PUBLICATION NO. 549
Environmental Sciences Division
Oak Ridge National Laboratory

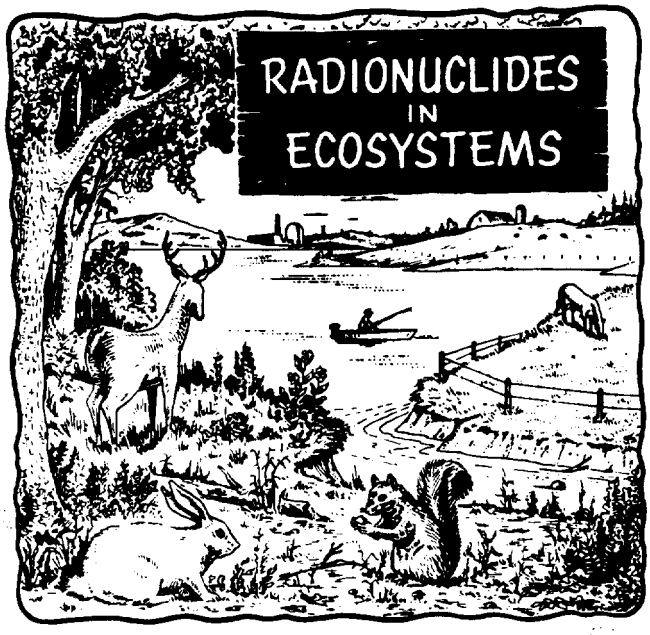
Ref 13
Area 1

EFFECTS OF SIMULATED FALLOUT RADIATION ON REPRODUCTIVE CAPACITY OF FESCUE

Roger C. Dahlman and John J. Beauchamp
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Yasuomi Tanaka
Department of Forestry, Institute of Agriculture
University of Tennessee, Knoxville

707639



Volume 1

Proceedings of the

THIRD NATIONAL SYMPOSIUM ON RADIOECOLOGY

MAY 10–12, 1971
OAK RIDGE, TENNESSEE

Sponsored by
The United States Atomic Energy Commission,
Oak Ridge National Laboratory,
and The Ecological Society of America

REPOSITORY Oak Ridge Ecology Syst.
COLLECTION
BOX No.
FOLDER
1024695
A-00045
Human Subjects Project

CONF-710501
Distribution Category UC-48

RADIONUCLIDES IN ECOSYSTEMS

Proceedings of the
THIRD NATIONAL SYMPOSIUM ON RADIOECOLOGY

May 10–12, 1971
Oak Ridge, Tennessee

D. J. Nelson, Editor

Sponsored by

The United States Atomic Energy Commission,
Oak Ridge National Laboratory,
and The Ecological Society of America

1024696

EFFECTS OF SIMULATED FALLOUT RADIATION ON REPRODUCTIVE CAPACITY OF FESCUE[1]

Roger C. Dahlman[2] and John J. Beauchamp[3]

Oak Ridge National Laboratory, Oak Ridge, Tennessee

Yasuomi Tanaka[4]

Department of Forestry, Institute of Agriculture
University of Tennessee, Knoxville

ABSTRACT

The effect of chronic irradiation (<21 rads/day) on the reproductive potential of tall fescue (*Festuca arundinacea* Shreb.) grass was investigated for a fescue community contaminated with ^{137}Cs fallout simulant. Internal daily dose rate to apical meristems from radioactivity in tissue was calculated as 9.1 rads beta and 0.3 rad gamma per day at the beginning of vegetative phenophase with an additional measured external exposure of 12 rads/day. By the end of first-year flowering, when the internal dose rate to meristematic tissues had decreased by a factor of 10 and total dose rate ranged from 10 to 21 rads/day, seed production was reduced approximately 50% relative to controls. At the conclusion of the second season, when dose rate had decreased by 40% and radioactivity concentration in tissue had decreased by a factor of 200 to 300, seed production was 20% less than controls. The number of germinable seeds per panicle, measured by seed germination, was not significantly reduced in either reproductive period. Diminished seed production indicates that ovule initiation and development may be significantly affected by low-intensity simulated fallout radiation.

INTRODUCTION

Numerous investigators have examined radiosensitivity of higher plants using diverse methods of exposure from external gamma sources (McCormick and Platt 1962, Woodwell and Oosting 1965, Monk 1966, Sparrow et al. 1968, 1970). In most studies, plants received either acute or uniform chronic dose rates with all exposures emanating from a point source. Under such conditions, Sparrow et al. (1971) reported that 2 to 4 kR at a rate of 30 R/min caused 50% yield reduction (YD_{50}) of meadow fescue (*Festuca elatior* L.). Meadow fescue is a close relative of Ky-31 tall fescue [*Festuca arundinacea* Shreb. (Pohl 1966)], the species used in this investigation. Similar YD_{50} data were not available for tall fescue.

Radioactivity decay rates from external sources have been simulated to resemble those of actual fallout from nuclear explosions by varying dose rates according to the $t^{-1.2}$ function (Clark et al. 1967, Sparrow and Puglielli 1969). Simulated fallout from a fallout decay simulation (FDS) ^{137}Cs gamma source was two times more effective than uniform rate exposure in causing 50% reduction in fresh weight and crop yield of numerous economic plants (Sparrow and Puglielli 1969). Total dose was similar for both exposures. High initial exposures from the simulated fallout radiation regime apparently caused damage which was not repairable, compared with equivalent doses at lower uniform rates.

Close-in fallout from nuclear explosions also can cause appreciable radiation damage, particularly when plant parts are heavily coated with dust particles (Rhoads et al. 1969a,b). Fallout deposits from Cabriolet and Palanquin test explosions caused greater damage to sage (*Artemisia* spp.) than was expected from measurements of gamma radiation intensity and chromosomal volume. The beta-to-gamma dose ratio was 10 on the center line of the fallout pattern in Cabriolet, and high beta dose from contact particles apparently was a major factor in the radiation damage to *Artemisia* spp. Results from these studies and other laboratory experiments and field observations indicate that several fallout attributes are important when evaluating the effect of fallout deposit radiation on vegetation: the extent of particle retention on vegetation, the beta-gamma dose ratio, and radioactivity decay rate. Additionally, Gunckel and Sparrow (1961) listed over 40 biological-radiological-environmental

1. Research sponsored by the U.S. Atomic Energy Commission and Office of Civil Defense under contract with Union Carbide Corporation.

2. Ecological Sciences Division.

3. Mathematics Division.

4. Research performed under subcontract 3502 with Union Carbide Corporation. Present address: Forestry Research Center, Weyerhaeuser Company, Centralia, Washington 98531.

1024697

factors which also may affect plant response to radiation, but Sparrow et al. (1971) narrowed the list to six major modifying factors that probably influence plant response to radiation. Three factors, chromosome size, age at exposure, and relative biological effectiveness (RBE), were specified as being most important. Recognizing that it is logistically difficult to include all attributes of fallout and interacting biotic-environmental factors in an investigation of the effects of simulated fallout contamination of ecosystems, a field experiment was designed to determine the effects on a fescue meadow ecosystem from contamination with low-level ^{137}Cs radioactivity which was applied as a fallout simulant. Research results on simulant particle behavior in vegetation (Dahlman 1971) and radiocesium distribution in plant components (Dahlman et al. 1969) have been reported elsewhere. Responses of plants and animals to a regime of chronic, low-level, beta-gamma, in situ radiation have been investigated for two successive growing seasons, and this paper reports observable effects on the reproductive capacity of fescue grass. The specific objective was to determine the effect of radiation on seed production and germination.

METHODS AND MATERIALS

Experimental area. A fescue meadow ecosystem was selected for a fallout simulant experiment because fescue grass is a dominant species in many southeastern pastures and hayfields. The experimental site is situated on flood-plain alluvium, a moderately fertile loamy soil. Moisture stress seldom occurs in this area, because a water table is present and varies in depth between 0 and 8 ft throughout the growing season. Wilting from moisture stress has never been observed during the past five growing seasons. The 5-acre experimental area was amended with 200:50:50 lb of NPK per acre four months prior to initiation of the experiment, causing substantial dry matter production. The quantity of living and dead fescue exceeded 1000 g/m^2 during the first three months of the experiment, and the stand of vegetation was considered to be in good condition (Fig. 1).

Eight 100-m^2 areas were enclosed by animal-proof sheet-metal fencing to provide experimental areas for contamination. These are designated as the P series in the experimental design (Fig. 2). Odd-numbered plots

Fig. 1. Early summer aspect of fescue meadow area where fallout simulant experiments were performed. Two-inch mesh nets on 100-m^2 plots ($P_{1,2,5,8}$) protected small mammal experiments from bird predation. Other contaminated and control plots were obscured by 1-m-high fescue grass.

1024698

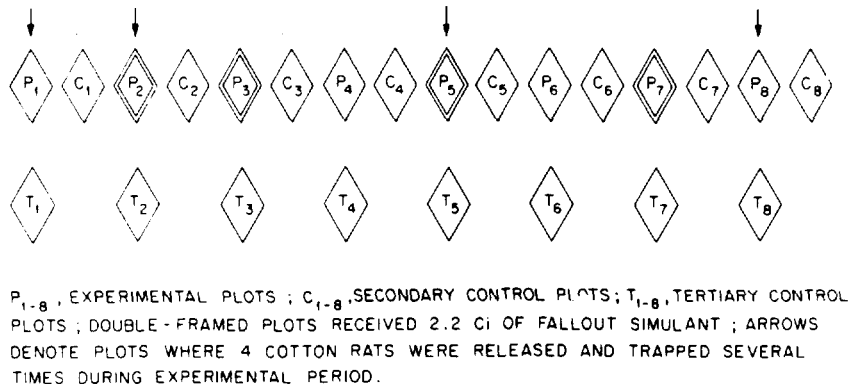


Fig. 2. Layout of experimental and control plots in fallout simulant experiment. Double framed plots received 2.2 Ci of simulant. Arrows denote plots where cotton rats were released and trapped during 1968 and 1969. Plot notation: $P_{1\text{-}8}$, experimental, 4 contaminated, 4 primary controls; $C_{1\text{-}8}$, secondary control; $T_{1\text{-}8}$, tertiary control.

($P_{3,5,7}$) were arbitrarily selected for contamination, and even numbered plots ($P_{4,6,8}$) were primary controls; P_1 and P_2 were interchanged to minimize personnel exposure at the site boundary. Primary controls and contaminated plots were given identical treatment, except that the former series received no radioactivity. For the seed production and germination experiment, secondary ($C_{1\text{-}8}$) and tertiary ($T_{1\text{-}8}$) controls were located on the same catena as contaminated areas (Fig. 2) in order to assess inherent variability of seed characteristics of tall fescue.

Fallout simulant contamination. Fallout simulant tagged with ^{137}Cs was applied to four areas ($P_{2,3,5,7}$) during midsummer 1968. Each area received 2.2 Ci of ^{137}Cs fused to silica sand at a mass load of 22 g/ft^2. Details on the tagging operation, simulant characteristics, and transient radioactivity behavior in the ecosystem are reported elsewhere (Dahlman et al. 1969). Aerial scans in 1968, 1969, and 1970 confirmed that the radioactivity was distributed uniformly over the 100-m^2 areas.

Dose rate to meristematic tissues. In this experiment meristematic tissues of plants received ionizing radiation from three different sources: (1) a beta + gamma flux from the ground deposit, (2) beta and gamma emissions from internal ^{137}Cs radioactivity, and (3) beta and gamma from microsite particle concentrations and adherence on plant structures. Dose to sensitive plant parts was estimated for the three different modes of exposure. The beta + gamma dose-rate profile (Fig. 3) in contaminated areas was determined with microthermoluminescent dosimeters (TLD), and this dose rate was defined as the external radiation source. Two weeks after contamination the maximum beta and gamma dose rate from the ground surface deposit was 12

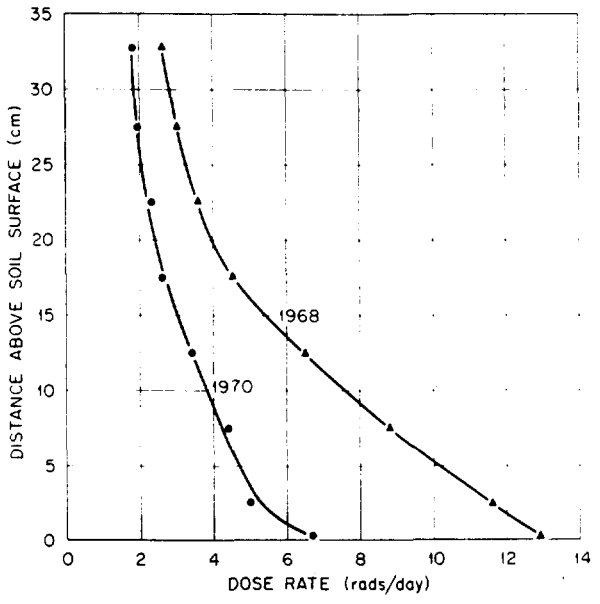


Fig. 3. External beta-gamma dose rates above fallout simulant deposit as measured with thermoluminescent dosimeters. Dose rate profiles were determined in August 1968 and July 1969.

rads/day at 1 cm height, the approximate region of apical meristems and principal derivative tissues. Thereafter, the dose rate decreased to 6 rads/day by midsummer 1970.

Emissions from internal sources of ^{137}Cs radioactivity constituted the second mode of exposure, and its magnitude was calculated from meristematic tissue geometry and radioactivity concentration. Beta dose rate (R_β) in rads/day was calculated from a modification of Hine and Brownell's formula (1956) (Eq. 2, Table 1), allowing for beta absorption in small cylinders

1024699

Table 1. Calculated beta and gamma dose rate to meristematic tissues[a] of fescue-assimilated ^{137}Cs

Date	C (μCi/g ^{137}Cs)	R_β[b] (rads/day)	R_γ[c] (rads/day)	$R_{\beta+\gamma}$ (rads/day)
August 1968	1.008	9.14	0.309	9.45
June 1969	0.109	0.988	0.033	1.02
July 1970	0.004	0.036	0.001	0.037

[a]Measured meristematic tissue dimensions were 0.3 to 0.6 cm diameter and 1 cm length. Average cylinder geometry was designated as 0.5 cm diam × 1.0 cm long.

[b]R_β = beta dose rate = $51.2 \cdot C \cdot \bar{E} \cdot F$ (from Hine and Brownell 1956), where

51.2 = time conversion constant,

C = radioactivity concentration (μCi/g),

$\bar{E}$ = average beta energy (0.23MeV),

F = fraction of beta energy absorbed by cylinder (0.77) as calculated from Parmley et al. (1962; pp. 438, 439).

[c]R_γ = gamma dose rate = $2.4 \times 10^{-2} \cdot C \cdot \rho \cdot \Gamma \cdot g_p \cdot f$ (from Hine and Brownell 1956), where

2.4×10^{-2} = combined radioactivity (10^{-3}) and exposure duration (rads/hr × 24 = rads/day) conversion constant,

C = radioactivity concentration (μCi/g),

ρ = density of tissue (~1),

Γ = gamma dose rate constant of ^{137}Cs (3.2),

g_p = tissue geometry factor (4.21) as calculated from formula given by Marienlli et al. (1948),

f = roentgen to rad conversion factor (0.95).

according to calculations by Parmley et al. (1962). The calculated linear energy absorption coefficient for ^{137}Cs was 16, and fractional beta energy absorbed was 0.77.

Gamma dose rate (R_γ) from absorbed radioactivity was calculated for the central region of a 0.5 × 1.0 cm cylinder (an approximated dimension for the developing reproductive tissue) according to Hine and Brownell's formula (1956) (Eq. 3, Table 1), with the tissue geometry factor (g_p) calculated as 4.21 from an expression given by Marinelli et al. (1948).

The third component contributing to radiation exposure of meristematic tissue was "hot spots" created by particle concentrations in contact with plant parts. These most commonly occurred in leaf axils, plant crevices, and stem channels. An attempt to measure radiation dose in these microsites met with limited success. The best estimate of dose rate from particle concentration was obtained by placing TLD's in fescue leaf axils, and these registered 25 to 100 rads/day when experimentally dosed with quantities of fallout simulant equivalent to amounts that were trapped in similar sites in the field situation.

Small-mammal grazing. Another independent investigation was in progress in the experimental plots when panicles were collected for the 1969 germination tests. Cotton rats (*Sigmodon hispidus*) occupied both irradiated ($P_{2,5}$) and control ($P_{1,8}$) plots during vernal vegetative growth and floral initiation in 1969. Appreciable disturbance to vegetation was caused by four to seven cotton rats confined in each 100-m^2 area, and this added effect was considered in the statistical treatment of seed production-germination results. In a further effort to determine the impact of cotton rats grazing on fescue vegetation, foliar and flower stalks from five 0.25 m^2 quadrats in each plot ($P_{1,8}$) were clipped when seeds were collected for germination tests in 1969.

Seed analysis. After seed set in June 1969, seeds were collected from experimental plots ($P_{1,8}$) and from

1024700

secondary (C_{1-8}) and tertiary (T_{1-8}) control plots. Six panicles were randomly selected from each plot, exercising care to collect from inside a 1-m peripheral buffer strip. Fewer panicles were used when six undamaged flower stalks could not be found in several plots containing cotton rats. Seeds were allowed to cure on intact panicles for 30 days at room temperature before testing for germination. Ripening promoted more uniform and higher germination than an absence of pretreatment or an exposure to cold temperature (6 C) for 30 days. Seeds were germinated on moist filter paper in Petri dishes in a controlled environment (25 C). Germination was scored after six days; then germinated seeds were recorded and removed daily over a two-week period.

Seeds were again collected from experimental plots (P_{1-8}) in the second growing season (1970). Analysis of variance of 1969 data indicated that no significant differences ($P < 0.01$) existed among controls ($P_{1,4,6,8}$; C_{1-8}; T_{1-8}); therefore, the C and T series were omitted from the 1970 collections. To intensify sampling in the experimental plots (P_{1-8}), each plot was subdivided into four subplots from which 15 panicles were collected at random, giving 60 panicles per plot. Ripening, germinating, and scoring procedures were followed as described for the 1969 collection.

Statistical analysis. Since the observations of total seed production represent a count, the data were transformed before the analysis was performed by means of a square-root transformation. In addition, an arc-sine transformation was similarly used on the observed percentages. These transformations were used in order to satisfy more nearly the general distributional assumptions (Snedecor 1956) inherent in the analysis of variance (ANOVA). Finally, ANOVA was performed on transformed data using a linear model, which considered all attributes of variation assumed to have contributed to the variability of the final product:

$$Y_{ijklm} = \mu + A_i + B_j + (AB)_{ij} + SP_{l(ijk)} + E_{ijklm} . \quad (1)$$

where

Y_{ijklm} = observed data set from a particular subplot (or plot in 1969 study) specified by ijklm,

μ = overall mean,

A_i = irradiation effect ($i = 1, 2$),

B_j = grazing effect ($j = 1, 2$),

AB_{ij} = interaction effect between irradiation and grazing,

$P_{k(ij)}$ = plot effect ($k = 1, 2$),

$SP_{l(ijk)}$ = subplot effect ($l = 1, 2, 3, 4$), (term only used for 1970 study),

E_{ijklm} = experimental error ($m = 1, 2, \ldots, n_{ijklm}$).

During germination tests of 1970, none of the 23,781 seeds collected from P_4 germinated (Fig. 4). The factor which caused this peculiarity remains a mystery, and it is not likely that complete germination failure is a natural phenomenon of seed variability in tall fescue grass. Seeds collected and tested from the same plot the previous year showed no such anomaly. Results from 1969 illustrated nearly an equal proportion of seed germination for both P_4 and P_6, the nongrazed control

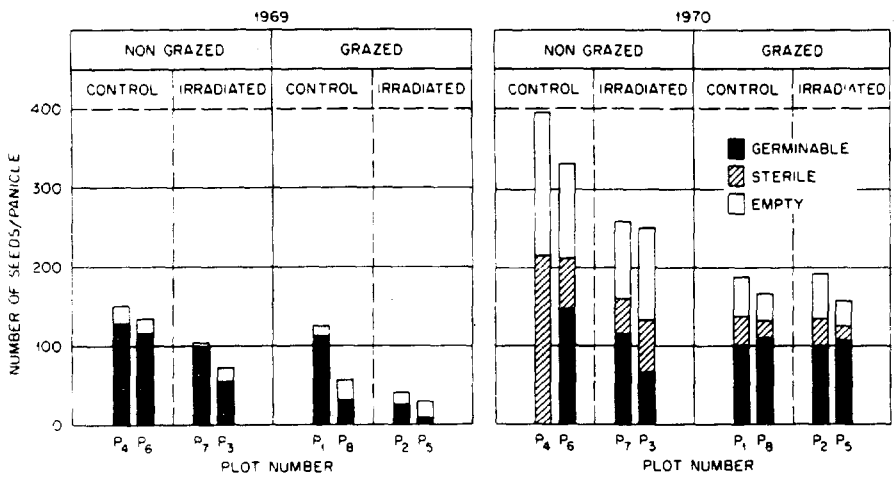


Fig. 4. Average number of germinable and nongerminable seeds per panicle in experimental plots, 1969 and 1970. Sterile and empty seeds were lumped as one category in 1969. No seeds germinated in control P_4 in 1970.

1024701

plots. Further examination of 1970 seed production and germination shows a consistent proportion of viable, sterile, and empty seed for other control areas ($P_{1,6,8}$). The proportion of full seed (viable + sterile) was similar for both P_4 and P_6 in 1970. Therefore, the germination data for P_4 in 1970 were considered missing, and the germination percentage for P_4 was estimated from the germination percentage of P_6.

RESULTS AND DISCUSSION

Radiation dose to meristematic tissue. At the time of fallout simulant application, a significant fraction of particles was retained initially by the plant canopy for two to three weeks, then became mixed with litter and moved to the soil surface within three to four months. Aboveground vegetation received gamma exposure from particle deposits, which were interspersed throughout the canopy and on the soil; this distribution was considered to be a three-dimensional source during the initial three to four months postcontamination. Measured beta and gamma radiation profiles are given in Fig. 3 for 1968 and 1970. Dose rate 1 cm above soil surface initially was 12 rads/day, and decreased to 6 rads/day two years later due to particle weathering and incorporation of radioactivity into soil. It was assumed that dose rate at a height of 1 cm would be most damaging to growth and development of grass, because intercalary and apical meristems are located near the ground and would receive maximum dose from a ground-surface particle deposit. Additionally, highest measured dose rates were nearest the soil surface.

There was appreciable ^{137}Cs movement from the silica-sand particles directly to vegetation at the time of initial contamination, thereby creating a radioactivity concentration of approximately 1 μCi/g in tissues. Additional dose to plant parts resulted from the internal ^{137}Cs sources, particularly due to the beta component (average energy 0.23 Mev). Calculated dose rates from this source are given in Table 1 for both beta and gamma internal sources of radioactivity. Both R_β and R_γ diminished by approximately an order of magnitude from one growing season to the next and contributed negligible dose to meristematic tissues one year after contamination. Calculated R_β/R_γ ratios ranged from 13 to 19, and were somewhat higher than the 4 to 12 ratios Rhoads et al. (1969b) observed in Palanaquin and Cabriolet fallout fields.

Combined data from field and laboratory measurements with TLD's indicated that dose rate from "hot spot" microsites such as leaf axils, crevices, and stem channels may range from 25 to 100 rads/day, while the deposit remained intact. There was no correlation, however, between dose rate and quantity of simulant applied to axils in the range of 40 to 120 mg/axil. High dose rates often were determined with TLD's which were adjacent to relatively smaller particle deposits. Intimate geometrical relationships between particles and dosimeters apparently affected the results of these attempts to measure doses to tissues adjacent to microsite deposits. Nevertheless, dose rate from the microsite source was potentially 1 to 6 times greater than the sum of internal plus external (beta plus gamma) from other sources (Table 2). Such microsite concentrations persisted for only a short interval, because low-velocity wind and phytotaxic movements dispersed the particles within a relatively short period (1 to 2 weeks). Maximum localized short-term dose to plant parts ranged from 350 to 1400 rads based on observed dose rate and particle retention time.

Summation of dose from external, internal, and microsite sources gives a maximum conceivable estimate

Table 2. Comparison of dose rate ($R_{\beta+\gamma}$) to meristematic tissue[a] receiving radiation exposure from external fallout field, internal radioactivity, and microsite particle concentrations

Date	$\beta + \gamma$ dose rate (rads/day)			
	External source	Internal source	Microsite	Total
August 1968	12	9.4	25-100	21 46–121[b]
June 1969	9[c]	1.0	0	10
July 1970	6	0.0	0	6

[a]Meristem assumed to be 1 cm above soil surface.

[b]Maximum possible dose rate assuming leaf axil is adjacent to intercalary meristem and receives a primary particle deposit. Many axils in this position will not receive primary deposit because upper canopy will intercept fallout.

[c]Interpolated from Fig. 3.

1024702

of initial dose rate to meristematic tissue. Estimates for the initial two-week period ranged from 46 to 121 rads/day. Only limited tissue sites would have received such an initial dose rate, however, because the upper canopy intercepted particles before the deposit could be trapped by lower leaf axils. This action minimized the maximum exposure to apical and intercalary meristems. Therefore, most tissue sites probably received not more than the combined external-internal initial dose rate (~21 rads/day), and only a few meristems received as much as 121 rads/day. At the maximum dose rate (121 rads/day), the cumulative estimated dose was 1700 rads for the initial two-week period after contamination.

If radiation exposure occurs during floral (ovule and pollen) organ initiation and early development, it can be a major factor influencing ultimate yield or production. Davies (1968) and Sparrow et al. (1971) found that exposure during the reproductive phase was more effective in reducing yield than when exposures are delivered during vegetative or postflowering phases. Thus, radiation exposure of fescue in midsummer would have less effect on seed production than if it were synchronized with floral initiation and seed production in early spring.

Based on the assumption that there was a linear decrease in dose rate from August 1968 to July 1970 (a graph of measured dose rate as a function of time had a negative slope and was slightly curvilinear), integrated dose was easily estimated for selected intervals prior to flowering. Integrated dose for the period from contamination (t_0 = August 1968) to floral initiation (mid-April 1969) was calculated at 4350 rads; the maximum cumulative dose, including possible microsite exposure, approximately 6000 rads. Exposures during a shorter interval preceding floral initiation would be more realistic for relating dose and effect according to results from acute exposures (Davies 1968, Sparrow et al. 1971). For the three-month period prior to flowering (February to May 1969), the dose was 1100 rads, not including exposure from microsite sources.

Integrated dose from t_0 to floral initiation in the second growing season was 6800 rads, not including exposure from microsite particle concentrations. The short-term cumulative dose from February to May in 1970 was 550 rads. The relationship of response to cumulative dose for a two-year period probably has limited value, because continuous replacement and turnover of plant structures (leaf, stem, tiller) represent a succession of tissues, with each generation receiving a finite amount of radiation. Succeeding tissue generations would be exposed to less than the cumulative dose. Derivative cells in meristematic regions may persist for several generations, however, the genetic apparatus of these cells could be affected by cumulative chronic radiation exposure.

Effects on seed production. Fescue seed production and germination results for 1969 and 1970 are given for control, irradiated, and grazed plots in Fig. 4. The histograms show that both radiation and animal grazing had an effect on seed production in 1969 and 1970. Based on combined grazed and nongrazed situations in 1969, panicles from irradiated plots possessed, on the average, about 50% fewer seeds than those from control plots. According to ANOVA tests, this irradiation effect was found to be significant at the 5% level (Table 3).

In 1970, panicles from plots exposed to the in situ radiation source possessed, on the average, about 20% fewer seeds than those from control plots. Based on ANOVA tests (Table 4), this difference between irradiated and control again was significant at the 5% level. Percentage reduction in the number of seeds per panicle was approximately half as much as in 1970 as in 1969 (20 vs 50%), and it roughly corresponded to the reduction in *dose rate* (<21 to <10 rads/day, Table 2) to meristematic tissue during periods of probable initiation of new reproductive tissue in 1969 and 1970. Results indicated that fescue seed production in this

Table 3. Analysis of variance for average seed production per panicle and germination for 1969

Source of variation	Seed production			Germination	
	df	MS	F-statistic	MS	F-statistic
Control vs irradiation	1	79.914	9.12*	114.876	2.51
Grazing vs no grazing	1	74.181	8.46*	197.388	4.31
Interaction between irradiation and grazing	1	3.500	0.40	35.115	0.77
Plots within a "treatment" combination	4	8.767	0.85	45.776	2.20
Error term	31	10.331		20.797	

*Significant at the 5% level.

1024703

Table 4. Analysis of variance for average seed production per panicle and germination for 1970

Source of variation	Seed production			Germination	
	df	MS	F-statistic	MS	F-statistic
Control vs irradiation	1	310.41	8.79*	165.811	1.09
Grazing vs no grazing	1	2036.10	57.63**	52.069	0.34
Interaction between irradiation and grazing	1	254.63	7.21	243.906	1.60
Plots within a "treatment" combination	4	35.33	1.77	152.796	3.93*
Subplots	24	19.99	2.69**	38.901	3.76**
Error term	448	7.44		10.338	

*Significant at the 5% level.
**Significant at the 1% level.

chronic radiation environment was related to dose rate rather than to cumulative absorbed dose, because cumulative does increased but dose rate decreased as a function of time.

Substantial differences in seed production were evident between 1969 and 1970. A major part of this difference was in the form of a larger proportion of empty seeds in the second-year collection. Since tall fescue grasses usually are cross-pollinated due to a high degree of self-sterility (Wheeler and Hill 1957), it is conceivable that environmental factors such as weather conditions or limited pollination period could have affected anthesis, anther dehiscence, or ovule fertilization for tall fescue in 1970. Grass pollen also characteristically is viable for approximately one day (John and Vasil 1961). General climatic information was collected for the period of floral initiation in 1970, but there is no knowledge of micrometeorological events which may have affected actual pollination, fertilization, or other reproductive processes. In any event, conditions were optimum for substantial floral initiation, but inadequate pollination, fertilization, or seed set resulted in large numbers of empty seeds.

Effects on seed germination. Seed germination is an end point which measures the quality factor of reproductive germinules. Percentage germination of irradiated seeds was only eight units less than that of controls (Fig. 4) in 1969, and this small difference was not significant according to ANOVA tests (Table 3). These results disclose that germination response was a less sensitive indicator of radiation effect than seed production. This effect can be explained by considering developmental sequences in sexual reproduction in angeosperms (including grass), where deleterious effects for each genome probably would not be transferred to subsequent reproduction events (i.e., anomolies at sporogenesis may vanish before the onset of fertilization). The anomoly would disappear from the genome and the population and would not be detected when scoring for effects at later stages of germinule development.

Seed germination results for the 1970 collection were inconclusive, because all 23,781 seeds collected from control plot P_4 failed to germinate, and the statistical test had to be performed using a germination value for P_4 which was estimated from P_6. Accordingly, ANOVA of 1970 germination data showed no significant difference between irradiated and control plants (Table 4). Seed set results were similar for both control plots (P_4, P_6) in 1970 (Fig. 4); therefore, anomolous germination in the control plot (P_4) was attributed to undefined factors which existed after seed set, because normal caryopses were evident in seeds at the time of collection. Fertilization presumably was normal: otherwise, mature caryopses would not have developed. Normal seed production was observed from P_4 collections in 1969; thus, peculiar results in 1970 germination tests are more likely to be related to undefined germination conditions in the laboratory rather than to radiation effects and seed production phenomena in the field.

Effect of animal grazing on fescue reproduction. Cotton rat grazing during floral initiation had a significant effect on inflorescence development, seed production, and seed germination in both control and irradiated areas. From four to seven cotton rats were present in $P_{1,2,5,8}$ areas during floral initiation (variable populations were a function of trapping efficiency), and the rats selectively grazed developing floral parts. Flower stalk destruction was appreciable, and the average number of flower stalks was reduced by 85% in 1969 (Fig. 5). Flower-stalk grazing seemed to be related to chewing rather than feeding activity, because large collections of destroyed flower stalks commonly were evident in the grazed areas. Additionally, rats often grazed only the stem parts and discarded the inflorescence, presumably the more nutritious plant part.

1024704

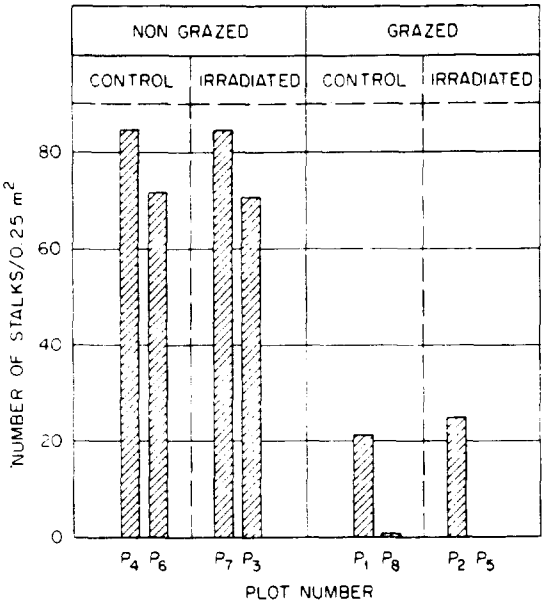


Fig. 5. Relative abundance of standing fescue stalks in 1969. Four to seven cotton rats were present in the grazed areas during floral initiation and stalk development.

Cotton rat grazing also reduced panicle seed production through direct but apparently subtle damage to the developing inflorescence. Suppressed panicle seed production also may have been caused by some form of grazing-induced stress on the plant community, the response being in terms of diminished sexual reproductive capacity. Relative to controls, the effect of grazing on seed production was significant in 1969 at the 5% level and in 1970 at the 1% level. The cotton rats were removed from the experimental areas prior to floral initiation in 1970, and supression of germination in the second year apparently was a carry-over effect from prior grazing impacts.

Relative effects from exposure to point source and in situ radiation. Results from this investigation clearly demonstrate that sexual reproduction was reduced appreciably by chronic in situ ^{137}Cs radiation. Combined internal-external radiation resulted in 50% less seed production and 8 percentage units less germination when the regime ranged from 21 rads/day initially to 10 rads/day at first-year floral initiation, excluding possible dose from microsite particle concentrations. Compared with point source exposures, the in situ radiation regime of these experiments would be more analogous to what would be expected from actual fallout particle contamination events. Cumulative absorbed dose for the three-month period prior to flowering was approximately 1100 rads and was equivalent to low doses which have induced stimulatory effects (Skok et al. 1965, Sparrow 1966) in angiosperms. Information from other experiments on yield reduction or stimulation at low dose rates for total exposures essentially is nonexistent for graminaceous plants, however.

Based on dose effects data for acute point source exposure of agronomic graminaceous plants such as wheat (Davies 1968) and maize (Sparrow et al. 1970), total dose from in situ field exposure for ORNL experiments was of sufficient magnitude to cause a seed yield reduction. Dose rates in the simulant study were substantially lower (as much as three orders of magnitude less) than in cases where plants were exposed to either constant acute or fallout decay radiation. In a chronic exposure of another fescue species, Miller (1968) observed that 8.7 kR of chronic external gamma radiation from a point source caused an effect on *Festuca sciurea* when the exposure rate was approximately 300 R/day. Total exposure in his study was twice as great as that received by tall fescue in our simulant study (8700 kR vs 4350 rads), and exposure rate was more than an order or magnitude greater (300 R/day vs 10 to 21 rads/day). Chronic exposure rates which have caused 50% mortality for other angiosperms can range from 32 R/day for *Viburnum* to 150 R/day for red maple (Sparrow et al. 1970). In these cases, exposure rates were approximately 1.5 to 10 times greater than the 21 rads/day dose rate estimated in the current experiment. Causation of effects in the ORNL chronic in situ radiation experiments supports other field observations where contact exposure from actual fallout deposits has reduced growth or caused mortality of plants. Considering integrated dose from gamma radiation only, Rhoads et al. (1969a) noted that fallout field irradiation was as much as five times more effective than ^{60}Co point-source exposure in causing damage to *Artemisia* (600-R fallout field vs 3000-R ^{60}Co). The difference was attributed to additional contact or beta-bath dose from fallout particles.

Fallout deposits on and in proximity to graminaceous vegetation apparently can provide more effective radiation exposure to basal meristems. Principal tissue irradiation occurs in the form of beta bath from external particle deposits and from internal sources of absorbed radioactivity. This combination of radiation dose caused a reduction in seed yield at relatively low dose rates; whereas doses from external sources alone have induced effects at substantially higher dose rates and total dose. While experimental data from point source exposure readily provide relative profile response information for various plants, actual response to sublethal levels of fallout radiation may be more accurately determined from experiments of simulated

1024705

Dahlman, R. C., S. I. Auerbach, and P. B. Dunaway. 1969. Behavior of ^{137}Cs-tagged particles in a fescue meadow pp. 153–65 in: Environmental Contamination by Radioactive Materials. IAEA, Vienna.

Dahlman, Roger C. 1971. Predictions of radionuclide contamination of grass from fallout-particle retention and behavior, pp. 492–508 in: Symposium on Survival of Food Crops and Livestock in the Event of Nuclear War, D. W. Benson and A. H. Sparrow (Eds.). Brookhaven National Laboratory, Upton, N.Y., September 15–18, 1970. AEC CONF-700909.

Davies, C. R. 1968. Effects of gamma irradiation on growth and yield of agricultural crops. I. Spring sown wheat. Rad. Bot. **8**: 17–30.

Gunckel, J. E., and A. H. Sparrow. 1961. Ionizing radiations, biochemical, physiological and morphological aspects of their effects on plants. Encyl. Plant Physiol. **16**: 555–611.

Hine, G. J., and G. L. Brownell. 1956. Radiation Dosimetry. Academic Press, New York.

John, B. M., and I. K. Vasil. 1961. Physiology of pollen. Bot. Rev. **27**: 337–38.

McCormick, J. F., and R. B. Platt. 1962. Effects of ionizing radiation on a natural plant community. Rad. Bot. **2**: 161–88.

Marinelli, L. D., E. H. Quimby, and G. J. Hine. 1948. Dosage determination with radioactive isotopes. Amer. J. Roent. **59**: 260–81.

Miller, Carl F., and Philip D. LaRiviere. 1966. Introduction to long-term biological effects of nuclear war. USAEC Report SRI-MU-5779.

Miller, G. E. 1968. The influence of season on the radiation sensitivity of an old field community. Ph.D. thesis, University of North Carolina, Chapel Hill.

Monk, C. D. 1966. Effects of short-term gamma irradiation on an old field. Rad. Bot. **6**: 329–35.

Odum, Eugene P. 1961. Fundamentals of Ecology. Saunders, Philadelphia. 546 pp.

Parmley, W. W., J. B. Jensen, and C. W. Mays. 1962. Skeletal self-absorption of beta-particle energy, pp. 437–53 in: Some Aspect of Internal Irradiation, T. F. Dougherty, Webster S. S. Jee, C. W. Mays, and B. J. Stover (Eds.). Pergamon, New York.

Pohl, R. W. 1966. The grasses of Iowa. Iowa State J. Sci. **40**: 341–566.

Rhoads, W. A., R. B. Platt, and R. A. Harvey. 1969a. Radiosensitivity of certain perennial shrub species based on a study of the nuclear excavation experiment, PLANAQUIN, with other observations of effects on the vegetation. USAEC Report CEX-68.4.

Rhoads, W. A., R. B. Platt, R. H. Harvey, and E. M. Romney. 1969b. Ecological and environmental effects from local fallout from CABRIOLET. I. Radiation doses and short-term effects on the vegetation from close-in fallout. USAEC Report PNE-956.

Skok, J., W. Charney, and E. J. Rakosnils, Jr. 1965. An examination of stimulatory effects of ionizing radiation in plants. Rad. Bot. **5**: 281–92.

Snedecor, G. W. 1956. Statistical Methods, 5th ed., Iowa State College Press, Ames.

Sparrow, A. H. 1966. Plant growth stimulation by ionizing radiation, in: Effects of Low Doses of Radiation on Crop Plants. IAEA Tech. Report Series **64**: 12–15.

Sparrow, A. H., A. F. Rogers, and S. S. Schwemmer. 1968. Radiosensitivity studies with woody plants. I. Acute gamma irradiation survival data for 28 species and predictions for 190 species. Rad. Bot. **8**:149–86.

Sparrow, A. H., and L. Puglielli. 1969. Effects of simulated radioactive fallout decay on growth and yield of cabbage, maize, peas and radish. Rad. Bot. **9**: 77–92.

Sparrow, A. H., S. S. Schwemmer, E. E. Klug, and L. Puglielli. 1970. Radiosensitivity studies with woody plants. II. Survival data for 13 species irradiated chronically for up to eight years. Rad. Res. **44**: 154–77.

Sparrow, A. H., S. S. Schwemmer, and P. J. Bottino. 1971. The effects of external gamma radiation from radioactive fallout on plants with special reference to crop production, pp. 670–711 in: Symposium on Survival of Food Crops and Livestock in the Event of Nuclear War, D. W. Benson and A. H. Sparrow (Eds.). Brookhaven National Laboratory, September 18, 1970. AEC CONF-700909.

Wheeler, W. A., and D. D. Hill. 1957. Grassland Seeds. Van Nostrand, New York.

Woodwell, G. M., and A. H. Sparrow. 1965. Effects of ionizing radiation on ecological systems, pp. 20–38 in: Ecological Effects of Nuclear War, G. M. Woodwell (Ed.). USAEC Report BNL-917 (C-43).

Woodwell, G. M., and J. K. Oosting. 1965. Effects of chronic gamma irradiation on the development of old field plant communities. Rad. Bot. **5**: 205–22.

1024707

contamination as used in this study. Decreased seed production of pasture or forage grass may not be a serious consequence of contamination in an actual fallout situation because grasses usually are maximized for vegetative rather than seed yield. But if the same effect applies to cereal crops, and it probably would apply because wheat and corn are more radiosensitive than forage grasses, then 50% reduction in grain yield could be expected in areas which receive close-in fallout from nuclear explosions.

Comparative radiosensitivity. Increasing public interest in potential biotic impacts from radioactivity released from nuclear technology calls for a brief discussion of comparative radiosensitivity of organisms and populations. Although various exposure and biological conditions influence radiation responses, summaries from many studies reveal that diverse groups of organisms exhibit varying degrees of sensitivity. For example, mammals are more sensitive than insects and bacteria and probably are the most sensitive of all organisms (Odum 1961); cereal grains generally are more sensitive than forage crops (Miller and LaRiviere 1966, Sparrow et al. 1971). The relative order of plant community sensitivity is conifer > deciduous forest > grassland (Woodwell and Sparrow 1965). Humans are among the more sensitive mammals. In situations where human populations are exposed to low levels of ionizing radiation, the objective is to keep exposure to a minimum and as low as practicable in connection with releases from nuclear facilities. Excepting medical doses, this minimum has been defined as less than 170 millirems/year, and for exposure to off-site populations from light-water-cooled reactors, the proposed limit should not exceed 5 millirems/year (Atomic Energy Commission 1971).

In the present study, a dose rate of 10 to 21 rads/day and a cumulative dose of approximately 4350 rads caused detectable effects in fescue reproduction, but these effects were demonstrable only when intensive sampling procedures and sensitive statistical analyses were employed. When compared with laboratory exposure data for approximately equivalent doses to meadow fescue (Sparrow et al. 1971), ORNL results indicate a factor of 10^3 reduction in the dose rates which will produce an effect on grass when the radioactivity is intimately associated with an organism's tissue and immediate environment. The dose rate in the present study was a factor of 20 lower than that which reduced *Festuca sciurea* density in Miller's (1968) old-field irradiation. Cautious comparison is recommended, however, because total exposure was dissimilar (tall fescue received 4350 rads vs 8700 R for *F. sciurea*) and end points were different in the two studies (seed production and germination vs plant density).

Cumulative dose which was required to produce an effect in the simulated fallout regime was still a factor of 10^4 higher than the allowable human exposure of 170 millirems/year, according to present standards. The experimental results reported herein provide additional support for the conclusion reached by Auerbach et al. (1971): "ecologists. . . have not found any organisms which, within an environmental context, have a radiosensitivity at the levels of release permitted under current standards."

By employing an extensive field experiment involving replicated fallout-simulant radiation sources, and using intensive sampling and statistical analysis, it was demonstrated that low-intensity radiation decreased seed production of tall fescue. In the agronomic context this effect easily could be manifested in terms of diminished yield of grain crops. A 50% decrease in seed yield in a native population would greatly affect a species' reproductive capacity in terms of reduced ecesis and establishment. Resultant ecological manifestations would be lowered species success and changes in community composition, both indirect impacts attributable to sublethal deposits of fallout radiation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the diligent efforts of Frank Day, Robert Bickers, and Linda Mann in collecting seed and scoring germination for this project. Radiation dose measurements by Clarence Styron and Jay Story contributed significantly to interpretation of data, and John Witherspoon's assistance with internal dose calculations is greatly appreciated.

LITERATURE CITED

Atomic Energy Commission. 1971. Licensing of production and utilization facilities (10 CFR part 50), light-water-cooled nuclear power reactors. Federal Register **36**: 11113–17.

Auerbach, S. I., D. J. Nelson, S. V. Kaye, D. E. Reichle, and C. C. Coutant. 1971. Ecological considerations in reactor power plant siting, pp. 805–20 in: IAEA Symposium on Environmental Aspects of Nuclear Power Stations. IAEA, Vienna.

Clark, G. M., F. Cheng, R. M. Roy, W. P. Sweaney, W. R. Bunting, and D. G. Baker. 1967. Effects of thermal stress and simulated fallout on conifer seeds. Rad. Bot. **7**: 167–75.

1024706