Response of a Native Shortgrass Plant Stand to Ionizing Radiation

L. Fraley and F. W. Whicker

Department of Radiology and Radiation Biology
 Colorado State University
 Fort Collins, Colorado 80521

ABSTRACT

An 8750 Ci Cs-137 source was installed in a native shortgrass plant stand near Nunn, Colorado. Treatments were chronic and semi-acute (30 da) seasonal exposures. Exposure rates varied from 650 R/hr to 7.8 mR/hr. The chronic exposure rate which resulted in a 50 per cent reduction in diversity was continuing to decrease after two growing seasons. The stand appeared to be more sensitive in the late fall, intermediate in the spring and most resistant in the summer. The phenological development of some species was retarded by a chronic exposure of 1 R/hr. There was a significant effect on the total standing crop for all treatments and a significant effect on the grass-sedge component of the standing crop with the late fall showing the greatest sensitivity. The overall results indicated that the shortgrass community was relatively radioresistant in comparison to other plant communities.

INTRODUCTION

The use of large gamma sources to expose natural ecosystems to ionizing radiation can lead to a better understanding of the effects of radiation on living systems, on individual components of the system, and can lead to estimates of damage to ecosystems that can be expected in case of nuclear disasters. This study was designed to determine the effect of gamma radiation on several structural and functional attributes of a native shortgrass prairie plant stand in north-central Colorado.

Sparrow and Sparrow (1965) related radiation sensitivity of plants to the interphase chromosome volume. Woodwell and Sparrow (1963) used chromosome number and nuclear volume to predict the sensitivity of a near-climax oak-pine forest. The results indicated the general usefulness of the method but the sensitivity was greater than that predicted. Environmental factors and plant life form appeared to modify the sensitivity from the predicted values. McCormick (1963) used a large source to study

NOTICE
 This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

the effects of radiation on a herbaceous plant community of the southeastern United States. There was a difference in the response of the spring and summer flora and one species was apparently stimulated by the radiation with a resulting ecotone shift during the year following irradiation. Monk (1966) irradiated an old field plant stand and found a 50 per cent reduction in diversity after a 400 hour exposure of 30 R/hr (12 kR total exposure). Miller (1968) used a large portable source to irradiate an old field in four seasons to assess the sensitivity through the seasons and reported that the stand was most sensitive in the spring and most resistant in the winter. Daniels (1963) found an apparent reversal or prolongation of the initial stages of succession after an old field was exposed to mixed neutron-gamma radiation. Past studies have shown a wide range of sensitivities of plant communities and exposure to radiation has generally resulted in a reduction in community diversity.

METHODS

An 8750 Ci ^{137}Cs source was installed in a native shortgrass plant stand on the Central Plains Experimental Range northeast of Nunn, Colorado. The area around the source was divided into six sectors, each subtending an angle of 60° of which 45° was usable for the study. The source was suspended one meter above the ground. The treatment of each sector was: sector 1, control (continually shielded); sectors 2 and 3, chronic (continually open); sector 4, spring exposure (shielded except April 1969); sector 5, summer exposure (shielded except July 1969); sector 6, late fall exposure (shielded except December 1969). Each sector was divided into 22 macroplots varying in distance from 2 to 50 meters from the source. The exposure rates varied from 650 R/hr at the back side of the first macroplot to 0.0078 R/hr at the back side for the most distant macroplot. For the seasonally exposed sectors, this gave a total exposure of 4.9×10^5 R to 5.9 R from the closest

to the most distant macroplot. The width of each macroplot was adjusted to give approximately a 50 per cent decrease in the exposure rate from each plot to the next. A group of twelve permanently marked microplots were located at the center of the back edge of each macroplot. (In macroplot one of each sector, fewer than 12 microplots were used due to space limitations.) Each microplot was marked by the use of two plastic stakes which mated with locating rings on a 25 by 25 cm quadrat.

The source was raised into the operating position on 3 April 1969 and has been in this position continually except for up to 4 hours per day down time allowed for work within the gamma field.

The microplots were scored three times during 1969 and 1970 for the density of each species (except for blue grama, Bouteloua gracilis, which was scored for basal ground cover in a 5 by 5 cm quadrat nested in one corner of the larger quadrat frame). The times of scoring were early April (pre-irradiation for 1969), mid to late June, and late September. The density data were used to calculate the frequency of occurrence for each species following the method used by Hyder, et al. (1965). The frequency data were used to calculate a diversity index in a method similar to that of Patten (1962). We used the relationship

$$\text{diversity index} = -1.433 \sum_{i=1}^n p_i \ln(p_i)$$

where p_i was taken as the frequency of occurrence of each of the n species. The diversity index data were related to the exposure rate with an arctan function using a nonlinear least squares technique. The arctan function was

$$y (\text{diversity index}) = \pi/2k + (1/k) \tan^{-1}(-(\log x)/a + b)$$

where the mean of the no radiation effects region, $\bar{y} = \pi/k$, x = exposure rate in R/hr, and a and b were the parameters to be fitted. The parameter a determines the breaking points on the curve and the slope and b determines the phase relationship or the location of the sloping portion of the

curve along the exposure rate axis. The value of k was determined by the zero slope portion of the diversity index versus exposure rate curve. The inflection point is at the $y = \pi/2k$ point on the curve. This gives the exposure rate which results in a 50 per cent reduction in diversity (D_{50}) and this was found by setting the argument of the arctan function equal to zero and solving for x , i.e., $-(\log x)/a + b = 0$ or $x = \text{antilog}(ab) = D_{50}$.

During the 1969 and 1970 growing seasons phenology was recorded for all species in the control and chronic sectors at approximately weekly intervals using the scale of 0= dead or dormant, 1= vegetative, 2= flower bud formation for forbs and shrubs or inflorescence emergence for grasses, 3= flowering for forbs and shrubs or anthesis for grasses, and 4= seed formed or dispersed. These data were then interplotted to determine a phenological index versus time relationship for isoexposure rates of 100, 30, 10, 3, 1 and .3 R/hr.

In September 1970 the microplots in sectors 2, 4, 5 and 6 were clipped at approximately 5mm above ground level (total standing crop) and the clipped material separated into the grass-sedge, forb and shrub components. These data were converted to dry weight and g/m^2 values.

RESULTS AND DISCUSSION

Diversity Index

The effect of the radiation on the plant community caused the formation of three zones. A sterile zone, closest to the source where essentially all plants were killed; a transition zone where more sensitive individuals and/or species were killed while the more resistant ones survived; and a "no effects" zone where methods used did not measure any changes and the slope of the diversity index versus exposure rate curve did not differ significantly from zero when tested with a linear regression model. The transition zone is the sloping portion of the arctan function. The location

of the sloping portion along the exposure rate axis indicated the effect of the radiation on diversity. The exposure rate which resulted in a 50 per cent reduction in diversity (D_{50}) is given in Table 1. The data in this zone were fit to a straight line using a linear regression model and the D_{50} values were calculated for comparison with those calculated from the arctan function. The resulting D_{50} values were similar to those derived from the arctan function with the regression line values averaging 15 per cent larger. After the linear regression model was fitted and the D_{50} value was calculated, the standard error for the value of y which equalled $\bar{y}/2$ was calculated (Table 2).

There were natural changes in diversity throughout the time of the experiment. In order to examine the data in the absence of these fluctuations, which were due largely to the presence of annuals during the June sampling date and the variation in the development of some perennial species, each data point was normalized to bring the no radiation effects average to the same value as the June 1970 control sector average. This adjusting procedure (multiplying each data point by a constant) had no effect on the nonlinear curve fitting process.

In the chronic sectors, the transition zone receded from the source with time (Figs. 1 and 8). The D_{50} values dropped continually with the largest percentage decrease from the April to the June sampling dates each year. No percentage decrease can be calculated for the first D_{50} value of 50 R/hr for June 1969. The change from April to June 1970 was from 21 to 12 R/hr or a 43 per cent decrease. Other decreases were approximately 34 per cent from one sampling date to the next (Table 1). No detectable changes in diversity were found at exposure rates of 3.4 R/hr or less for the September 1970 sampling date. There is no way to predict future changes but it is expected that the D_{50} values for the chronic sectors will continue to decrease although the rate of decrease may change.

The lethal zone in the spring exposure sector was smaller than that in the chronic sectors (Fig. 2). The June 1969 D_{50} value was larger indicating that the transition zone was closer to the source. By September 1969 recovery was taking place and a much larger D_{50} value occurred. By spring 1970 sufficient recovery had taken place that the arctan function no longer applied to the data. The data points for the three righthand curves ($t = 377, 443$ and 535 days after 1 April 1969) in Fig. 2 for the first five macroplots out from the source are the actual, adjusted data points. Data points from macroplots farther from the source are from the no effects zone and the line plotted is the no effects average.

The summer exposure sector had a lethal zone smaller than the spring sector (Fig. 3). The D_{50} value for the first sampling date (September 1969) after exposure was over twice as large (180 compared to 72 R/hr) as the spring sector. By April 1970 no significant recovery had taken place and there was a sharp decline in the D_{50} value (to 65 R/hr). Some of this decline was due to temporary effects on the blue grama and other perennials. These had partially recovered by June 1970 and this recovery plus invasion by annuals increased the diversity in macroplots 3, 4 and 5 and the arctan function no longer applied to the data. The data for the June and September 1970 sampling dates was plotted in the same manner as the data from the spring sector for those dates.

The late fall exposed sector did not show any measurable effect on diversity the first sampling date (April 1970) after irradiation (Fig. 4). The June 1970 diversity index data indicated a zonation similar to the other sectors but the lethal zone was larger and the D_{50} value smaller (58 R/hr compared to 72 for spring and 180 for summer). No recovery was apparent by September 1970. The diversity index data indicated that the shortgrass plant stand was most sensitive during the late fall and least

sensitive during the summer. There was greater damage to the blue grama, the dominant species, in the late fall exposure sector than in either the spring or summer sectors. This effect can be seen in Fig. 8.

Plants that are dormant during a semi-acute exposure may exhibit more damage because the average amount of energy absorbed per cell would be greater than in the rapidly dividing cells of growing plants. The damage resulting from the greater absorbed energy would not be manifest until the time when cell division started to increase.

Recovery in the spring and summer sectors was primarily due to invasion of the annuals russian tumble thistle (Salsola kali), slimleaf goosefoot (Chenopodium leptophyllum), ridgeseed euphorbia (Euphorbia glyptosperma) and prairie pepperweed (Lepidium densiflorum). Part of the recovery was due to perennials whose perennating organs were underground and only the upper portions of the plant were killed. Four species which reacted in this manner were scarlet globemallow (Sphaeralcea coccinea), rush skeletonplant (Lygodesmia juncea), scarlet gaura (Gaura coccinea) and evening primrose (Oenothera coronopifolia). By mid-1970, the plant stand had at least partially recovered as measured by diversity but it had a different species composition than the pre-irradiation plant stand. The lack of recovery in the lethal zone of the winter exposure sector may have been due to sterilization of seeds of the invader species. No explanation can be given at the present time for the failure of the perennial species to recover in the winter sector as they did in the spring and summer sectors. In the chronic sectors, there was no evidence of more resistance species invading areas where competition had been eliminated by the killing of the more sensitive species.

Phenology

The effect of chronic irradiation on the phenological development of four species; prairie spiderwort (Tradescantia occidentalis), broom snakeweed (Gutierrezia sarothrae), plains pricklypear (Opuntia polyacantha) and blue grama (Bouteloua gracilis) is shown in Fig. 5. Thirty R/hr was lethal to all species listed except blue grama. Ten R/hr delayed and suppressed the development of spiderwort although some individuals developed flower buds at this exposure rate. Ten R/hr was lethal to some individuals of broom snakeweed with some of the surviving plants developing flower buds, was almost totally lethal to plains pricklypear and only slightly delayed the development of blue grama. Three R/hr both delayed and suppressed development of spiderwort with nearly all individuals forming flower buds and some flowering. Most of the plains pricklypear individuals remained vegetative at 3 R/hr with some developing flower buds which later aborted. There was no detectable difference between the development of the control plants and those exposed to 3 R/hr for broom snakeweed and blue grama. The lowest exposure which caused a detectable delay or suppression in the development of plains pricklypear and spiderwort was 1 R/hr. There appeared to be a slight delay in the development of seed in plains pricklypear and no seed was formed in any spiderwort plant at this exposure rate although there was no apparent delay in flowering.

A careful interpretation of the phenological index may be necessary in order to get a true indication of the sensitivity of the species shown in Fig. 5. There appears to be a very narrow band (10 to 3 R/hr) of exposure rates for going from lethality to no effect on plant development for broom snakeweed while there is a much larger band (10 to .3 R/hr) for spiderwort. However, the life forms are very different for these two species. Broom snakeweed is a small shrub with the meristematic tissue fully exposed

to the radiation during the year (a phanerophyte). Spiderwort is a monocotyledon with the meristematic tissues 5 to 10 cm underground most of the year (a cryptophyte). This species probably survived higher levels of irradiation because of the shielding effect of the soil and, based on the exposure rate which resulted in no seed production, may actually be more radiosensitive than broom snakeweed. Blue grama, which also shows a relatively narrow band (30 to 10 R/hr) is a hemi-cryptophyte with the meristem located at approximately ground level. Thus small portions of the meristematic tissues might be shielded by soil and thereby receive a smaller exposure rate than the average measured for that site.

Standing Crop

In the chronic sectors there was a significant difference in the September 1970 total standing crop in the first 13 macroplots (Fig. 6). This was due to the death of individuals and/or species combined with a suppression of growth of those remaining. Contrary to results reported by Woodwell and Oosting (1965) there was no evidence of an increase in standing crop of any species due to decreased interspecific competition. Considerable recovery had occurred in the spring and summer sectors when the total standing crop was harvested. In the spring sector, the first macroplot standing crop was significantly lower than the overall no radiation effects mean. This plot lacked the recovery evidence in macroplot two although no explanation can be offered for this at the present time. The second macroplot had standing crop of over 1800 g/m^2 but due to a high variance, the value could not be shown to be significantly different than the mean of the unaffected plots. One microplot in this macroplot had one large russian tumble thistle (1200 g) which contributed to the large variance. None of the microplots in the no effects zones had a standing crop greater than a few tens of grams. In the summer sector, the standing

crop in the first macroplot was significantly higher than the mean of the unaffected plots. This difference was due to the presence of russian tumble thistle, slimleaf goosefoot and pepperweed.

A better insight into the amount of radiation damage for each treatment can be obtained by looking only at the grass-sedge component of the standing crop (Fig. 7). A straight line was fitted to the sloping portion of these data and the exposure rate which resulted in a 50 per cent reduction in the grass-sedge component of the standing crop (SC_{50}) were calculated from the regression line (Table 3). Except for the chronic sectors, the late fall sector was most sensitive, the summer sector the most resistant and the spring sector intermediate. The primary factor effecting yield in the semi-acute sectors was probably lethality since these data were taken one growing season after irradiation. This was also indicated by the survival data for blue grama. In the chronic sectors the SC_{50} value was 6.7 R/hr. This was probably influenced by lethality as well as the effect of physiological adjustments to the radiation by the living plants remaining in the microplots.

CONCLUSIONS

The data presented in this paper, when compared to data presented by other authors reporting on similar studies, indicated that the shortgrass prairie plant community was among the most radioresistant plant communities studied to date. McCormick (1969) summarized the radiosensitivity of five plant communities and reported that the exposure necessary to produce severe effects ranged from 2 to 3 kR for a pine forest to 45 kR for abandoned crop land. The shortgrass prairie plant community required exposures of 45 to 135 kR to produce comparable effects, depending on the season of exposure. Miller (1968) concluded that an old field plant community was most sensitive to radiation during the spring while the shortgrass plant

community was the most sensitive during the late fall (December) season.

No increase in the density of radioresistant species in the chronic sectors was observed as reported by Woodwell and Rebuck (1967).

Woodwell and Rebuck (1967) reported a measurable reduction in the height growth of stems of pines and oaks in areas receiving as little as 1 R/day. The minimum exposure for which measurable effects were found in the shortgrass plant community was 1 R/hr (24 R/day). The exposure rate which resulted in a 50 per cent reduction in diversity was 8.1 R/hr at the end of 1 1/2 years of continuous exposure and was still decreasing.

ACKNOWLEDGMENTS

We would like to thank Drs. D. N. Hyder and R. E. Bement of the U. S. Department of Agriculture, Agricultural Research Service for their cooperation, help in planning this research and help in the identification of plant species. We would like to thank Drs. R. T. Ward and R. L. Dix of the Department of Botany and Plant Pathology for their assistance in the early planning of this research. We would like to thank R. B. Smith, Northern Arizona University, Flagstaff, Arizona for his help in the early stages of the field work. We would like to thank J. Doerges for his help in conducting the field work. This study was funded by the U. S. Atomic Energy Commission, contract AT(11-1)-1156. The use of the land area was made possible by the cooperation of the U. S. Department of Agriculture, Agricultural Research Service.

Literature cited

- Daniels, C. P. 1963. Study of succession in fields irradiated with fast neutron and gamma radiation. p 277-282 in: Radioecology. V. Schultz and A. W. Klement, Jr. (Eds.). Reinhold, New York.
- Hyder, D. N., R. E. Bement, E. E. Remmenga, and C. Terwilliger, Jr. 1965. Frequency sampling of blue grama range. J. Range Manage. 18:90-93.
- McCormick, F. 1963. Changes in a herbaceous plant community during a three-year period following exposure to ionizing radiation gradients. p 271-276 in: Radioecology. V. Schultz and A. W. Klement, Jr. (Eds.).
- _____. 1969. Effects of ionizing radiation on a pine forest. p 78-87 in: Symposium on Radioecology. D. J. Nelson and F. C. Evans (Eds.). CONF-670503. U. S. Atomic Energy Commission, Division of Technical Information Extension, Oak Ridge, Tennessee.
- Miller, G. L. 1968. The influence of season on the radiation sensitivity of an old field community. Ph. D. Thesis. University of North Carolina, Chapel Hill, North Carolina. 250 p.
- Monk, C. D. 1966. Effects of short-term gamma irradiation on an old field. Radiation Bot. 6, 329-335.
- Patten, B. C. 1962. Species diversity in net phytoplankton of Raritan Bay. J. Marine Res. 20, 57-75.
- Sparrow, R. C., and A. H. Sparrow. 1965. Relative radiosensitivities of woody and herbaceous spermatophytes. Science. 147, 1449-1451.
- Woodwell, G. M. and J. K. Ossting. 1965. Effects of chronic gamma irradiation on the development of old field plant communities. Radiation Bot. 5, 205-222.
- Woodwell, G. M. and A. L. Rebeck. 1967. Effects of chronic gamma radiation on the structure and diversity of an oak-pine forest. Ecological Monographs. 37, 53-69.
- Woodwell, G. M. and A. H. Sparrow. 1963. Predicted and observed effects of chronic gamma radiation on a near-climax forest ecosystem. Radiation Bot. 3, 231-237.

Table 1. Exposure rates (R/hr) at which 50 per cent reduction in diversity (D₅₀ values) occurred for treatments at various sampling dates and the fitted parameters for the arctan function.

sampling date	chronic exposure	seasonal exposure		
		spring	summer	late fall
6-69	50	72 (55)*		
9-69	33	320 (243)	180 (135)	
4-70	21		65 (49)	
6-70	12			58 (44)
9-70	8.1			74 (56)
6-69	.21 ± .049**8.0 ± 1.9	.17 ± .081 11.1 ± 5.2		
9-69	.11 ± .051 13.6 ± 6.4	.22 ± .21 11.6 ± 11.5	.096 ± .10 23.6 ± 25.8	
4-70	.20 ± .085 6.5 ± 2.9		.056 ± .051 32.3 ± 30.9	
6-70	.078 ± .019 14.0 ± 3.4			.18 ± .078 9.9 ± 4.4
9-70	.18 ± .072 5.2 ± 2.2			.11 ± .079 17.1 ± 11.3

*Value in parentheses is the total exposure in kR.

**The first value is the fitted parameter a ± one standard error and the second value is the fitted parameter b ± one standard error.

Table 2. Values of $\bar{y}/2 \pm$ one standard error for the irradiation treatments on various sampling dates.

sampling date	chronic exposure	seasonal exposure		
		spring	summer	late fall
6-69	1.58 $\pm$.51	1.73 $\pm$.70		
9-69	.88 $\pm$.34	.93 $\pm$.56	.88 $\pm$.68	
4-70	.67 $\pm$.30		.61 $\pm$.42	
6-70	2.45 $\pm$ 1.07			2.67 $\pm$.93
9-70	1.30 $\pm$.52			1.34 $\pm$.58

* $\bar{y}/2$ = mean diversity index in no radiation effects zone/2.

Table 3. SC_{50} values (R/hr) for the grass-sedge component of the September 1970 total standing crop and the standard errors (g/m^2) for the $SC/2$.

Attribute	chronic exposure	seasonal exposure		
		spring	summer	late fall
SC_{50}	6.7	79	125	35
$\overline{SC}/2 \pm s.e.$	26 ± 11	26 ± 12	26 ± 13	26 ± 15

List of figure captions

Fig. 1. Normalized diversity index as a function of time and exposure rate for the chronically irradiated sectors.

Fig. 2. Normalized diversity index as a function of time and exposure rate for the spring irradiated sector (shaded rectangle on time axis indicates period of irradiation).

Fig. 3. Normalized diversity index as a function of time and exposure rate for the summer irradiated sector (shaded rectangle on time axis indicates period of irradiation).

Fig. 4. Normalized diversity index as a function of time and exposure rate for the late fall irradiated sector (shaded rectangle on time axis indicates period of irradiation).

Fig. 5. Phenological index as a function of time after 1 April 1970 for selected chronic exposure rates and for four selected shortgrass prairie species; Tradescantia occidentalis (Troc), Gutierrezia sarothrae (Gusa), Opuntia polyacantha (Oppo), and Bouteloua gracilis (Bogr).

Fig. 6. Total standing crop for September 1970 as a function of exposure rate for seasonal and chronic treatments.

Fig. 7. Grass-sedge component of the September 1970 standing crop as a function of exposure rate for seasonal and chronic treatments with the fitted regression lines.

Fig. 8. Shortgrass plant stand on 20 June 1970, nearly 15 months after the initiation of radiation in the chronic sectors. Sector one was the control, 2 and 3 were the chronically irradiated, 4 was irradiated during April 1969, 5 was irradiated during July 1969, and 6 was irradiated during December 1969.

Days after 1 April 1969

EQUATION: $\ln R_T = 0.09 - 0.01056(T) + 0.0397 \ln(W_T/T_p)$, $R = 0.896$

EQUATION: $TB\ 1/2 = 36.1 + 1.75(W_0/T_p) + 36.0(W_f - W_i)/W_i$, $R=0.7568$