0.50
32	-0.20	-0.01	-0.22
33	-0.32	-0.03	-0.35
34	-0.69	-0.34	-1.03
35	-0.18	-0.58	-0.76
36	-0.10	-0.47	-0.56
37	-0.23	-0.16	-0.39
38	-0.02	0.00	-0.02
39	-0.79	0.76	-0.03
40	-0.64	-0.61	-1.25
41	-1.01	1.18	0.17
42	-0.62	-0.47	-1.08
43	-0.88	-0.56	-1.44
44	-0.32	-0.37	-0.69
45	-0.60	-0.30	-0.90
46	-0.35	0.22	-0.13
47	-0.45	0.31	-0.14
48	-1.10	0.47	-0.62
49	-0.23	-0.12	-0.35
50	-0.87	0.43	-0.44
51	-0.25	-0.48	-0.73
52	-0.43	-0.13	-0.56
53	-0.22	0.02	-0.20
54	-0.94	0.75	-0.19
55	-1.13	0.95	-0.18
56	-0.61	0.05	-0.57
57	-0.24	0.00	-0.24
58	-0.86	0.16	-0.70
59	-0.97	0.61	-0.37

Figure 2. Location of Trees with a Net Increase in Radius between February and June, 1990. Fourteen out of the seventeen trees with a net increase were Douglas fir. The northeast quadrant is conspicuously devoid of trees with a net increase. This quadrant is mainly populated by southwestern white pine.



61.1 Tree Number
33 Electrode Wire Number
12 LVDT Channel Number
36 LVDT Wire Number

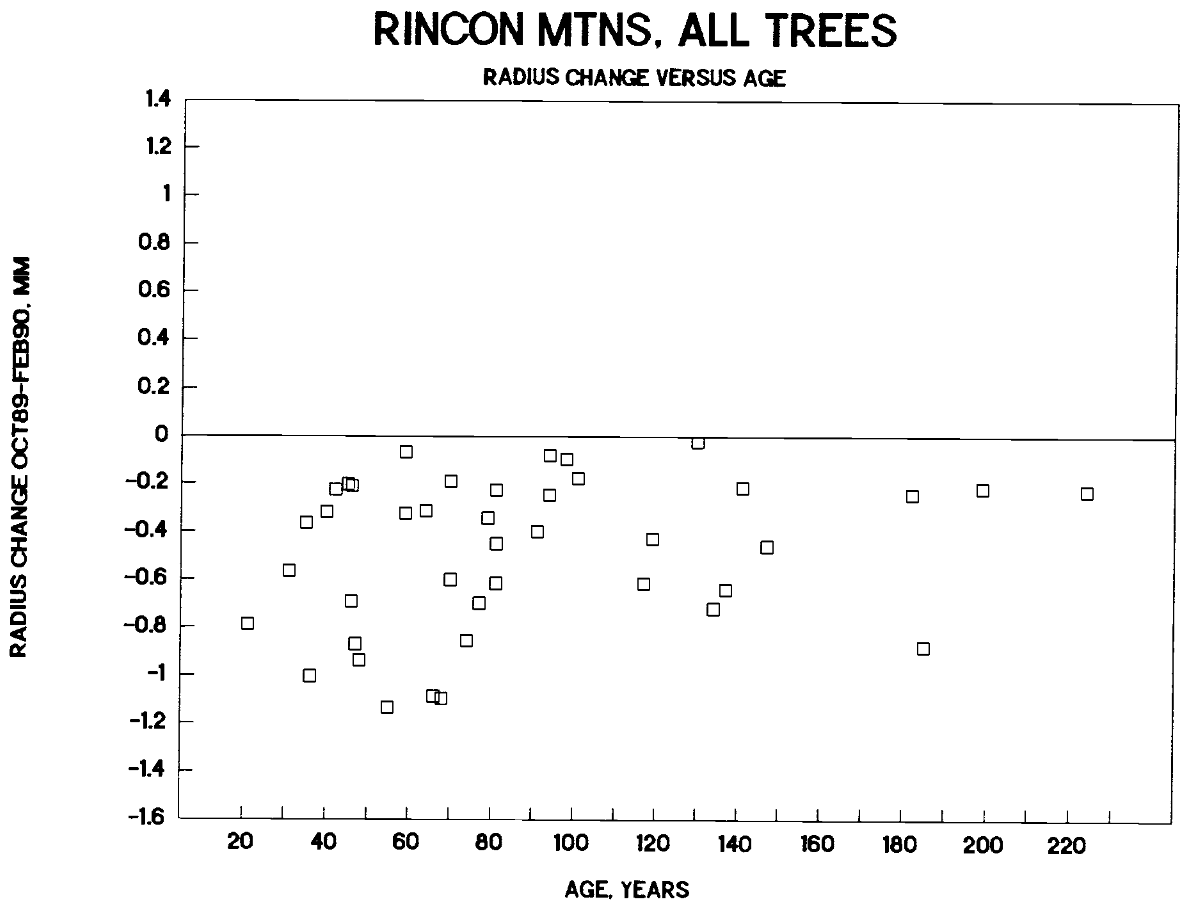


Figure 3. Radius Change versus Age between October, 1989 and February, 1990.

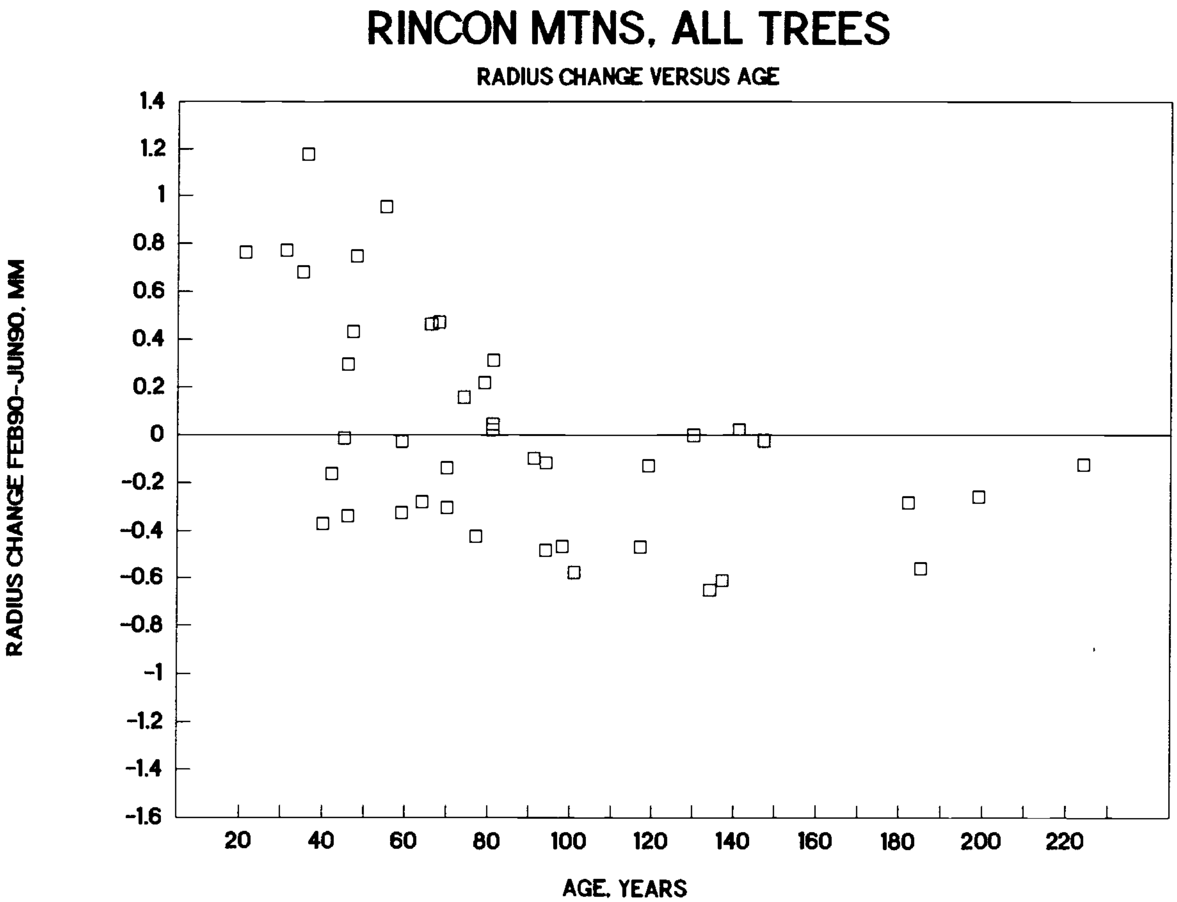


Figure 4. Radius Change versus Age between February, 1990 and June, 1990.

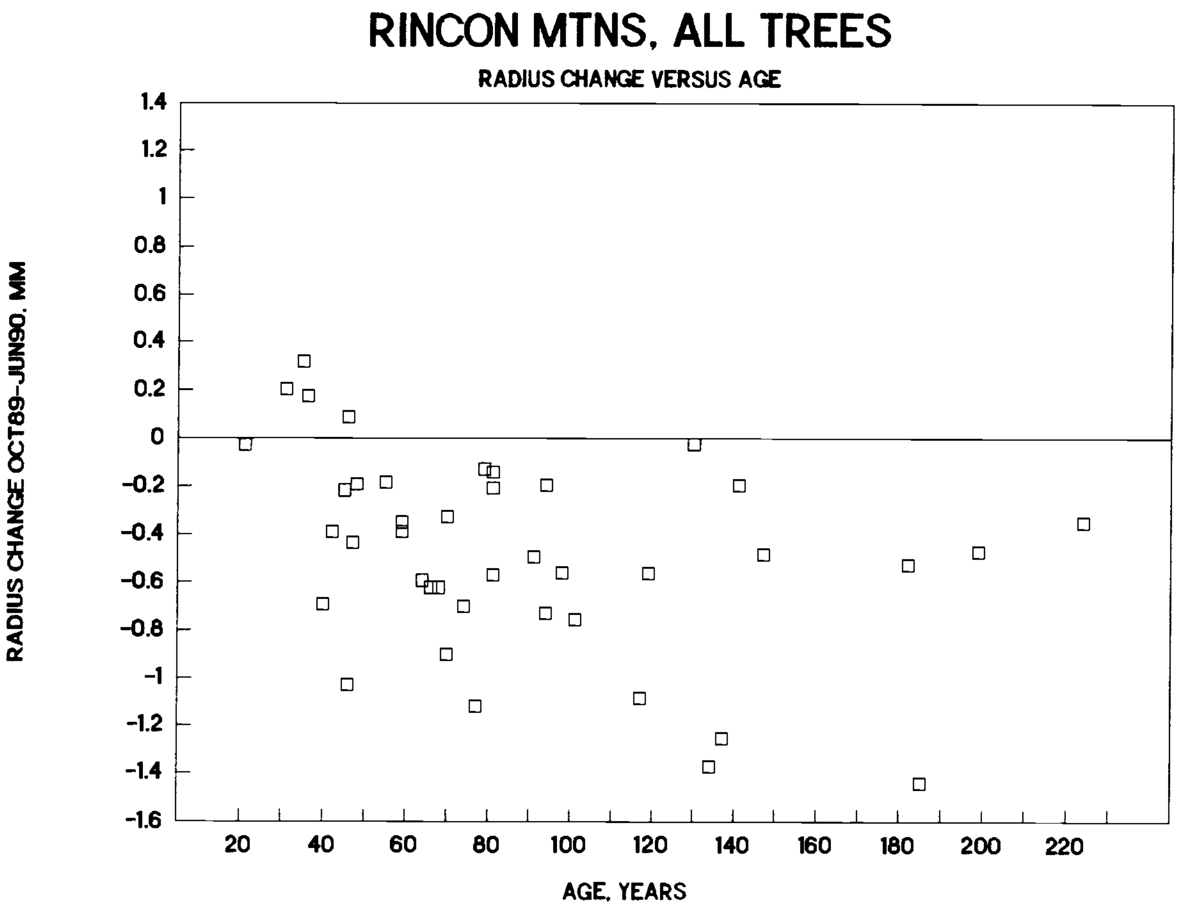


Figure 5. Radius Change versus Age between October, 1989 and June, 1990.

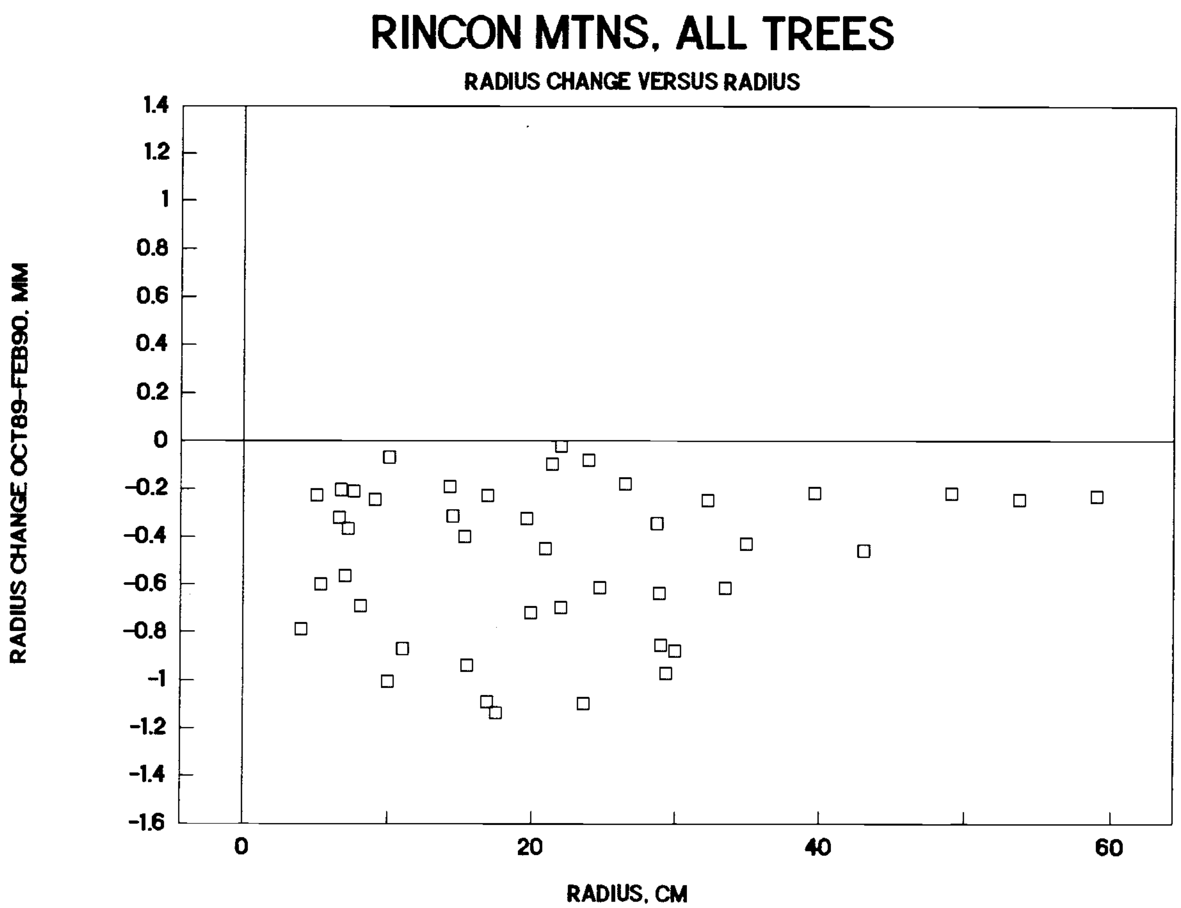


Figure 6. Radius Change versus Radius between October, 1989 and February, 1990. The absolute value of radius is arbitrary.

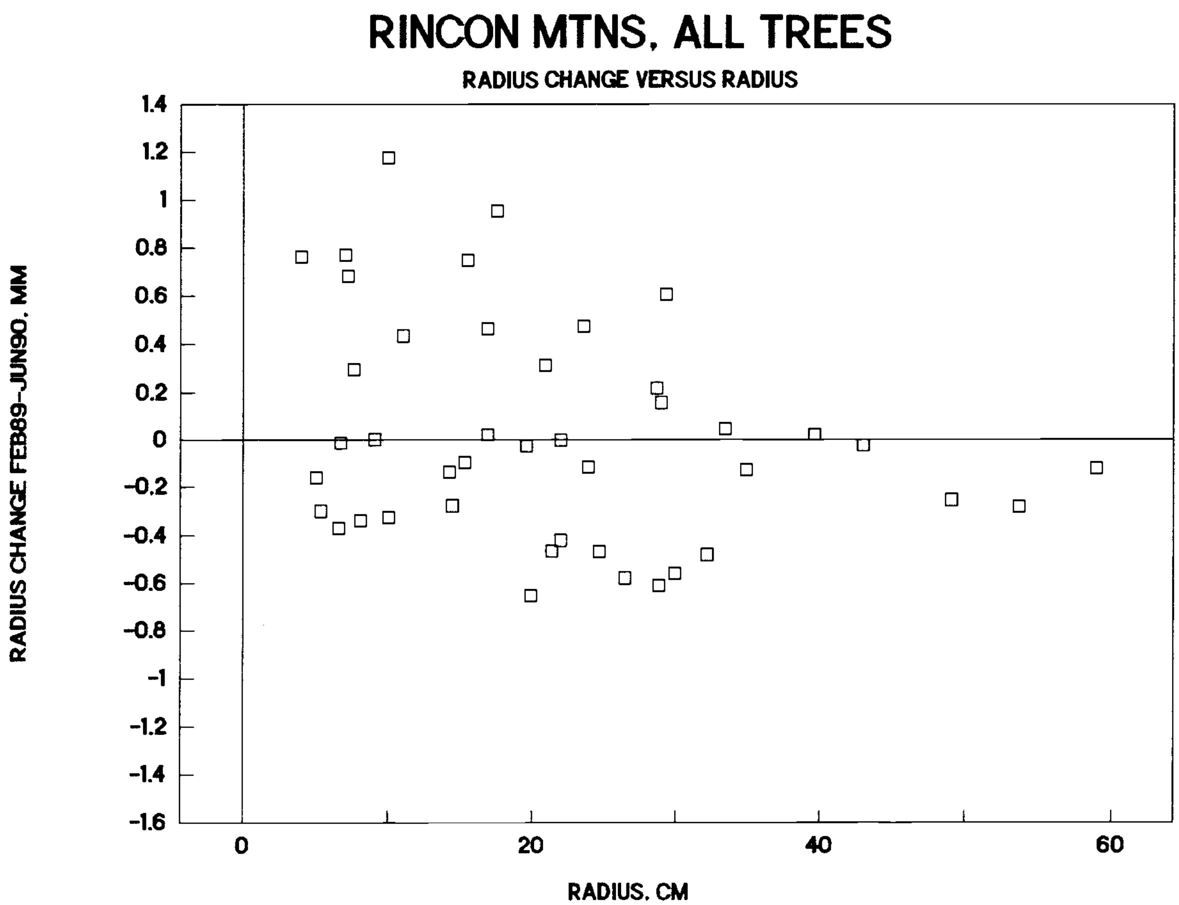


Figure 7. Radius Change versus Radius between February, 1990 and June, 1990. The absolute value of radius is arbitrary.

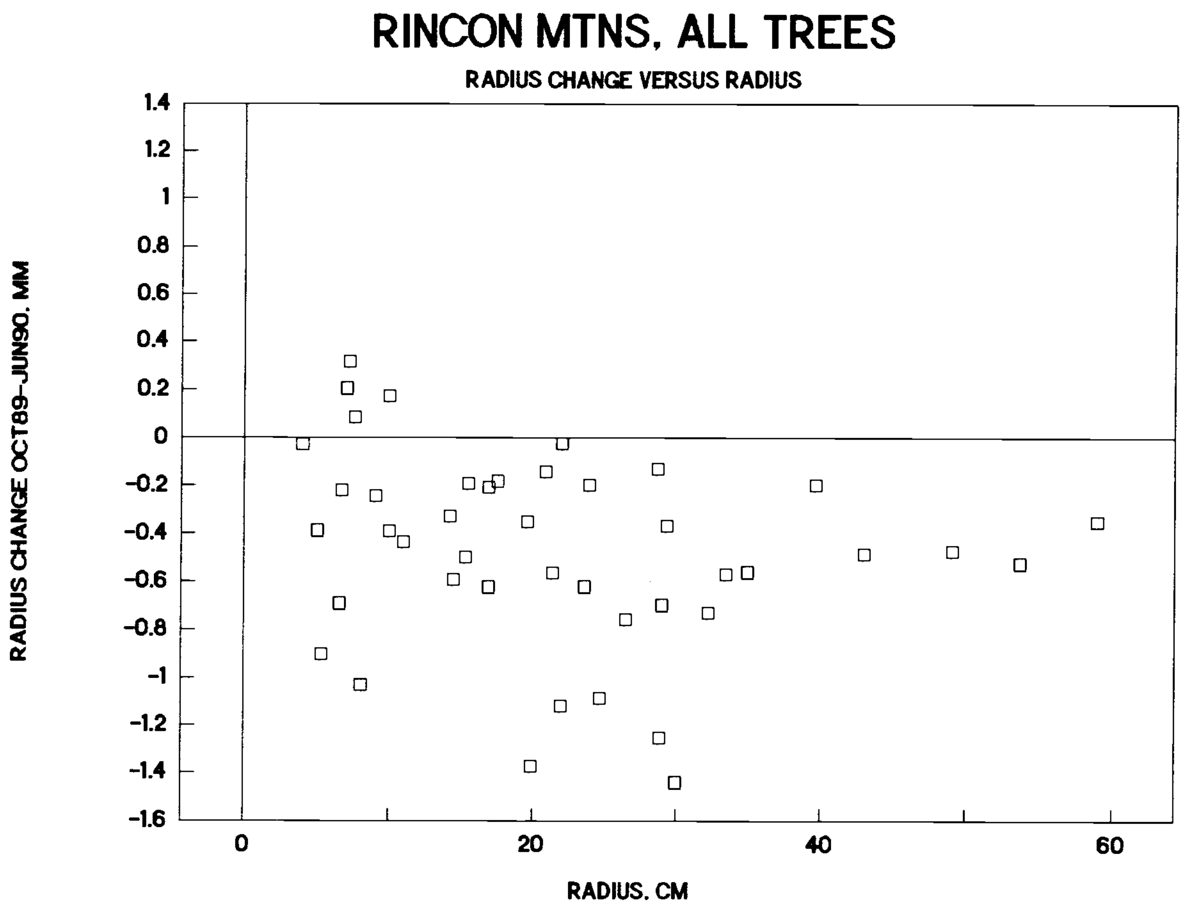


Figure 8. Radius Change versus Radius between October, 1989 and June, 1990. The absolute value of radius is arbitrary.

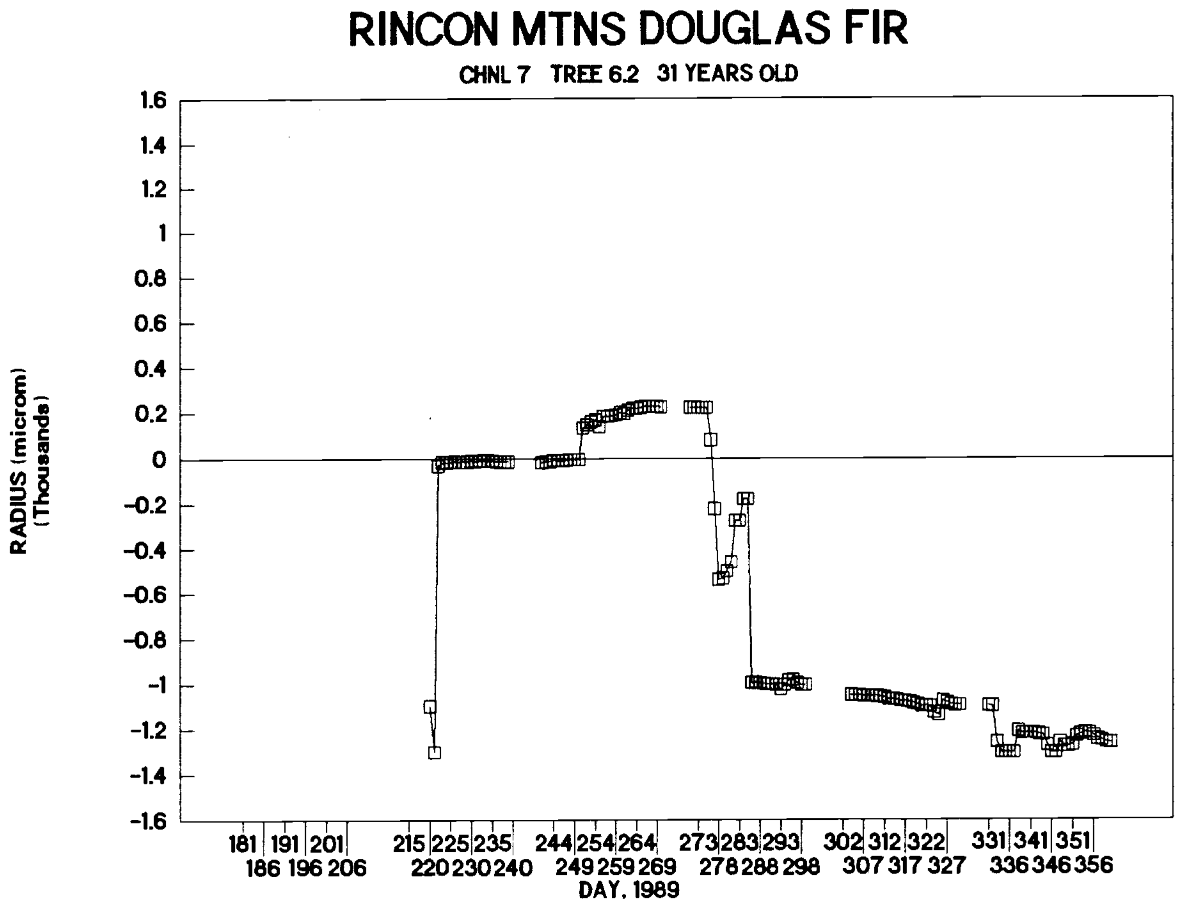


Figure 9. Example of the Radius Readings from the Automatic Dendrographs, Tree 6.2, Pin 25, 31 years old, Douglas fir. The dendrographs were set on day 285 near the negative limit of the instrument with the anticipation of a positive increase in radius.

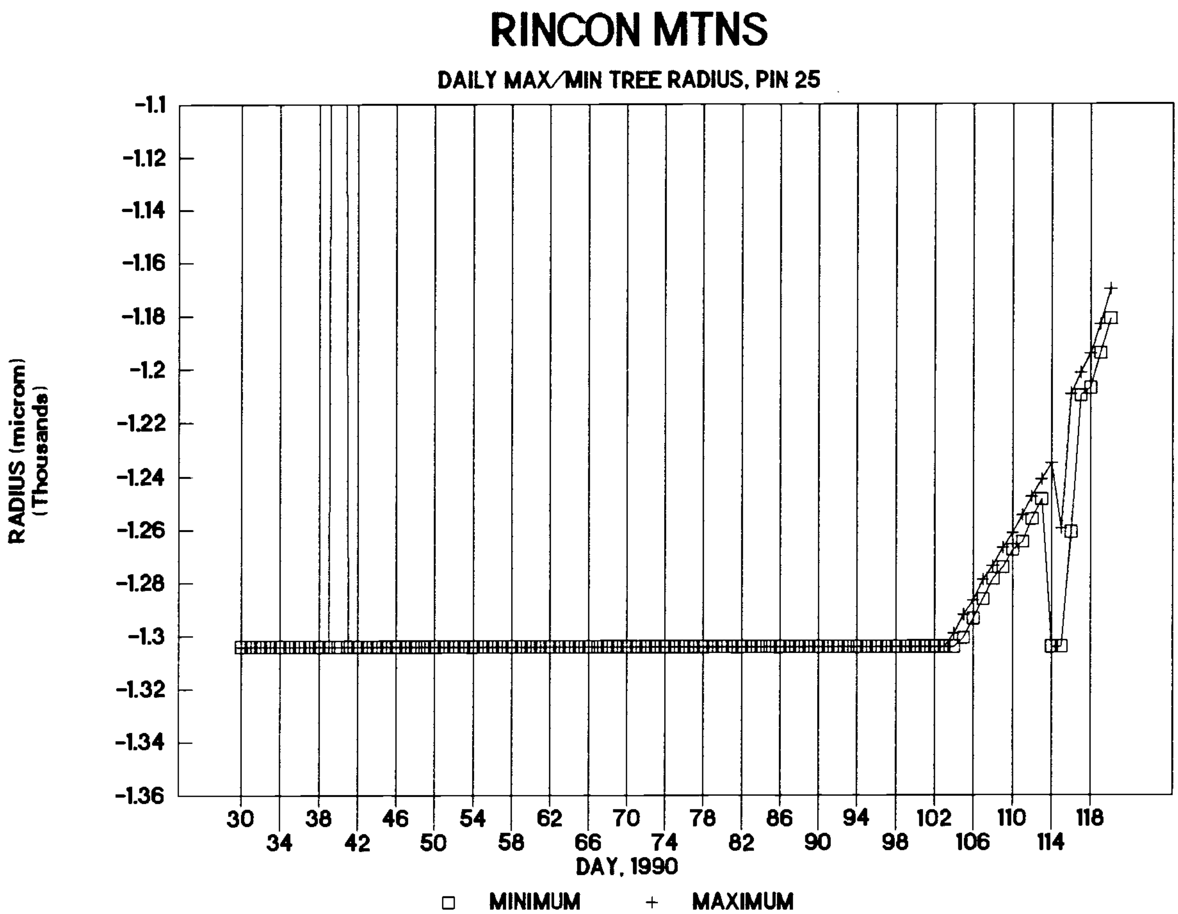


Figure 10. Example of the Radius Readings from the Automatic Dendrographs, Tree 6.2, Pin 25, 31 years old, Douglas fir. The rate of rise from day 104 to day 114 is approximately 6 micrometers/day/

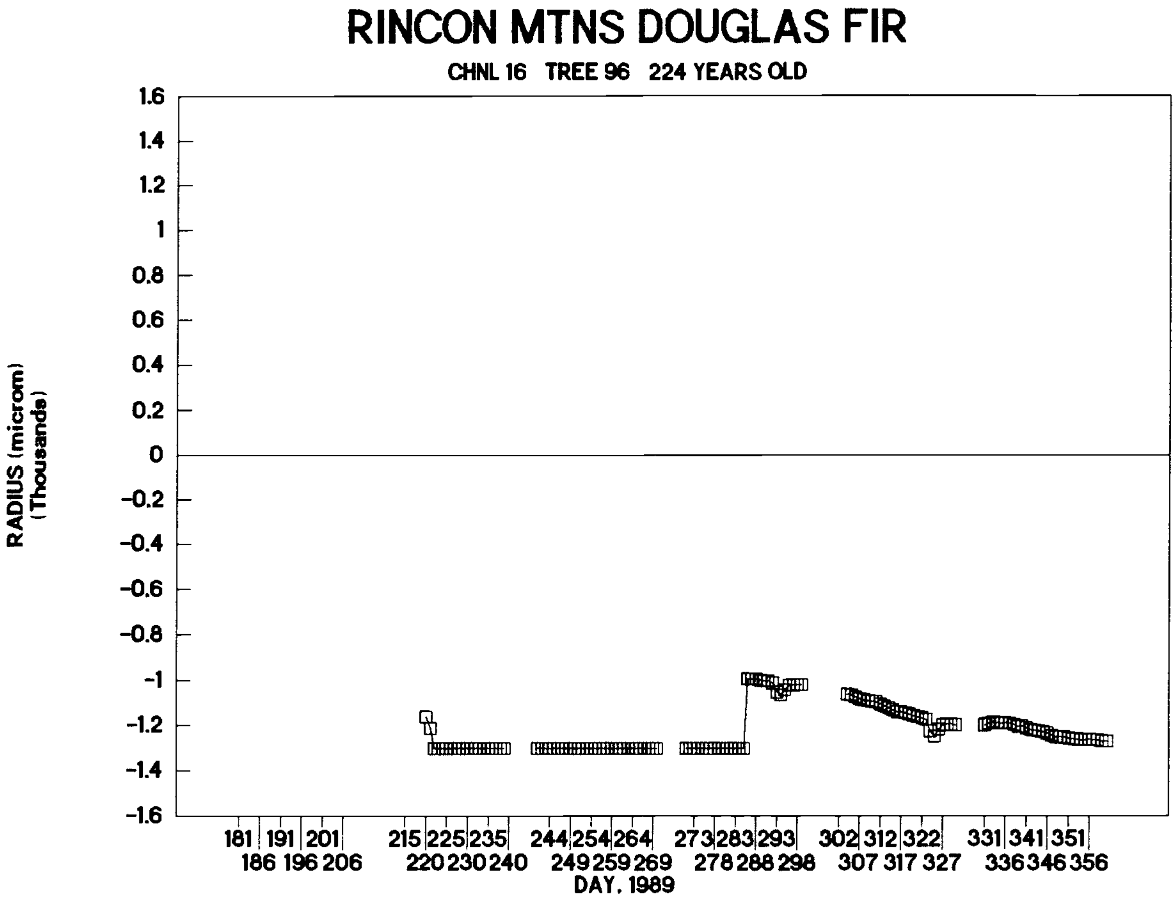


Figure 11. Example of the Radius Readings from the Automatic Dendrographs, Tree 96, Pin 49, 224 years old, Douglas fir. The dendrographs were set on day 285 near the negative limit of the instrument with the anticipation of a positive increase in radius.

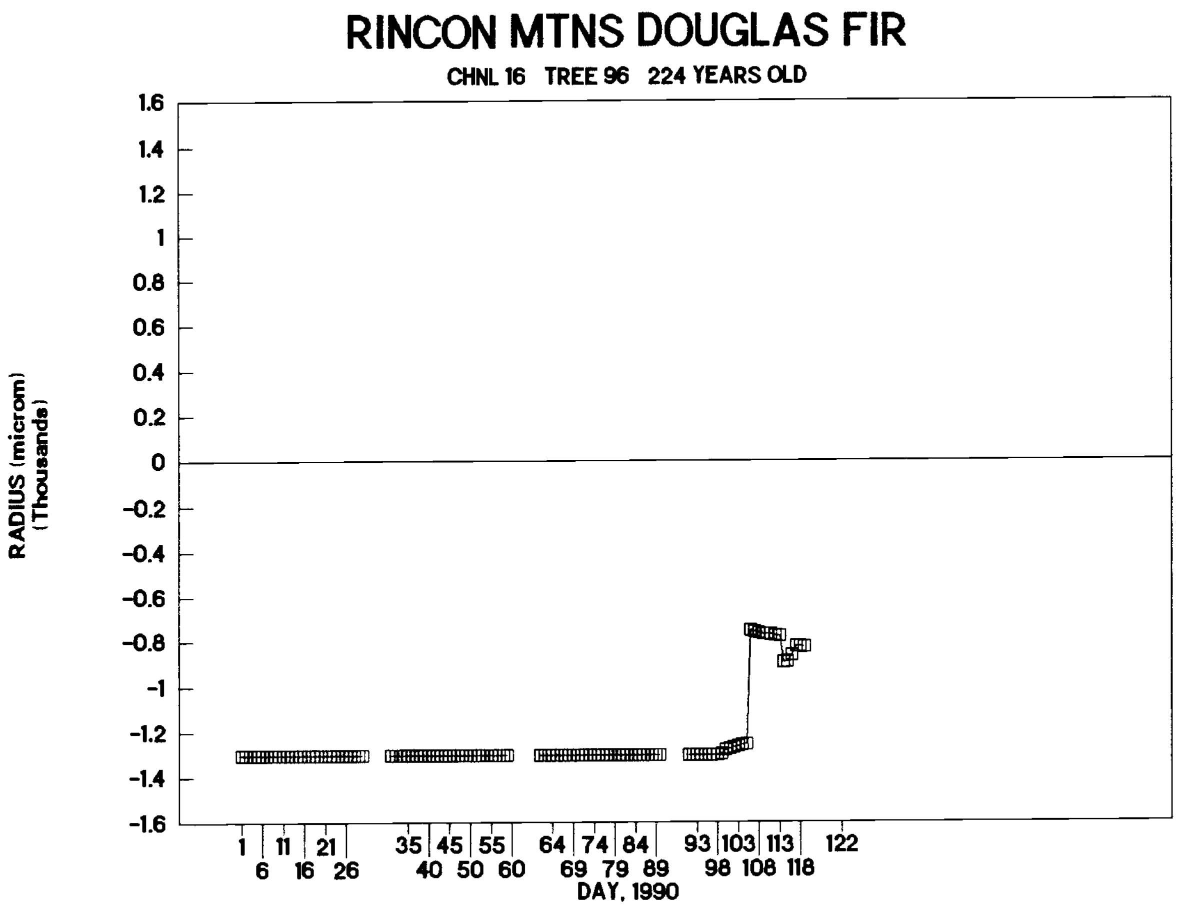


Figure 12. Example of the Radius Readings from the Automatic Dendrographs, Tree 96, Pin 49, 224 years old, Douglas fir.

The comparison of the young (31 years old) versus the old (224 years old) Douglas fir is quite interesting. The magnitude of the overall contraction from day 285 to day 365 is quite similar. For the old tree the contraction was 278 micrometers over 76 days (3.65 micrometers/day), for the young tree the contraction was 378 micrometers over 76 days (4.2 micrometers/day). This would suggest that the change in radius is the same for the two in spite of the wide difference in age.

A comparison of the response to individual weather disturbances of the young versus the old tree indicates that there is much more volatility in the younger tree. Both trees responded to the weather disturbance on days 292 and 322. However, the younger tree initially contracted, then expanded back to the pre-disturbance radius and overshoot the steady state level. There was a very slow and muted expansion in the older tree in the period following day 331. The younger tree elicited a very strong contraction and then a recovery, but to a level well below the day 331 level. This same strong contraction and then a recovery well below the pre-disturbance level was observed on several of the young trees (pin 39, tree 7.2, 21 years old and pin 37, tree 42, 42 years old) during this time interval. In like manner, a second old Douglas fir (pin 19, tree 84, 199 years old) elicited the same behavior as the 224 year old tree. This would suggest a generalization wherein the older trees are better able to withstand short term adverse disturbances.

Figure 13 illustrates the comparative radius response beginning on day 292, 1989. Both radii followed the same pattern until erratic temperature change on day 293 and a generally lower temperature caused a strong difference in response, The younger tree expanded with the lower temperature while the older tree contracted. Figure 14 is a second illustration of the comparative response of these two trees. In this case a steady decline in temperature caused a sudden contraction in radius of the younger tree while the older tree elicited almost no response.

CORRELATION BETWEEN THE POTENTIAL AND RADIUS

The potential and radius changes were examined on an hourly time scale to determine the relation between these two measures. The responses that will be presented are examples of responses to definite temperature disturbances and are indicative of the response of many of the combinations.

Figure 15 shows the response of the electrode connected to pin 25 and the automatic dendrograph on the same tree. In order to place this figure in context see figure 10. The weather front that moved in at 0900 hours on day 114 caused a simultaneous drop in potential and radius. The potential appears to have dropped slightly before the radius. The fact that the radius went off scale at the bottom of the response precludes a comparison of the amplitude of the drop.

The return to the pre-disturbance levels also occurred in concert. Both the radius and potential also moved in response to the rise in temperature at 2200 hours on day 114. In this case the response of the potential was greater in amplitude. Notice that the radius before and after the response is in a relatively straight line. This suggests that the response was in a sense superimposed on a steady increase in the radius.

Figure 16 shows a second example of the simultaneous change in potential and radius. In this case the potential and radius reached a low point and then began to recover in concert. But at 2300 hours on day 114 the potential moved negative once again while the radius continued to expand. The steady increase in radius was interrupted at 0800 hours on day 115 whereupon the radius contracted for about four hours and then expanded in a nearly monotonic manner until its return to the pre-disturbance level. The potential and radius both moved together from day 116 onward but the steady state level of the potential following the disturbance was not the same as the value obtained before the disturbance.

Figure 17 shows the potential radius correlation of another electrode-dendrograph combination. In this case the potential moved actively over a one hundred millivolt range. A downward movement of potential was accompanied by an increase in radius on six days. On day 114 neither the potential nor the radius performed in the "normal" manner.

Figure 18 shows a fourth example of the potential-radius correlation. In this case the potential and radius change occurred simultaneously, but within a few hours the potential moved back to one hundred millivolts. It is interesting to observe that the potential and radius moved in concert at 0800 hours on day 117 and day 118.

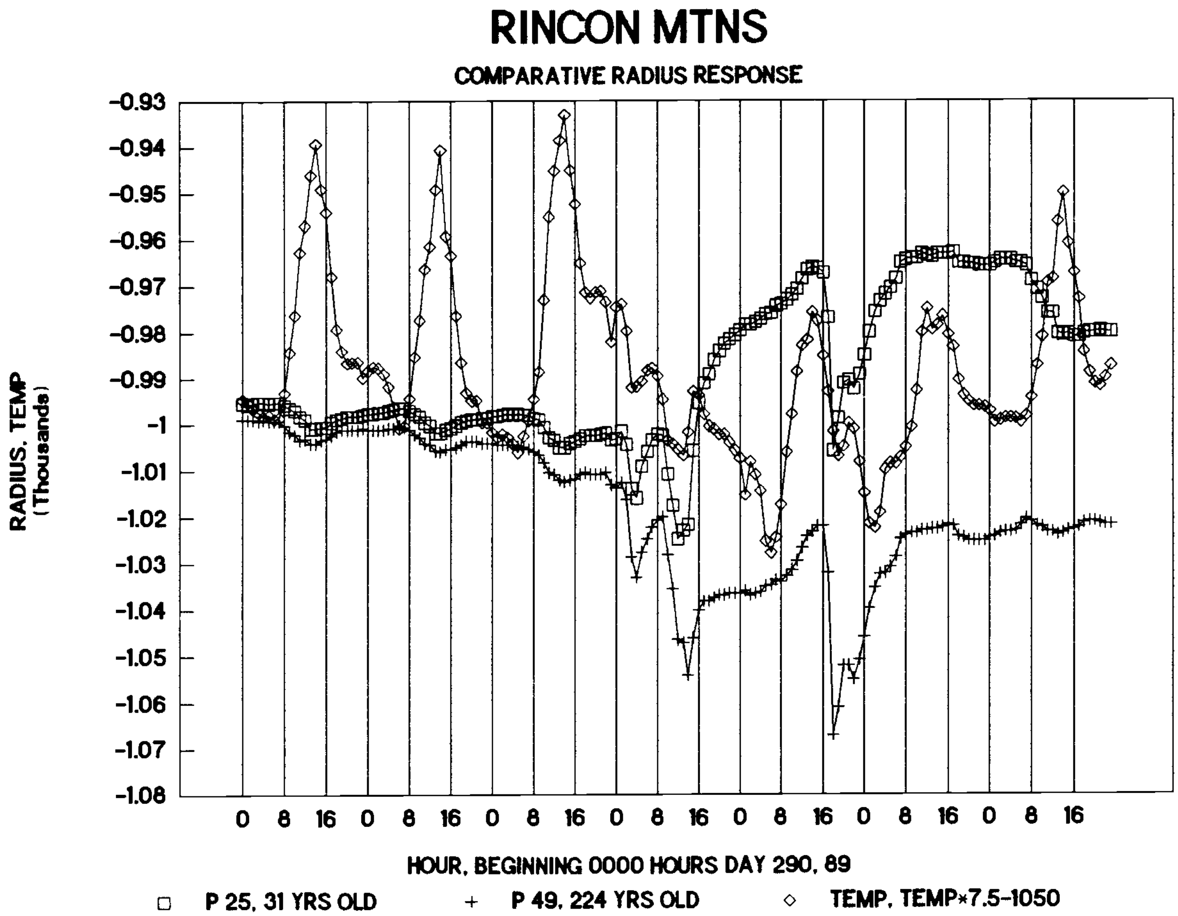


Figure 13. Comparative Radius Response between a Young (Pin 25, 31 years old) and an Old Tree (Pin 49, 224 years old). The response of both trees appeared to be caused by the erratic temperature cycle on day 293. The temperature at 0200 hours on day 293 began to rise. This rise lasted until about 0730 whereupon the temperature began to fall until 1400 hours. At this time the temperature began to rise again. The radius of both trees initially responded in the same manner. At 0200 hours on day 292 the radii responded in the same manner. Both reversed their contraction and began to expand. The expansion lasted until 0800 hours when the temperature decline was already under way. The two trees responded with even greater magnitude this time until 1500 hours when they once again both began to rise The expansion of the old tree was substantially different insofar as it did not rise past its pre-disturbance level. By contrast, the younger tree expanded well past its pre-disturbance level. The potential was substantially below its pre-disturbance level during this expansion. Both trees responded very strongly to what appears to be a normally occurring temperature drop in the afternoon. The only difference in this temperature drop compared to other which provoked very little response was the temperature level. The temperature level this time was substantially lower than before.

The radius scale is arbitrary on this graph, but the change in radius is absolute. The temperature scale is absolute.

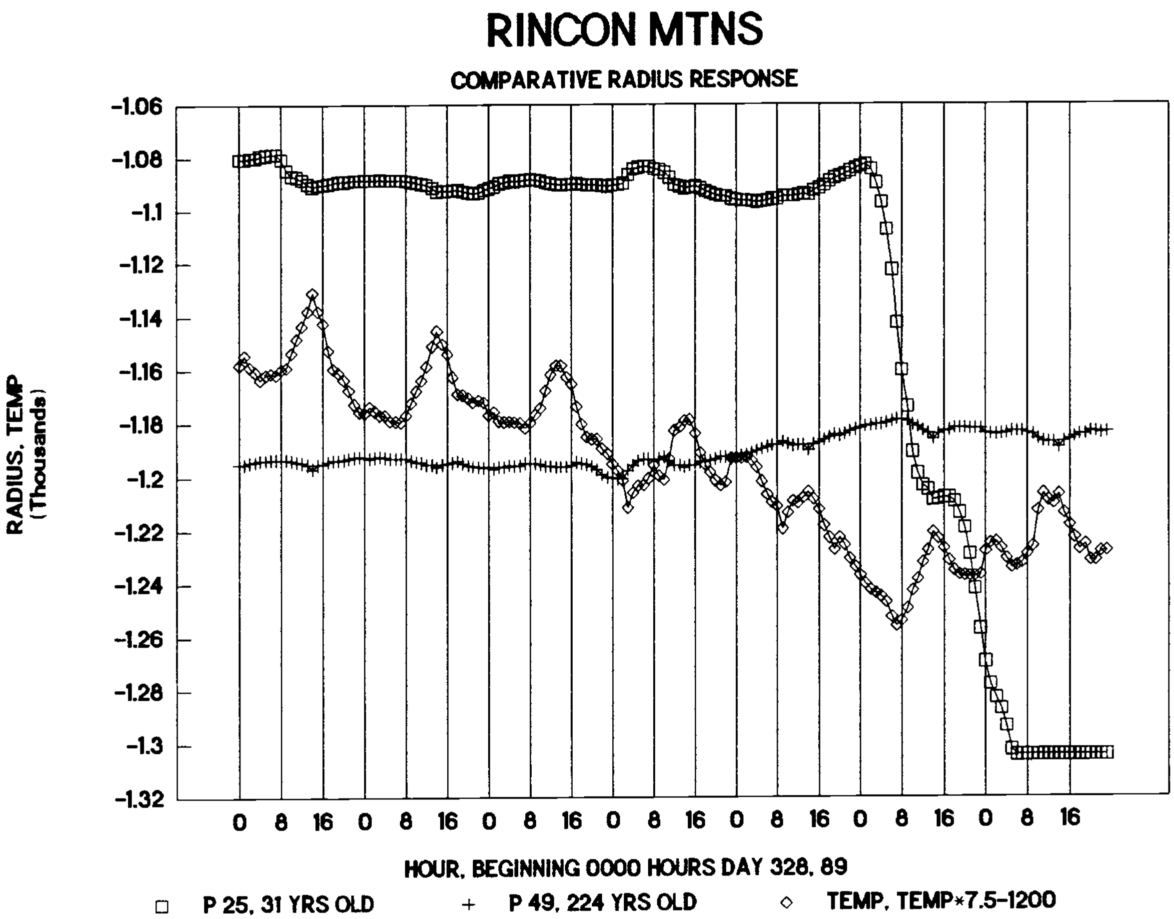


Figure 14. Comparative Radius Response between a Young (Pin 25, 31 years old) and an Old Tree (Pin 49, 224 years old). The temperature dropped continuously below freezing at approximately 0000 hours on day 332. Both trees expanded approximately twenty micrometers. At 0200 hours on day 333, the young tree went into a sharp contraction and decreased 240 micrometers in radius before going off scale in the negative direction. Several trees elicited this same sharp decline at this time, a fact which strongly suggests that there were no problems with the individual sensors. By contrast, the older tree showed no evidence of a decline. The temperature at the site was below freezing for a full twenty-four hours before the sharp decline began.

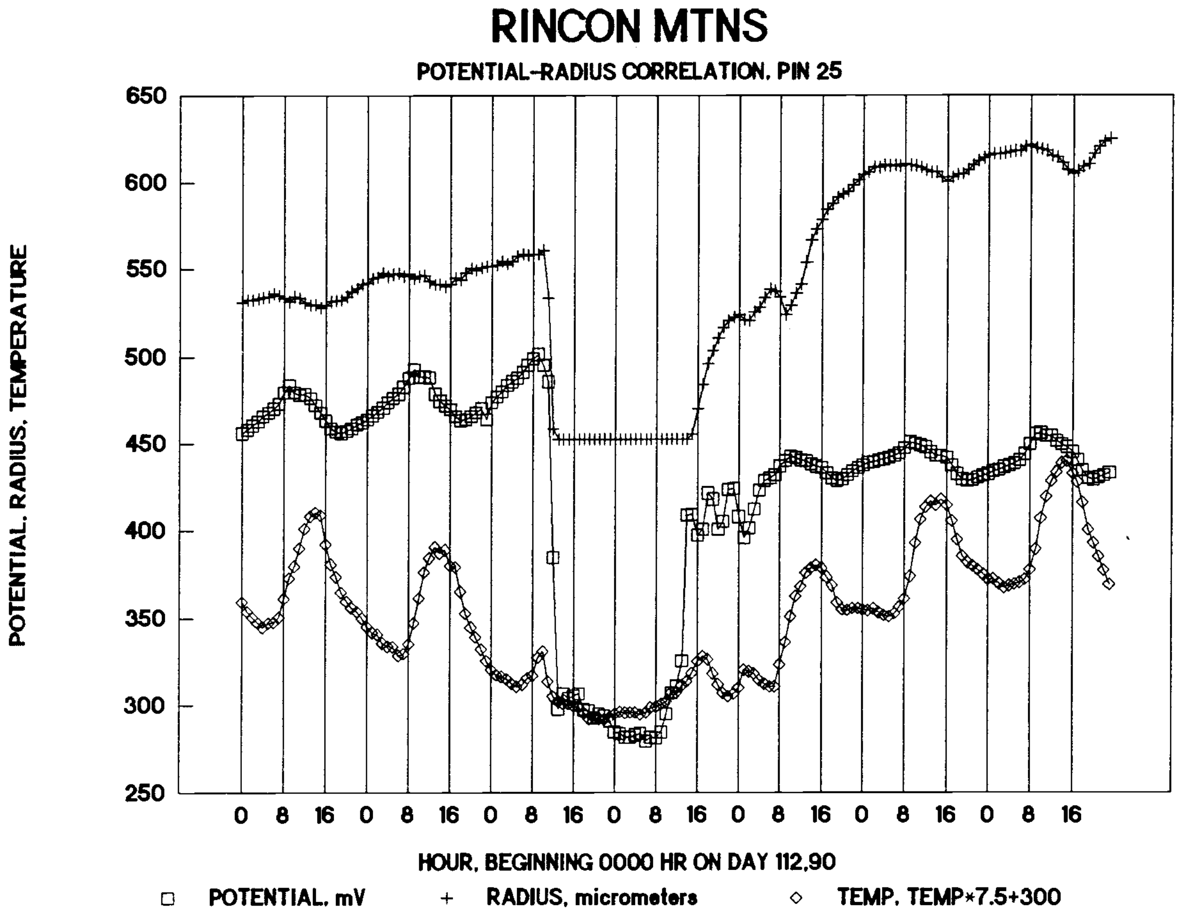


Figure 15. Example of the Potential-Radius Correlation, Pin 25, Tree 6.2, 31 years old. The diurnal cycle of the radius has a minimum at 1600 hours with an amplitude of approximately 25 micrometers. The radius contracted sharply due to the sharp drop in temperature at 0900 hours on day 114. The diurnal cycle of the potential reached at 1400 hours and a minimum at 0630 hours. Amplitude of the diurnal potential cycle was approximately 75 millivolts. The drop in potential appears to have begun slightly before the contraction. The magnitude of the contraction is not known since the dendrometer bottomed out at the negative limit during the response.

There was a series of reversals in both the radius and potential after 1600 hours on day 115 due to the reversals in the temperature. The reversal in the radius lags the reversal in the potential.

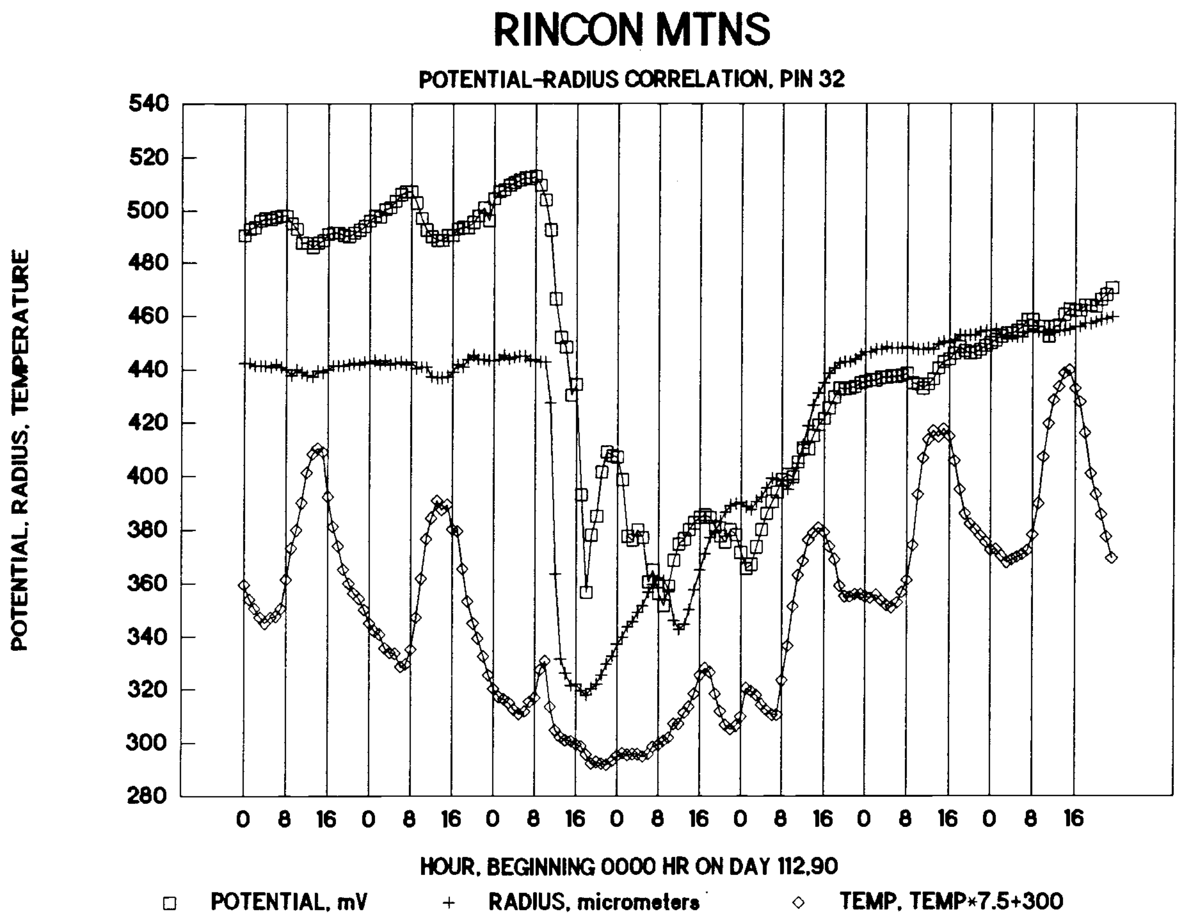


Figure 16. Example of the Potential-Radius Correlation, Pin 32, Tree 2.1, 45 years old. The diurnal cycle of the radius is almost indiscernible. The diurnal cycle of the potential has a peak at 0800 hours and a minimum at 1400 hours. Both the potential and radius responded sharply at 0900 hours on day 114. The low temperature on day 112 was about 5.3 and the high was 14.6. The radius and potential drop began when the temperature was above freezing. Potential scale is valid but the radius scale is arbitrary. Change in radius are according to the scale. The actual value of temperature can be obtained from the formula given.

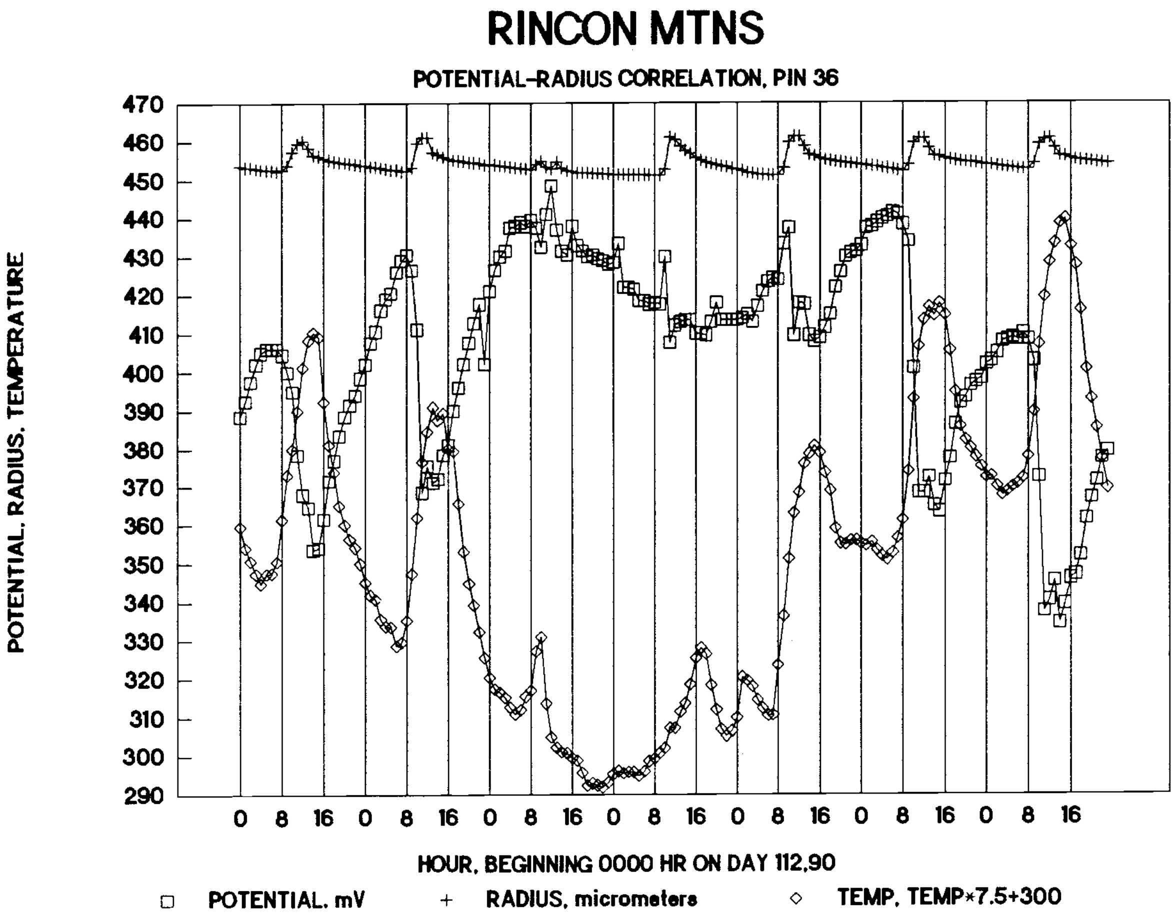


Figure 17. Example of the Potential-Radius Correlation, Pin 36, Tree 63.1, 98 years old. The diurnal cycle of radius is about ten micrometers and noticeably absent on day 114. Both the radius and potential failed to respond to the weather front at 0900 hours on day 114 in contrast to the response in figure 14. The diurnal cycle of the potential is reversed from that shown in figures 13 and 14. The peak potential occurs in the morning and the low point in the cycle occurs in the afternoon at about 1500 hours. This phase in the diurnal cycle is commonly observed in cotton under conditions of extreme drought stress.

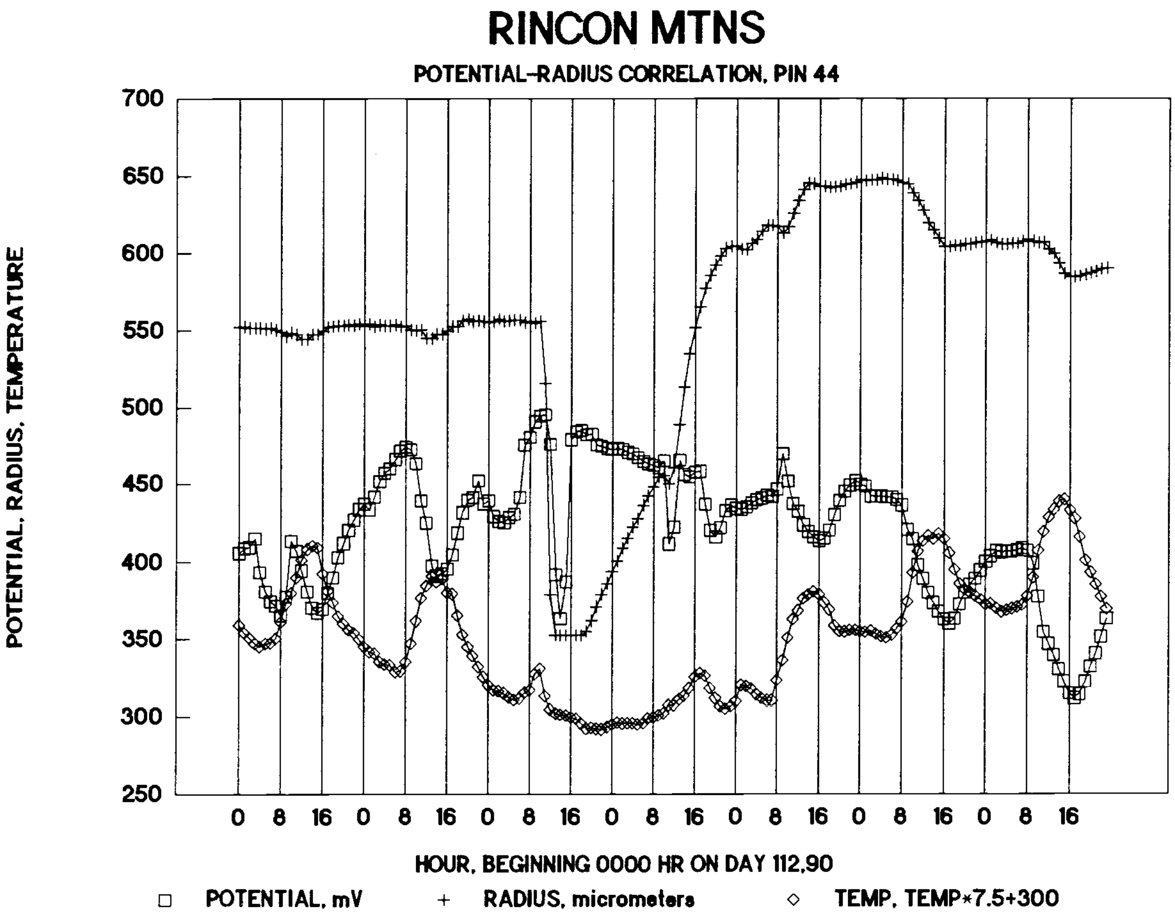


Figure 18. Example of the Potential-Radius Correlation, Pin 44, Tree 9.1, 40 years old. The radius and potential dropped in concert with the arrival of the cold front at 0900 hours on day 114. But in this case the potential recovered three hours later to virtually its initial level. The diurnal cycle of the potential in this case follows the same pattern as figure 15, that is, there is a peak at about 0800 and a minimum at 1400 hours. There was no response to the temperature reversals beginning on day 115 at 1800 hours.

DISCUSSION AND CONCLUSIONS

There are a number of definite conclusions that can be obtained from the analysis of the data from the three types of sensors. First of all, the manual dendrometers indicate quite clearly that the magnitude of the hydration/rehydration cycle is great enough to obscure the determination of the biomass increment during the time interval under analysis. The contraction due to water loss in the fall of 1989 was not compensated for by the snowmelt in the spring of 1990. The part of the seasonal hydration cycle observed in this data set commonly had amplitudes in the order of 300 to 400 micrometers and reached as high as 1100 micrometers.

The daily hydration cycle has an amplitude which is relatively small with respect to the response of the radius to individual weather disturbances of the seasonal cycle. Peak to Peak amplitudes in the order of ten to twenty micrometers in radius were observed.

Weather disturbances have a major influence on the radius. So much so that the reading of the manual dendrometer on a particular day must take into account the weather several days before that day. It appears that weather disturbances can cause changes in radius as high as 225 micrometers.

There was very little pattern in the change in the radius with respect to either age or radius as measured with the manual dendrometers. This means that the trees must be analyzed on an individual basis until a pattern is determined that can lead to a generalization. This further suggests that microsite variations and/or intrinsic genetic variations are quite strong.

The automatic dendrographs confirmed the broad conclusion obtained with the manual dendrometers. Most of the trees contracted in radius. The magnitude of this contraction was unknown at the onset of data acquisition. Any initial settings of the dendrographs must take into account this contraction. This would obviate the problem of the readings going off scale in the negative direction.

The four micrometer resolution of circumference of the dendrographs is necessary to discern the magnitude and form of the diurnal cycle in radius. The range of the automatic dendrographs at this resolution is 2500 micrometers in radius. If the seasonal diurnal radius cycle is in the order of 1000 micrometers or more, then it will be necessary to set the initial value of the dendrograph with some care. This already has been found to be true.

The question of species difference was only briefly examined. A computation of the average PG11 index of the Douglas fir had a relatively steady level of 400. The southwestern white pine had a PG11 magnitude of 285 with a substantial increase in magnitude between day 69 to 75. The author of this report felt that it is premature to place emphasis on this difference in index level because the age of the Douglas fir is generally older than the southwestern white pine. However, the fact that fourteen out of seventeen trees that experienced a positive increase in radius in the spring during a time period that corresponded to this index computation would suggest that there may indeed be a significant difference between the two species. The higher index values are a sign of more vigorous trees. This would suggest that the Douglas fir were able to sustain the rigors of the north slope climate better than the southwestern white pine during the time interval under consideration. This is not in keeping with the common observation that southwestern white pine are able to grow in drier climates than Douglas fir.

The potential-radius plots indicate there is a very definite correlation between changes in the radius and changes in the potential. Potential and radius respond virtually simultaneously. In other words, the correlation with regard to the question of "when" is excellent.

This simultaneity is to be expected since the author measured the same simultaneity in 1982 in cotton (see the References for the published results). In cotton (a woody perennial) the sudden drop in potential was accompanied by an increase in the radius of the main stem. The change in radius and potential occurred following irrigation of the field. The plants and the soil in the agricultural setting were all relatively uniform

The correlation with regard to "how much" and "in what direction" in the case of the trees in this project must be further investigated. There were examples in the tree population observed wherein the potential rose in the morning and fell in the afternoon. This has been shown in numerous data sets in various species and in various parts of the continent to be concomitant with healthy, well watered trees. By contrast, the data set in this project had examples whereby the potential fell in the morning and rose in the afternoon. This has also been shown to be an indicator of relatively extreme drought stress. In other words, the conditions of the trees at the site does not appear to be uniform.

In this data set, there were examples wherein the radius expanded as the potential dropped, but other examples whereby the radius contracted as the potential dropped. A more detailed examination of each tree must be made to separate out these changes. In other words, the potential and radius are correlated, but the question of direction and magnitude of the potential radius correlation requires further investigation of this data set and additional data at this site under other conditions.

This problem is to be expected since the microsite and age variations are apparently very strong, and in addition, one has a variable drought stress embodied in the present data set. A four season analysis would go a long way towards the determination of the essential performance of the trees at this site.

These conclusion indicate that a cross correlation with archived tree ring data may be possible if the objective is to determine response to drought stress. The determination of the response to airborne pollutants within the present data set is premature.

REFERENCES

Reference 1-9,20,21 pertain to the early development of the PHYTOGRAM technique. Reference 11,12,13,14 provide background for stem diameter measurements and the interpretation of the potential change in resource translocation. Reference 15-19,23-25,28,29 relate to the oxygen hypothesis and the formation of indices. Reference 26 and 27 contain many of the ideas presented in this report. Reference 30 discusses the mid day change in plant status. Reference 31 gives support for the anaerobic interpretation of the low potentials. Of particular interest in this list is reference 13 which shows the simultaneous change in potential and radius of cotton in the same manner as figure 15 through 18 of this report.

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APPENDIUX I, INDIVIDUAL TREE DATA SET

The following graphs are the data set for the individual trees. The order is by Pin number, that is, pin 17 through 59.