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LONG-TERM RECOVERY OF A LONGLEAF PINE (PINUS PALUSTRIS MILL) POPULATION FOLLOWING SEASONAL EXPOSURES TO IONIZING RADIATION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jackie A. Cunningham

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ABSTRACT

The long-term effects of ionizing radiation on growth of a longleaf pine population were investigated. Height, diameter and annual increment of radial growth were measured for 81 irradiated trees and 34 control trees. Data were analyzed in a two-way ANOVA, with exposure dose (2.1, 0.7, and 0.17kR) as one variable and season of exposure (spring, summer, fall, and winter) as the other variable. Effects of radiation on radial growth were detectable after 20 years. Trees exposed to higher levels of radiation and trees exposed during seasons of greatest cell activity had the greatest reduction in growth. Trees exposed to the highest dose level (2.1kR) were significantly shorter and had smaller diameters than trees exposed to other dose levels. Trees exposed to radiation in the spring, summer or fall had significantly smaller diameters than trees irradiated in the winter or the control group. Radial growth of all irradiated trees (2.1, 0.7, and 0.17kR) was significantly less than the radial growth of the control trees during all time periods analyzed--1970-1975, 1975-1980, and 1980-1985.

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I. INTRODUCTION

Ecological effects of acute and chronic ionizing radiations on plants and plant communities were studied extensively prior to 1975. Research has been summarized by Schultz and Klement (1963), Klechkovskii et al. (1973), Whicker and Fraley (1974), and Whicker and Schultz (1982).

Nonlethal doses of ionizing radiations reduce photosynthesis and temporarily increase respiration (Bourdeau & Woodwell 1964), decrease auxin levels (Gunckel & Sparrow 1961), cause disorganization of apical meristems, reduce activity of the vascular cambium, delay lignification of xylem elements (Bostrack & Sparrow 1969), and possibly cause starvation from the loss of a critical amount of photosynthetic tissue (Bostrack & Sparrow 1970).

Temperate forests exposed to ionizing radiations include a southeastern mixed deciduous-pine forest (Platt 1963, Pedigo 1963, Cotter & McGinnis 1965), a southeastern coastal plain pine forest (Monk 1966, Miller 1968, McCormick 1969), a northeastern oak-pine forest (Woodwell & Miller 1962, Woodwell & Rebuck 1967), and a northern deciduous forest (Murphy et al. 1977). Long term forest recovery has been investigated in the southern coniferous forest (McCormick & Dyer 1985), the northeastern oak-pine forest (Kroot 1986), and the northern deciduous forest (Murphy et al. 1977).

This research analyzes long term recovery of a longleaf pine plantation on the Savannah River Plant Reservation near Aiken, South Carolina. Each of four, one-hectare sites were irradiated for one month--one site during each season--during 1966-67. Miller (1968) investigated initial damage and recovery during the year following exposure. He investigated seasonal influences because radiation damage varies directly with chromosome volume (Sparrow & Evans 1961) and chromosome volume varies with season. Larger chromosomes absorb more radiation energy than smaller chromosomes per unit of exposure. Therefore, chromosomes exposed to radiation during the spring, when nuclear volume is largest, should sustain greater damage than they would if irradiated during winter when chromosome volume is smallest (Taylor 1965). Quite simply, the larger the target, the greater the damage.

Consistent with target theory, Miller (1968) reported that tree survival, terminal and lateral bud survival, tree growth, and time required to produce observable radiation damage were affected less during fall and winter exposures than during the spring and summer exposures. Mishenkov et al. (1983) reported similar findings. Radiosensitivity of pine was 2-3 times greater for trees irradiated in the spring than in the fall. These results were based upon tree growth, loss of needles, decrease in woody biomass, changes in primary productivity and mortality.

The objective of this study was to extend Miller's (1968) investigation by 20 years in order to determine the long-term influence of ionizing radiation and season of irradiation on the growth of a longleaf pine population. Stating this objective in a testable format yields 4 questions:

(1) Do mean height and diameter of longleaf pine vary inversely with the radiation exposure received twenty years earlier?

(2) Do mean height and diameter of a longleaf pine population vary according to season of irradiation twenty years earlier?

(3) Have irradiated trees been growing at the same rate as control trees?

(4) How many years after irradiation did annual growth of previously irradiated trees continue to be suppressed?

II. METHODS

Study Area

Criteria for selecting the 16 hectare study site were adequate area and uniform vegetation and soils (Miller 1968). The area had to accomodate four radiation fields of approximately one hectare each, with no overlap of radiation exposure (Figure 1). Soils are characterized as yellow-brown sandy loams to a depth of 140-178 cm, followed by red sandy loams to a depth of 203 cm (Miller 1968). Spring, fall, and winter exposure sites had a site index of 78 for loblloly pine (Pinus taeda) based on one soil core per site (Rogers 1985). The site index for the summer exposure site was only slightly higher at 80. The area was in cultivation until 1945, at which time it was abandoned. In 1960 the U. S. Forest Service cleared the area and planted two year old longleaf pine seedlings. By 1965, natural mortality had reduced pine density to approximately 101 trees per hectare. Herbaceous vegetation in the area was similar to that described by Odum (1960) for early secondary succession in the lower edge of the Piedmont Plateau.

Radiation Treatments

Development of a portable 9200 c ^{137}Cs gamma irradiator (McCormick & Golley 1966) allowed replication of the experiment during the four seasons. Spring irradiation (April 6-May 5) occurred at the beginning of the growing season and included the period of initial bolting of the longleaf pine population. The summer exposure (July 12-August 10) occurred in the middle of the growing

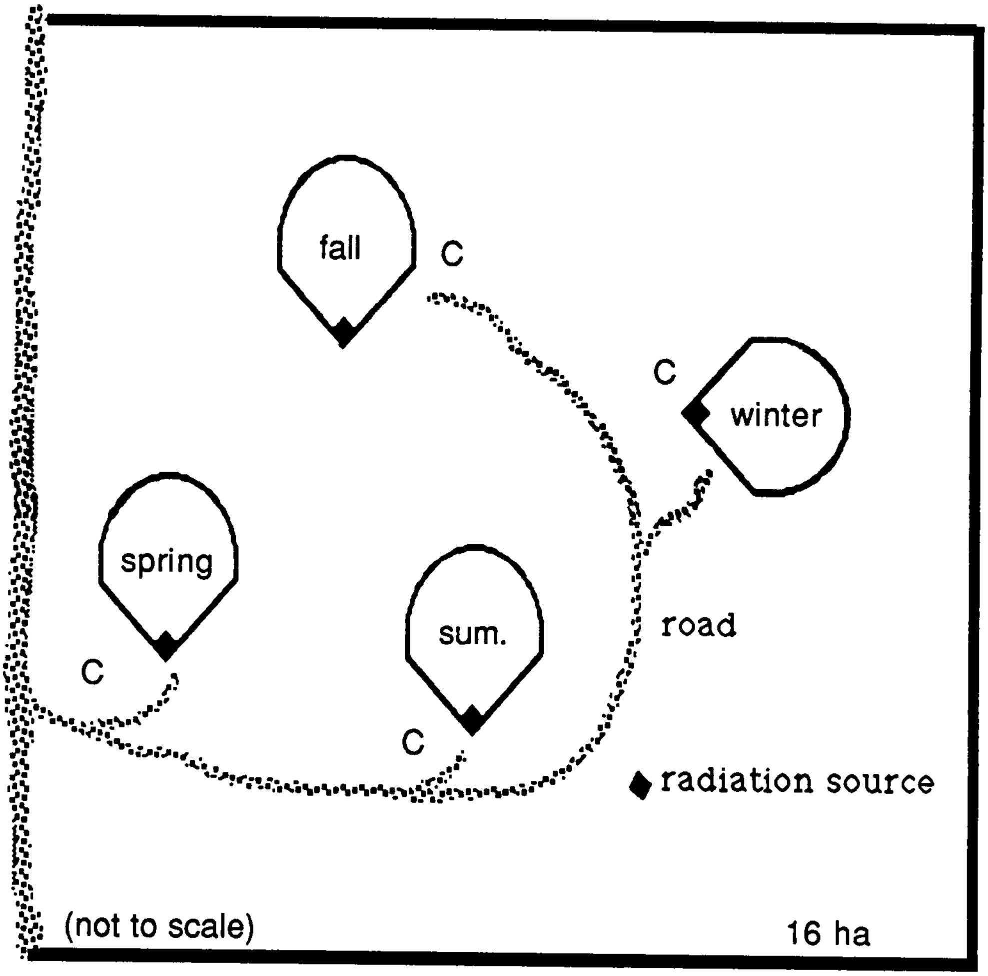

Figure 1. Map of the study area on the Savannah River Plant reservation. C = control trees.

season. The fall exposure (September 26-October 25) occurred just prior to dormancy. The winter exposure (December 22-January 20) occurred in the middle of dormancy. Exposures ranged from several hundred R/hr, a few meters from the source, to .10R/hr at 125 m from the source.

Experimental Design

There were two independent variables--radiation exposure dose and season of irradiation. The first variable, dose, was analyzed at three exposure levels: (1) 2.1 kR, (2) 0.7 kR, and (3) 0.17 kR. They were selected because Miller (1968) observed distinct differences in ecological responses to these radiation exposures. The second variable, season, consisted of (1) spring, (2) summer, (3) fall, and (4) winter exposures. Collectively, this resulted in 12 different treatment combinations. Control trees were selected at random from the vicinity of the four radiation sites. Height, diameter and annual increment of radial growth were measured for each tree.

A weakness of the statistical design was that seasonal exposures were not replicated, so error terms may not be independent. Since it was not practical to replicate each seasonal exposure, this concern was minimized by selecting a uniform study area.

Variability due to initial size differences in individual trees cannot be removed. Since productivity is related to tree size, larger trees should produce more wood each year than smaller trees. This variability was minimal because only 6% of the trees were in the "grass" stage at the time of treatment.

Sampling Criteria and Measurement

A total of one hundred and thirty longleaf pines were sampled on December 26-29, 1985, and March 31-April 3, 1986. Trees were permanently identified with aluminum tags. Height and diameter were measured, and tree cores were removed. At least twenty trees were sampled from each seasonal exposure site. Ten trees were selected as controls from an area adjacent to each of the four sites.

Selection of trees for coring was based on three criteria. The most important criterion was that trees be located along a selected isodose line, to assure that they received identical radiation exposures. Three isodose lines were selected on the basis of Miller's (1968) description of initial results. He described severe effects at 2.1kR, intermediate effects at 0.7kR and negligible effects at 0.17kR (Figure 2). Trees along the isodose line were randomly selected for sampling. Each had to be free from the competition of other trees on three sides. Measurements of 16 trees were discarded for several reasons. Four cores were from deformed trees, three cores were from control trees too young to have been planted in 1960, three cores were from trees too old to have been planted in 1960, and six cores had rings that could not be accurately dated.

Height was measured with a Suunto clinometer to the nearest 0.25 m, diameter was measured at breast height (1.5 m) with a steel diameter tape to the nearest 0.1 cm.

One core was taken from each tree 1.5 m above the ground with a 5 mm Suunto increment borer. Cores were taken from the irradiated side of the tree. Cores were air dried, mounted on a wooden board, sanded with four grades of sandpaper (200, 320, 400, and 600) and polished with lamb's wool to clarify ring structure. Only trees with rings which could be unmistakably dated and measured were analyzed. Ringwidths were measured to the nearest 0.01 mm

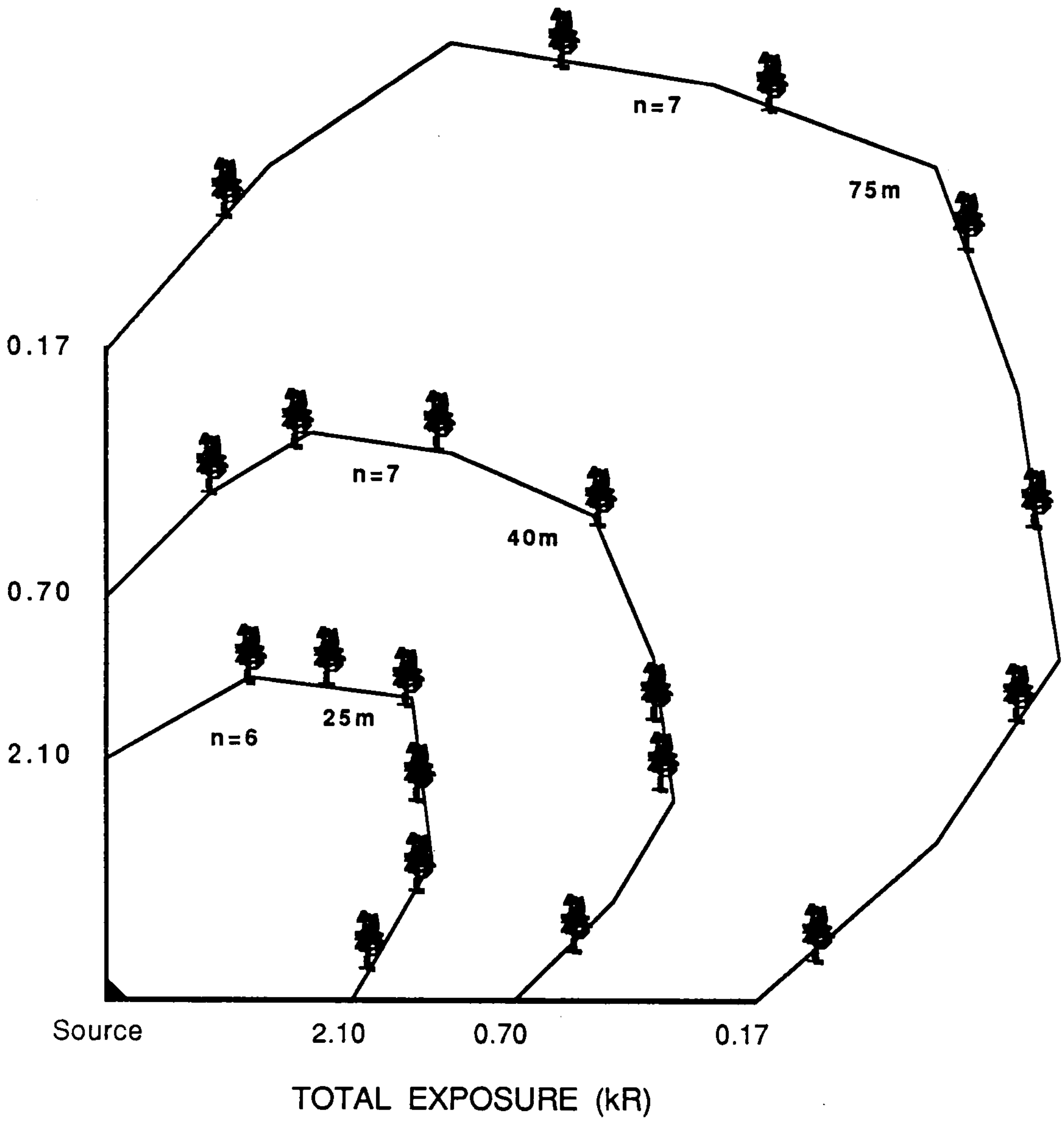

Figure 2. Sampling pattern in each seasonal radiation site.

using an electronic microcaliper (Henson full-range measuring machine) and checked for accuracy (Fritts 1976).

Statistical Analysis

Diameter and Height

Mean diameter and height were analyzed separately with a two factor analysis-of-variance (SAS 1982). Two experimental variables, radiation exposure dose and season of exposure were arranged in a 3 X 4 factorial design. Data for control trees were aggregated (n=34). Multiple comparison procedures were used in follow-up analyses. Paired comparisons to determine the influence of exposure dose were--2.1kR vs 0.7kR, 0.7kR vs 0.17kR, and 0.17kR vs controls. Paired comparisons to determine the influence of season were--spring vs controls, summer vs controls, fall vs controls, and winter vs controls. Type III sums of squares analysis was used to compare main effects in the presence of interaction (SAS 1982).

The Bonferroni method (Neter, Wasserman & Kutner 1985) was used to control Type 1 familywise error rate at the alpha = 0.05 level for preplanned comparisons. The three comparisons to determine the effect of exposure dose were each conducted at the 0.05/3 = 0.0167 level of significance. The four tests to determine the effects of season were each conducted at the 0.05/4 = 0.0125 level of significance.

Rate of Growth

Annual ringwidth measurements were used to reconstruct radial annual growth by subtracting ringwidths from the 1985 radius (DBH/2). Rate of growth was analyzed by comparing slopes of the growth curves. Slope was determined by fitting a regression line for each treatment and multiplying the coefficients for linear orthogonal polynomials by the appropriate radial value (Kirk 1982).

Comparisons of rate of growth among treatments were analyzed using a two factor multivariate analysis of variance method (MANOVA) for repeated measures (O'Brien & Kaiser 1985). This approach did not assume that variances among repeated measures were equal or that correlations between pairs of repeated measures were equal. Significant differences among slopes indicated differences in rate of growth.

The MANOVA model for rate of growth was similar to the ANOVA model used for analysis of diameter and height. Dose and season were the two experimental variables. The same paired comparisons were used to determine the influence of dose on growth and to determine the influence of season of irradiation on growth. Protection against a Type 1 error at the alpha = 0.05 level was determined by the Bonferroni method as previously discussed.

Annual Increment of Growth

Effects of radiation on radial growth during three post-radiation time intervals was analyzed by calculating average radial growth for 1970 to 1975, 1975 to 1980, and 1980 to 1985, respectively. Within each time period, mean growth was compared among treatments using the MANOVA method for repeated measurements as previously discussed (O'Brien & Kaiser 1985).

III. RESULTS

Diameter and Height *

Twenty years after irradiation trees exposed to the highest dose level (2.1kR) were significantly smaller in diameter than all other trees ($p < 0.05$) (Table 1). In contrast, mean diameters of trees exposed to lower dose levels (0.7 and 0.17kR) were not significantly different from mean diameters of control trees. Season of irradiation was found to have a significant effect on growth of spring, summer and fall irradiations, when data for each dose level within a season were averaged together. Mean diameters of trees irradiated during these seasons was significantly smaller ($p<0.05$) than mean diameters of trees irradiated in winter or of control trees. A summary of these results is presented in Figure 3. Mean diameter values were lowest for trees irradiated in the spring and increased with each succeeding season, regardless of dose level, except in the 2.1kR/summer and the 0.7kR/fall treatment groups.

Exposure to the highest dose level (2.1kR) also had a significant effect on tree height. Mean height of trees exposed to 2.1kR was significantly less ($p<0.05$) than the mean height of control trees. Mean height of trees exposed to lower dose levels (0.7 and 0.17kR) was not significantly different from mean height of control trees. Season of irradiation did not have a significant effect on height growth. These results are summarized in Figure 4. Mean height was fairly uniform except in the 2.1kR /summer irradiation group where mean height was very low.

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* Raw data describing mean height and diameter are summarized in Table 4 in the appendix.

Table 1. ANOVA Summary of Diameter and Height as Related to Radiation Dose and Season

		Diameter			Height		
Source of Variation	df	MS	F	p	MS	F	p
Between treatments	15	147.83	5.1	0.0001	8.83	2.68	0.0019
Season	3	206.26	7.11	0.0002	0.80	0.24	0.8667
Dose	3	340.38	11.73	0.0001	24.79	7.51	0.0001
Season/Dose	9	57.35	1.98	0.0499	6.54	1.98	0.0491
Error	99	29.01			3.30		
Dose Main Effect							
2.1 vs 0.7	1	315.97	10.89	0.0013	48.46	14.69	0.0002
2.1 vs 0.17	1	417.03	14.37	0.0003	57.01	17.28	0.0001
0.17 vs Control	1	101.51	3.51	0.0644	1.84	0.56	0.4575
Season Main Effect							
Spring vs Controls	1	785.63	27.08	0.0001	7.67	2.33	0.1304
Summer vs Controls	1	554.09	19.1	0.0001	8.09	2.45	0.1204
Fall vs Controls	1	336.52	11.6	0.001	1.74	0.53	0.4699
Winter vs Controls	1	10.41	0.36	0.5499	1.28	0.39	0.5354

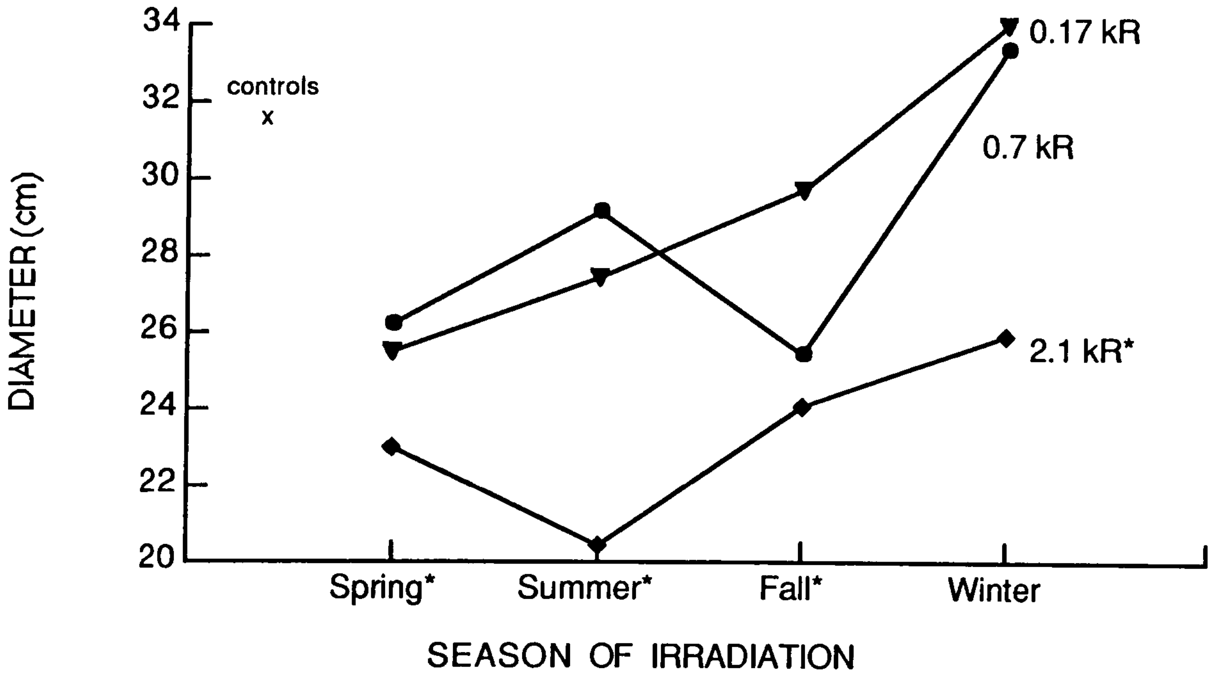

Figure 3. Mean 1985 diameter of trees previously exposed to ionizing radiation. * indicates significant differences from controls ($p<0.05$, Bonferroni method).

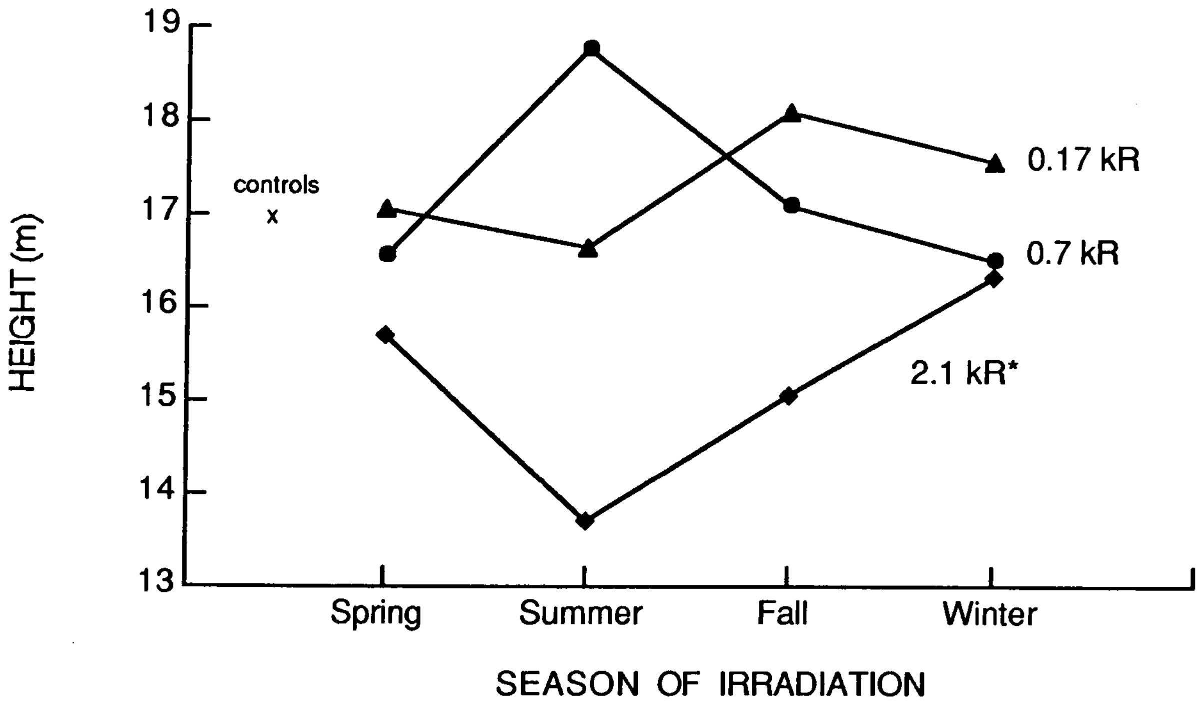

Figure 4. Mean 1985 height of trees previously exposed to ionizing radiation.
* indicates significant difference from controls (P<0.05, Bonferroni method).

Rate of Growth*

An analysis of growth rates for the past 20 years indicated that trees exposed to the radiation levels sampled (2.1, 0.7, and 0.17kR) are growing at a slower rate ($p<0.05$) than control trees (Table 2). Trees exposed to radiation in the summer and winter exhibited growth rates slightly higher than growth rates of trees which received spring and fall exposures. Figure 5 summarizes these results.

Annual Increment of Growth

Results of the MANOVA for the three 5-year time periods, 1970-1975, 1975-1980, and 1980-1985 indicated that radial growth of all irradiated trees sampled was significantly less ($p<0.05$) than radial growth for the control trees (Table 3). The influence of season of exposure also persisted for 20 years. Radial growth of trees irradiated in spring and fall was significantly less than growth of control trees (Figure 6).

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* Values of mean tree radii in three-year class intervals are summarized in Table 5 and presented in Figures 7-9 in the appendix.

Table 2. MANOVA Summary of Rate of Radial Growth

Source of Variation	df	MS	F	p
Between treatments	15			
Season	3	395.11	5.4	0.0018
Dose	3	552.02	7.55	0.0001
Season/Dose	9	281.74	3.85	0.0003
Error	99	73.16		
Dose Main Effect				
2.1 vs 0.7	1	8.39	0.11	0.7356
0.7 vs 0.17	1	6.8	0.09	0.7611
0.17 vs Control	1	1217.34	16.64	0.0001
Season Main Effect				
Spring vs Controls	1	647.86	0.07	0.7972
Summer vs Controls	1	24613.01	2.54	0.1187
Fall vs Controls	1	1533.78	0.16	0.6927
Winter vs Controls	1	9260.51	0.96	0.3339

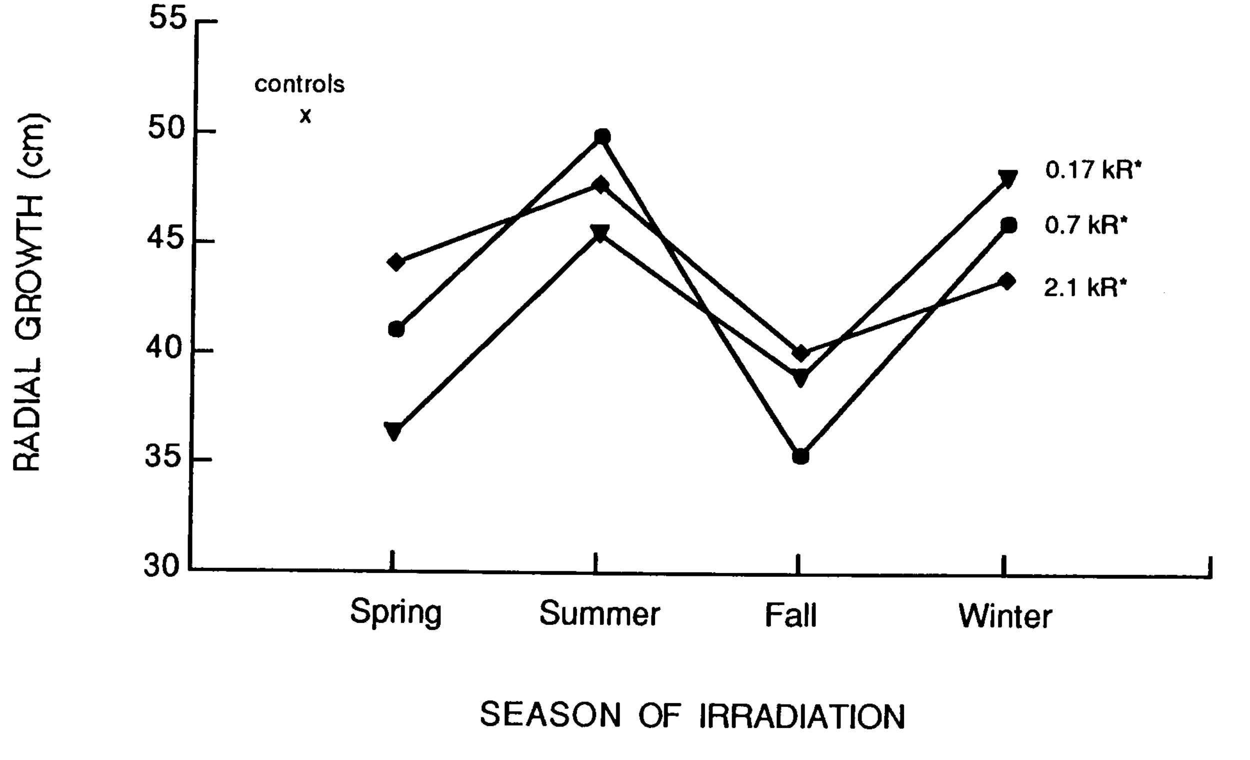

Figure 5. Mean rate of radial growth from 1970 to 1985. * indicates a significant difference from controls ($p<0.05$, Bonferroni method).

Table 3. MANOVA Summary of Radial Growth for Post-radiation Time Intervals: 1970-1975, 1975-1980, 1980-1985

		1970-1975			1975-1980			1980-1985		
Source of Variation	df	MS	F	p	MS	F	p	MS	F	p
Between treatments										
Season	3	228.35	2.93	0.0374	65.18	2.82	0.0427	125.12	5.93	0.0009
Dose	3	521.74	6.7	0.0004	104.66	4.54	0.0051	95.55	4.53	0.0051
Season/Dose	9	282.85	3.63	0.0006	51.53	2.23	0.026	48.2	2.28	0.0227
Error	97	77.92			23.07					
Dose Main Effect										
2.1 vs 0.7	1	14.17	0.18	0.6707	18.46	0.8	0.3732	60.73	2.88	0.093
0.7 vs 0.17	1	14.07	0.18	0.6719	7.74	0.34	0.5638	14.33	0.68	0.4119
0.17 vs Control	1	1056.81	13.56	0.0004	267.97	11.61	0.001	145.63	6.9	0.01
Effect of Season										
Spring vs Controls	1	1727.49	22.17	0.0001	322.19	13.96	0.0003	430.39	20.4	0.0001
Summer vs Controls	1	166.06	2.13	0.1476	37.17	1.61	0.2074	25.62	1.21	0.2732
Fall vs Controls	1	1761.59	22.61	0.0001	262.77	11.39	0.0011	191.85	9.09	0.003
Winter vs Controls	1	445.59	5.72	0.0187	81.99	3.55	0.0624	48.78	2.31	0.1316

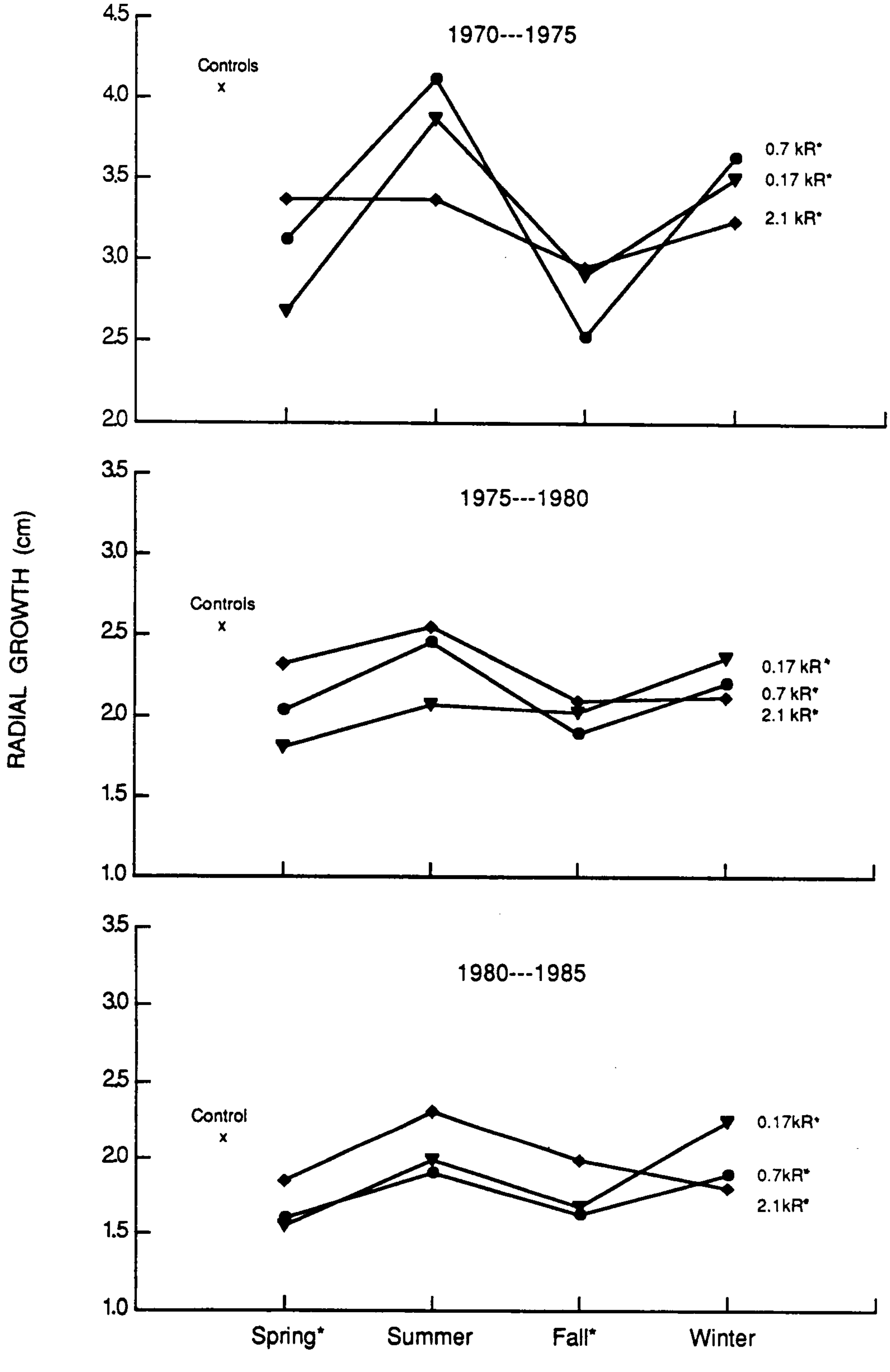

Figure 6. Mean radial growth for three post-radiation time intervals: 1970-1975, 1975-1980, 1980-1985. * indicates a significant difference from controls ($p<0.05$, Bonferroni method).

IV. DISCUSSION

Diameter and Height

Results of this study were generally consistent with results reported by Miller (1968). In both studies trees exposed to 2.1kR were severely impacted. During the first year after irradiation, this population experienced up to 40% mortality and 100% terminal bud death. Significant reduction in height and diameter growth of trees 20 years later appears to be a direct consequence of severe impacts reported initially.

In 1968 impacts to trees exposed to lower dose levels were less severe---trees exposed to 0.7kR experienced 0-9% mortality, and 50-96% terminal bud death. Trees exposed to 0.17kR experienced 0% mortality, 0% terminal bud death, and no significant differences in growth when compared to the control population. After 20 years, height and diameter of these trees were not significantly different from the control trees.

Miller (1968) also described distinct responses to season. Trees exposed in the spring and summer sustained greater damage than trees exposed in the fall and winter; and damage was expressed more quickly after irradiation. Trees exposed to radiation in the fall and winter exhibited only minor damage until a hot, dry period occurred in April and May, 1967. After 20 years, diameter growth of trees irradiated in the spring and summer was significantly less than diameter growth of controls. Trees irradiated in the fall also exhibited significantly less diameter growth than controls. This reduction was unexpected since only minor damage was observed in 1968. It may be explained by the fact that in the fall, when meristematic cells were quiescent, they absorbed radiation and were damaged; however, the damage was not visible until cell activity resumed.

Tree height and diameter of the 2.1kR/summer population were particularly low. Tree ring analysis revealed that these trees did not reach breast height until 1972. Miller (1968) noted the occurrence of a severe drought during the summer treatment which killed above ground tissues. He later observed growth of lateral buds, which were, presumably, shielded during treatment. The two stresses, radiation and drought, appear to have had a cumulative effect resulting in the most severe damage sustained by any treatment group. Similar additive responses have been observed in laboratory studies for pine seedlings (McCormick & McJunkin 1965) and in a field study (Woodwell & Miller 1962). Woodwell and Miller (1962) reported that reduced, discontinuous or missing tree rings were common in chronically irradiated trees and that severity of the effect was influenced by size of the tree crown and climatic stress.

Rate of Growth

Results showed that the rate of growth of trees exposed to the three dose levels was lower than the rate of growth of control trees. Growth rates of trees exposed to radiation in the summer were higher than expected at all dose levels. This suggests that growth was influenced by some factor in addition to radiation. The summer exposure site has a slightly higher clay content in the soil. This would provide higher water and nutrient retention. Friebaum (1987) found depth to the clay layer to be the most important factor influencing productivity on a similar site on the Savannah River Plant Reservation.

Annual Increment of Growth

At all radiation dose levels, trees irradiated 20 years ago have not produced as much wood as unirradiated trees. This prolonged suppression of growth is unexpected, particularly for trees that received only 0.17kR. However, there is collaborative evidence in a recent study. Mishenkov et al. (1983) reported that six years after exposure to acute gamma irradiation a decrease in primary production was only partially reversible following doses of 15--25 Gy (1.5--2.5kR).

V. CONCLUSIONS

The effects of ionizing radiation on height and radial growth of longleaf pine were detectable 20 years after irradiation. Trees exposed to highest levels of radiation and trees exposed during seasons of greatest cell activity had the greatest reduction in growth. Trees exposed to 2.1 kR were significantly shorter and had smaller diameters than control trees and trees exposed to lower dose levels. Trees exposed in spring, summer, and fall had significantly smaller diameters than trees irradiated in winter or than controls. Rate of growth during the 20 years since irradiation was significantly less for trees exposed to 2.1, 0.7, and 0.17kR than for control trees. Influence of all three exposure doses studied was detectable after 20 years. Radial growth of all irradiated populations was significantly less than controls during all time periods (1970-1975, 1975-1980, and 1980-1985) following irradiation. The influence of season of irradiation also persisted for 20 years. Radial growth of trees irradiated in the spring and fall was significantly less than radial growth of control trees during all three post treatment time periods.

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APPENDIX

Table 4. Means and Standard Errors of Diameter and Height for the 12 Treatment Groups

Dose X Season		n	Diameter Mean	Diameter Std Err	Height Mean	Height Std Err
2.1	Spring	8	22.97	1.51	15.70	0.59
	Summer	6	20.45	0.95	13.72	0.58
	Fall	5	24.10	0.73	15.06	0.36
	Winter	6	25.90	1.63	16.33	0.55
0.7	Spring	9	26.20	1.77	16.57	0.39
	Summer	7	29.16	2.05	18.77	0.85
	Fall	5	25.44	0.87	17.10	0.74
	Winter	4	33.37	0.85	16.50	0.95
0.17	Spring	11	25.49	1.78	17.07	0.59
	Summer	11	27.45	3.05	16.66	0.74
	Fall	5	29.70	2.48	18.10	0.84
	Winter	4	33.97	1.73	17.56	1.39
Control		34	31.81	1.53	16.99	0.58

Table 5. Mean Radii Every Three Years for the 12 Treatment Groups

Dose X Season		1967	1970	1973	1976	1979	1982	1985
2.1	Spring	2.15	3.95	6.12	7.9	9.32	10.42	11.49
	Summer	---	1.99	4.19	5.94	7.47	8.92	10.23
	Fall	3.83	5.31	7.17	8.72	10.01	11.21	12.35
	Winter	3.62	5.78	7.83	9.59	10.87	11.99	12.95
0.7	Spring	4.28	6.34	8.32	9.99	11.25	12.13	13.1
	Summer	4.08	6.11	8.73	10.87	12.35	13.48	14.58
	Fall	5.19	6.68	8.3	9.62	10.82	11.8	12.72
	Winter	6.84	8.97	11.36	13.15	14.52	15.61	16.69
0.17	Spring	5.23	7.08	8.87	10.2	11.33	12.23	13.12
	Summer	3.76	6.21	8.6	10.47	11.88	13.07	14.27
	Fall	6.54	8.25	10.14	11.59	12.83	13.97	14.85
	Winter	6.58	8.88	11.2	12.92	14.41	15.72	16.99
Control		4.86	7.22	9.81	11.84	13.65	14.63	15.9

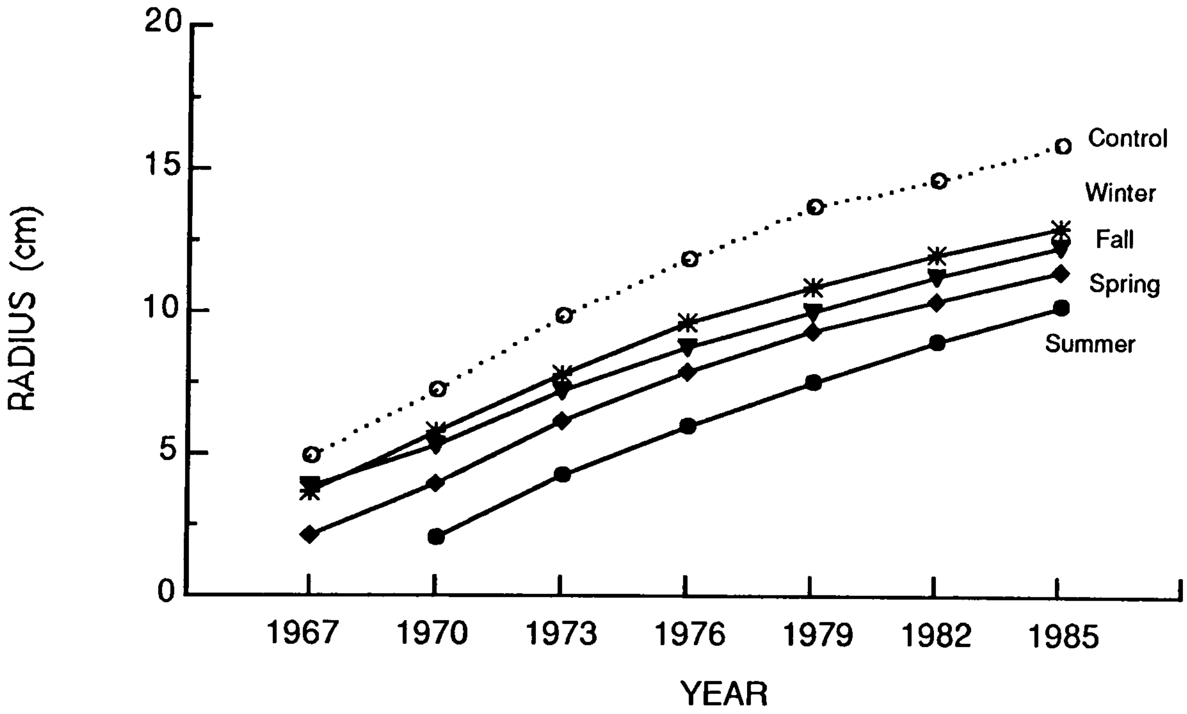

Figure 7. Mean radial growth from year after treatment to 1985 of trees exposed to 2.1kR.

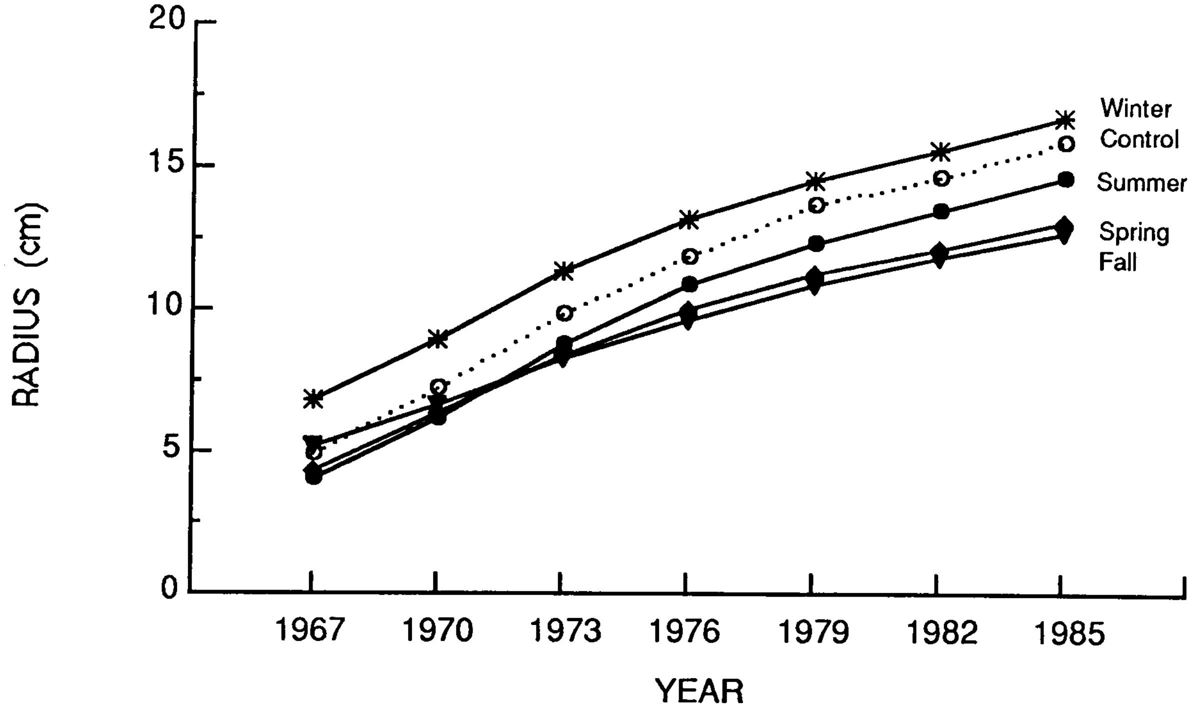

Figure 8. Mean radial growth from year after treatment to 1985 of trees exposed to 0.7kR.

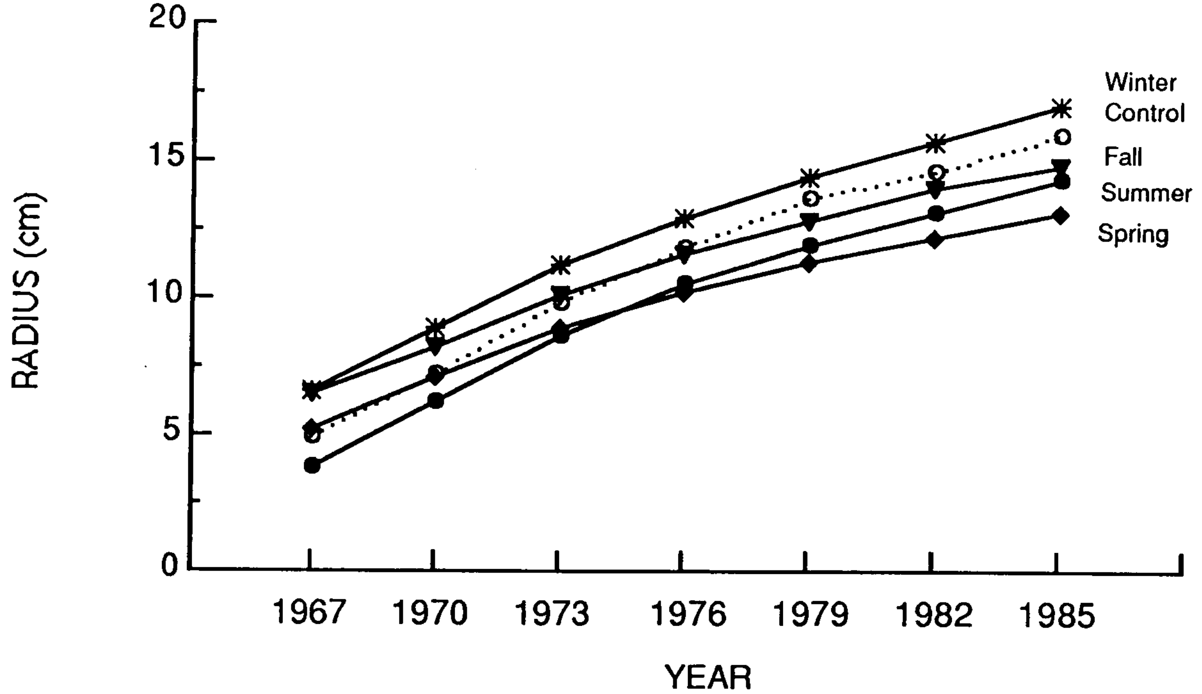

Figure 9. Mean radial growth from year after treatment to 1985 of trees exposed to 0.17kR of radiation.

VITA

Jackie A. Cunningham was born in Leeds, Alabama. She attended schools in England, Florida, Maine, and Mississippi. She graduated from Leeds High School, in Leeds, Alabama, and attended Auburn University, where she received a Bachelor of Science degree in Botany and a Master of Education degree in Secondary Education.

She was employed by the Federal government for nine years in the areas of environmental impact assesment and natural resource management. As an employee of the Tennessee Valley Authority at Norris, Tennessee, she collected and used endangered species information in land planning. At the Corps of Engineers in Nashville, Tennessee, she was responsible for compliance of Corps projects with Federal legislation. She completed the environmental portion of seven water resource development projects and received awards for special achievement and exceptional performance.

She entered the Graduate Program in Ecology at the University of Tennessee and received a research stipend from the University of Tennessee Center of Excellence in Waste Management, Research and Education. While attending graduate school, the Energy Division of Oak Ridge National Laboratory employed her as a Research Specialist in environmental impact assessment. She received the Master of Science degree in Ecology.

She is married to J. Vann Cunningham and has one child, Seth Walker McKitrick.