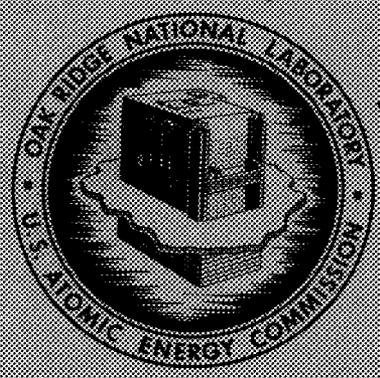


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THE EFFECTS OF BIOTIC COMPLEXITY AND FAST
NEUTRON RADIATION ON CESIUM-137 AND
COBALT-60 KINETICS IN AQUATIC MICROCOSMS
(THESIS)



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HEALTH PHYSICS DIVISION

THE EFFECTS OF BIOTIC COMPLEXITY AND
FAST NEUTRON RADIATION ON CESIUM-137 AND
COBALT-60 KINETICS IN AQUATIC MICROCOSMS

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Submitted as a dissertation by H. L. Ragsdale to the Graduate Council
of the University of Tennessee in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

DECEMBER 1968

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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ABSTRACT

Aquatic microcosms consisting of various combinations of physical components (soil, water, and container surface) and biological components (Physa heterostropha, Najas flexilis, and Elodea canadensis) were used to determine the effect of increased biotic complexity on mineral cycling parameters. The stability of mineral cycling parameters was tested by stressing selected complexity levels with sublethal and lethal doses of fast neutron radiation.

Replicate microcosms were prepared for each experiment and equilibrated in a controlled environmental chamber which was maintained at 16 C, 75 ft-c light intensity on a 12 hour light-dark cycle. One microcurie each of ^{137}Cs and ^{60}Co was added to the water component of each microcosm and changes in compartmental activity were determined by sacrificing replicate microcosms at fixed time intervals with subsequent radiometric analysis.

Inter-compartmental transfer rates varied among complexity levels. The transfer rate of ^{60}Co from the water and that of ^{137}Cs to the soil increased with increased complexity, while for other compartments no such linear relationship was observed. The ^{137}Cs flux patterns for most microcosm compartments were similar among complexity levels, but the ^{60}Co flux patterns of most compartments were dependent on the complexity level.

The pattern of ^{137}Cs distribution among microcosm compartments was independent of complexity and was one of flow through non-soil compartments with rapid accumulation in the soil. In contrast to ^{137}Cs patterns, the ^{60}Co pathway patterns depended on complexity level with accumulation

of ^{60}Co in non-soil compartments in simpler microcosms and flow of ^{60}Co through non-soil compartments to the soil in complex microcosms.

Microcosm components assumed different mineral cycling roles based on changes in cycling parameters with increased complexity. Generally, these roles were different for ^{137}Cs and ^{60}Co and among complexity levels for each radionuclide.

Radiation stress affected ^{60}Co cycling but no radiation effect on ^{137}Cs cycling was observed. The radiation effect on ^{60}Co cycling was dependent on the complexity level and, in general, radiation stress decreased the cycling rate of ^{60}Co .

Generalizations from this study were that 1) cycling parameters for different elements were dissimilar in less complex systems but converged toward similarity as complexity increased; 2) microcosm components had one or more mineral cycling roles, some of which changed with complexity levels; 3) increased functional complexity had the greatest effect on mineral cycling, although an increase in unifunctional species modified the mineral cycling parameters; 4) ecosystem stability was related to the sensitivity of the biological interactions and not necessarily to the sensitivity of the organisms; and 5) on the basis of mineral cycling parameters, the simpler microcosms were less stable than the complex ones when subjected to a moderate radiation stress (sublethal dose), but more stable than complex systems when subjected to an extreme stress (lethal dose).

The use of microcosms as ecological research units provides a means of performing experiments which would be difficult or impractical to conduct in nature, but the results are subject to the criticisms that they

may not be representative of a naturally occurring ecosystem. However, if certain microcosm designs can be shown to accurately reflect an ecosystem, then microcosms can be used to test the effect of unusual environmental stresses and hypotheses about ecosystem behavior.

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I. INTRODUCTION

Studies of the ecological effects of ionizing radiation have been performed on individuals, populations and communities. At the level of the individual, radiation studies of aquatic and terrestrial organisms have emphasized morphological abnormalities (Gunkel and Sparrow, 1961; Witherspoon and Taylor, 1966) and effects on various stages of life cycles (Willard, 1965; Ravera, 1967; Heaslip, 1959; Bonham and Welander, 1963; and Witherspoon, 1967). At the population level, radiation studies have stressed lethality (Sparrow, 1964; Witherspoon, 1965; Palumbo, 1951), changes in population characteristics (Marshall, 1963) and population interactions after radiation treatment (Blaylock, 1968; McCormick, 1963). Radiation effects at the community level have been documented in terms of productivity (Woodwell and Miller, 1963; and Beyers, 1965), changes in community structure (Woodwell and Sparrow, 1963; Daniels, 1963; McCormick and Platt, 1962), and most recently in terms of community function (Woodwell and Dykeman, 1966).

Rate of mineral cycling is a parameter which has received little attention as an index of radiation stress in ecosystems. Brown and Taylor (1965) reported long term decreased ^{65}Zn uptake by red oak seedlings after exposure to acute doses of fast neutrons. Barber and Neary (1958) reported increased short term uptake of non-exchangeable ^{86}Rb by Chlorella after X-irradiation and a decreased concentration if radionuclide uptake occurred during irradiation. Such changes in mineral uptake rates and concentration of an element in a species could be important with respect to maintenance of an ecosystem. In complex ecosystems, where many of the species are coupled in a mineral cycling pattern, a

stress having a significant effect on mineral relations of one biotic component may disrupt the pattern of cycling among all components related to it.

The objectives of this study were to investigate the uptake and movement of radio-cobalt and -cesium in increasingly complex ecosystems and to determine the effects of acute, fast neutron radiation on the flux of these radionuclides in the system.

An aquatic microcosm consisting of two plants, Elodea canadensis and Najas flexilis; the snail, Physa heterostropha; and three physical components, soil, water, and the container surface, was selected as an appropriate experimental unit. Experiments were performed with tagged microcosms containing selected combinations of organisms, some combinations receiving acute doses of radiation (Table 1). Thus, microcosm complexity levels (biotic composition) and fast neutron radiation were treatments.

Table 1. Experimental Design

Microcosm Combination	Microcosm Components	Radiation Treatment		
		(0 rads)	(100 rads)	(1000 rads)
Physical	soil, water, container surface	X		
<u>Elodea alone</u>	soil, water, con- tainer surface, <u>Elodea</u>	X	X	X
<u>Najas alone</u>	soil, water, con- tainer surface, <u>Najas</u>	X	X	X
<u>Physa alone</u>	soil, water, con- tainer surface, <u>Physa</u>	X		X
<u>Elodea-Najas</u>	soil, water, con- tainer surface, <u>Elodea</u> <u>Najas</u>	X		
<u>Physa-Najas</u>	soil, water, con- tainer surface, <u>Physa-Najas</u>	X		
<u>Physa-Najas-Elodea</u>	soil, water, con- tainer surface, <u>Physa</u> , <u>Najas</u> , <u>Elodea</u>	X	X	X

II. MATERIALS AND METHODS

Microcosm Components

The plants used in these experiments, Elodea canadensis and Najas flexilis, were collected from Clear Creek, Norris, Tennessee. These species were introduced into three 60 gallon tanks, which were maintained in a greenhouse in flowing water. Collections of both species were made at 4 month intervals and added to the culture tank in order to keep an abundant supply of plant material.

The snail, Physa heterostropha, which occurs with E. canadensis and N. flexilis in Clear Creek, was to be collected from Clear Creek, but sufficient numbers of this snail were not available there. Physa heterostropha were available in numbers at a spring located 0.5 miles north of the Oak Ridge reservation in Roane County, Tennessee and all snails were collected from this spring. The snails were not cultured, but were collected prior to each experiment.

The soil used for the microcosms was Huntington silt loam obtained from the south shore of Watts Bar Lake at Clinch River Mile 13.5 in Roane County, Tennessee. X-ray diffraction analysis of the clays showed that they were primarily micaceous with some kaolinitic material. The pH of a soil-water microcosm was 7.8 which agreed closely with the acidity (7.7) of the stream bed of Clear Creek.

Physical Microcosm and Experiment Preparation

A microcosm unit was designed so that replicate microcosms could be sacrificed for each sampling period. The microcosm consisted of a one quart, wide mouth jar, lined with a one quart polyethylene freezer bag and provided with a top having an air inlet and outlet.

Replicate microcosms were established 5 days before the beginning of an experiment. Forty grams of air dry soil were added to each microcosm, followed by 600 ml of spring water. The microcosms were sealed and undisturbed for two days.

Biological components used in a given experiment were collected five days prior to an experiment. Plants showing good apical growth were harvested from the culture tanks and cut to an average length of 9 cm. Five individuals of a given species were added to each replicate microcosm. When both plant species were present, 5 individuals of each species were placed in a microcosm. When snails were present, three individuals of Physa were placed in each microcosm. The biological components were added to the microcosms three days before an experiment began.

The 54 replicate microcosms were placed randomly in a growth chamber maintained at 16 C, 75 ft-c light intensity on a 12 hour dark-light cycle for each experiment. Aeration was provided for each microcosm. The microcosms were allowed to remain in the growth chamber for three days, after which they were tagged with ^{60}Co and ^{137}Cs as described below.

Tagging and Sampling in Microcosms

Stock solutions of ^{137}Cs and ^{60}Co were prepared and mixed to provide a microcurie each of ^{137}Cs and ^{60}Co in a 2 ml aliquot. The ratio of ^{60}Co to ^{137}Cs in the tag solution always approximated 1.

The total radioactivity for each experiment was determined experimentally by tagging replicate microcosms with the stock solution to be used for that experiment. Three replicate microcosms, containing only 600 ml of water were prepared and each tagged with 2 ml of the mixed stock solution. Two minutes after tagging, a 5 ml aliquot was removed from the water. Total activities were determined in this way for each experiment

in order to allow for slight deviations due to changes in syringes, variations in volume measurements of water, and sub-sampling error.

Replicate microcosms were tagged on a delayed time sequence. Six microcosms representing a given sampling period were tagged in pairs, the time interval between pairs being approximately 15 minutes. This design allowed time for sampling a pair of microcosms such that the time elapsed between tagging and sampling was the same for all microcosms sacrificed at a given sample period.

The tagging procedure consisted of drawing 2 ml of stock ^{60}Co - ^{137}Cs solution into a syringe and emptying the syringe into the water of each microcosm via the air outlet. Even pressure was applied to the syringe to avoid splashing the isotope solution onto the sides of the container. The syringe was directed to the center of the microcosms for delivery.

The microcosms were sacrificed on an exponential time series of 2^n hr, where $n = 1, 2, \dots, 9$. This time series was selected because the isotopes were distributed rapidly in the microcosms.

Microcosms were removed from the growth chamber at the specified sampling times and carried to the laboratory. Empty quart jars were placed in the vacant positions in order to minimize changes in the physical geometry of the growth chambers. In the laboratory, the water was sampled by transferring a 5 ml aliquot from the center of the microcosm water column to a 25 x 150 mm counting tube. Plants were removed from the microcosms with forceps and rinsed three times in water and soil was washed from the roots. The plants were drained of excess water and then placed in counting tubes containing 1 ml of 10% formaldehyde. Snails were removed from the microcosms with forceps and rinsed in the tagged water to remove loose soil particles from the shell and foot. They were then placed in a clinical

sterilizer and parboiled for several minutes, after which the body and shell were easily separated with forceps or a needle probe. Snail bodies were placed in a counting tube containing 1 ml of 10% formaldehyde and shells were placed in another counting tube. Soil was removed from the polyethylene container and then the container was washed in water to remove loose particles. After blotting dry, the container was folded and placed in a counting tube.

Counting Procedures

A Packard, model 314 EX, dual channel spectrometer, having a 3" NaI (Tl) well crystal, was used for activity determinations. Labelled samples were placed in 25 x 150 mm counting tubes so that the height of the samples was less than 1" from the base of the counting tube. One channel of the spectrometer was set to a full scale of 1 Mev with the window width adjusted from 613 to 713 Mev, which included the photopeak for ^{137}Cs counting. The ^{60}Co channel was adjusted to 2 Mev full scale with a window width of 1.07 to 1.43 Mev.

The background activity of all microcosm components was monitored and compared to background counts of an empty counting tube. None of the background counts exceeded the background counts of the glass counting tubes and the latter were used for background counts in routine counts. After exposure to neutron radiation, all microcosm components showed some activation, which resulted in an increase in the background count. Corrections were made for this additional activity, or the counting was delayed until three days after radiation exposure to allow for decay of most of the activation products.

Counting times for the various microcosm samples varied from 5 to 30 minutes. Whenever possible, 50,000 counts were accumulated for each

sample. However, it was not always possible to accumulate this many counts and in the case of the water samples as few as 5000 counts would be registered in either the cesium or cobalt channel for a 30 minute count.

A significant counting problem occurred from the use of a dual tag because of contributions of ^{60}Co counts to the ^{137}Cs channel. Differential uptake and retention of ^{60}Co and ^{137}Cs in both plant species resulted in up to 65% of the total cobalt occurring in plants with cesium representing only .5% of the total cesium. When the ratio of ^{60}Co to ^{137}Cs was this large, accurate determination of cesium activity was not possible.

The effect of ^{60}Co activity levels on the activity determination of ^{137}Cs was tested experimentally. Various dilutions of ^{137}Cs were prepared and counted, and .1 μCi of ^{60}Co was added to each dilution. They were then recounted on the dual channel spectrometer and on a Packard multi-channel analyzer, which corrects for dead time. The counting results from the multi-channel analyzer were processed through a statistical program, RESAP, which solved for the activity of several isotopes. The comparison of activity estimates of ^{137}Cs in the presence of ^{60}Co to the absolute amount of ^{137}Cs that was present (Table 2) showed that both analyses were equally poor in detecting the absolute amount of ^{137}Cs present when the ratio of cobalt to absolute cesium exceeded 10 to 1. Based on these results, the cesium levels in plants were allowed to go to zero when the cobalt activity increased. It is reasonable to assume that at least .1% of the total ^{137}Cs remained in the plant, but it is not possible to document this assumption.

Neutron Radiation Facility

The Health Physics Research Reactor (HPRR) at Oak Ridge served as a source of fission fast neutrons for these experiments. The reactor

Table 2. ^{137}Cs Assay in the Presence of ^{60}Co

Absolute ^{137}Cs (μCi)	^{137}Cs activity in presence of ^{60}Co (% of absolute ^{137}Cs)		
	Single Channel	Dual Channel	Multichannel
.1184	98.7	102.8	
.0594	100.7	105.9	
.0149	104.9	109.6	
.0014	227.5	199.5	
.0006	362.5	345.2	
.0001	1849.0	2200.0	

facility, described by Lundin (1962), is capable of delivering chronic or acute doses. The average spectral energy (Fig. 1) is 1 Mev with 2% of the neutrons having energies between 1 Kev and 0.75 Mev, 38.5% between 0.75 and 1.5, 15.6% between 1.5 and 2.5, and 21.5% less than 2.5 Mev. Slow and thermal neutrons comprise the remaining 0.6% of the spectrum. The reactor delivers a mixed neutron-gamma dose, with a neutron/gamma ratio of 9 between 1 and 3 m from the core.

Microcosms were transported to the HPRR facility and arranged in a semicircle approximately 1 m above the concrete floor and 2 m from the reactor, which was operated at 1.7 m above the ground. Doses were delivered acutely, no more than 10 minutes being required for any reactor run. Calculations of doses and exposure distances were determined by the HPRR personnel (Johnson and Poston, 1966). In a semicircle arrangement, and at the distances stated above the dose actually received will vary $\pm 10\%$ from the measured dose. Doses of 100, 400, and 1000 rads were specified for various experiments and actual measurements of dose delivered varied within 10% of the specified dose. In these experiments, the acute dose will be referred to as 100, 400, or 1000 rads.

Distribution of dose within microcosms was determined with Phylatron fast neutron microdosimeters which were placed at various vertical and horizontal positions in a soil-water microcosm.

Material Balance

The use of closed microcosms permits the assumption of total radionuclide recovery by sampling, allowing variation in initial tagging, counting, and sub-sampling. The use of this assumption would expedite calculation of one of the compartments by simply subtracting the sum of activities of all the other compartments from the initial activity.

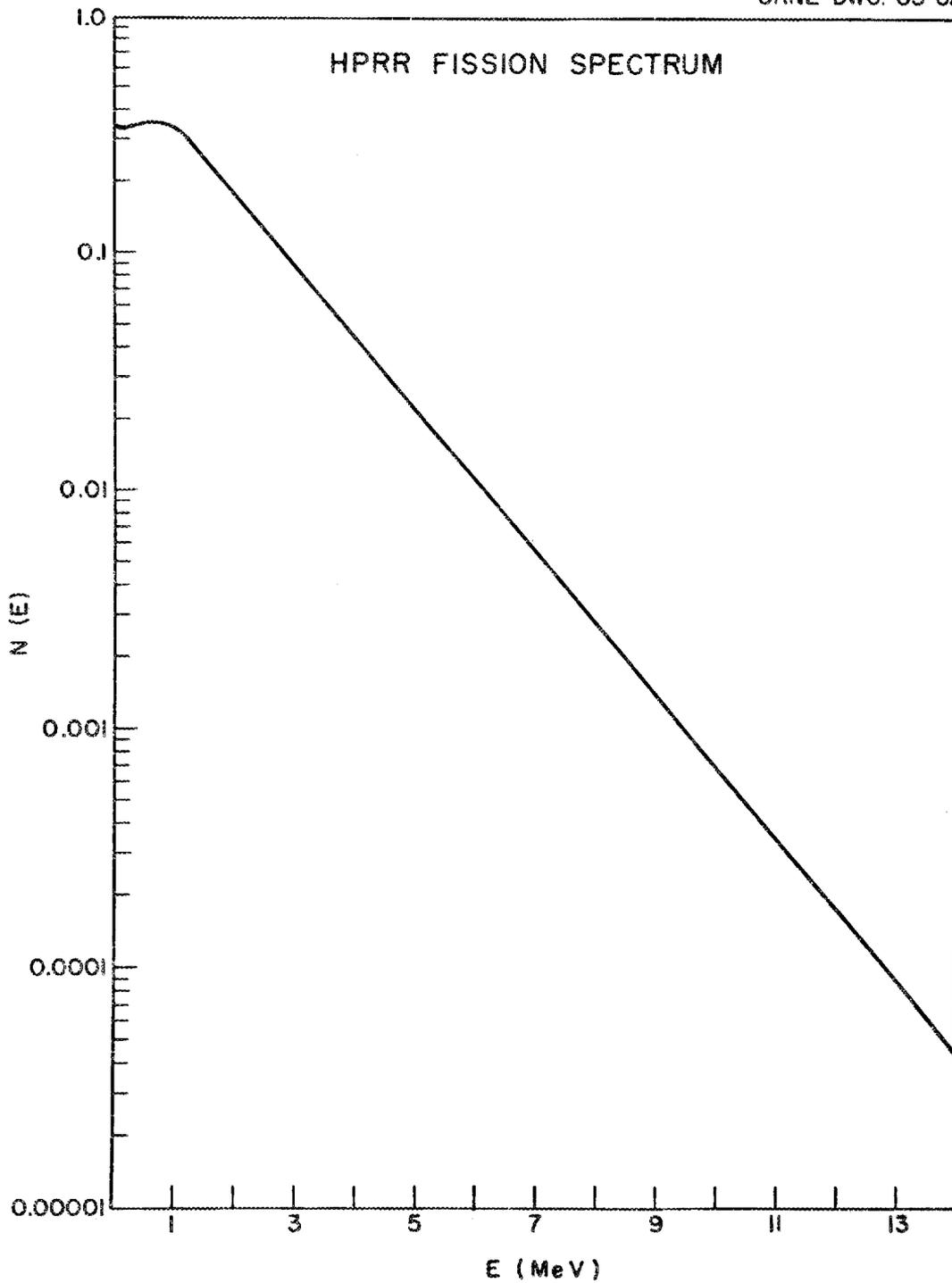


Figure 1. Fast neutron spectrum from the Health Physics Research Reactor.

$N(E)$ is the fraction of neutrons at any given energy.

The assumption of total recovery of radionuclide is not valid unless it is demonstrated experimentally. The assumption of total recovery was considered valid for these studies based on a material balance of ^{137}Cs calculated for four replicate microcosms having water, soil and a container as components (Table 3). The initial activity of $1.25 \pm .046$ microcuries was based on measurements taken from 4 samples of 600 ml of water, each supplied with 1 ml of a standard ^{137}Cs stock solution. Basing percent recovery on the mean inoculum, the range of percent recovery was $\pm 4\%$; the average recovery agreeing with the average inoculum. In this particular study it appeared feasible to assume that total recovery of the spike was possible and on this basis the subtraction method was used to determine the activity in the soil for the later experiments.

Radiosensitivity Assay

The effect of radiation on whole plants was measured by observing change in dry weight or length of plants. Dry weight was determined after drying the samples at 100 C for 24 hours and then cooling them in a dessicator for another 24 hour period. Elongation of plants was taken as an index of growth. Individual plants were measured to the nearest 0.05 cm with a caliper. Measurements were made to the tip of the growing apex with the plant axis fully extended such that curvature did not effect the measurement of total elongation.

Mortality of snails was measured by determining the number of dead snails in each microcosm. In many cases, the bodies of the snails were separated from the shell. It was observed that some snail bodies remained in the shell even though dead. These individuals were determined by spraying a jet of water between the retracted foot and shell. If the snail was

Table 3. ^{137}Cs Budget for Four Microcosms

microcosm	microcosm component	$\mu\text{Ci}/\text{component}$	total activity	initial activity	%recovery	%difference
1	soil	0.1818	1.2021	1.25	96.17	-3.83
	water	0.9288				
	container	0.0915				
2	soil	0.2032	1.2455	1.25	99.64	-0.36
	water	1.0080				
	container	0.0344				
3	soil	0.1770	1.2452	1.25	99.62	-0.38
	water	1.0332				
	container	0.0350				
4	soil	0.3146	1.3015	1.25	104.12	+4.12
	water	0.9600				
	container	0.0269				
composite	---	---	1.2488	1.25	99.89	-0.11

dead the body was easily pushed out of the shell by the water pressure developing behind it. If the snail was alive, it was difficult to direct the water behind the foot and even then, the body was not pushed out of the shell.

Statistical Procedures

Count determinations for each microcosm compartment were converted to picocuries. These activity determinations were transformed to compartmental percent of total radionuclide for each replicate microcosm. This conversion makes comparisons among experiments independent of differences among initial concentrations of radionuclides used in each experiment. The average percent radionuclide for each compartment was then calculated from six replicate observations for each of 9 sampling periods.

Uptake curves were compared with respect to the maximum and end-point quantities of the radionuclides. The final, or end-point, observations were made at 512 hours although the graphs appearing in later sections have a time scale extended to 256 hours or to an observation period beyond which no activity could be detected. Comparisons of final concentrations were made with the data obtained at 512 hours which usually differed by less than 5% from that at 256 hours.

A one-way analysis of variance was used to make point comparisons. The treatments for a given comparison consisted of the different types of microcosms with a common compartment. The compartmental percent radionuclide concentration was compared among treatments for a specified sampling period. If the F statistic indicated differences among treatments at the .05 level, then a Duncan's multiple range test (Duncan, 1955),

hereafter referred to as Duncan's test, was used to compare the mean radionuclide content among treatments.

Net uptake or loss rates of a compartment of interest were compared among treatments. Many of the uptake curves showed a rapid initial uptake followed by a much slower period of uptake. In each case, the use of uptake rate refers to the initial, rapid, uptake either to the maximum concentration or to within 10% of the final observed concentration.

The rate determinations for a compartment were made by least squares determinations. The equation, $Y = a + b \ln X$, gave the best fit to this data as determined by comparing the correlation coefficients of several exponential models. Regression coefficients were compared by an analysis of homogeneity (Steel and Torey, 1960) and if the F statistic indicated significant differences among the treatments at the .05 level, the regression coefficients were then analyzed by a multiple range test.

Duncan's test was used for the multiple comparison of regression coefficients. The error mean square, $s^2_{y.x}$, appropriate for the comparison of treatments, t , was defined as the ratio of the sum of the residual sums of squares, $\sum_{i=1}^t (\sum y_i - (\sum x_i y_i)^2 / \sum x_i^2)$, to the appropriate sum of degrees of freedom, $\sum_{i=1}^t (n_i - 2)$. The standard error of the mean, $s^2_{\bar{b}}$, was defined as the square root of the ratio of the variance to r , $\sqrt{s^2_{y.x}/r}$, where r was the number of observations used to determine the regression coefficients. The procedure for an unequal Duncan's test (Kramer, 1956) was used when the r values were not equal among treatments.

III. RESULTS AND DISCUSSION

Dosimetry in the Microcosms

The dose delivered to the surface of a microcosm was not representative of the dose through a microcosm. The dose through a microcosm decreased with distance from the surface of the microcosm toward the radiation source as a result of the water-neutron interaction.

Dose measurements at several points inside and outside the microcosm were made relative to the surface dose and expressed as percent of the surface dose (Fig. 2). The glass attenuated only 5% of the dose, whereas 4 cm of water attenuated approximately one-half the surface dose, the remaining 4 cm of water attenuated the dose to one-fourth of the surface dose.

As the positions of the organisms in the microcosms were not specified, a given organism could receive a relatively high or low dose compared to the incident dose. Since it was desirable to separate the effects of different dose treatments, doses were chosen which did not have overlapping ranges. Thus, while the effect of an absolute dose cannot be stated, it is possible to compare the effects of the two dose ranges represented by an incident surface dose of 1000 and 100 rads.

Dose Calculations in the Microcosm

Organisms in the microcosms were subject to exposure from three possible radiation sources: 1.) an internal dose from absorbed radio-cesium and -cobalt, 2.) an external dose resulting from radio-cesium or -cobalt in the surrounding media, and 3.) a neutron dose which was an experimental variable. The acute neutron dose was measured, but the internal and external chronic dose due to the radionuclides had to be calculated. Such calculations may be quite accurate where precise

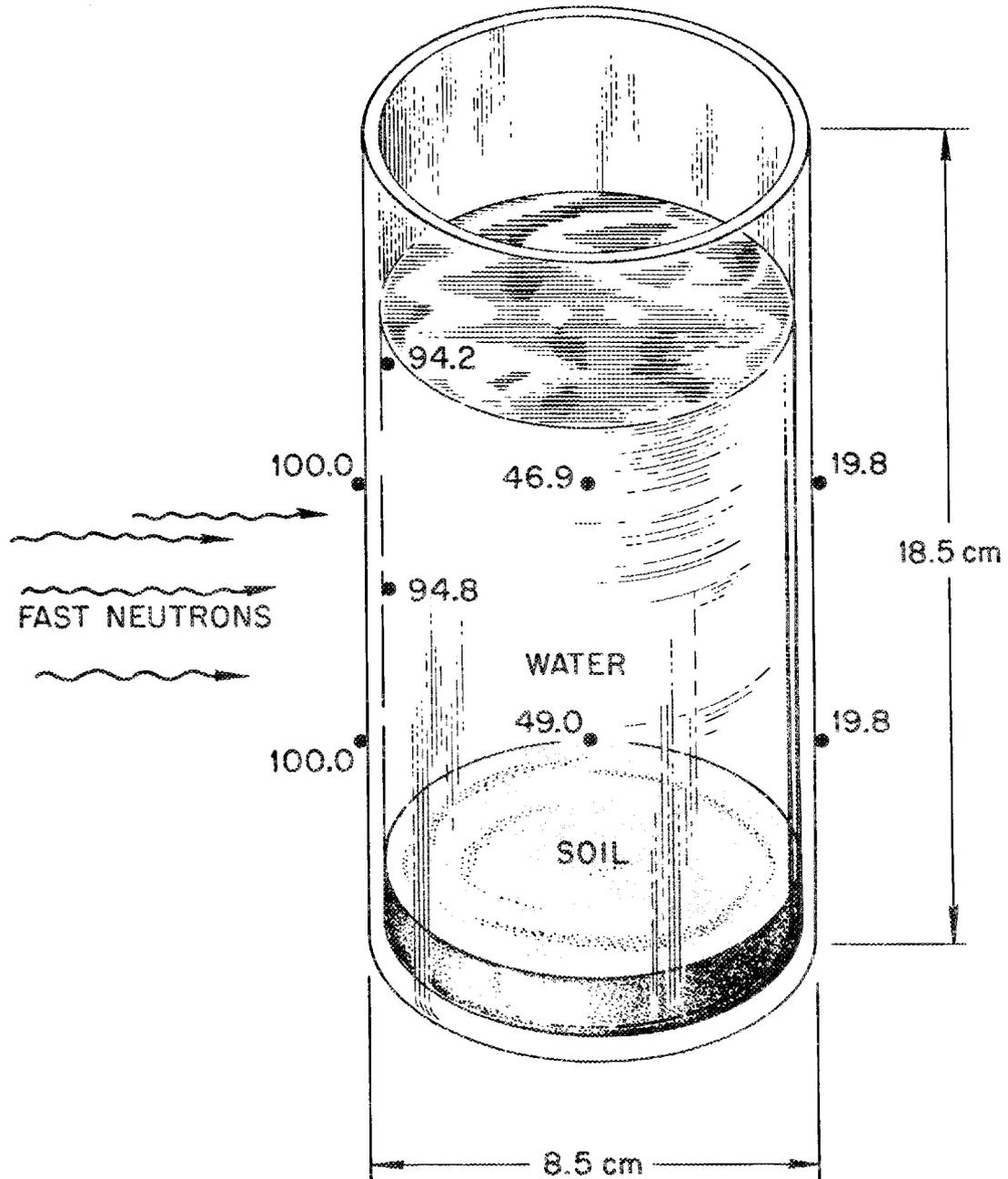


Figure 2. Relative fast neutron dose distribution through a microcosm.

The blackened symbols show the distribution of dosimeters and the numbers express the dose as a percentage of the incident dose.

information on the distribution of nuclide, the biological half-life, and the geometry of the tissue are available (Hine and Brownell, 1956). However, certain assumptions about radionuclide distribution, geometry, and half life, which simplify dose calculations, yet provide reasonable dose estimates, can be made. Here it was assumed that radionuclides were uniformly distributed in the tissue, that maximum activity concentrations were constant, and that geometry of tissues approximated either a cylinder or a sphere. Calculations based on these assumptions probably lead to overestimates of absorbed dose and are intended to provide only an upper estimate of the dose absorbed by an organism.

The greatest concentration of either ^{137}Cs or ^{60}Co in the water was taken as $1.833 \times 10^{-3} \mu\text{C/ml}$. The following equation was used to calculate the gamma-ray dose rate from the medium (Hine and Brownell, 1956):

$$R = 10^{-3} C \rho \Gamma g_p \text{ r/hr} \quad (1)$$

where C is concentration of nuclide in $\mu\text{C/ml}$, ρ is the tissue density in g/cc , Γ is the gamma dose rate constant of the radionuclide in $\text{cm}^2\text{-r/mc-hr}$ and g_p is a geometrical factor for a cylinder 11 cm high and 4.3 cm radius.

The geometrical factor, g_p , was calculated by the following equation (Hine and Brownell, 1965):

$$g_p = 2\pi(z \ln(1 + \frac{r^2}{z^2}) + 2r \tan^{-1}(\frac{z}{r}) - \mu(z\sqrt{z^2+r^2} - z^2 + r^2(\ln(z + \sqrt{z^2+r^2}) - \ln r))) \quad (2)$$

where z is the height of the water cylinder measured as 11 cm, r is the radius measured as 4.3 cm, and μ is the absorption coefficient for soft tissue 0.03.

The beta dose rate from the media was calculated by the following equation (Hine and Brownell, 1956):

$$R = 51.2 \bar{E}_B C f \text{ rad/day} \quad (3)$$

where \bar{E}_B is the average beta energy of the nuclide, C is the radionuclide

concentration in $\mu\text{Ci}/\text{ml}$ and f is the fraction of energy absorbed in a cylinder of 4.3 cm radius. This fraction is given for cylinders and spheres by Daugherty (1962).

Elodea was chosen to represent the plants because the greatest concentration of either radio-caesium or -cobalt occurred in Elodea. The concentration of ^{137}Cs for wet Elodea tissue was $0.00363 \mu\text{Ci}/\text{gm}$ and for ^{60}Co $0.07965 \mu\text{Ci}/\text{gm}$. The internal gamma dose rate was calculated by equation (1), using a spherical model where the average geometrical factor \bar{g} , for a radius of 0.332 cm was 3. The internal beta dose rate was calculated by equation (3), where for a cylinder of .0664 cm, f is .75 for ^{60}Co and .23 for ^{137}Cs .

The highest concentration of ^{137}Cs for wet Physa tissue was $0.09857 \mu\text{Ci}/\text{gm}$. The internal gamma dose rate was calculated by equation (1) using a cylindrical model in which the geometrical factor, g_p , was evaluated by equation (2), height being 1.35 cm and radius .25 cm. The internal beta dose rate was calculated by equation (3), where for a cylinder of diameter .5 cm f is .97 for ^{60}Co and .78 for ^{137}Cs .

Gamma dose rate calculations were converted from r/hr to rad/hr using a conversion factor of .95 (N.B.S. Handbook No. 88). The dose rates were then converted to total dose for 512 hours (Table 4).

Complexity and Radionuclide Flux in Compartments

Water Compartment - The ^{60}Co flux pattern of the water compartment (Fig. 3a) was similar among complexity treatments. There was an initial period of rapid loss which was completed by 32 or 64 hours. This was followed by a period of slower loss which lasted from 32 to 256 hours. The water compartment of all treatments reached or closely approached a steady state content of ^{60}Co by 256 hours.

Table 4. Integrated Beta and Gamma Dose (Rads) Absorbed by Elodea and Physsa in a Microcosm

	gamma from media	beta from media	gamma internal to <u>Elodea</u>	beta internal to <u>Elodea</u>	gamma internal to <u>Physsa</u>	beta internal to <u>Physsa</u>	total beta-gamma to <u>Elodea</u>	total beta-gamma to <u>Physsa</u>
^{60}Co	.1770	.1882	.1549	6.1256	3.4777	12.0511	6.6457	15.8940
^{137}Cs	.7062	.4604	.0018	0.2466	7.0377	19.3109	1.4150	27.5152
Total	.8832	.6486	.1567	6.3722	10.5154	31.3620	8.0607	43.4092

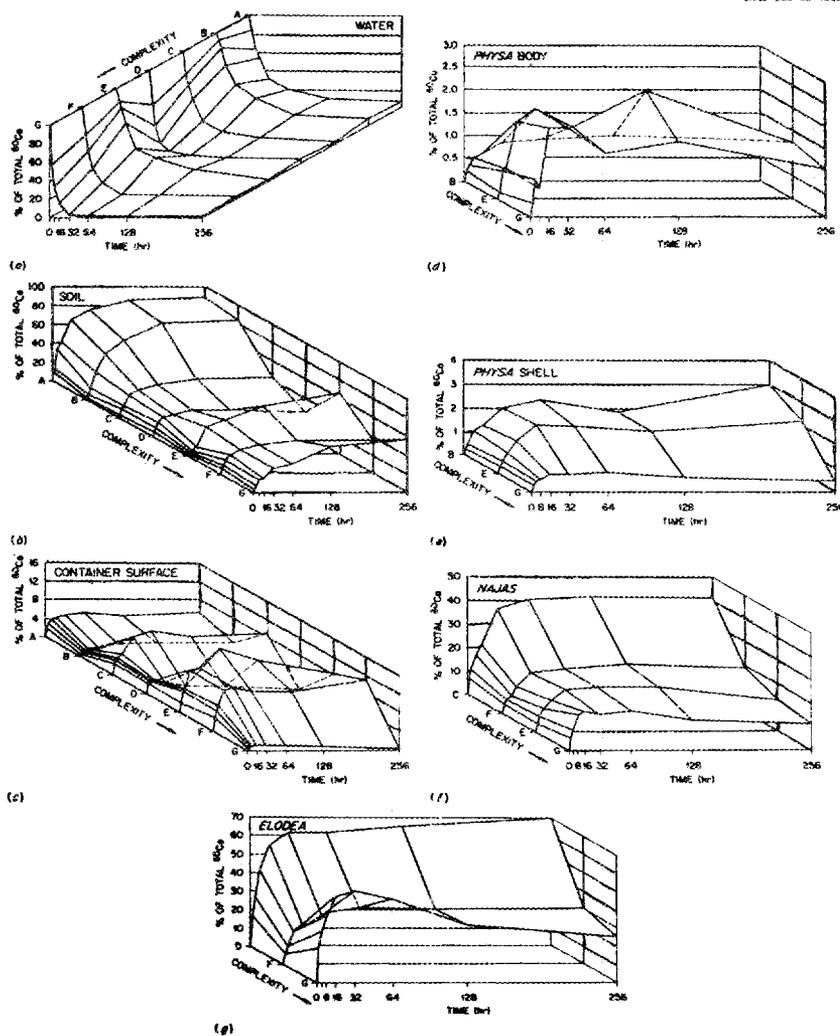


Figure 3. Relationship between complexity and compartmental ^{60}Co dynamics.

Complexity levels represent combinations of microcosm components:

- A = physical components only
- B = Physsa and physical components
- C = Najas and physical components
- D = Elodea and physical components
- E = Physsa, Najas, and physical components
- F = Najas, Elodea and physical components
- G = Physsa, Najas, Elodea and physical components

The loss rate of ^{60}Co from the water compartment varied among complexity treatments, but there were no statistical differences (Table 5). The results do suggest that treatments consisting of Elodea and other components effect a more rapid ^{60}Co loss from the water than the remaining treatments. The apparent effect of Elodea of increasing the loss rate of ^{60}Co from the water may result from the fact that the surface area of Elodea was seven times greater than that of Najas. Physa alone or combined with Najas had no effect on the loss rate. However, when Physa occurred with Najas and Elodea the most rapid loss rate of ^{60}Co from the water compartment was obtained. This suggested that there was an interaction between Elodea and Physa, as Physa combined with Najas had no effect on the rate as compared to the physical microcosm and Elodea combined with Najas did not produce as rapid a loss rate. These data suggested a trend of increased loss rate with increased surface area and possibly a trend of increased loss rate with complexity as exemplified by the Physa-Najas-Elodea interaction.

The ^{60}Co content of the water compartments at 512 hours was compared among complexity treatments (Table 6). Najas alone, the physical microcosm, and Physa alone formed a set of treatments which left the greatest amount of ^{60}Co in the water compartment. The plants alone and in combination formed a nonsignificant set which left more ^{60}Co in the water compartment than the final nonsignificant range consisting of snail-plant(s) treatments.

These data showed a trend of decreased ^{60}Co content of the water compartment with increased complexity. Physa alone and Najas alone did not reduce the ^{60}Co content of the water compartment any more than the physical microcosm. Elodea alone and Najas-Elodea decreased the ^{60}Co content

Table 5. Duncan's Comparison of ^{60}Co Loss Rates From the Water Compartment Among Complexity Levels

Value of p^*	2	3	4	5	6	7	
$r_{p.05}$	2.919	3.066	3.160	3.226	3.276	3.315	
R_p	0.0127	0.0134	0.0138	0.0141	0.0143	0.0146	
Treatment	physical <u>Physa</u>	physical	physical <u>Najas</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>
Mean(beta)	-20.07	-21.37	-21.71	-21.72	-23.18	-24.55	-26.29
Statistical Significance							

* p represents the number of means included in the ranked comparisons.

Table 6. Duncan's Comparison of ^{60}Co in the Water
Compartment at 512 Hours Among Complexity Levels

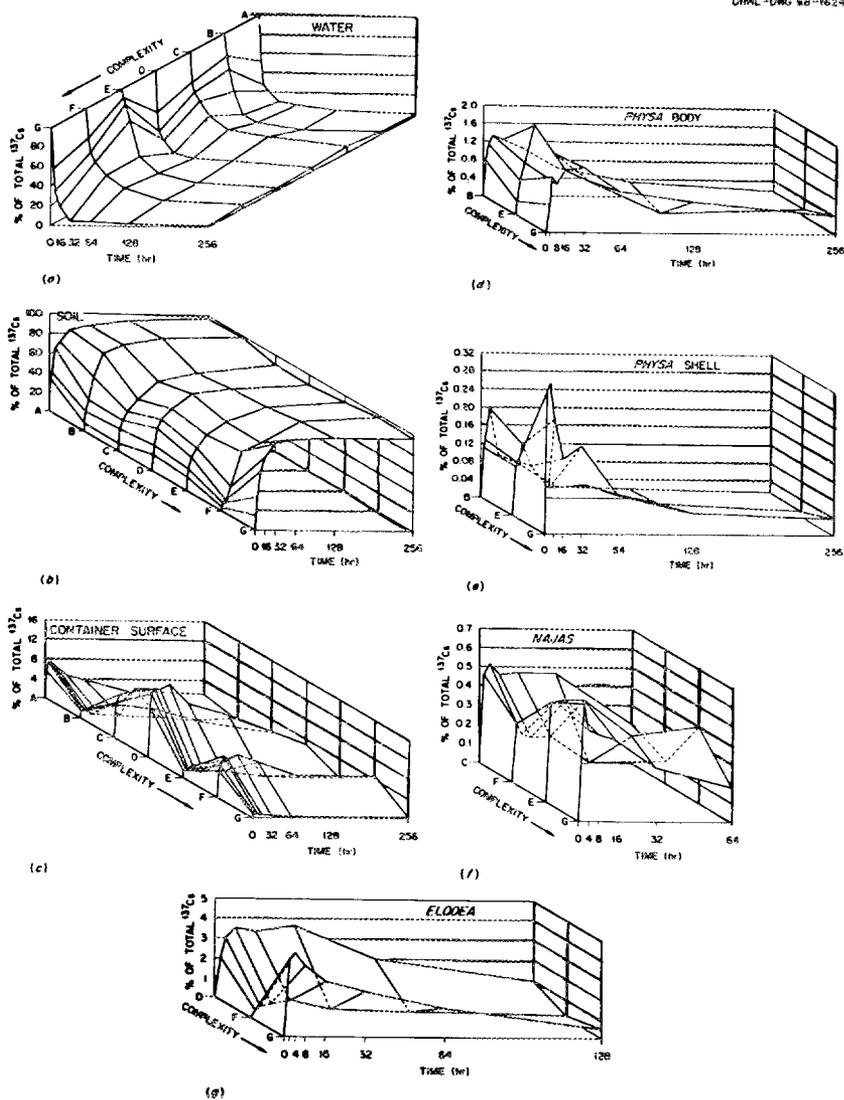
Value of p	2	3	4	5	6	7	
$r_{p.05}$	2.873	3.020	3.116	3.185	3.237	3.278	
R_p	0.81	1.03	1.07	1.09	1.10	1.12	
Treatment	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physsa</u> <u>Najas</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>	physical <u>Najas</u>	physical	physical <u>Physsa</u>
Mean(%)	1.58	1.69	2.66	2.80	3.59	3.96	4.27
Statistical Significance	_____		_____			_____	

of the water which reflected the difference in surface area between the plants. The snail-plant(s) combinations further reduced the ^{60}Co content of the water compartment and this suggested an interaction between the plants and snail. That such an interaction existed was evidenced by the fact that the combined surface area of Elodea and Najas did not reduce the ^{60}Co content of the water as low as the snail-plant(s) combinations and that Physa alone did not reduce the ^{60}Co content as compared with the physical microcosm.

The pattern of ^{137}Cs flux in the water compartment (Fig. 4a) was similar among complexity treatments. A period of rapid loss lasted to 32 hours and was followed by a period of slower loss to 256 hours. Among all treatments the water compartment had reached or closely approached a steady state ^{137}Cs content by 256 hours.

The loss rate of ^{137}Cs from the water compartment differed among treatments. A comparison of these rates (Table 7) showed that all complexity treatments containing Physa formed a nonsignificant set with loss rates significantly more rapid than all other treatments. The treatments of Physa-Najas-Elodea and Elodea alone formed a nonsignificant sub-set with the loss rates significantly higher than those of the remaining treatments. Finally, the treatment of Elodea alone formed a nonsignificant range with all treatments having a slower loss rate. These data showed that the presence of Physa significantly increased the loss rate of ^{137}Cs from the water compartment. There is no apparent relationship between plant surface area and ^{137}Cs loss rates and the effect of Physa if increasing the loss rate is independent of the plant combinations.

The ^{137}Cs content of the water compartments was compared among treatments (Table 8). The snail-plant(s) combinations maintained a significantly



137 Figure 4. Relationship between complexity and compartmental ^{137}Cs dynamics.

Complexity levels represent combinations of microcosm components:

- A = physical components only
- B = Physsa and physical components
- C = Najas and physical components
- D = Elodea and physical components
- E = Physsa, Najas, and physical components
- F = Najas, Elodea, and physical components
- G = Physsa, Najas, Elodea, and physical components

Table 7. Duncan's Comparison of ^{137}Cs Loss Rates From the Water Compartment Among Complexity Levels

Value of p	2	3	4	5	6	7	
$r_p .05$	2.950	3.097	3.190	3.255	3.303	3.339	
R_p	7.12	7.47	7.69	7.85	7.96	8.05	
Treatment	physical <u>Najas</u>	physical <u>Najas</u> <u>Elodea</u>	physical	physical <u>Elodea</u>	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physsa</u> <u>Najas</u>	physical <u>Physsa</u>
Mean(beta)	-16.64	-16.69	-18.53	-19.65	-26.71	-27.14	-28.63
Statistical Significance							

Table 8. Duncan's Comparison of ^{137}Cs in the Water Compartment
at 512 Hours Among Complexity Levels

Value of p	2	3	4	5	6	7	
$r_p.05$	2.873	3.021	3.117	3.186	3.237	3.278	
R_p	0.66	0.70	0.72	0.74	0.75	0.76	
Treatment	physical	physical <u>Physsa</u>	physical <u>Najas</u>	physical <u>Najas</u> <u>Eloëea</u>	physical <u>Eloëea</u>	physical <u>Physsa</u> <u>Najas</u>	physical <u>Physsa</u> <u>Najas</u> <u>Eloëea</u>
Mean	0.29	0.39	0.82	1.00	1.10	1.77	2.03
Statistical Significance	_____					_____	

higher cesium content in the water than other complexity treatments. The remaining plant combinations, together with Physa alone, formed a set of treatments which maintained significantly more cesium in the water than the physical microcosm. Finally the treatments of Najas alone, Physa alone, and the physical microcosm formed a nonsignificant range which maintained the least amount of ^{137}Cs in the water.

These data showed consistent trend of increased ^{137}Cs in the water compartment with increased complexity. Physa alone had no effect compared to the physical microcosm. The plants increased the ^{137}Cs content of the water and the difference between Najas alone and Elodea alone showed a surface area effect. The snail-plant(s) combinations demonstrated a significant interaction between snails and plants as ^{137}Cs in the water exceeded that maintained by the plants, alone or combined, and Physa alone. The difference between Physa-Najas and Physa-Najas-Elodea may be due to a plant surface area effect.

Radionuclide loss rates from the water compartment showed no consistent trend with increased complexity. The effect of each complexity treatment on this radionuclide loss rate was apparently independent of the degree of complexity. The only exception occurred with the Physa-Najas-Elodea combination which increased the loss rate of both radionuclides from the water compartment over all other combinations (Table 9).

The radionuclide content of the water compartment at steady state (512 hours) had divergent trends with increased complexity. The ^{60}Co steady state content decreased as complexity increased. Physa alone had no apparent effect, the plants, alone or combined, decreased the content, and the snail-plant(s) combinations reduced the steady state content to the lowest amount. The ^{137}Cs steady state content increased with increased

Table 9. The Effect of Increasing Complexity on the Ratio of ^{60}Co to ^{137}Cs Loss Rates From the Water Compartment

Microcosm Combination	physical	physical <u>Physsa</u>	physical <u>Najas</u>	physical <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physsa</u> <u>Najas</u>	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>
Loss Rate of Cobalt-60	-21.37	-20.07	-21.71	-24.55	-23.18	-21.72	-26.29
Loss Rate of Cesium-137	-18.53	-28.63	-16.64	-19.65	-16.69	-27.14	-26.71
Ratio of Cobalt to Cesium Loss Rates	1.15	0.70	1.30	1.25	1.39	0.80	0.98

complexity. Compared to the physical microcosm, Physa alone had no effect, the plant(s), alone or combined, increased the cesium content, and the snail-plant(s) combinations resulted in the highest ^{137}Cs content in the water compartment.

The ratio of ^{60}Co to ^{137}Cs loss rates from the water compartment for complexity treatments (Table 9) showed the effect of each combination in altering the relationship of the ^{60}Co and ^{137}Cs flux. In the physical microcosm, the ^{60}Co loss was more rapid than that of ^{137}Cs . The only other combinations which had the same effect were those with plants, alone or combined. All plant combinations had the similar effect of increasing the ratio and values ranged from 1.25 to 1.39. The effect of the plant(s) was to lower the ^{137}Cs loss rate, increase the ^{60}Co loss rate, or both. Physa alone decreased the ratio, below 1, by increasing the ^{137}Cs loss rate as compared to the physical microcosm. The Physa-Najas treatment increased the ratio as compared to Physa alone, although it was still less than 1. The combination of Physa-Najas-Elodea increased the ratio over that of Physa-Najas to approximately 1.

These data showed that the effect of the plant compartments was to increase the Co/Cs loss rate ratio while the snail compartment decreased this ratio, as compared to the physical microcosm. The snail-plant(s) tended to increase the ratio over that of Physa alone. The pattern illustrated by these ratios in the water was one of diverging loss rates of ^{60}Co and ^{137}Cs which were converged by the effect of increased complexity.

The ratio of per cent ^{60}Co to ^{137}Cs in the water compartment at steady state (Table 10) showed a consistent trend with increased functional complexity. Compared to the physical microcosm, Physa alone slightly increased the ^{137}Cs content of the water, which resulted in

Table 10. The Effect of Increasing Complexity on the Ratio of ^{60}Co to ^{137}Cs in the Water Compartment at 512 Hours

Microcosm Combination	physical	physical <u>Physsa</u>	physical <u>Najas</u>	physical <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physsa</u> <u>Najas</u>	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>
% Cobalt-60	3.69	3.68	3.59	2.81	2.67	1.61	1.53
% Cesium-137	0.29	0.39	0.82	1.10	1.00	1.77	2.03
Ratio of Cobalt- 60 to Cesium-137	13.65	9.44	4.38	2.55	2.67	0.91	0.78

lowering the ratio. The plants, alone or combined, reduced the ratio even more. The effect of Najas alone increased the ^{137}Cs content of the water, while Elodea, alone or combined with Najas, decreased the ^{60}Co and increased the ^{137}Cs content of the water. The combination of snail-plant(s) reduced the ratio to approximately 1. The interaction of plant(s) and snails increased the ^{137}Cs content and decreased the ^{60}Co content of the water compartment. The trend of these ratios for the water compartment showed that increased functional complexity converged the steady state concentrations of both radionuclides toward equality.

Soil Compartment - The pattern of ^{60}Co flux through the soil compartment (Fig. 3b, p. 21) differed with complexity treatments. Each treatment had a period of rapid uptake extending to 16 or 32 hours. In most treatments this period was followed by a slower uptake to a steady state content by 256 hours. However, in all treatments with Physa present (B, E, and G) a steady state content was not reached by 512 hours.

The comparison of ^{60}Co uptake rates of the soil compartment (Table 11) showed that the treatments of Physa alone and the physical microcosm formed a nonsignificant range with more rapid ^{60}Co loss rates than the other treatments. The Physa-Najas and physical microcosms formed a nonsignificant set with higher loss rates than the remaining treatments. The microcosms of Physa-Najas-Elodea and Najas alone formed a set with significantly faster loss rates than those of remaining treatments. The treatment of Najas alone and remaining treatments formed the final nonsignificant range.

These data showed two trends. The presence of plants decreased the uptake rate and the presence of Physa increased the uptake rate compared to the physical microcosm. In the case of the plants, the effect correlated with surface area; Elodea with the greater surface area reduced

Table 11. Duncan's Comparison of ⁶⁰Co Uptake Rates of the Soil Compartment Among Complexity Levels

Value of p	2	3	4	5	6	7	
$r_p \cdot 05$	2.870	3.017	3.114	3.182	3.235	3.276	
R'_p *	10.62	11.17	11.53	11.78	11.98	12.13	
Treatment	physical <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>	physical	physical <u>Physa</u>
Mean(beta)	6.00	7.53	9.45	12.06	17.92	19.93	22.73
Statistical Significance							

* R'_p indicates the square root of the variance.

the rate and Najas with less surface area had less effect. When Physa was combined with Najas, the effect of Najas in lowering the soil uptake rate was negated and the effect of Physa in increasing this rate was reduced. Combining Elodea with Physa and Najas, the effect of Physa alone or plants combined was moderated, which resulted in the intermediate soil uptake rates. The change in uptake rate when plants were combined with Physa demonstrated an interaction of these biological components which moderated the extreme effects of these components when they occurred alone and produced a soil uptake rate slower than when none of these components were present. Increased complexity had the effect of converging divergent soil uptake rates of ^{60}Co .

The ^{60}Co content of the soil compartment at 512 hours was compared among treatments (Table 12). These values represented a steady state content for all treatments except those in which Physa occurred. Physa alone and the physical microcosm formed a nonsignificant set with significantly more ^{60}Co content than all the other treatments. Physa-Najas and Physa-Najas-Elodea formed a range with significantly more ^{60}Co in the soil compartment than the remaining treatments with plants. Najas alone formed an independent set with significantly more ^{60}Co than either Elodea treatment, treatments which formed a range with the lowest ^{60}Co content in the soil compartment.

The plants, alone or combined, decreased the ^{60}Co content of the soil compartment, while Physa alone slightly increased the content, as compared with the physical microcosm. The interaction of Physa and plant(s) moderated the extreme effects of the components considered independently and resulted in an intermediate ^{60}Co content of the soil compartment. Among

Table 12. Duncan's Comparison of ^{60}Co in the Soil Compartment
at 512 Hours Among Complexity Levels

Value of p	2	3	4	5	6	7	
$r_{p.05}$	2.873	3.020	3.116	3.185	3.237	3.278	
R_p	8.42	8.85	9.13	9.33	9.48	9.60	
Treatment	physical <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>	physical	physical <u>Physa</u>
Mean	30.69	33.89	42.43	69.86	74.99	88.15	91.81
Statistical Significance	_____		_____	_____		_____	

the treatments involving plants, the evidence of a surface area effect is that Elodea and Najas-Elodea produced a lower content than Najas alone. This same surface area effect is evidenced in Physa-Najas and Physa-Najas-Elodea. Similar to the results of the rate comparison, increased complexity had the effect of converging divergent ^{60}Co content of the soil compartment.

The pattern of ^{137}Cs flux through the soil compartment (Fig. 4b, p. 26) was similar for all complexity treatments. A period of rapid uptake, which lasted between 32 and 64 hours, was followed by a period of slower uptake. All treatments reached a steady state by 256 hours.

A comparison of ^{137}Cs uptake rates of the soil compartments (Table 13) showed that all treatments with Physa had a significantly faster uptake rate than other complexity treatments, which together formed the final nonsignificant set with the slowest soil uptake rates.

The data showed that the effect of all Physa combinations was to increase the soil uptake rate of ^{137}Cs . The plants had only a slight effect compared to that of the snails. An interaction of plants and snails was not clearly shown. While Physa-Najas appeared to effect a soil uptake rate which could be judged a result of interaction, Physa-Najas-Elodea did not show such evidence. However, the magnitude of differences among treatments containing Physa was small compared to the difference between Physa combinations and other microcosms. Thus, these data show a significant effect of the snail compartment on the soil uptake rate of ^{137}Cs , but show no trend with complexity.

The steady state content of ^{137}Cs in the soil compartments was compared among treatments (Table 14). The results showed a graded series

Table 13. Duncan's Comparison of ^{137}Cs Uptake Rates of the Soil Compartment Among Complexity Levels

Value of p	2	3	4	5	6	7	
$r_p \cdot 05$	2.888	3.035	3.131	3.199	3.250	3.290	
R'_p	14.31	14.75	15.22	15.55	15.80	15.99	
Treatment	physical	physical <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u>	physical <u>Physa</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>
Mean(beta)	15.58	15.94	17.13	17.41	26.55	27.59	30.29
Statistical Significance							

Table 14. Duncan's Comparison of ^{137}Cs in the Soil Compartment at 512 Hours Among Complexity Levels

Value of p	2	3	4	5	6	7	
$r_{p.05}$	2.873	3.020	3.116	3.185	3.237	3.278	
R_p	1.93	2.03	2.09	2.14	2.17	2.20	
Treatment	physical <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>	physical	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Najas</u>	physical <u>Physa</u>
Mean	93.97	95.38	97.03	97.82	97.95	98.48	99.41
Statistical Significance							

series of overlapping nonsignificant ranges. The difference between the highest and lowest content was only 5 per cent, which showed that none of the complexity treatments were significant in terms of ^{137}Cs movement to the soil. Even so, Physa alone increased the amount of ^{137}Cs in the soil and Elodea alone and Najas-Elodea appeared to slightly increase the amount of radiocesium in the soil, all compared to the physical microcosm. Although the data showed some trends, the lack of large differences among treatments in the ^{137}Cs content of the soil was of more significance. These data demonstrated that the biological components were not particularly effective in delaying ^{137}Cs transfer to the soil compartment.

Radionuclide uptake by the soil compartment showed a trend with ecosystem complexity in the case of ^{60}Co and a single effect in the case of ^{137}Cs . Soil uptake rates of ^{60}Co decreased when plants were present and increased when Physa was present. Increasing complexity by combining snails and plant(s) converged the extreme effects of both biological components considered independently. Soil uptake rates of ^{137}Cs were unaffected by the presence of plants, but when Physa was present the uptake rate was increased

Radionuclide concentration in the soil at 512 hours showed a trend for ^{60}Co and no trend for ^{137}Cs . In the case of radiocobalt the divergent effects of plants and snails were converged when these biological components were combined. An increase in complexity had no significant effect on the steady state concentration of ^{137}Cs in the soil component.

Soil uptake rate ratios of ^{60}Co to ^{137}Cs were compared (Table 15) and showed that the physical microcosm had a ratio of 1.28 while all other complexity treatments had a ratio of less than 1. The ratio for

Table 15. The Effect of Increasing Complexity on the Ratio of ^{60}Co to ^{137}Cs Uptake Rates of the Soil Compartment

Treatment	physical	physical <u>Physa</u>	physical <u>Najas</u>	physical <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>
^{60}Co	19.93	22.73	9.44	6.00	7.53	17.92	12.06
^{137}Cs	15.58	23.71	17.41	15.95	17.14	30.30	27.59
$^{60}\text{Co}/$ ^{137}Cs	1.28	0.96	0.54	0.37	0.44	0.59	0.44

Physsa alone approached 1, although the ^{60}Co and ^{137}Cs rates were greater than those for the physical microcosm. The ratio for plant combinations was lowered to between 0.37 and 0.54 due to the effect of the plant(s) on the ^{60}Co rate. When Physsa was combined with plant(s), the ratio was maintained between 0.44 and 0.59. This was a result of Physsa increasing the ^{137}Cs uptake rate over the physical microcosm and increasing the ^{60}Co uptake rate over the plant(s) microcosms. Except for Physsa alone, increased complexity did not have an effect on the Co/Cs uptake rate ratios. The significant result was that the presence of biological components lowered the ratio as compared to that of the physical microcosm.

Considering the ratio of ^{60}Co to ^{137}Cs content of the soil compartment at 512 hours (Table 16), Physsa alone and the physical microcosm had similar ratios of 0.9, although the presence of Physsa increased the amount of radio-cesium and -cobalt in the soil compartment. The plant combinations had ratios of 0.3 to 0.4 and the cesium content was unaffected while the ^{60}Co content was lowered as compared to the physical microcosm. The combination of Physsa and plant(s) increased the ratio to 0.7 due to the Physsa-plant(s) interaction which increased the ^{60}Co content of the soil compartment. These Co/Cs content ratios showed no linear trend with increased complexity, but demonstrated the effect of the individual biological components in lowering the ratio and the effect of the biological interactions in increasing the ratio.

Container Surface Compartment - The ^{60}Co flux pattern to the container surface compartments differed among treatments (Fig. 3c, p. 21). The pattern of uptake to a steady state content was characteristic of the physical microcosm (A), Physsa alone (B), Najas alone (C), and

Table 16. The Effect of Increasing Complexity on the Ratio of ^{60}Co to ^{137}Cs Content of the Soil Compartment at 512 Hours

Treatment	physical	physical <u>Physa</u>	physical <u>Najas</u>	physical <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>
^{60}Co	88.15	91.81	42.43	30.69	33.89	74.99	69.86
^{137}Cs	97.03	99.41	98.48	95.38	93.97	97.95	97.82
$^{60}\text{Co}/$ ^{137}Cs	0.91	0.92	0.43	0.32	0.36	0.76	0.71

Najas-Elodea (F). A pattern of uptake to a maximum content with subsequent loss characterized Elodea alone (D), Physa-Najas (E), and Physa-Najas-Elodea (G).

The initial ^{60}Co uptake rates were compared among complexity treatments (Table 17), except for the treatment of Elodea alone in which uptake was completed by 2 hours. The Physa-Najas combination had a significantly higher uptake rate than all other treatments. Najas alone and Najas-Elodea formed a set with significantly higher uptake rates than the remaining treatments. Najas-Elodea and the remaining combinations formed a nonsignificant range with the slowest uptake rates.

The uptake rate data showed that the presence of Najas increased the uptake except when combined with Elodea and Physa. The presence of Physa alone or combined with Elodea and Najas effected similar rates which were lower than those of the Najas combinations. These data showed that Najas and Physa each had a distinct effect on the uptake rate, and that the specific result in combination was not predictable from knowledge of each component alone.

A comparison of the maximum ^{60}Co content of the container surface compartment among treatments (Table 18) showed that all treatments with Najas alone or combined with Elodea or Physa and the physical microcosm formed three successive overlapping ranges which had significantly higher content than the remaining treatments of Physa alone, Elodea alone, and Physa-Najas-Elodea. The latter treatments formed a nonsignificant range.

These results showed that the presence of Najas had the significant effect of increasing the ^{60}Co content of the container surface compartment. Physa or Elodea alone reduced the content. The interesting result

Table 17. Duncan's Comparison of ^{60}Co Uptake Rates of the Container Surface Compartment Among Complexity Levels

Value of p	2	3	4	5	6	
$r_p \cdot 05$	2.950	3.097	3.190	3.255	3.303	
R'_p	2.212	2.322	2.392	2.441	2.477	
Treatment	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physsa</u>	physical	physical <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u>	physical <u>Physsa</u> <u>Najas</u>
Mean(beta)	0.3838	0.5740	0.9416	1.5313	2.0819	3.2649
Statistical Significance	_____					

Table 18. Duncan's Comparison of ⁶⁰Co Maxima on the Container Surfaces Among Complexity Levels

Value of p	2	3	4	5	6	7	
r _p .05	2.873	3.020	3.116	3.185	3.237	3.278	
R _p	3.44	3.62	3.74	3.82	3.88	3.93	
Treatment	physical <u>Physo</u> <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>	physical <u>Physo</u>	physical	physical <u>Najas</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physo</u> <u>Najas</u>
Mean	1.29	2.60	2.62	6.71	9.18	11.90	13.96
Statistical Significance	_____			_____	_____	_____	

was that when Elodea or Physa were combined with Najas, the effect of Najas predominated. However, when Najas was combined with Elodea and Physa the effect of Elodea and Physa predominated. These results showed that the interaction of Physa and Elodea was significant in reducing the effect of Najas.

A comparison of the ^{60}Co content on the container surface at 512 hours (Table 19) showed that the physical microcosm and all Najas treatments, except Physa-Najas-Elodea, formed a nonsignificant range with a significantly higher content than the remaining treatments which formed a nonsignificant range. These data showed that Najas was effective in maintaining a higher content in the container surface than Elodea or Physa alone and Physa-Najas-Elodea. Further, there was a trend of decreasing ^{60}Co content for Najas combinations of increased complexity.

The pattern of ^{137}Cs flux through the container surface compartments (Fig. 4c, p. 26) was different among complexity treatments. A period of uptake to a maximum, which lasted up to 32 hours, was followed by a continuous loss through 512 hours for treatments of plant combinations (C,D,F). All other treatments had a pattern of uptake to a maximum, followed by loss to a steady state content.

The maximum content of the container compartment was compared among treatments (Table 20). The treatment of Elodea alone had a significantly higher content than all other treatments. Najas alone, Najas-Elodea and the physical microcosm formed two overlapping ranges with significantly higher content than the remaining treatments of Physa combinations. The Physa combinations formed a nonsignificant range with the lowest ^{137}Cs content.

Table 19. Duncan's Comparison of ⁶⁰Co in the Container Surface
Compartment at 512 Hours Among Complexity Levels

Value of p	2	3	4	5	6	7	
$r_{p.05}$	2.873	3.020	3.116	3.185	3.237	3.278	
R_p	2.77	2.39	2.47	2.53	2.56	2.59	
Treatment	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>	physical <u>Physsa</u>	physical <u>Najas</u> <u>Elodea</u>	physical	physical <u>Physsa</u> <u>Najas</u>	physical <u>Najas</u>
Mean	0.89	1.05	2.02	6.22	6.71	7.63	8.37
Statistical Significance	_____			_____			

Table 20. Duncan's Comparison of ^{137}Cs Maxima on Container Surfaces Among Complexity Levels

Value of p	2	3	4	5	6	7	
$r_p .05$	2.873	3.020	3.116	3.185	3.237	3.278	
R_p	1.48	1.55	1.60	1.64	1.67	1.69	
Treatment	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u>	physical <u>Physa</u> <u>Najas</u>	physical	physical	physical <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>
Mean	0.69	1.54	2.17	7.50	8.67	9.36	15.81
Statistical Significance	_____			_____		_____	

These results showed that the presence of plants either significantly increased the radiocesium content of the container surface or had no effect as compared to the physical microcosm, whereas the presence of the snail reduced the content as compared to the physical microcosm. Among plants, the data indicated that increased surface area increased the ^{137}Cs content, as Elodea with the greatest surface area had the greatest content. The trend of these data showed that plants alone or combined increased the content, the snail alone decreased the content, and when the snail and plant(s) were combined the effect of the snail predominated.

The ^{137}Cs content of the container surface at 512 hours was compared among complexity treatments (Table 21). The treatment of Najas-Elodea maintained significantly more ^{137}Cs on the container surface than all other treatments. Elodea alone and the physical microcosm formed a range which had a significantly higher ^{137}Cs content than the remaining treatments. Najas alone and all Physa treatments formed the final range with the lowest content. In general, these data showed that the plant compartments maintained approximately the same ^{137}Cs content on the container surface as the physical microcosm, while the snail compartment significantly reduced the ^{137}Cs content of the container surface compartment.

Changes in complexity changed the flux pattern of both radionuclides through the container surface compartment. The pattern showed no similarity between radionuclides for a given complexity level, except for the physical microcosm, Physa alone, and Elodea alone. In general, the behavior of either radionuclide was not predictable from knowledge of the behavior of the other radionuclide.

Table 21. Duncan's Comparison of ¹³⁷Cs in the Container Surface Compartment at 512 Hours Among Complexity Levels

Value of p	2	3	4	5	6	7
r _p .05	2.873	3.028	3.116	3.185	3.237	3.278
R _p	1.47	1.54	1.59	1.63	1.65	1.67

Treatment	physical <u>Physsa</u> <u>Najas</u>	physical <u>Physsa</u> <u>Najas</u>	physical <u>Physsa</u>	physical <u>Najas</u>	physical	physical	physical <u>Najas</u>
Mean (%)	0.08	0.10	0.11	0.69	2.67	2.95	4.65
Statistical Significance	_____				_____		_____

The ratio of maximum ^{60}Co to ^{137}Cs content of the container surface compartment (Table 22) showed that the physical microcosm had a ratio of 0.89, similar to that of Najas alone of 0.98. Except for a magnitude change, the relationship of these two nuclides remained constant. Elodea alone had a significant effect by reducing the ratio to 0.16. Physa-Najas increased the ratio to 6.43 and all other treatments increased the ratio over that of the physical microcosm. Thus, the relationship of these maxima at higher complexity levels was not predictable from the results at lower complexity levels.

The ratio of ^{60}Co to ^{137}Cs content of the container surface at 512 hours (Table 23) showed that the plants, combined or alone, had a varied effect on the Co-Cs ratio. However, the intermediate response of the combination could have been predicted from the results of both plants alone. Likewise, the nature of the ratio for Physa-Najas and Physa-Najas-Elodea could be predicted from knowledge of each component alone. These results indicated that the relationship of radio-cobalt to cesium could be predicted for a combination of components by information of the Co-Cs ratios from each component considered independently.

These data showed that the presence of Elodea, either alone or combined with Najas, maintained the same or higher cesium content than the treatments of Najas alone or Physa combinations. In general, the plant compartments maintained the same content as the physical microcosm while the snail compartment significantly reduced ^{137}Cs content of the container surface.

Physa Body Compartment - The pattern of ^{60}Co flux through the Physa body compartment was similar for all complexity levels (Fig. 3d, p. 21).

Table 22. The Effect of Increasing Complexity on the Ratio of ^{60}Co to ^{137}Cs Uptake Rates of the Container Surface Compartment

Treatment	physical	physical <u>Elodea</u>	physical <u>Najas</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>
^{60}Co	6.71	2.60	9.18	11.90	2.60	13.96	1.29
^{137}Cs	7.50	15.81	9.36	8.67	1.54	2.17	0.69
$^{60}\text{Co}/$ ^{137}Cs	0.89	0.164	0.98	1.37	1.68	6.43	1.86

Table 23. The Effect of Increasing Complexity on the Ratio of ^{60}Co to ^{137}Cs Content of the Container Surface Compartment at 512 Hours

Treatment	physical	physical <u>Elodea</u>	physical <u>Najas</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>
^{60}Co	7.63	1.05	8.37	6.22	2.02	6.71	0.89
^{137}Cs	2.67	2.95	0.69	4.65	0.11	0.08	0.10
$^{60}\text{Co}/$ ^{137}Cs	2.85	0.35	12.13	1.33	18.36	83.87	8.90

A period of uptake to the maximum content was followed by a net loss which continued through 512 hours. Although the pattern was similar, there were differences in the time at which a maximum content was reached and the duration of this maximum. In the treatment of Physa alone (B), a maximum content was reached by 64 hours and maintained to 128 hours. For Physa-Najas (E), the maximum was reached at 32 hours and maintained to 128 hours, while for Physa-Najas-Elodea (G) a maximum content was reached by 16 hours and maintained to 32 hours. There was a trend of decreasing both the time for a maximum to be reached and the duration of this maximum with increased complexity.

The comparison of uptake rates among treatments (Table 24) showed that Physa combined with one or both plants formed a range with significantly higher rates than that of Physa alone. The magnitude of the rates was small, but they differed by a factor of three. The analysis of the ^{60}Co maxima of the Physa body compartment (Table 25) showed that the presence of either Najas or Najas and Elodea had the effect of significantly increasing the ^{60}Co content over that of Physa alone.

The ^{60}Co content of the Physa body compartment at 512 hours was compared among treatments (Table 26). The results showed that the treatments of Physa-Najas resulted in the highest end-point content which was significantly greater than those of Physa-Najas-Elodea and Physa alone. The latter two treatments formed a nonsignificant range. Since none of these values at 512 hours represented a steady state content, the difference reflected the difference in pattern and time among the treatments. The loss from the Physa body compartment was slower in the treatment of Physa alone than either Physa-Najas or Physa-Najas-Elodea and the loss from the Physa

Table 24. Duncan's Comparison of ^{60}Co Uptake Rates of the Physsa Body Compartment Among Complexity Levels

Value of p	2	3	
$r_{p.05}$	3.055	3.200	
R'_p	0.74	0.77	
Treatment	physical <u>Physsa</u>	physical <u>Physsa</u> <u>Najas</u>	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>
Mean(beta)	0.20	0.56	0.67
Statistical Significance	_____	_____	_____

Table 25. Duncan's Comparison of ^{60}Co Maxima in the
Physsa Body Compartment Among Complexity Levels

Value of p	2	3	
$r_p .05$	3.014	3.160	
R_p	0.77	0.81	
Treatment	physical <u>Physsa</u>	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physsa</u> <u>Najas</u>
Mean	1.05	2.08	2.35
Statistical Significance	-----	-----	-----

Table 26. Duncan's Comparison of ^{60}Co in the Physa Body
Compartment at 512 Hours Among Complexity Levels

Value of p	2	3	
$r_p .05$	3.014	3.160	
R_p	0.24	0.26	
Treatment	physical <u>Physa</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>
Mean	0.34	0.44	0.78
Statistical Significance	—————		—————

body of Physa-Najas-Elodea began earlier than that of Physa-Najas, and could be expected to be lower than that of Physa-Najas-Elodea.

The pattern of ^{137}Cs movement through the Physa body compartment for three complexity levels (Fig. 4d, p. 26) showed a rapid uptake to a maximum content which was followed by a loss of ^{137}Cs . The period of initial uptake ranged from 0 to 16 hours with a slight difference in rates among complexity levels. However, the addition of Najas (E) increased this uptake period by 8 hours as compared to Physa (B) alone. When Elodea and Najas (F) were both present, the maximum content was maintained from 16 to 32 hours and then followed by a loss. There was no statistical difference among loss rates. The increase in complexity had little effect on uptake or loss rates, but delayed the time at which a maximum ^{137}Cs content was reached and increased the duration of this maximum phase.

Maximum ^{137}Cs content and ^{137}Cs content in the Physa body compartment at 512 hours were 1.31% and 0.08%, respectively, for Physa alone; 1.99% and 0.06% for Physa-Najas; and 1.45% and 0.07% for Physa-Najas-Elodea. An F test revealed no difference among the treatments in either maximum or final ^{137}Cs content. The ^{137}Cs content of the Physa bodies was a small percent of the total activity and appeared to represent a steady state content.

The effects of complexity on ^{137}Cs and ^{60}Co flux through the Physa body compartment were divergent. The ^{137}Cs uptake and loss rates, maximum concentration and end point content of this compartment were similar for all three complexity levels, while ^{60}Co uptake rates and maximum content increased with increased complexity. The presence of plants delayed the time at which a peak cesium concentration occurred and if both plants

delayed the time at which a peak cesium concentration occurred and if both plants were present the duration of this peak concentration was increased as well. For ^{60}Co , the addition of a single plant decreased the time at which a maximum content was reached but had no effect on the duration of this maximum phase. When two plants were present the time at which a maximum content was reached was further reduced and the duration of the maximum phase was reduced as well. Thus, increased complexity increased the cycling time of ^{137}Cs through the Physa body and decreased the cycling time of ^{60}Co through the Physa body.

Physa Shell Compartment - The flux pattern of ^{60}Co through the Physa shell compartment (Fig. 3e, p. 21) showed a period of uptake for all complexity levels. After this initial period of uptake, Physa alone (B) and Physa-Najas (E) had a more gradual increment to 256 hours while the Physa-Najas-Elodea treatment (G) had loss of ^{60}Co after 64 hours.

The initial ^{60}Co uptake rates for the Physa shells were compared among treatments (Table 27). Physa alone and Physa-Najas form a non-significant set with uptake rates significantly higher than Physa-Najas-Elodea.

Inspection of the ^{60}Co pattern in the Physa shell compartment (Fig. 3e) showed that increased complexity reduced the duration of the uptake phase. Physa alone and Physa-Najas showed evidence of continued uptake to 256 hours, while in Physa-Najas-Elodea the Physa shell uptake was terminated at 16 hours. Thus, in addition to decreasing the uptake rate of ^{60}Co , increased complexity decreased the length of the uptake period.

The maximum ^{60}Co levels in the Physa shell compartment were compared among complexity levels (Table 28). The ^{60}Co content of this compartment

Table 27. Duncan's Comparison of ^{60}Co Uptake Rates of Physa Shells Among Complexity Levels

Value of p	2	3	
$r_p .05$	3.113	3.250	
R'_p	0.460	0.481	
Treatment	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u>
Mean(beta)	0.142	0.640	0.674
Statistical Significance	_____	_____	_____

Table 28. Duncan's Comparison of ^{60}Co Maxima of the Physa Shell Compartment Among Complexity Levels

Value of p	2	3		
$r_p .05$	3.014	3.160		
R_p	1.71	1.20		
Treatment	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u>	
Mean	0.80	2.30	4.30	
Statistical Significance	_____		_____	

in Physa alone was significantly higher than that when plants were present. Physa-Najas and Physa-Najas-Elodea formed a nonsignificant range with the lowest maximum ^{60}Co content. These data show a trend of decreased ^{60}Co content in the Physa shell compartment with increased complexity.

There was a significant difference among these treatments in the time at which the maximum ^{60}Co concentration occurred. In Physa alone this peak was at 256 hours. When Najas was present with Physa the peak was attained by 32 hours and when Najas and Elodea were present with Physa the peak occurred even earlier, at 16 hours. Thus, with regard to the maximum ^{60}Co content of the Physa shell compartment, increased complexity reduced the maximum content and also reduced the time required for this maximum level to be reached.

The ^{60}Co content of the Physa shell compartment at 512 hours was lower than the maximum concentrations for all treatments. These end point contents were compared among treatments (Table 29). The results showed an overlapping of nonsignificant ranges with the trend of decreased ^{60}Co content with increased complexity. The end point measurement for Physa-Najas-Elodea may represent a steady-state level. However, for the other two treatments it was not possible to determine if the drop in ^{60}Co at 512 hours represented a trend toward loss or just an unusually large variation in the sampling.

The loss rates of ^{60}Co from the Physa shell compartment in the Physa-Najas-Elodea treatment had a significant loss rate while the other treatments showed no loss. Since the nature of the pattern of ^{60}Co behavior for the Physa alone and Physa-Najas was not discernible from the observations it is reasonable to assume that they either did not change or

Table 29. Duncan's Comparison of ^{60}Co on Physa Shells
at 512 Hours Among Complexity Levels

Value of p	2	3	
$r_p .05$	3.014	3.160	
R_p	0.94	0.99	
Treatment	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u>
Mean	0.39	1.28	2.17
Statistical Significance			

began a period of net ^{60}Co loss. In either event, the most complex treatments showed no loss.

The pattern of ^{137}Cs flux through the Physa shell compartment (Fig. 4e, p. 26) showed that each treatment had an uptake phase extending to 16 hours, which was followed by an immediate and continued loss. Comparison of uptake and loss rates among treatments and maximum and final ^{137}Cs content of the Physa shell compartment showed no statistical differences. The content of this compartment by 512 hours had dropped to less than 0.1% of the total ^{137}Cs . These data indicated that the movement of ^{137}Cs through the Physa shell compartment was rapid and ^{137}Cs appeared to be completely eliminated from this compartment by 512 hours. There was no evidence of any effect of complexity on the flux of ^{137}Cs through the Physa shell compartment.

The effects of complexity on the flux of both radionuclides were different. In the case of ^{137}Cs , cycling appeared to be independent of complexity. However, for ^{60}Co , increased complexity increased the cycling rate by reducing both the duration of the uptake phase and the maximum content, as well as inducing a pattern of ^{60}Co loss from the Physa shell compartment.

Najas Compartment - The pattern of ^{60}Co flux through the Najas compartment (Fig. 3f, p. 21) was different among complexity treatments. In treatments which had only plants (C, F) Najas had an uptake to a maximum which was maintained as the steady state content to 512 hours. When Physa was present (E, G), there was a similar initial uptake, but after a maximum was reached there was a period of loss which continued through 512 hours.

A comparison of the net uptake rates for the Najas compartment (Table 30) showed that in the treatment of Najas alone, Najas had a significantly higher uptake rate than in all other treatments. The remaining treatments formed a nonsignificant range. The addition of Physa, Elodea, or both, caused a reduction in the uptake rate of ^{60}Co into the Najas compartment. The net effect of increased complexity was to reduce the uptake rate.

Although the flux patterns of ^{60}Co in the Najas compartment were similar, there were temporal differences among the patterns. In the treatment of Najas alone, Najas reached a maximum content by 64 hours. When Najas was combined with Elodea or Physa, the maximum ^{60}Co content was attained by 32 hours. Combining Najas, Elodea, and Physa resulted in a maximum content between 8 and 16 hours. Thus, increased complexity reduced the time required for the Najas compartment to reach a maximum content of ^{60}Co .

The maximum ^{60}Co content of the Najas compartment was compared among complexity treatments (Table 31). When Najas was alone, a significantly greater amount of ^{60}Co accumulated in the Najas compartment than in all other treatments. The remaining treatments formed a nonsignificant range. The presence of Elodea or Physa with Najas reduced the maximum by approximately one-half and when all three components were combined the maximum was even further reduced. These data show the trend of decreased maximum ^{60}Co content of the Najas compartment with increased complexity.

Radiocobalt in the Najas compartment at 512 hours was compared among complexity treatments (Table 32). In Najas alone this compartment maintained a significantly higher content than in all other treatments.

Table 30. Duncan's Comparison of ^{60}Co Uptake Rates of the Najas Compartment Among Complexity Levels

Value of p	2	3	4	
$r_p.05$	2.984	3.130	3.222	
R'_p	6.09	6.39	6.58	
Treatment	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physo</u> <u>Najas</u>	physical <u>Physo</u> <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u>
Mean(beta)	4.51	5.32	5.63	9.47
Statistical Significance	_____			_____

Table 31. Duncan's Comparison of ^{60}Co Maxima in the Najas Compartment Among Complexity Levels

Value of p	2	3	4	
$r_p .05$	2.950	3.097	3.190	
R_p	7.59	7.97	8.21	
Treatment	physical <u>Physo</u> <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physo</u> <u>Najas</u>	physical <u>Najas</u>
Mean	16.87	21.06	21.36	45.67
Statistical Significance	_____			_____

Table 32. Duncan's Comparison of ^{60}Co in the Najas Compartment at 512 Hours Among Complexity Levels

Value of p	2	3	4	
$r_p .05$	2.950	3.097	3.190	
R_p	7.75	8.15	8.38	
Treatment	physical <u>Physo</u> <u>Najas</u> <u>Elodea</u>	physical <u>Physo</u> <u>Najas</u>	physical <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u>
Mean	10.53	13.76	19.33	45.67
Statistical Significance				_____

Najas-Elodea and Physa-Najas formed a nonsignificant range with significantly higher content than with Physa-Najas-Elodea. Finally, Physa-Najas and Physa-Najas-Elodea formed a range with the least content at 512 hours. These data showed a trend of decreased ^{60}Co content with increased complexity.

The pattern of ^{137}Cs flux through the Najas compartment (Fig. 4f, p. 26) differed among complexity levels. All treatments had a period of uptake to a maximum by 4 hours. When Najas was alone (C), this maximum was maintained through 32 hours, after which there was a loss. When Elodea or Physa was combined with Najas (E, F), the duration of the maximum period was reduced to 16 hours and followed by a loss. In the combination of Physa-Najas-Elodea (G), a maximum was reached at 2 hours and followed immediately by a loss. Increased complexity changed the pattern of ^{137}Cs flux through the Najas compartment toward a more rapid cycling.

The maximum radiocesium content of the Najas compartment was compared among complexity levels (Table 33). The treatments of Physa-Najas-Elodea, Physa-Najas and Najas alone formed a nonsignificant range with significantly higher ^{137}Cs in this compartment than in the remaining treatment of Najas-Elodea. The combination of Najas-Elodea reduced the maximum by one-half, but when Physa was added to the combination of Najas and Elodea the effect of Elodea was negated. Thus, the presence of Physa significantly altered the relationship of Najas and Elodea.

The behavior of both radionuclides in the Najas compartment was significantly changed by increased complexity. In the case of ^{60}Co , the pattern of a steady state maximum was changed to that of loss. For ^{137}Cs , the pattern of a period of duration of a maximum was changed to that of no

Table 33. Duncan's Comparison of ^{137}Cs Maxima in the Najas Compartment Among Complexity Levels

Value of p	2	3	4	
$r_p \cdot 05$	2.950	3.097	3.190	
R_p	0.182	0.191	0.197	
Treatment	physical <u>Najas</u> <u>Elodea</u>	physical <u>Najas</u>	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>
Mean(%)	0.30	0.51	0.53	0.63
Statistical Significance	—	—————		

steady state maximum. For both radionuclides, increased complexity decreased the time required for a maximum content to be attained. Thus, increased complexity induced temporal and pattern changes in the ^{60}Co and ^{137}Cs flux which effectively increased the cycling rate of these nuclides through the Najas compartment.

There was a great difference in the quantity of ^{60}Co and ^{137}Cs accumulated in the Najas compartment. ^{60}Co maxima ranged between 17 and 46% as compared to maxima of less than 1% for ^{137}Cs . In these microcosms, ^{60}Co accumulation in the Najas compartment was much greater than that of ^{137}Cs .

Elodea Compartment - The pattern of ^{60}Co flux through the Elodea compartment differed among treatments (Fig. 3g, p. 21). All treatments had a period of uptake to a maximum. In Elodea alone (D) and Najas-Elodea (F), the maximum content was maintained as a steady state through 512 hours. In the combination of Physa-Najas-Elodea (G) a maximum content was reached after which there was an immediate and continuous loss from this compartment through 512 hours. Increased complexity resulted in changing the pattern of ^{60}Co flux.

In addition to the pattern change, the time at which a ^{60}Co maximum was reached in the Elodea compartment differed among treatments. In Elodea alone, the maximum content was reached between 64 and 128 hours. When Najas was combined with Elodea, the maximum was attained by 64 hours. The combination of Physa-Najas-Elodea resulted in a maximum being reached by 32 hours. The trend of these data showed that increased complexity decreased the time required for a ^{60}Co maximum to be reached by the Elodea compartment.

Uptake rates of the Elodea compartment were compared among complexity levels (Table 34). The treatment of Elodea alone had a significantly higher uptake rate than the other treatments and the microcosm consisting of Physa-Najas-Elodea had a significantly higher uptake rate than that of Najas-Elodea. These data showed that increased complexity reduced the uptake rate of the Elodea compartment. However, in the most complex microcosm the presence of Physa increased the rate.

The maximum ^{60}Co content of the Elodea compartment was compared among treatments (Table 35). Each treatment formed an independent set. When alone, Elodea accumulated significantly more ^{60}Co than in all other treatments. When combined with Najas, Elodea accumulated the least amount of ^{60}Co . The combination of Physa-Najas-Elodea resulted in a maximum Elodea content greater than that of Najas-Elodea, and less than that of Elodea alone. These data showed that the effect of Najas in reducing the maximum content of Elodea was not as great when Physa was present, which suggested a significant relationship between Elodea and Physa. Increased complexity reduced the ^{60}Co maximum of the Elodea compartment.

The results of the comparison of Elodea ^{60}Co content at 51.2 hours (Table 36) showed that each treatment formed an independent set. Elodea alone had the greatest content, Najas-Elodea was next, and Physa-Najas-Elodea had the least content. These data showed that increased complexity reduced the Elodea ^{60}Co content.

Cesium-137 flux through the Elodea compartment (Fig. 4g, p. 26) was different among treatments. In all treatments, Elodea had an uptake of ^{137}Cs to a maximum. This maximum was maintained for a period as a steady state for treatments of Elodea alone (D) and Najas-Elodea (F), after which

Table 34. Duncan's Comparison of ^{60}Co Uptake Rates of the Elodea Compartment Among Complexity Levels

Value of p	2	3	
$r_p .05$	3.199	3.339	
R_p	2.64	2.75	
Treatment	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physsa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>
Mean(beta)	8.03	11.72	17.36
Statistical Significance	—	—	—

Table 35. Duncan's Comparison of ^{60}Co Maxima in the Elodea Compartment Among Complexity Levels

Value of p	2	3	
$r_p \cdot 05$	3.014	3.160	
R_p	5.06	5.31	
Treatment	physical <u>Najas</u> <u>Elodea</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>
Mean	35.08	50.06	69.26
Statistical Significance	_____	_____	_____

Table 36. Duncan's Comparison of ^{60}Co in the Elodea Com-
partment at 512 Hours Among Complexity Levels

Value of p	2	3	
$r_p .05$	3.014	3.160	
R_p	8.13	8.52	
Treatment	physical <u>Physa</u> <u>Najas</u>	physical <u>Physa</u> <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>
Mean	15.63	35.08	65.44
Statistical Significance	—	—	—

there was a loss. However, in the case of Physa-Najas-Elodea (G) a maximum was reached and immediately was followed by a loss.

In addition to pattern differences, there were temporal differences among the patterns. The maximum content was reached by 2 hours in all treatments. This maximum was maintained to 32 hours in Elodea along (D), but when Najas was added to Elodea (F), the maximum was maintained to 16 hours. There was no steady state maximum for the treatment of Physa-Najas-Elodea (G). These data showed that increased complexity reduced the duration of the maximum ^{137}Cs content in the Elodea compartment. The trend of temporal and pattern changes induced by an increase in complexity resulted in a faster ^{137}Cs cycling rate through the Elodea compartment.

Comparison of the maximum ^{137}Cs content of the Elodea compartment among treatments (Table 37) showed that Elodea when alone or combined with Physa and Najas had a significantly higher maximum than in the Najas-Elodea treatment. These data showed that the effects of Najas in reducing the maximum were negated if Physa was added to the combination of Elodea and Najas. The presence of Physa was significant in changing the relationship of Elodea and Najas.

There were temporal and pattern changes in the flux of both radio-nuclides through the Elodea compartment. For ^{60}Co , increased complexity changed the pattern of a steady state maximum to that of a loss. In the case of ^{137}Cs , the pattern of duration of a maximum content was changed to that of no duration of a maximum content. The time at which a maximum ^{60}Co content was reached decreased with increased complexity, and for ^{137}Cs , the duration of the steady state maximum was decreased with increased complexity. Increased complexity effected temporal and

Table 37. Duncan's Comparison of ^{137}Cs Maxima in the Elodea Compartment Among Complexity Levels

Value of p	2	3	
$r_{p.05}$	3.014	3.160	
R_p	1.29	1.36	
Treatment	physical <u>Najas</u> <u>Elodea</u>	physical <u>Elodea</u>	physical <u>Physo</u> <u>Najas</u> <u>Elodea</u>
Mean	0.82	3.69	4.28
Statistical Significance	_____	_____	_____

pattern changes which resulted in more rapid cycling of both radionuclides through the Elodea compartment.

Complexity Effects on Cycling Parameters

The pattern of final distribution and net pathways of the radionuclides among the microcosm compartments and the time to steady state of compartments can be obtained from the dynamics of the radionuclides in each compartment (Fig. 3, p. 21 and 4, p. 26). Changes in one or more of these cycling parameters with increased complexity provided a means of assigning a regulatory role to the compartment or compartments which effected the change. Analysis of cycling in terms of these parameters also elucidated both the functional role of compartments and the significance of the functional role in cycling at each level of complexity.

For most compartments, the time to steady state can be determined from the dynamics of net radionuclide flux through the compartment. However, in the case of the water compartment it was not always apparent that a steady state had been reached by the end of the experiment. The changes occurring after the rapid loss of ^{60}Co or ^{137}Cs were slow. The final observations showed a trend of continued loss, but differences among observations often were less than 1%. In order to assign a steady state value to the water compartment for comparative purposes, the time at which 95% of the total radionuclide was eliminated from the water was chosen as the time at which the steady state content was reached.

Radiocobalt - The transfer of ^{60}Co through the physical microcosm (Fig. 5a) showed a net transfer of 7% of the total ^{60}Co from the water compartment to the container surface compartment, which reached a steady state after 32 hours. There was a transfer of 89% of the ^{60}Co from the

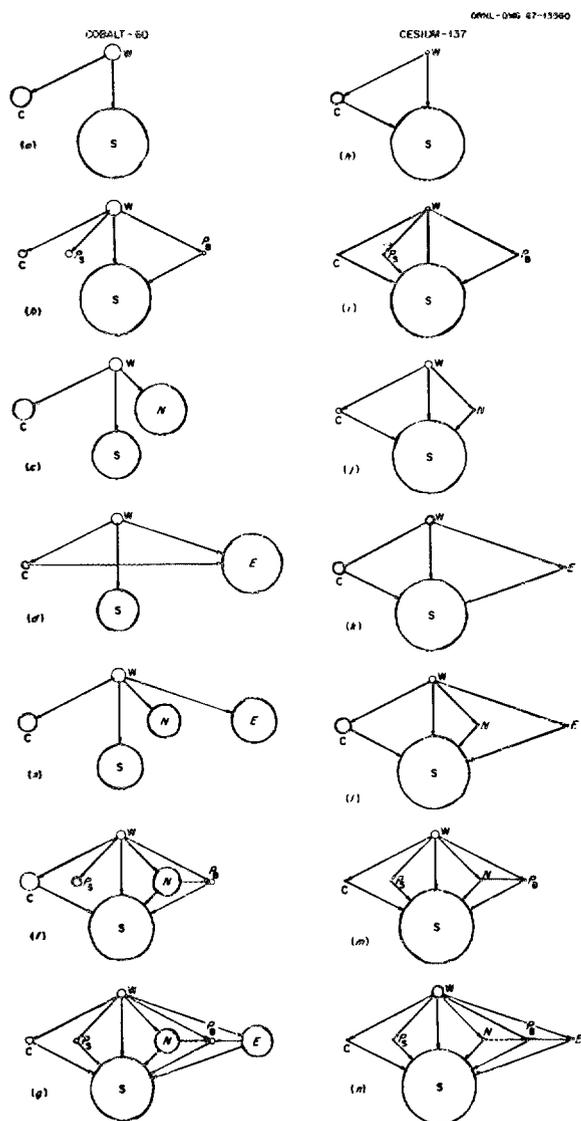


Figure 5. The effect of complexity on radionuclide flux patterns.

The arrows represent net flow pathways and the circles represent microcosm compartments. Size of circle represents relative accumulation of radionuclide in the compartment at time of steady state.

Compartments:

W - water

S - soil

C - container surface

P_B - Physa body

P_S - Physa shell

N - Najas

E - Elodea

water to the soil which continued until a steady state content was reached at 256 hours. In the physical system, most of the ^{60}Co accumulated in the soil and both the water and soil compartments reached a steady state content after 256 hours. On the basis of distribution the soil was the primary regulatory compartment.

The presence of Physa alone caused changes in both magnitude and time to steady state of the system. The pattern of pathways in the physical system were not changed by the presence of Physa (Fig. 5b). The Physa shell gained 2% of the ^{60}Co from the water compartment and reached a steady state after 32 hours. The container surface also gained 2% of the ^{60}Co from the water compartment and reached steady state content after 64 hours, 32 hours longer than the physical system. The Physa body compartment, which had both net gains and losses, held 0.34% of the ^{60}Co at 512 hours and did not reach steady state. The soil gained 91% of the ^{60}Co from the water and had either closely approached or reached a steady state content by 512 hours. The water compartment reached steady state after 512 hours.

Compared to the physical microcosms, the presence of Physa delayed the rise to steady state of the water and soil compartments, decreased the ^{60}Co content of the container surface compartment and slightly increased the content of the soil compartment. The magnitude and temporal changes can be related to the activity of Physa in the microcosms. The accumulation of particulate matter, both visible soil particles and assumed microbial biomass on the container surface was removed as Physa crawled over the container surface. Since the snails were added to the microcosms several days prior to tagging, there were no visible signs of particulate matter on the container surface at the time the radionuclides were added

to the water compartment. This function of Physa could explain the smaller quantity of ^{60}Co on the container surface. The delayed steady state content of the soil and water compartments and the increased quantity of ^{60}Co in the soil may be related to the effect of Physa on the soil compartment. In moving over the soil, the snails altered the microtopography of this surface. The net effect of this activity was to increase the effective surface area of the soil. Since this activity continued throughout the experiment, it can be assumed that the snails increased the depth of ^{60}Co penetration into the soil by turning over the soil and exposing the deeper layers. Also, Physa had a direct input to the soil in the form of feces. Since organic matter has a great affinity for cobalt, it was possible that this situation increased the capacity of the soil compartment for ^{60}Co . This activity of Physa in the microcosms effectively increased the capacity of the soil for ^{60}Co accumulation, which delayed the occurrence of steady state content of the soil and consequently the water compartment.

Although Physa accumulated only a small percentage of the total ^{60}Co , the effect of Physa activity on the physical compartments changed the distribution and significantly changed the time to steady state of the compartments. Physa regulated both the pattern of distribution and temporal parameters. Except for the expected loss from the Physa body, the pathway pattern of net input with no net loss was unchanged as compared to the physical microcosm. Thus, the soil regulated the pathway pattern.

The pattern of pathways among the compartments was not changed when Najas alone was added to the physical microcosm (Fig. 5c, p. 80). However, there were changes in the pattern of distribution and time to steady state

of the microcosm compartments. The container surface compartment, similar to that in the physical microcosm, gained 8% of the ^{60}Co from the water compartment and reached a steady state content after 32 hours. There was a net ^{60}Co transfer of 46% from the water to the Najas compartment, which reached a steady state between 64 and 128 hours. Najas had no net loss of ^{60}Co . The soil gained 42% from the water and both of these compartments reached a steady state after 128 hours. Najas accumulated and retained approximately one-half of the ^{60}Co that was transferred to the soil in the physical microcosm. This function of Najas can be related to the surface area of the plant. By reducing the total ^{60}Co to be distributed among the physical components, the time to steady state of the soil and water components was reduced one-half. In this microcosm, Najas regulated the pattern of distribution and time to steady state. Since no pathways of net loss were observed, the pathway pattern was still regulated by the soil.

The addition of Elodea alone to the physical microcosm changed the pattern of pathways of ^{60}Co (Fig. 5d, p. 80), the distribution pattern, and time to steady state of the microcosm compartments. The container surface compartment had a net gain from the water and a subsequent net loss to the Elodea compartment. The net steady state content of the container surface was 1% and occurred at 256 hours. The Elodea compartment had net gains from the water and container surface compartments. Elodea accumulated 64% of the ^{60}Co from the water compartment after 32 hours and an additional 1% from the container surface between 32 and 128 hours. The soil compartment gained 31% of the ^{60}Co from the water and both of these compartments reached a steady state after 64 hours.

The changes which occurred with the addition of Elodea to the physical microcosm can be related to surface area effects of Elodea. Elodea accumulated 65% of the total ^{60}Co , which exceeded that accumulated by Najas alone. Elodea with a greater surface area than Najas had a greater capacity for accumulation. By reducing the quantity of ^{60}Co to be distributed among the physical compartments, the time required to steady state of the water and soil was reduced to 64 hours, 4 times earlier than in the physical microcosm. The increased capacity of Elodea for accumulation induced an additional pathway of net input from the container surface, and delayed the time to steady state of this compartment. On the basis of changes in pathway and distribution patterns and time to steady state of the compartments, Elodea was the regulatory compartment.

The combination of Elodea and Najas with the physical compartments resulted in no changes in the pathway patterns as compared to the physical microcosm (Fig. 5e, p. 80). However, the distribution pattern and time to steady state of compartments were changed. The container surface gained 9% of the ^{60}Co from the water and reached steady state by 64 hours. The Najas compartment reached steady state by 32 hours with a net gain of 19% from the water. This quantity represented less than one-half that of Najas alone and the time to steady state also was reduced by one-half. Elodea reached steady state by 64 hours with a net gain of 35% of the ^{60}Co from the water. This quantity represented slightly more than one-half of that when Elodea was alone and the time to steady state was also reduced by one-half. The summation of the ^{60}Co content of Elodea and Najas represented 54% of the total, a quantity less than that in Elodea alone, and more than that in Najas

alone. In fact, this quantity was the same as the average calculated from that in treatments of Elodea and Najas alone. The soil compartment had a net gain of 34% of the ^{60}Co from the water and both of these compartments reached steady state after 128 hours.

In the combination of Elodea and Najas, the pathway of ^{60}Co from the container surface to Elodea was eliminated and the ^{60}Co content of this container surface was similar to that when Najas occurred alone. The ^{60}Co content of the soil and water compartments was similar to that in Elodea alone, but the time to steady state was the same as that in Najas alone. The pattern of distribution was regulated by the Elodea compartment and the time to steady state was regulated by the Najas compartment. Since there were no new pathways of net loss, as compared to the physical microcosm, the regulation of pathway patterns was by the soil compartment.

When Physa was combined with Najas there was a significant change in distribution and pathways patterns (Fig. 5f, p. 80) and times to steady state of the compartments. The container surface had a net gain from the water with a subsequent new pathway which represented a net loss to the soil compartment. The content of this compartment at 512 hours was 7% and no steady state was reached during the experiment. The Physa shells gained 1% of the ^{60}Co from the water and reached a steady state after 32 hours. The Najas compartment had a net gain from the water followed by net losses to the soil and Physa body compartments. These losses represented two new pathways from the Najas compartment. Najas had continued net losses of ^{60}Co down to 14% at 512 hours and there was no evidence that a steady state was being approached in this compartment.

The Physa body compartment had a content of 0.7% of the ^{60}Co at 512 hours and this value was twice as great as that in Physa alone. This evidence indicated that Physa had an additional input from the Najas compartment. There was an expected net loss of ^{60}Co to the soil and the Physa body did not reach steady state by 512 hours. The water compartment reached a steady state by 256 hours with a net content of 1.5% of the ^{60}Co at 512 hours. The soil, with the additional new inputs, did not reach a steady state during the experiment and had a content of 75% of the ^{60}Co at 512 hours.

The increase of net inputs to the soil compartment were related to the interaction of Najas and Physa. In addition to the earlier effects of Physa movement on the physical components, the snail also crawled over the surface of Najas. There was no evidence that Najas tissue was consumed by Physa, but microscopic observation of Najas indicated the presence of periphyton. Thus, it is possible that the snails did consume the periphyton and perhaps small amounts of Najas tissue. There were other possible explanations for the increase of net pathways to the soil. The increased surface area due to the constant turning over of the soil, plus the presence of snail fecal material, may have increased the amount of ^{60}Co in the soil. Since the container surface compartment continued to show a loss without reaching a steady state, this hypothesis is supported.

The condition of a steady state ^{60}Co content, which was characteristic of almost all compartments in other microcosms, did not occur here except in the water compartment. This imbalance of gains and losses, shown by additional pathways of net loss, was the result of increased

functional complexity. Thus, the regulation of distribution and pathway patterns and time to steady state of compartments were regulated by the biological interaction.

The combination of Elodea, Najas, and Physa with the physical compartments did not change the quality of results from the Physa-Najas treatment (Fig. 5g, p. 80). However, there were additional net inputs to the soil compartments and further changes in compartmental ^{60}Co content and times to steady state.

The container surface and Physa shell compartments each had a net gain from the water and a subsequent net loss to the soil. The net loss from the Physa shell compartment represented a new pathway. The container surface had less than 1% of the ^{60}Co and the Physa shell had less than .5% ^{60}Co after 512 hours. Neither compartment reached a steady state during the experiment. Both Najas and Elodea had a net gain from the water compartment with a net loss to the soil. The net loss from Elodea represented another new pathway of ^{60}Co movement. Neither plant compartment reached a steady state by 512 hours and Elodea had 16% and Najas 10% of the total ^{60}Co at the end of the experiment. The water compartment reached a steady state after 32 hours and a ^{60}Co content of 1.6% at 512 hours. The soil had accumulated 70% of the total ^{60}Co from the various net inputs by 512 hours and did not reach a steady state during the experiment.

The increased plant surface area in the Elodea compartment increased the number of pathways of net movement, decreased the time to steady state of the water compartment, and decreased the ^{60}Co content of various compartments. The container surface and Physa shells had a lower ^{60}Co content

than that in previous microcosms and the shell compartment showed a new pathway of net loss to the soil. These changes can be attributed to the Elodea compartment and its capacity for accumulation of ^{60}Co since these events did not occur when Elodea was absent. The content of the Najas compartment at 512 hours was lower than that in Physa-Najas. This suggests an effect of a greater accumulation capacity of Elodea for ^{60}Co and is analogous to the situation in Najas-Elodea. The rapid loss of ^{60}Co from the water compartment of this microcosm was a result of the presence of Elodea as this compartment had a much slower loss rate in Physa-Najas. Finally, the soil ^{60}Co content at the end of the experiment was less than that of Physa-Najas microcosms because of the accumulation of ^{60}Co by Elodea.

Although the presence of Elodea had a distinct effect on some compartments, all the changes which occurred could not be explained by the simple addition of Elodea to Physa and Najas. While the water compartment in Elodea alone had the fastest time to steady state (64-128 hours) this compartment of the current microcosm reached a steady state in 32 hours, 2 to 8 times faster than in all other microcosms.

The net loss from the Elodea compartment was a result of the Elodea-Physa interaction. The possible explanations of this induced net loss from Elodea were given earlier for the Najas compartment. In the case of Elodea there was additional evidence that Physa was removing plant tissue without ingesting it. In many instances, the lower leaves of the plant axis were partially or wholly missing and inspection of the microcosms revealed an accumulation of particulate green matter on the soil surface. This indicated that the snails moved senescent plant organs to

the soil compartment either without ingesting them or by passing them through their bodies without digestion and assimilation.

Thus, similar to the situation in the Physsa-Najas microcosm, the regulation of cycling parameters was accomplished by the interaction of the biological components. However, the comparison of this microcosm to the Physsa-Najas microcosm showed that Elodea had a greater influence than Najas on ^{60}Co cycling.

The functional role of the physical compartments in these microcosms can be discerned from the ^{60}Co content and pattern of movement through these compartments (Fig. 3a-c, p. 21). The water compartment represented a medium through which the ^{60}Co was distributed to the various microcosm components. The container surface and soil compartments may be viewed as sinks. The container surface represented a temporary sink as the ^{60}Co associated with this compartment became available. However, the soil represented a permanent sink. Of these compartments only the soil had a regulatory role.

The biological compartments (Fig. 3d-g, p. 21) had variable roles which were specified by the different levels of complexity. The plant compartment, alone or combined, accumulated ^{60}Co and represented a sink. The degree of accumulation or storage was related to surface area. The snail compartment alone did not accumulate large amounts of ^{60}Co but through its churning effect on the soil and container surface compartments, it altered the holding capacity of the physical components. The role of the snail was similar to that of a catalyst.

The combination of plants and the snail significantly altered the roles played by either alone. The plants had been sinks of ^{60}Co with no

net losses, but when combined with the snail they showed net losses and assumed the role of processors. The role of the snail did not change when combined with plants, but its catalytic effect on ^{60}Co cycling was greatly enhanced as the steady state, characteristic of most compartments, was disrupted.

The biological components occurring alone always had a regulatory role, which usually changed the distribution pattern or time to steady state. When they were combined, patterns of distribution and pathways and time to steady state were regulated by the functional interaction of these biological components.

Increased complexity both increased and decreased the time to steady state in the compartments of these microcosms. The time required to reach steady state in the water compartment generally decreased with increased complexity and ^{60}Co was most rapidly cleared from the water in the most complex microcosm. The plants decreased the time to steady state of the other compartments, while the snail increased the time. Additional complexity from combining plants and animals resulted in conditions in which none of the compartments reached a steady state.

Radiocesium - The pattern of net ^{137}Cs movement through the physical microcosm (Fig. 5h, p. 80) showed an input and loss from the container surface compartment. The container surface reached a steady state after 128 hours with a content of 2.7% of the ^{137}Cs . The soil had net inputs from the water and container surface and reached a steady state content of 97% after 256 hours. The water reached a steady state between 64 and 128 hours with a final ^{137}Cs content of .3%.

The net loss from the container surface compartment to the soil compartment and the very low ^{137}Cs content of the water showed that the

pathway and distribution patterns in this physical microcosm were regulated by the soil compartment.

When Physa was combined with the physical components the pattern of pathways to the soil was not changed (Fig. 5i, p. 80). However, there were changes in time to steady state and distribution of ^{137}Cs among the compartments. The container surface reached a steady state ^{137}Cs content of 0.1% after 256 hours. Physa shells, which had net input from the water and net loss to the soil, did not reach a steady state and had no detectable ^{137}Cs at 512 hours. The Physa body compartment had a net gain from the water and loss to the soil. The snails did not reach steady state and had a content of 0.08% of the ^{137}Cs at the end of the experiment. There was a continual accumulation of ^{137}Cs in the soil and by 512 hours 99% of it was in the soil. The water compartment had a content of 0.39% of the ^{137}Cs by 512 hours and reached a steady state between 64 and 128 hours.

The presence of Physa lowered the ^{137}Cs content of the container surface and increased that of the soil. These effects can be attributed to the "stirring" effect of Physa on these physical compartments as was found in the ^{60}Co experiment. Since there was no change in the pathway pattern as compared to that of the physical microcosm, the soil still regulated this pattern. However, Physa regulated both the pattern of distribution and time to steady state of compartments.

The combination of Najas with the physical compartments effected no changes in the pattern of pathways (Fig. 5j, p. 80), but changes occurred in time to steady state and ^{137}Cs content of microcosm compartments. The container surface did not reach a steady state and had 0.7%

of the ^{137}Cs at 512 hours. Najas had both a net input from the water compartment and a subsequent net loss to the soil. Najas had a ^{137}Cs content of .2% at 64 hours and did not reach a steady state by this time. The soil did not reach a steady state and had a ^{137}Cs content of 98% at 512 hours. The water compartment reached steady state between 256 and 512 hours with a content of 1% at 512 hours.

Najas had no large accumulation of ^{137}Cs , but did increase the content of this radionuclide in the water as compared to both the physical and Phyca treatments. Also, the ^{137}Cs content of the container surface compartment was reduced as compared to that of the physical microcosm. Since Najas accumulated little of the ^{137}Cs , the effect of Najas of increasing the water content of this radionuclide can be attributed to a rapid exchange of ^{137}Cs between the water and Najas. Najas increased the time to steady state of the water compartment as compared to that of the physical microcosm. Neither the container surface nor the soil reached a steady state in this microcosm, whereas in the physical microcosm both compartments reached a steady state.

Since the pattern of pathways to the soil compartments was unchanged as compared to the physical microcosm, the soil regulated this pattern. However, the pattern of radionuclide distribution and time to steady state of the compartments were regulated by Najas.

The addition of Elodea to the physical microcosm had no effect on the pattern of pathways of ^{137}Cs to the soil (Fig. 5k, p. 80). However, the time to steady state and ^{137}Cs content of compartments was affected. The container surface did not reach a steady state and had a ^{137}Cs content of 3% at 512 hours. Elodea had a net input from the water and a net loss

to the soil. The ^{137}Cs content of Elodea was 1% at 128 hours and no steady state was reached by that time. The soil did not reach a steady state and had accumulated 95% of the ^{137}Cs by 512 hours. A steady state was reached by the water between 64 and 128 hours and the content at 512 hours was 1%.

The effect of Elodea in increasing the ^{137}Cs content of the water over that of the physical microcosm was similar to the effect of Najas on this same compartment. It is presumed that the mechanism was that of rapid exchange of ^{137}Cs between Elodea and water. Elodea also reduced the time to steady state of the water compartment. The soil accumulated less ^{137}Cs in this microcosm than in the physical microcosm and neither the soil nor the container surface compartments reached a steady state, a condition observed for both compartments in the physical microcosm. Similar to the previous microcosm with biological components present, the soil regulated the pathway pattern and Elodea regulated the distribution pattern and time to steady state of compartments.

When Elodea and Najas were combined with the physical compartments, there was no change in the pathway patterns (Fig. 51, p. 80), but there were changes in the distribution pattern and time to steady state of compartments. The container surface reached a steady state ^{137}Cs content of 49% after 128 hours. Najas and Elodea both had net input from the water and net loss to the soil and neither reached a steady state. Najas had a content of 0.14% of the ^{137}Cs at 64 hours and Elodea had 0.3% at 128 hours. The soil compartment accumulated 93% of the ^{137}Cs by 512 hours and did not reach a steady state. The water compartment reached a steady state between 128 and 256 hours with a content of 1% at 512 hours.

The effect of the Elodea and Najas combination on the ^{137}Cs content of the water was similar to that of each species occurring alone. The time to steady state of the water was intermediate between that of either species alone. The container surface compartment did not reach a steady state when either Najas or Elodea occurred alone, but in this experiment the container surface did reach a steady state and the ^{137}Cs content was greater than that when either species occurred alone.

As in the preceding microcosms, the soil compartment regulated the pathway pattern. The time to steady state of compartments and the distribution of ^{137}Cs was regulated by the interaction of the plant species.

The addition of Physa and Najas to the physical microcosm effected no change in the pattern of pathways (Fig. 5m, p. 80), but the parameters of time to steady state and ^{137}Cs content of compartments were changed. The container surface reached steady state at 256 hours with a content of 0.1% at 512 hours. The Physa shells, which had input from the water and loss to the soil, did not reach steady state during the experiment and had a content of 0.1% of the ^{137}Cs at 512 hours. No steady state was reached by the Physa body compartment and continued net losses resulted in a content of 0.1% of the ^{137}Cs at 512 hours. Najas did not reach a steady state by 64 hours and had a content of 0.4% of the ^{137}Cs at that time. The soil reached a steady state after 128 hours and had accumulated 98% of the total ^{137}Cs by 512 hours. The water reached a steady state between 128 and 256 hours and had a ^{137}Cs content of 2% at 512 hours.

The combination of Physa and Najas increased the ^{137}Cs content of the water over that when either species occurred alone and the time to steady state was intermediate between that when either species occurred

alone. The low ^{137}Cs content of the container surface and the time to steady state were similar to that observed when Physa occurred alone. The presence of Physa served to reduce the ^{137}Cs content of the container surface, and thus provided an additional 1-2% of "available" ^{137}Cs . The increased content of the water probably resulted from a rapid exchange of this "available" cesium between the water and plant compartments.

As in previous microcosms, the net pathway was regulated by the soil. In general, the time to steady state and distribution of ^{137}Cs among compartments was regulated by the interaction of Physa and Najas.

The combination of Physa, Najas and Elodea with the physical components had no effect on the pathway pattern (Fig. 5n, p. 80) and the interaction among the biological components produced the same results as did the Physa-Najas interaction except for the ^{137}Cs content of Elodea and Najas, and the time to steady state of the container surface compartment. Elodea had a ^{137}Cs content of .6% at 128 hours and Najas had .2%. The container surface reached a steady state content of 0.6% of the ^{137}Cs after 128 hours. Thus, as observed in the results for Physa-Najas microcosms, the soil regulated the pattern of pathways and the biological interaction regulated the distribution pattern and time to steady state of the compartments.

Physical compartments had several roles in the cycling of ^{137}Cs in the microcosms. The water compartment served as a medium through which ^{137}Cs was distributed to the other compartments and, when plants were present, the water also served as the storehouse of available radiocesium. Container surfaces represented a temporary sink of available ^{137}Cs and the magnitude of this sink changed with the various complexity levels. The soil was a permanent sink of radiocesium. Of these physical components,

the soil regulated the pattern of pathways among the other compartments at all complexity levels.

All biological components had similar functional roles in the cycling of ^{137}Cs in the microcosm. Plants, alone or combined, and the snail alone increased the ^{137}Cs content of the water. When the plants and the snail were combined, the ^{137}Cs content of the water was increased even more. Since none of the biological components accumulated large amounts of ^{137}Cs , the functional roles of these biological components were that of processors. When one or more biological compartments were present, both the pattern of distribution and time to steady state of compartments were thereby regulated.

Cobalt-60 and ^{137}Cs cycling was different in microcosms of similar complexity and the cycling was affected differently by increased complexity. ^{60}Co and ^{137}Cs cycling parameters were regulated by different compartments, or combinations of compartments, and the functional role of a given compartment was not always similar for the two radionuclides.

The pattern of pathways among compartments for ^{60}Co and ^{137}Cs (Fig. 5, p. 80) was strikingly different in the microcosms. Radiocesium cycling was characterized by pathways of net input and loss from all compartments except the soil and water. In ^{137}Cs cycling, the number of non-soil compartments was equal to the number of net inputs to the soil compartment and this 1:1 ratio was not changed with increased complexity. Cobalt-60 cycling was characterized by an increase in the number of pathways to the soil compartment with an increase in functional complexity. When no biological components were present, or if biological components with the same functional role were present, the ratio of nonsoil compartments to

the number of net inputs to the soil was 2:1 or greater. Thus, although the behavior of ^{60}Co and ^{137}Cs was entirely different at the simpler levels of complexity, in the higher complexity levels the patterns of ^{60}Co pathways among compartments converged toward similarity to those of ^{137}Cs .

The distribution of ^{60}Co or ^{137}Cs was regulated by the biological compartments or their interactions. The biological components affected the distribution of ^{137}Cs among all other compartments. However, the effect on the soil content amounted to only a few percent of the total ^{137}Cs . Ignoring the slight effect on the soil content, only about 5% of the total ^{137}Cs was associated with nonsoil compartments. The distribution of this 5% was changed with an increase in functional complexity. For the water compartment, the plants, either alone or combined, and the snail alone had a similar effect of increasing the quantity of ^{137}Cs in the water. When functional complexity was increased, even more ^{137}Cs was maintained in the water. Biological components had a relatively greater effect on the distribution of ^{60}Co among compartments, changing the ^{60}Co content of the soil by up to 50% of the total. Lower complexity levels reduced the ^{60}Co in the water. When functional complexity was increased, the amount of ^{60}Co maintained in the water was further decreased. Thus, increased complexity had opposite effects for ^{60}Co and ^{137}Cs ; the amount of ^{137}Cs in the water increased and the amount of ^{60}Co in the water decreased. The net result of these changes in radionuclide content of the water was to converge the amounts of radionuclide until the ratio of ^{60}Co to ^{137}Cs was approximately 1. Comparison of the effect of the biological components on the distribution of the radionuclides showed that ^{60}Co was affected to a much greater degree than was ^{137}Cs .

The effects of increased complexity on the time to steady state of compartments was different for the two radionuclides. Increased complexity decreased the time to steady state of ^{60}Co in the water and increased in the case of ^{137}Cs . Radiocesium cycling through nonwater compartments was characterized by few steady state conditions for compartments at the lower levels of complexity and by steady state conditions at the higher levels of complexity. Radiocobalt cycling through nonwater compartments was characterized by steady state conditions at the lower complexity levels and few steady state conditions at higher complexity levels. Increased complexity reduced the time to steady state of ^{137}Cs in compartments and increased the time to steady state of ^{60}Co .

The functional roles of the microcosm components were not always identical for ^{60}Co and ^{137}Cs cycling. The container surface and soil compartments had similar roles for both ^{60}Co and ^{137}Cs cycling. The water compartment served as a distribution medium for both ^{60}Co and ^{137}Cs . In the case of ^{137}Cs , the water also served as a temporary reservoir or pool. The plant compartments acted either as storehouses or processors in ^{60}Co transfers, whereas in ^{137}Cs cycling the plants had only the role of processors. Physa acted both as a catalyst and processor in ^{60}Co cycling and only as a processor in ^{137}Cs cycling.

The comparison of compartmental roles in the cycling of ^{137}Cs and ^{60}Co shows that 1) roles may be interchangeable between physical and biological components (storehouse), 2) that the same component (plants, snails) may have entirely different roles in the cycling of different nuclides, 3) that the same component (water, snails) may have more than one role in the cycling of a given nuclide, and 4) that a role which is

significant in the cycling of one nuclide may not even occur in the cycling of another nuclide (catalyst).

Radiosensitivity of Organisms

In order to use radiation stress effectively as an experimental parameter it is necessary to determine the radiosensitivity of the species to be used. It was desired that the doses to the microcosms be sublethal, but capable of producing effects which would range from no detectable growth effects to inhibitory effects. Biological end points considered were mortality, growth rate, morphological change, and uptake and concentration of radionuclides.

Elodea - The effects of doses of 100, 400, and 1000 rads of fast neutrons were observed on Elodea cultured in spring water under the given experimental conditions.

The growth and elongation pattern for the four treatments (Fig. 6) showed no essential differences among the treatments from 0 to 430 hours. At this time both the controls and 100 rad treatment showed reduced growth, while the plants receiving higher doses continued to grow.

A normal morphological development under the conditions of this experiment was the formation of lateral shoots and roots on the Elodea axis. This differentiation was followed for all treatments and the results (Fig. 7) showed that the 100 rad dose had no effect on the initiation of lateral shoots, but did inhibit adventitious root formation for 75 hours. Ultimately, the 100 rad treatment limited adventitious root formation to 60% of the value for the controls. The 400 and 1000 rad treatments inhibited lateral shoot elongation compared to the controls. However, the end point measurements of 80 and 90% indicated evidence of

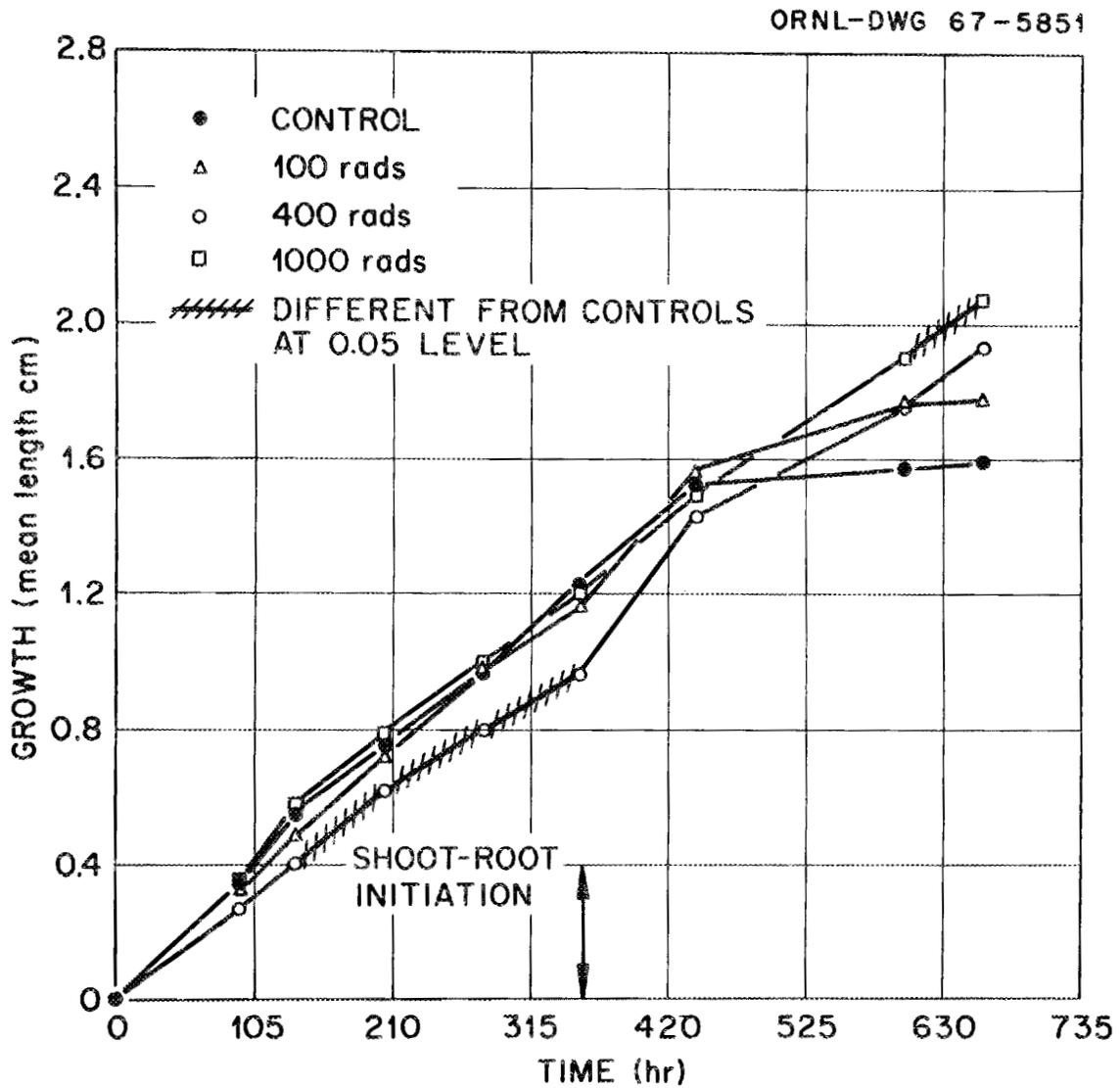


Figure 6. The effect of fast neutron radiation on *Elodea* growth.

The hatching indicates a portion of the line which is significantly different from the control group.

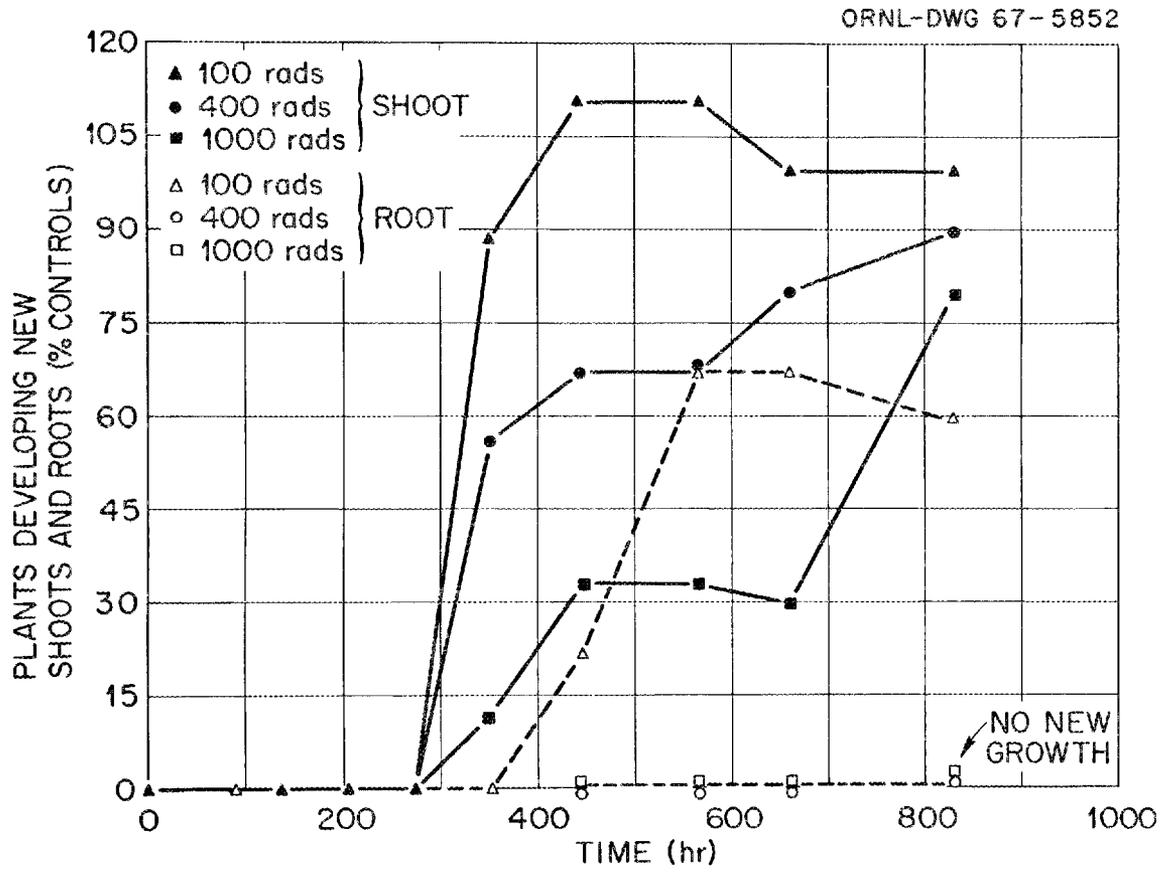


Figure 7. The effect of fast neutron radiation on shoot-root initiation by Elodea.

recovery from the radiation effect. Root formation on the Elodea axis was inhibited during this experiment after doses of 400 and 1000 rads.

The uptake of ^{137}Cs by the control groups exceeded uptake by all radiation treated groups, even during the early observations (Fig. 8). During the first 200 hours of the experiment, the uptake curves for all treatments were lower than the controls and were statistically lower as indicated by a "t" test for most of this period. After 348 hours, when shoot-root initiation occurred in the controls and 100 rad treatment, the ^{137}Cs concentration was observed to decrease with increased dose.

Considering the time of shoot-root initiation, the array of end points for ^{137}Cs concentration may be the result of a difference in surface area and mitotic activity. However, the differences in ^{137}Cs concentration before shoot-root initiation, at a time when elongation was similar for all treatments, cannot be explained on the basis of differential surface area. The early differences can be attributed to the effect of radiation on mitotic rate or physiological mechanisms.

The uptake of ^{60}Co (Fig. 9) was initially faster than that of ^{137}Cs . At 64 hours there was little difference in the end point concentrations for the control, 400, or 1000 rad treatments, all of which were higher than the 100 rad treatment. A "t" test comparison of the control against the 100 rad dose showed that the end points were significantly different.

The uptake curves for each treatment showed the same pattern, but the uptake rates and times of maximum concentration showed differences. The lowest dose, 100 rads, had the earliest peak with a subsequent rapid loss to a concentration less than the controls. The maximum and minimum concentration of the 100 rad dose were tested against the controls for

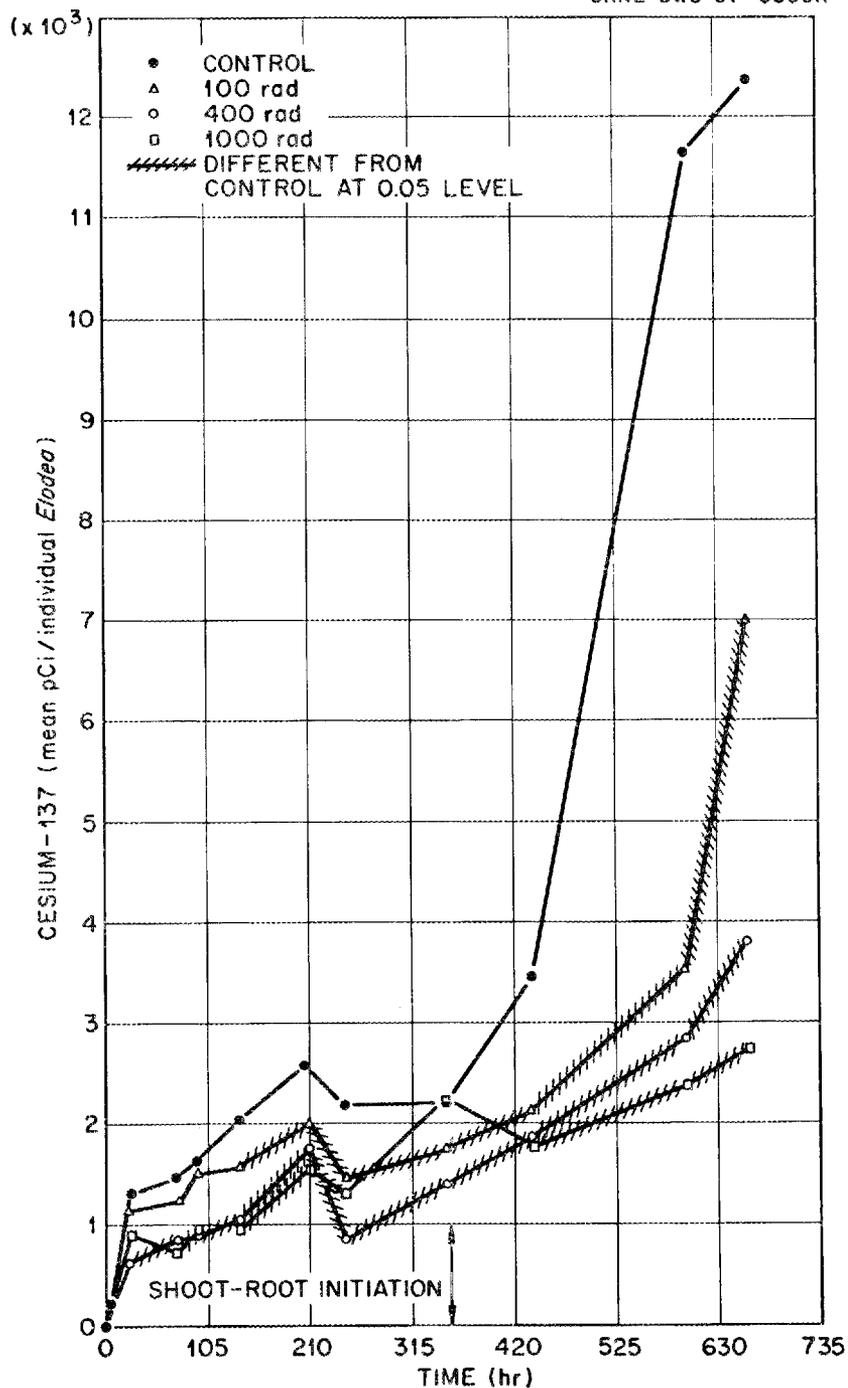


Figure 8. The effect of fast neutron radiation on ^{137}Cs accumulation by *Elodea*.

The hatched lines indicate portions of the uptake curves which are significantly different from the controls.

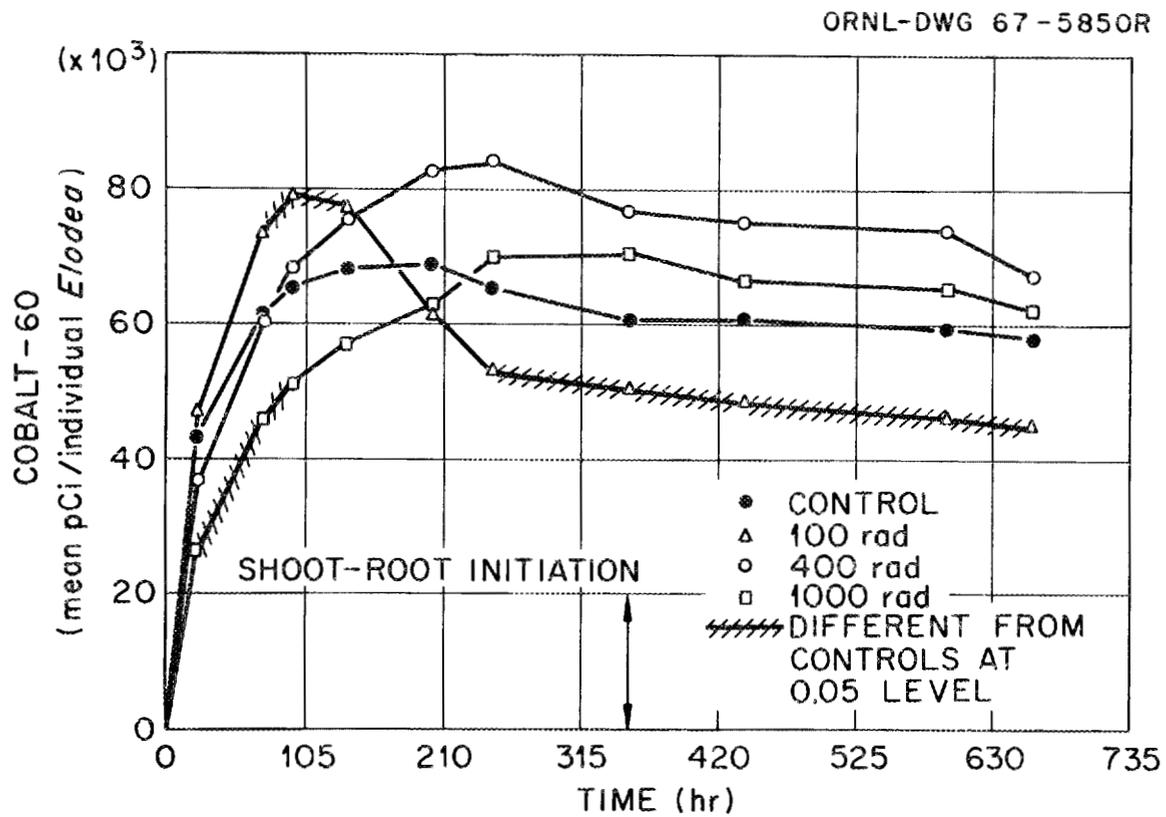


Figure 9. The effect of fast neutron radiation on ^{60}Co accumulation by Elodea.

The hatched lines indicate portions of the uptake curves which are significantly different from the controls.

each hour using a "t" test which showed significant differences between these treatments for most of the comparisons. The uptake rates of the control and 400 rad treatment occurred later and was higher than that of the controls. The initial uptake rates of the 100 rad treatment appeared lower than the controls, and the first three points of the uptake curve were statistically different from the controls. The maximum concentration of ^{60}Co for this treatment occurred later than either the controls or 400 rad treatment.

Since the major differences in uptake and concentration of ^{60}Co occurred before shoot-root initiation, differences in surface area would not account for them. A difference in mitotic activity could be postulated as a causal factor. However, there was no evidence that such differences existed as the growth and elongation of these plants during this period were similar, since ^{60}Co uptake rates for the 100 and 400 rad treatments were similar to the controls.

Physa - Physa mortality in the Physa-Najas-Elodea combination after fast neutron doses of 0, 100, and 1000 rads was calculated for different sample periods and for the entire experiment (Table 38). Comparing percent mortality by sampling period, mortality occurred early in both radiation treatments. At 256 hours, control mortality exceeded mortality at 100 rads, while mortality at 1000 rads exceeded both the controls and the 100 rad treatment. By 512 hours mortality at 100 rads exceeded controls by 33%. Total mortality for the 100 rad dose exceeded controls by a factor of 1.1 and the 1000 rad dose by a factor of 2.4.

Fast neutron doses of 100 and 1000 rads represented two radiation treatments which can be considered different as a result of their effects

Table 38. Physa Mortality in the Physa-Najas-Elodea Combination

Dose(rad)	0	100	1000
Percent Mortality by hour($X_{ij}/18$)			
32	00.00	00.00	00.00
64	00.00	00.00	11.11
128	00.00	5.55	5.55
256	00.00	16.66	38.88
512	22.22	33.33	55.55
Total Percent Mortality ($EX_{ij}/162$)			
	5.55	6.17	12.96

on Physa and Elodea. The 100 rad dose showed little effect on the growth and morphology of Elodea. While Physa had an 11% higher mortality than the controls at 100 rads, this dose had an effect which was essentially independent of events leading to death of the snails. Thus, the 100 rad dose may be considered as sublethal. At 1000 rads there was a more noticeable effect on Elodea, and Physa mortality was 33% higher than controls. Therefore, the 1000 rad dose represented a radiation level considerably more inhibitory to Elodea and lethal for 30% of the Physa population.

Radiation Effects on Organisms in Microcosms

Elodea - Initial dry weight measurements of Elodea in microcosms with Elodea alone were converted to mg/individual. Mean values of 11.4, 11.6, and 11.9 mg/individual for treatments of 0, 100, and 1000 rads were compared by analysis of variance which showed no significant difference. In a comparison of all means at 512 hours (Table 39) there was no difference between the 0 and 100 rad treatments which were both significantly higher than the 1000 rad treatment. A comparison of the 100 and 1000 rad dose showed that there was no significant difference between the two means.

Initial mean weights for Elodea in combination with Najas and Physa receiving 0, 100, and 1000 rads were 12.6, 7.6 and 9.51 mg/individual with final weight values of 11.7, 8.9 and 8.9 mg/individual. An analysis of variance showed no significant differences between initial and final dry weights for any treatment.

In microcosms with Elodea alone, the control plants had a constant weight increase during the experiment. The plants receiving 100 rads showed evidence of dry weight increase only after 128 hours and the plants at 1000 rads showed no evidence of weight gains.

Table 39. Duncan's Comparison of Final Weights of Elodea
(Elodea Alone) Among Radiation Treatments

Value of p	2	3	
$r_{p.05}$	3.01	3.16	
R_p	1.88	1.97	
Radiation Treatment(rads)	1000	100	0
Mean (mg/plant)	13.1	14.1	16.0
Statistical Significance			

The lack of a difference between initial and final dry weights of Elodea in combination with Physa and Najas may have been partially due to the presence of Physa. The lower leaves were missing from many stems and observations of the microcosms revealed leaf fragments on the soil and in the water. Also, in experiments where many replicates were used, it was possible to begin an experiment wherein the final replicates of some microcosms had less plant mass than the initial replicates of others, the result being no evidence of growth. This situation probably occurred in these experiments since the mean dry weight for Elodea controls at 256 hours was 13.9 mg, which exceeded both initial and final dry weights. Inspection of earlier weight values for the 100 and 1000 rad doses showed no trend toward weight increase. It is believed that the combination of snail activity and the experimental error cited above masked a weight gain in the Elodea controls.

Najas - Initial dry weights of Najas in treatments of Najas alone of 3.2, 4.5 and 5.0 mg/individual were compared to final mean weights of 3.5, 5.5 and 4.8 mg/individual for treatments of 0, 100, and 1000 rads. An analysis of variance showed no significant differences between initial and final dry weights.

Najas in combination with Physa and Elodea had initial weights of 3.7, 3.4 and 3.4 mg/individual with final weights of 3.7, 3.4 and 3.4 mg/individual for treatments of 0, 100, and 1000 rads. Comparison of initial and final dry weights by analysis of variance demonstrated no differences between these values for any treatment.

Observations of Najas at each sampling period in each experiment showed that the plants were elongating and otherwise growing during

the experiment. Najas grew more slowly than Elodea in the culture tanks, and the slow growth rate coupled with the low weight and high variability among replicates contributed to the lack of statistical difference between initial and final weights.

Physa - In the treatment of Physa alone, Physa mortality after doses of 0 and 1000 rads of fast neutrons was calculated for different sample periods and for the entire experiment (Table 40). Comparing percent mortality by sampling period, mortality occurred early in the radiation treatment. At 256 hours, control mortality exceeded mortality at 1000 rads, but by 512 hours mortality at 1000 rads exceeded controls by 11%. Total Physa mortality for the 1000 rad dose exceeded controls by a factor of 2.7.

Dry weight measurement of Physa (Physa alone) bodies which had received 0 and 1000 rads of fast neutron radiation were converted to mg dry weight per individual. A comparison of these weights was made among radiation treatments and time periods. Individual weights were pooled for sampling times up to 64 hours and compared to the weight values at 128, 256 and 512 hours. Duncan's test was used to compare mean weight values within a treatment. The controls (Table 41) showed a significant weight loss by 512 hours while the 1000 rads treatment had a significant weight loss by 256 hours.

The same trend of weight loss at later observation periods was seen in Physa (Physa-Najas-Elodea) for treatments of 0, 100 and 1000 rads. Comparing pooled observations between 2 and 64 hours to those at 128, 256 and 512 hours by Duncan's test (Table 42) showed a significant weight decrease at 512 hours for controls while the 100 and 1000 rads treatments had significant decreases by the 128th and 256th hour periods.

Table 40. Physo Mortality in the Combination of Physo
 Alone Among Radiation Treatments

Dose(rad)	0	1000
Percent Mortality by hour($X_{ij}/18$)		
32	00.00	5.55
64	00.00	27.77
128	00.00	11.11
256	22.22	5.55
512	5.55	16.66
Total Percent Mortality ($EX_{ij}/162$)	2.78	7.40

Table 41. Duncan's Comparison of mg Dry Weight/Physa Individual (Physa Alone) Among Time Periods Within Radiation Treatments

Treatments	Value of p	2	3	4	
	$r_p .05$	2.858	3.006	3.102	
0 rads	R_p	1.616	1.700	1.754	
1000 rads		1.802	1.895	1.956	
	Time(hr)	512	256	128	2-64
0 rads	Mean(mg/ individual)	5.388	7.575	7.688	8.986
	Statistical Significance				
	Time(hr)	512	256	128	2-64
1000 rads	Mean (mg/ individual)	6.616	8.078	10.585	11.778
	Statistical Significance				

Table 42. Duncan's Comparison of mg Dry Weight/Physa Individual (Physa-Najas-Elodea) Among Time Periods Within Radiation Treatments

Treatments	Value of p	2	3	4	
	$r_p .05$	2.858	3.006	3.102	
0 rads	R_p	2.065	2.172	2.242	
100 rads	R_p	1.421	1.494	1.542	
1000 rads	R_p	1.456	1.531	1.580	
	Time(hr)	512	256	128	2-64
0 rads	Mean	5.40	10.83	11.51	12.85
	Statistical Significance				
	Time(hr)	512	256	128	2-64
100 rads	Mean	7.57	8.55	9.51	11.06
	Statistical Significance				
	Time(hr)	512	256	128	2-64
1000 rads	Mean	5.17	6.05	6.65	8.05
	Statistical Significance				

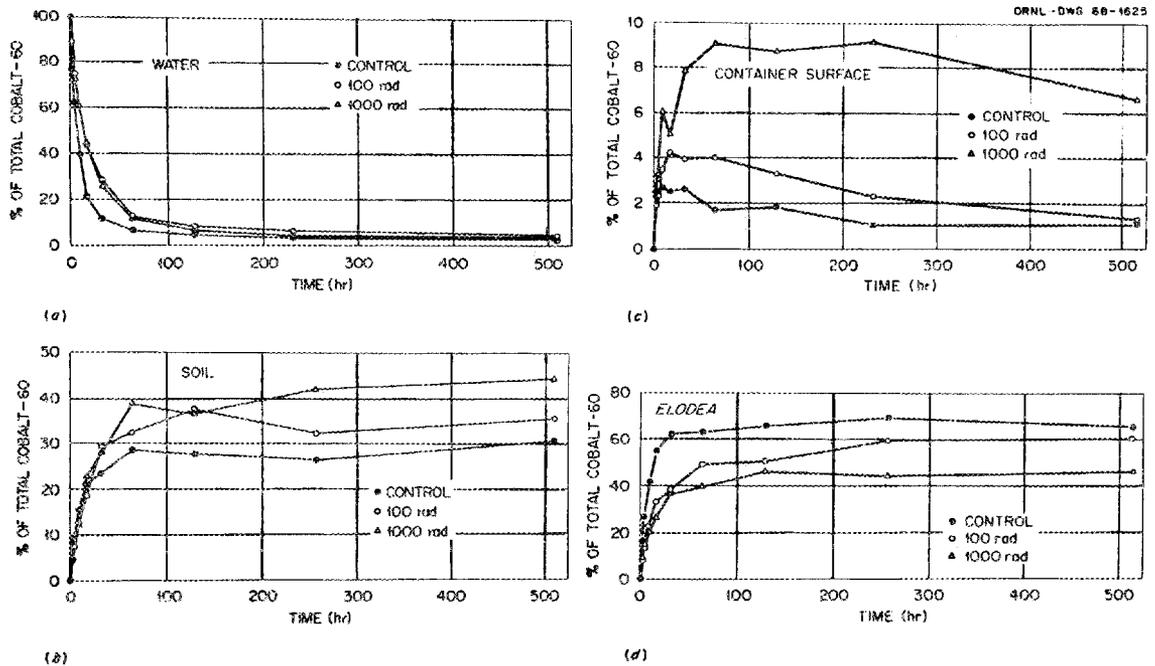
The consideration of weight change gives some indication of degree of metabolic disturbance. Populations of Physa could be maintained in the laboratory for about 20 days at which time a large portion of the population died. Thus, the weight loss in the controls at 512 hours was not unexpected. The significance of the radiation effect is not, therefore, in weight loss but rather in the time that weight losses occurred.

Radiation Effects on ^{60}Co Cycling

Elodea alone - The general pattern of ^{60}Co flux through the microcosms containing only Elodea (Fig. 10) showed no change within a compartment among radiation treatments. However, the radiation treatments did appear to affect the rates of ^{60}Co flux, the ^{60}Co content of a compartment, and delayed the occurrence of steady states and maximum concentrations in compartments.

The pattern of ^{60}Co flux from the water compartment (Fig. 10a) was similar for all treatments, but more ^{60}Co remained in the water in the 100 and 1000 rad treatments. The comparison of initial ^{60}Co loss rates from the water compartment by Duncan's test showed no difference among treatments. However, the loss rates of -24.55, -22.22 and -20.28%/ln hr for doses of 0, 100, and 1000 rads showed a consistent trend of decrease with increased radiation stress.

Although ^{60}Co content of the water compartment at 100 and 1000 rads remained higher than that of the controls through 256 hours, the difference among the treatments became less as the water compartment approached a steady state content. A comparison of the ^{60}Co content of the water compartment at 512 hours (Table 43) showed that the 100 and 1000 rad



60 Figure 10. The effect of fast neutron radiation on compartmental ^{60}Co dynamics in microcosms of Elodea and physical components.

- (a) Water compartment
- (b) Soil compartment
- (c) Container Surface compartment
- (d) Elodea compartment

Table 43. Duncan's Comparison of ^{60}Co in the Water
Compartment (Elodea Alone) at 512 Hours
Among Radiation Treatments

Value of p	2	3	
$r_p .05$	3.014	3.160	
R_p	0.73	0.076	
Treatments (rad)	0	1000	100
Mean	2.80	3.03	3.73
Statistical Significance			

treatments formed a nonsignificant subset with a significantly higher ^{60}Co content than the controls. The 1000 rad and 0 rad treatments also formed a nonsignificant range with a lower ^{60}Co content. Although there was a statistical difference among these compartments at 512 hours, the important point is that there was only a difference of 1% between the controls and irradiated microcosms. Thus, the ^{60}Co content of the water compartment was similar among treatments at 512 hours.

Losses of ^{60}Co from the water compartment in the irradiated microcosms were not as rapid as those from the control microcosm and the ^{60}Co content of the water compartments in the radiation treated microcosms remained higher than that of the controls through 256 hours. However as this compartment approached a steady state at 512 hours, the difference among the treatments was reduced. Thus, although the radiation stress caused an initial perturbation of the ^{60}Co movements in the water there were no effects on the pattern or final content of the water compartment.

The ^{60}Co flux pattern into the soil compartment (Fig. 10b, p. 115) was similar for the 0 and 100 rad treatments in that both compartments had an initial uptake of ^{60}Co and reached a steady state content at about 64 hours. The soil compartment of the 1000 rad treatment had a similar initial uptake and then a slower uptake phase which lasted through 512 hours. No steady state ^{60}Co content was reached by this compartment during the experiment.

The net ^{60}Co uptake rates of the soil compartment were compared among radiation treatments (Table 44). The results showed that treatments of 100 and 1000 rads formed a nonsignificant subset with significantly higher

Table 44. Duncan's Comparison of ^{60}Co Uptake Rates
of the Soil Compartment (Elodea Alone)
Among Radiation Treatments

Value of p	2	3	
$r_{p.05}$	3.085	3.225	
R_p	2.63	2.75	
Treatment (rad)	0	100	1000
Mean(beta)	6.95	9.16	9.85
Statistical Significance		_____	

uptake rates than the controls. The radiation stress increased the ^{60}Co uptake rate of the soil compartment.

The radiocobalt content of the soil compartment in the radiation treatments appeared to be higher than that of the control treatment at 512 hours. A comparison among the treatments (Table 45) showed that the 1000 rad treatment accumulated significantly more ^{60}Co than the 0 or 100 rad treatments. The control and 100 rad treatments formed a nonsignificant range with the lower content. Although of no statistical significance, the 100 rad treatment had more ^{60}Co than the controls. These data showed a trend of increased ^{60}Co content in the soil compartment with increased radiation stress.

The radiation perturbation initially resulted in increased uptake rates of the soil compartment. However, the lower dose treatment reached a steady state content about the same time as the control treatment. In the case of the 1000 rad treatment, the radiation delayed a steady state in the soil compartment until 512 hours or later. Radiation stress increased the ^{60}Co content of the soil compartment in these microcosms.

The ^{60}Co flux through the container surface compartments (Fig. 10c, p. 115) was similar for all treatments. Radiocobalt content of the container surface compartment in the control treatment was at a maximum by 2 hours. However, maxima were reached in the 100 rad treatment only after 16 hours and in the 1000 rad treatment after 64 hours. The maximum content was maintained from 2 to 32 hours in the control, 16 to 64 hours in the 100 rad treatment and 64 to 256 hours in the 1000 rad treatment. Thus, while the pattern was not changed, increased radiation stress delayed the times at which maxima occurred and increased their duration time in the container surface compartment.

Table 45. Duncan's Comparison of ^{60}Co in the Soil
 Compartment (Elodea Alone) at 512 Hours
 Among Radiation Treatments

Value of p	2	3	
$r_p.05$	3.014	3.160	
R_p	6.06	6.36	
Treatment (rad)	0	100	1000
Mean(%)	30.69	35.64	44.21
Statistical Significance	_____		_____

The magnitude of the maximum ^{60}Co content of the container surface compartment varied among treatments. A comparison of the maxima (Table 46) showed that the 1000 rad treatment accumulated significantly more ^{60}Co than the other treatments which formed a nonsignificant range. The maximum content of the 100 rad treatment was higher than that of the controls, even though not statistically so. These data showed that increased radiation stress increased the maximum ^{60}Co content of the container surface compartment.

While the container surface in all treatments had a net loss of ^{60}Co , the time at which a minimum steady state content occurred increased with the radiation stress. In the control treatment this steady state was reached by 256 hours. The steady state minimum was apparently reached by 512 hours in the 100 rad treatment but in the 1000 rad treatment it was delayed until after 512 hours. The increased radiation stress delayed the occurrence of a steady state minimum in the container surface compartment.

The ^{60}Co flux pattern of the Elodea compartment (Fig. 10d, p. 115) was similar for all treatments. After a period of uptake, a maximum ^{60}Co content was reached and maintained as a steady state for the duration of the experiment. The maximum ^{60}Co content of the Elodea compartment was reached between 32 and 64 hours for the control treatment. The steady state maximum was delayed to 256 hours in the 100 rad treatment and to 128 hours in the 1000 rad treatment. The fact that the 100 rad dose delayed the steady state maximum longer than the 1000 rad dose suggests that there may have been recovery from the effect of the 100 rad dose. In addition to the delay in reaching a steady state maximum, the quantity of ^{60}Co at this steady state was decreased with radiation stress.

Table 46. Duncan's Comparison of ^{60}Co Maxima on the Container Surface (Elodea Alone) Among Radiation Treatments

Value of p	2	3	
$r_p .05$	3.014	3.160	
R_p	3.11	3.27	
Treatment (rads)	0	100	1000
Mean	2.60	4.23	9.06
Statistical Significance	_____		_____

The initial net uptake rates of the Elodea compartment were compared among treatments (Table 47). The uptake rate of the control treatment was significantly higher than those of both the 100 and 1000 rad treatments, which formed a nonsignificant range. The 100 rad dose appeared to be a threshold for this effect on the uptake rate as there was no statistical difference between the rates at 100 and 1000 rads. These data showed that the radiation stress decreased the uptake rate of the Elodea compartment.

The ^{60}Co content of the Elodea compartment was compared among radiation treatments (Table 48). The results showed that in the control treatment, Elodea accumulated significantly more ^{60}Co than in the 100 rad treatment, which accumulated significantly more ^{60}Co than the 1000 rad treatment. Increased radiation stress decreased the steady state maximum content of the Elodea compartment.

In the non-irradiated microcosms in which Elodea occurred alone, the plant regulated ^{60}Co pathways and distribution pattern and the time to steady state of compartments. The functional role of Elodea was that of a storehouse of ^{60}Co . Thus, any changes in the ^{60}Co flux through the Elodea compartment will be reflected by changes in other microcosm components.

Radiation stress affected all the parameters of ^{60}Co cycling. In the 100 rad treatments, the pathways of ^{60}Co from the container surface to Elodea was utilized, but a new pathway from the container surface to the soil compartment was evident (Fig. 11a,b). After treatment with 1000 rads, the pathway from the container surface to Elodea was lost and only the net pathway from the container surface to the soil was evident

Table 47. Duncan's Comparison of ^{60}Co Uptake Rates of the Elodea Compartment (Elodea Alone) Among Radiation Treatments

Value of p	2	3	
$r_p .05$	3.033	3.178	
R'_p	10.34	10.84	
Treatment (rads)	1000	100	0
Mean(beta)	9.30	10.31	17.36
Statistical Significance	_____		_____

Table 48. Duncan's Comparison of ^{60}Co in the Elodea Compartment
(Elodea Alone) at 512 Hours Among Radiation Treatments

Value of p	2	3	
$r_{p.05}$	3.014	3.160	
R_p	5.84	6.13	
Treatment (rads)	1000	100	0
Mean(%)	46.14	59.28	65.44
Statistical Significance	_____	_____	_____

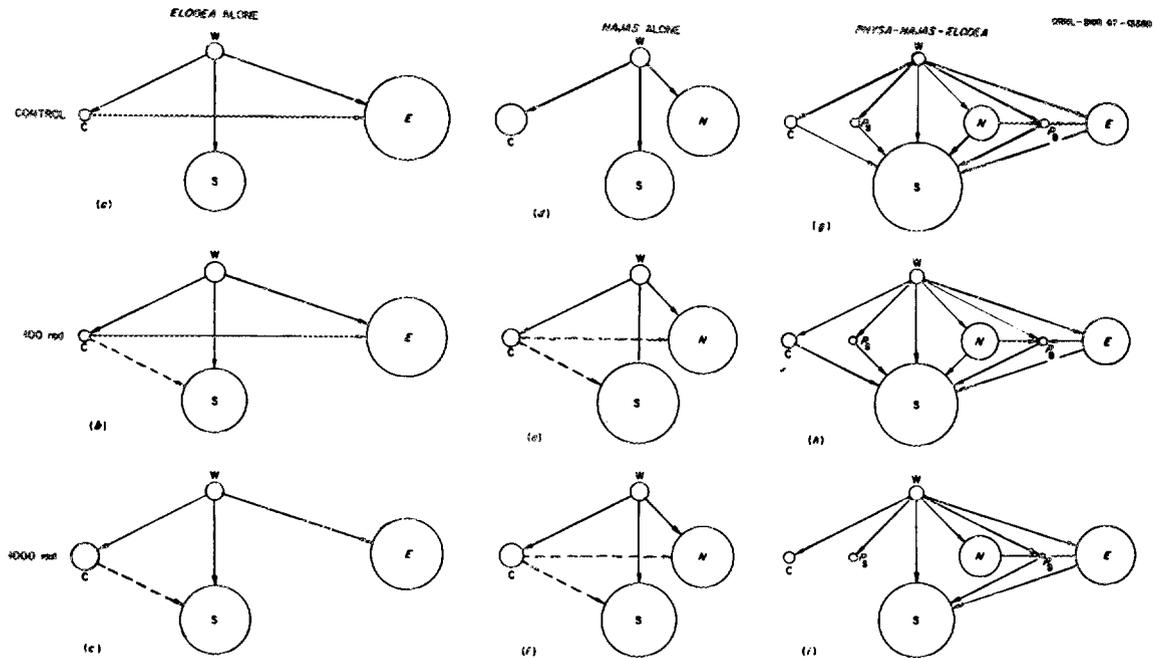


Figure 11. The pattern of net ^{60}Co flux among microcosm compartments as affected by fast neutron radiation.

(a-c) Elodea and physical components

(d-f) Najas and physical components

(g-i) Physa, Najas, Elodea and physical components

The area of the circles represents the percent ^{60}Co in the compartment at the end of the experiment. The broken lines show pathways which did not occur in the control experiment.

(Fig. 11c). Thus, radiation treatment resulted in a new pattern of pathways of ^{60}Co movement among compartments.

The pattern of distribution of ^{60}Co among the compartments also changed (Fig. 11a-c). Elodea had decreased accumulation and the container surface and soil compartment had increased accumulation with increased radiation stress. Final ^{60}Co concentrations in the water compartment varied less than 1% among treatments and were independent of radiation stress.

The time to steady state (5% remaining) in the water compartment was increased with increased radiation stress. In the controls the water compartment reached steady state between 64 and 128 hours. After doses of 100 and 1000 rads, steady state conditions were delayed to between 200 and 512 hours. The time to steady state of the other compartments was previously discussed, and in all cases, radiation increased the time to steady state conditions.

These results showed that the regulatory role of Elodea was significantly lessened by sublethal radiation stress. Increased radiation stress decreased the net accumulation rate of Elodea, thereby changing the patterns of distribution and pathways of ^{60}Co and the time to steady state of compartments.

Fast neutron radiation did not change the functional roles of the microcosm compartments from that described earlier for the non-irradiated microcosm. However, the water compartment assumed an additional, new role in the irradiated microcosms. The decreased net accumulative capacity of Elodea after radiation stress, created an "excess" amount of ^{60}Co in the other microcosm compartments as compared to the controls. This "excess"

was available for distribution among compartments and the changes which occurred in the distribution and pathways patterns were related to distribution of this "excess".

In the 100 and 1000 rad treatments, the ^{60}Co content of the water compartment exceeded that of the controls between 0 and 256 hours. The amount of "excess" in the water was similar for both radiation treatments. From 256 to 512 hours ^{60}Co content of the water decreased continually until it was similar to the controls at 512 hours. The "excess" had moved from the water to other compartments in the irradiated microcosms.

Beginning as early as 8 hours, the container surface compartment in the 100 and 1000 rad treatments showed an increased ^{60}Co content over the controls (Fig. 10c, p. 115). In the 100 rad treatment the ^{60}Co content of the container surface reached a maximum by 16 hours and remained at steady state through 64 hours. In the 1000 rad treatment, uptake to a maximum continued to 64 hours with a steady state prevailing through 256 hours. While some of the "excess" ^{60}Co remained in the water compartment during the early part of the experiment, part of it moved into the container surface compartment (Fig. 11b,c, p. 126).

During the time period from 0 to 16 hours the amount of ^{60}Co in the soil compartment was similar for all treatments (Fig. 10b, p. 115). None of the "excess" ^{60}Co moved into the soil compartment. At 32 hours, the ^{60}Co content of the soil in the 100 and 1000 rad treatments was higher than that of the controls. The soil compartment of the controls and 100 rad treatments reached a steady state at about 64 hours. Thus, between 16 and 64 hours part of the "excess" ^{60}Co in the water compartment of the 100 rad treatment moved into the soil compartment. The soil compartment

of the 1000 rad treatment did not reach a steady state during the experiment, indicating the "excess" ^{60}Co in the water must have moved continuously into the soil compartment.

In the controls a net ^{60}Co loss followed the period of steady state maximum in the container surface compartment, while the water compartment also continued to lose ^{60}Co (Fig. 10a,c, p. 115). Together, these losses represented 4% of the total ^{60}Co which appeared as a gain of approximately 4% in the Elodea compartment between 64 and 128 hours (Fig. 10d, p. 115). In the 100 rad treatment, a steady state maximum in the container surface compartment extended to 64 hours, after which time a net loss of ^{60}Co from this compartment extended to 512 hours. The water compartment also had a loss between 64 and 256 hours and the total loss from both water and container surface compartments was 8%. As in the controls, these losses appeared as gains in the Elodea compartment up to 256 hours (Fig. 11b, p. 126). After this time, losses from the container surface and water moved into the soil compartment (Fig. 11b, p. 126). For the 1000 rad treatment, the container surface compartment was at a steady state maximum until 256 hours, after which time there was a net loss of 2.5% ^{60}Co . The water compartment was also losing ^{60}Co after 128 hours. The total loss from these two compartments from 128 to 512 hours was 6.5%. Unlike conditions in the controls and 100 rad treatments, this additional loss was not reflected by a gain in the Elodea compartment, but appeared as a gain in the soil compartment (Fig. 11c, p. 126).

The detailed analysis of the net movement of the "excess" ^{60}Co demonstrated an additional new role of the water compartment as that of a temporary storehouse of readily available ^{60}Co . The importance of the

role of the container surface as a temporary sink of ^{60}Co was also demonstrated in that increasing amounts of ^{60}Co were stored on the container surface with increased radiation stress.

Functional roles which provide for temporary storage of ^{60}Co may be of ecological importance as a mechanism contributing to the homeostasis of distribution and pathway patterns within the microcosm. Homeostasis of patterns occurred in the microcosm receiving the 100 rad dose. Elodea accumulated most of the "excess" ^{60}Co which had been stored in the water and container surface compartments, with the result that the pattern of distribution and pathways of ^{60}Co among compartments was similar to that of the control treatment. Thus, the compartments of temporary storage represented a homeostatic mechanism in that they provided a means through which the pattern of distribution and pathways of ^{60}Co among compartments could be maintained. Although the same homeostatic mechanism was operative in the 1000 rad treatment, Elodea was unable to accumulate much of this "excess" ^{60}Co . This condition resulted in a significant change in the distribution and pathway patterns of ^{60}Co among compartments. The new role of the water as a temporary storage compartment contributed to the preservation of the pathway pattern as will be shown later for the Najas microcosm.

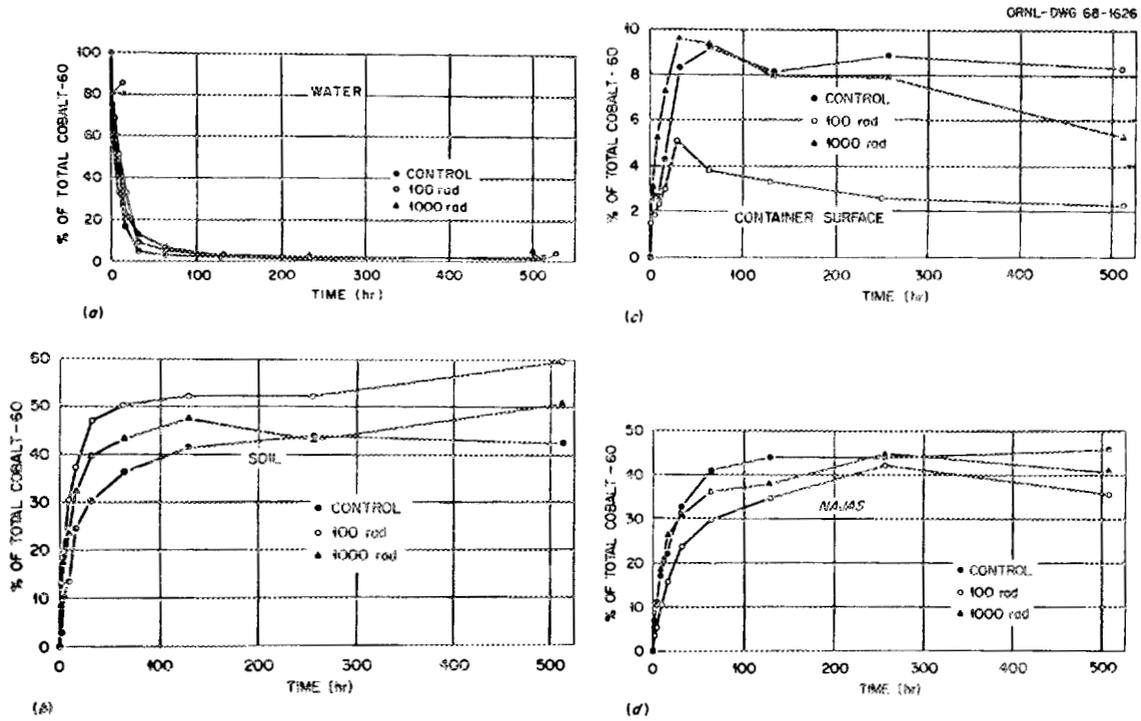
Radiation stress perturbed ^{60}Co cycling in the Elodea microcosms as demonstrated by changes in the cycling parameters. These changes in cycling parameters were related to the effect of radiation on the uptake rate and possibly the accumulative capacity of Elodea. A tendency toward homeostasis of the distribution and pathway patterns was demonstrated for the 100 rad treatment, but did not occur in the 1000 rad treatment.

The mechanisms of homeostasis with regard to ^{60}Co cycling were related to temporary storage of ^{60}Co in the physical compartments and the capacity of compartments to play dual roles in element transfers.

Najas alone - The pattern of ^{60}Co flux through the microcosm compartments (Fig. 12) showed differences among radiation treatments in all except the water compartment. The initial compartmental uptake or loss rates were similar for all radiation treatments. However, there were differences among radiation levels in the amount or flux pattern of ^{60}Co in compartments.

The ^{60}Co loss pattern and the amount of ^{60}Co in the water compartment were similar for all treatments (Fig. 12a). There was a rapid decline in the ^{60}Co content of the water compartment to 64 hours which was followed by a slower decrease from 64 to 512 hours, at which time the compartment apparently reached a steady state. Loss rates of ^{60}Co from the water compartment varied between -19.8 and -22.0%/ln hr and were not statistically different. The quantity of ^{60}Co in the water compartment at 512 hours varied between 2.7 and 3.6% with no statistical difference among the treatments. These data show the water compartment to be independent of radiation effects.

The soil compartment had a pattern of rapid ^{60}Co uptake to 64 hours for all radiation treatments (Fig. 12b). In the controls, there was a slight net gain to 128 hours after which time this compartment appeared to be in a steady state. Both the 100 and 1000 rad treatments showed continued ^{60}Co uptake into the soil compartment to 128 hours. After this time the trend of both uptake curves suggested additional net ^{60}Co gains. The uptake rates of ^{60}Co by the soil compartment varied between 9.75 and



60 Figure 12. The effect of fast neutron radiation on compartmental ^{60}Co dynamics in microcosms of Najas and physical components.

- (a) Water component
- (b) Soil component
- (c) Container Surface component
- (d) Najas component

10.07%/ln hr and were not statistically different. The ^{60}Co content of the soil at 512 hours was compared among radiation treatments (Table 49). The results showed that the 100 rad dose effected the highest ^{60}Co content in the soil compartment and the 1000 rad dose resulted in a significantly higher ^{60}Co content in the soil compartment than in the controls. The effect of radiation stress on the soil compartment was a change in the flux pattern of ^{60}Co which resulted in higher ^{60}Co accumulation in the soil.

The pattern of ^{60}Co flux through the container surface compartment (Fig. 12c, p. 132) was that of a rapid initial uptake to a maximum by 32 hours. In the controls, the container surface reached a steady state content between 32 and 64 hours which extended to 512 hours. For the 100 and 1000 rad treatments there was a net loss of ^{60}Co from this compartment after 32 hours which continued to 512 hours. The initial net uptake rates varied from 1.20 to 2.65%/ln hr and were not statistically different. The maximum ^{60}Co content of the container surface compartment was not statistically different among radiation treatments. However, the comparison of the ^{60}Co content of this compartment at 512 hours (Table 50) showed that the controls had significantly more ^{60}Co than the 100 and 1000 rad treatments, while the 1000 rad treatment had significantly more ^{60}Co than the 100 rad treatment. These results indicated that radiation stress changed the flux pattern of ^{60}Co in the container surface compartment.

The pattern of ^{60}Co flux through the Najas compartment (Fig. 12d, p. 132) showed a period of rapid uptake to 64 hours for all treatments. In the controls there was a slower uptake to 128 hours after which time the Najas compartment appeared to be in a steady state. For the 100 and

Table 49. Duncan's Comparison of ^{60}Co in the Soil Compartment
(Najas Alone) at 512 Hours Among Radiation Treatments

Value of p	2	3	
$r_{p.05}$	3.014	3.160	
R_p	7.95	8.34	
Treatment (rads)	0	1000	100
Mean	42.34	50.92	59.78
Statistical Significance	_____	_____	_____

Table 50. Duncan's Comparison of ^{60}Co in the Container Surface Compartment (Najas Alone) at 512 Hours Among Radiation Treatments

Value of p	2	3	
$r_{p.05}$	3.014	3.160	
R_p	2.42	2.54	
Treatment (rads)	100	1000	0
Mean(%)	2.34	5.32	8.37
Statistical Significance	—	—	—

1000 rad treatments there was also a period of slower uptake which continued to 256 hours. After 256 hours there was an apparent net loss of ^{60}Co from the Najas compartment.

The comparison of initial ^{60}Co uptake rates of the Najas compartment by Duncan's test showed no significant difference among treatments. However, the rate of 9.80%/ln hr for the controls was higher than that of approximately 8.00%/ln hr for the microcosms at 100 and 1000 rads. These data suggested that the radiation stress reduced the uptake rate.

The ^{60}Co content of the Najas compartment at 512 hours was compared among radiation treatments (Table 51). The results showed that the control and 1000 rad treatments formed a nonsignificant range and contained significantly more ^{60}Co than the 100 rad treatment.

The Najas compartment has been shown to be coupled to the physical compartments and it regulates both the pattern of distribution and the time to steady state of compartments. Therefore, a radiation stress which affects ^{60}Co flux through the Najas compartment will also cause changes in ^{60}Co cycling through the physical compartments.

The pattern of distribution of ^{60}Co has already been shown to change with radiation stress. Increased radiation stress was shown to decrease the final ^{60}Co content of Najas and the container surface and increase the content of the soil compartment. The final ^{60}Co content of the water compartment was independent of radiation stress.

The time to steady state of most compartments was shown to be increased with increased radiation stress and the soil, the container surface, and Najas compartments did not reach a steady state after treatment with 100 or 1000 rads. The water compartment reached steady state (5% remaining) after 256 hours in all treatments.

Table 51. Duncan's Comparison of ^{60}Co in the Najas Compartment
(Najas Alone) at 512 Hours Among Radiation Treatments

Value of p	2	3	
$r_{p.05}$	3.014	3.160	
R_p	8.49	8.91	
Treatment (rads)	100	1000	0
Mean(%)	35.03	41.07	46.67
Statistical Significance		_____	

The pattern of net ^{60}Co pathways among compartments was changed after a radiation stress (Fig. 11d-f, p. 126). Two new pathways leading from the container surface to Najas and to the soil compartment occurred in both the 100 and 1000 rad treatments.

These results showed that the regulatory role of Najas in ^{60}Co cycling was changed. Although the accumulation rate of this plant appeared to have been reduced after radiation treatment, the regulatory role of Najas was enhanced. In addition to the regulation of the pattern of final distribution and time to steady state of compartments, Najas also regulated the pathway pattern of ^{60}Co among compartments.

The radiation stress did not change the functional roles of the various microcosm compartments from that described earlier for the control microcosms. However, the radiation stress demonstrated the importance of temporary storage as a regulating mechanism in ^{60}Co cycling. The decreased accumulation rate of Najas after radiation treatment created an "excess" amount of ^{60}Co in the other compartments of the microcosm as compared to the control. The fate of this "excess" was related to the change in pathways and distribution patterns.

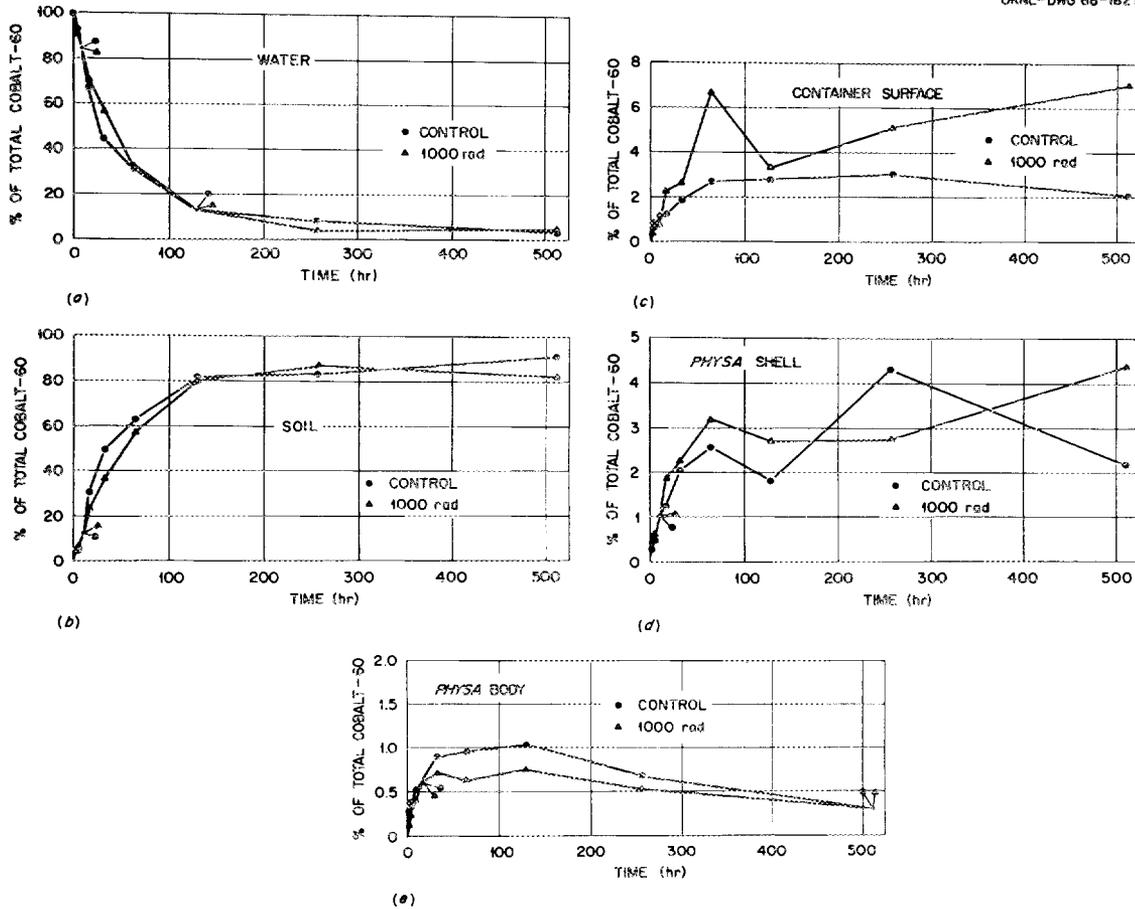
Since the ^{60}Co content of the water compartment at any time during the experiment was similar for all treatments (Fig. 12a, p. 132), most of the "excess" ^{60}Co must not have remained in the water. The soil compartment of the irradiated microcosms had a greater ^{60}Co content than that of the control beginning as early as 8 hours (Fig. 12b, p. 132) and since the container surface accumulated no more ^{60}Co than the control, this excess ^{60}Co apparently moved to the soil. The continued rapid uptake by irradiated Najas between 32 and 256 hours resulted from the movement of ^{60}Co from the water and container surface compartments into Najas

The change in the ^{60}Co flux pattern of the Najas compartment stressed the ^{60}Co relations among compartments. The "excess" ^{60}Co immediately moved into a permanent sink, leaving the only available ^{60}Co in the water and container surface compartments. The accumulation of this ^{60}Co into the Najas compartment effected the change in the pattern of distribution and pathways of the container surface compartment.

The physical compartment's role of temporary storage of ^{60}Co in the Najas microcosm provided a mechanism by which Najas could accumulate the expected amount of this radionuclide even though the net accumulation rate of the plant was apparently reduced. The change in the pathway pattern of a physical compartment was the mechanism maintaining homeostasis of the biological component.

Radiation stress perturbed ^{60}Co cycling in Najas microcosms as demonstrated by changes in cycling parameters. The changes were related to the effect of radiation in altering the flux pattern of ^{60}Co to Najas, without reducing its accumulative capacity. The lack of adequate temporary storage of ^{60}Co in the water compartment and the continued "demand" of ^{60}Co by Najas created new pathways of ^{60}Co from the container surface compartment. Temporary storage of ^{60}Co in the container surface compartment was shown to be a homeostatic mechanism for the biological compartment.

Physa alone - The flux of ^{60}Co through the microcosm compartments (Fig. 13) showed no differences in patterns between the controls and the 1000 rad treatments. Both flux rates and content in a compartment were similar between treatments and there was no indication of temporal differences in the flux of ^{60}Co through a compartment.



60 Figure 13. The effect of fast neutron radiation on compartmental ^{60}Co dynamics in microcosms of Physa and physical components.

- (a) Water component
- (b) Soil component
- (c) Container Surface component
- (d) Physa Shell component
- (e) Physa Body component

The flow of ^{60}Co from the water compartment (Fig. 13a) had a pattern of rapid loss to 128 hours with a more gradual loss from 128 to 512 hours, at which time a steady state was reached. There was no statistical difference between loss rates or the steady state content of the water compartment, and the ^{60}Co content was similar at all observation periods throughout the experiment. These data gave no indication of radiation effects on the water compartment.

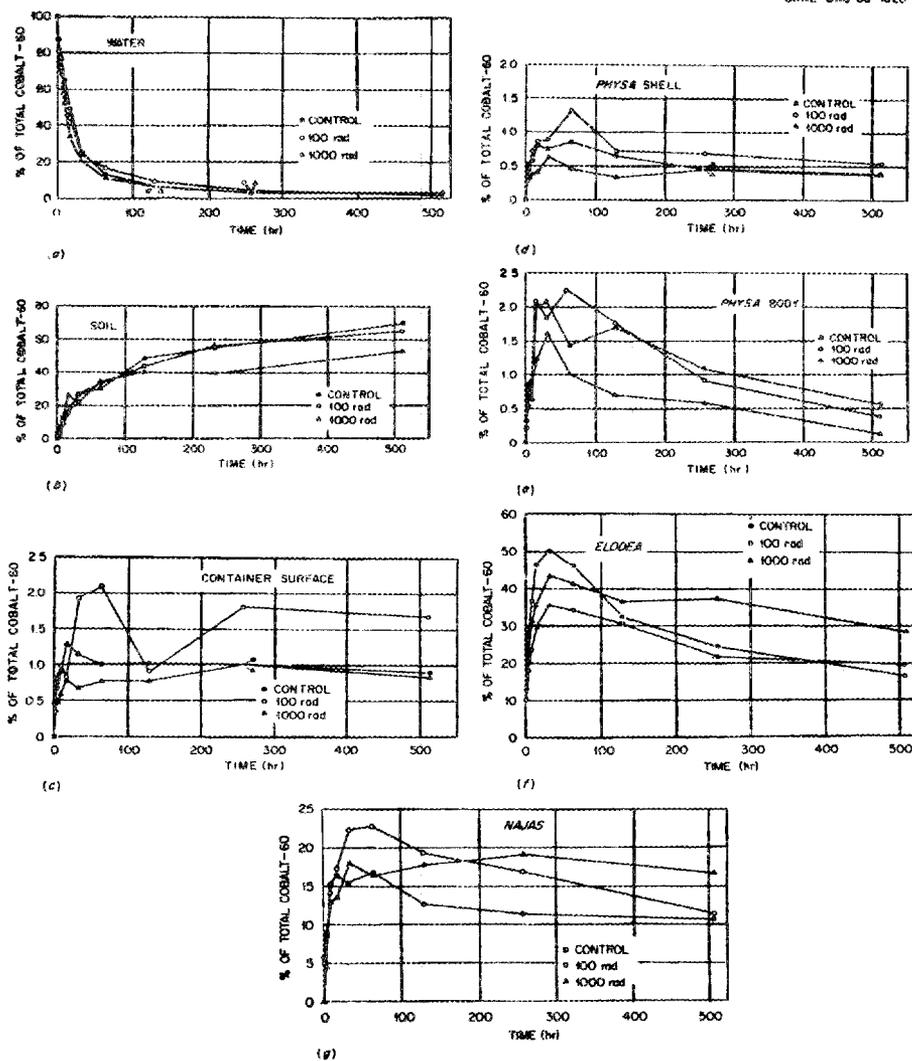
Both the control and the 1000 rad treatment had a net increase in the ^{60}Co content of the soil compartment until 128 hours, at which time this compartment reached a steady state content (Fig. 13b). There was no statistical difference between soil uptake rates. The ^{60}Co content of the soil compartment was similar at each observation period and a comparison of ^{60}Co in soil compartments between 128 and 512 hours showed no statistical difference between treatments. There was no evidence of a radiation effect on the soil compartment from these data.

The behavior of ^{60}Co in the container surface compartment (Fig. 13c) showed a period of uptake to a maximum at 64 hours after which there was essentially no change. The maximum ^{60}Co content of 7.5% in the 1000 rad treatment was statistically higher than the 3% in the control. A comparison of the ^{60}Co content of this compartment between the treatments at 512 hours gave results similar to the comparison of the maximum content. However, the behavior of ^{60}Co in the container surface compartment was erratic for the 1000 rad treatment. Although it had a higher ^{60}Co content than the control, the erratic behavior plus the small difference of 3% between treatments suggests that radiation effects here were either nonexistent or of little consequence.

The Physa shell compartment had a similar ^{60}Co behavior pattern in both treatments (Fig. 13d, p. 140). A period of uptake to a maximum content was followed by a steady state of this maximum at 512 hours. A comparison of the uptake rates between treatments showed no statistical difference. Although a statistical difference can be obtained in a comparison of the ^{60}Co content of these compartments at 512 hours, the relatively erratic behavior of this compartment precluded a valid comparison at any one point. These data were presumed to represent fluctuation about a steady state content which at most would have a difference of less than 1.5% between treatments.

The flux of ^{60}Co through the Physa body compartment (Fig. 13e, p. 140) was similar for both treatments. There was a period of uptake to a maximum content at 32 hours and this level was maintained to 128 hours. After 128 hours there was a net loss of ^{60}Co from Physa bodies which continued through 512 hours. There was no statistical difference between treatments in uptake or loss rates, maximum ^{60}Co values or content at 512 hours. That the Physa body compartment at 1000 rads had consistently lower ^{60}Co content than that of the control suggests that the ^{60}Co content of the irradiated Physa body was lowered as a result of the radiation treatment. However, the difference between treatments is less than 0.5%. These data do not show any statistically significant effects on the Physa body compartment.

Physa-Najas-Elodea - The pattern of ^{60}Co flux through each compartment (Fig. 14) was similar among radiation treatments, except for the container surface, the Physa shell, and the Najas and Elodea compartments. However, there were differences among uptake and loss rates as well as ^{60}Co content of a given compartment among the treatments.



60 Figure 14. The effect of fast neutron radiation on compartmental ^{60}Co dynamics in microcosms consisting of Physa, Najas, Elodea and physical components.

- (a) Water component
- (b) Soil component
- (c) Container Surface component
- (d) Physa Shell component
- (e) Physa Body component
- (f) Elodea component
- (g) Najas component

The water compartment of all treatments had an initial period of rapid ^{60}Co loss for 32 hours (Fig. 14a). Duncan's comparison of the rate of loss among treatments showed no significant difference among treatments. The calculated loss rates decreased from $-26.29\%/ \ln \text{ hr}$ for the controls to $-22.26\%/ \ln \text{ hr}$ for the 1000 rad treatment which suggested a possible radiation effect. The ^{60}Co content of the water compartment in the 100 and 1000 rad treatments was consistently lower than that of the control up to 64 hours. At 128 hours there was only a 2% difference in ^{60}Co content among treatments and between 256 and 512 hours all treatments had a similar content varying between 1.5 and 2.0%. A comparison of the ^{60}Co content of the water compartment among treatments showed no statistical difference. The ^{60}Co content of the water compartment in irradiated microcosms was higher than that of the control at first, but there was no difference in the time at which steady state occurred or in the steady state ^{60}Co contents of the water compartment.

The ^{60}Co flux pattern through the soil compartment of all treatments (Fig. 14b, p. 143) showed a period of rapid uptake to 128 hours, with a constant but slower uptake from 128 to 512 hours. During the period from 0 to 64 hours the ^{60}Co content of the soil compartment was similar for all treatments. After this time there was a marked reduction in the content of the soil compartment at 1000 rads. The uptake rates were compared among treatments by Duncan's test. Although no significant difference was indicated, the control and the 100 rad treatment had rates of $12.07\%/ \ln \text{ hr}$ as compared to $9.32\%/ \ln \text{ hr}$ for the 1000 rad treatment. The comparison of ^{60}Co in soil at 512 hours (Table 52) showed that the control accumulated more ^{60}Co than the 100 rad treatment and these two

Table 52. Duncan's Comparison of ^{60}Co in the Soil Compartment
(Physa-Najas-Elodea) at 512 Hours Among Radiation
Treatments

Value of p	2	3	
$r_{p.05}$	3.014	3.160	
R_p	9.31	9.76	
Treatment (rads)	1000	100	0
Mean	52.05	65.75	69.86
Statistical Significance	_____	_____	

treatments formed a nonsignificant range with significantly more ^{60}Co than the 1000 rad treatment. There was no radiation effect on the ^{60}Co flux pattern of the soil compartment and no statistical difference among uptake rates. Initially, there was no difference in ^{60}Co content of the soil compartment among treatments but by 512 hours, the data showed a trend of decreased content with increased radiation stress.

The pattern of ^{60}Co flux through the container surface compartment (Fig. 14c, p. 143) was similar for the 0 and 100 rad treatments with a period of uptake to maxima followed by a slight loss to a steady state content. The 1000 rad treatment had a similar initial uptake, followed by another slower period of uptake to 256 hours, after which there was no apparent change in ^{60}Co content through 512 hours. There was no statistical difference among uptake rates or among the maximum ^{60}Co contents of this compartment. The comparison of ^{60}Co content at 512 hours (Table 53) showed that the container surface at 100 rads accumulated significantly more ^{60}Co than the 0 and 1000 rad treatments which formed a nonsignificant range.

The results for the container surface compartment showed a radiation effect on the ^{60}Co flux pattern in the 1000 rad treatment. There was no statistical difference among the uptake rates or maximum ^{60}Co contents of the container surface compartment, but in the 100 rad treatment this compartment accumulated significantly more ^{60}Co than the other treatments. However, this difference was only 1%. Of greater import was the difference in pattern between the 0, 100 rad treatments and the 1000 rad treatment. The 0 and 100 rad treatments had a similar pattern, but there were temporal differences between the patterns. The period of

Table 53. Duncan's Comparison of ^{60}Co in the Container Surface Compartment (Physa-Najas-Elodea) at 512 Hours Among Radiation Treatments

Value of p	2	3	
$r_p .05$	3.014	3.160	
R_p	0.58	0.59	
Treatment (rads)	1000	0	100
Mean(%)	0.85	0.89	1.68
Statistical Significance	_____		_____

uptake to a maximum content continued to 16 hours for the control treatment and 64 hours for the 100 rad treatment. After this maximum was reached there was a slight decrease in the ^{60}Co content to 64 hours, after which this compartment remained in a steady state through 512 hours. The container surfaces in the 100 rad treatment had a slight loss after 64 hours, with a steady state being maintained through 512 hours. This pattern for the 0 and 100 rad treatments was contrasted to the pattern of the 1000 rad treatment which had continued uptake to 256 hours with no apparent change after that time. The effect of radiation on the container surface was to delay the occurrence of a steady state content or to change the pattern of ^{60}Co flux through this compartment.

The flux of ^{60}Co through the Physa shell compartment (Fig. 14d, p. 143) showed a similar pattern of initial uptake to maxima for all compartments. A comparison of these rates showed no statistical difference among the treatments. The control and 100 rad treatments reached a maximum which was followed by a net loss of ^{60}Co through 512 hours. The 1000 rad treatment reached a maximum with no apparent change in ^{60}Co content after this value was reached. A comparison of the maximum content of this compartment among treatments showed that the 100 rad treatment accumulated significantly more ^{60}Co than the other treatments. However, this difference was less than 1%. By 512 hours all treatments had reached a similar content, apparently at or approaching a steady state content. These data showed no radiation effect on the Physa shell compartment at the 100 rad dose, but the ^{60}Co flux pattern was changed by a dose of 1000 rads.

The ^{60}Co flux pattern through the Physa body compartment (Fig. 14e, p. 143) was similar for all treatments. A period of rapid uptake to a

maximum was followed by a net loss which continued to 512 hours. There was no statistical difference among uptake rates, maximum content, or loss rates. However, the time at which the maximum content occurred differed among treatments. In the control and 100 rad treatments, maxima were reached at 16 hours while the 1000 rad treatment delayed this event to 32 hours. When ^{60}Co contents of the Physa body compartment were compared, the results showed no statistical difference among treatments.

These data showed no radiation effects on ^{60}Co cycling in the Physa body compartment, except for the delay in the time at which a maximum ^{60}Co content occurred in this compartment. Even though the difference between the control and 100 rad treatments was not statistically significant, the ^{60}Co content at the 1000 rad dose was lower than that of the control treatment. This same relationship was true of the Physa body compartment in microcosms of Physa alone. Since this result occurred twice, it suggests that there was a reduction in the ^{60}Co content of this compartment in the 1000 rad treatment.

The pattern of ^{60}Co flux through the Elodea compartment (Fig. 14f, p. 143) was similar for all treatments. An initial period of rapid uptake to a maximum was followed by a net loss of ^{60}Co through 512 hours. The comparison of initial uptake rates of the Elodea compartment among treatments (Table 54) showed that the control had a significantly higher uptake rate than either the 100 or 1000 rad treatments, which formed a nonsignificant range. The maximum ^{60}Co content of the compartment was compared among treatments (Table 55) and showed that each treatment formed an independent set, with the control higher than either radiation treatment and the 1000 rad treatment higher than the 100 rad treatment. These

Table 54. Duncan's Comparison of ^{60}Co Uptake Rates of the Elodea Compartment (Physa-Najas-Elodea) Among Radiation Treatments

Value of p	2	3	
$r_p .05$	3.261	3.399	
R'_p	3.17	3.31	
Treatment (rads)	100	1000	0
Mean(beta)	8.99	10.29	13.35
Statistical Significance	_____		_____

Table 55. Duncan's Comparison of ^{60}Co Maxima in the
Elodea Compartment (Physa-Najas-Elodea)
 Among Radiation Treatments

Value of p	2	3	
$r_p .05$	3.014	3.160	
R_p	6.02	6.32	
Treatment (rads)	100	1000	0
Mean(%)	35.61	43.44	50.06
Statistical Significance	_____	_____	_____

data showed that both the uptake rate and maximum ^{60}Co content of Elodea were reduced with increased radiation stress.

The loss rate of ^{60}Co from the Elodea compartment was compared among treatment (Table 56). The loss rate in the control was significantly faster than those of the 100 and 1000 rad treatments. The loss rate in the 100 rad treatment exceeded that of the 1000 rad treatment, but there was no statistical difference between them. The ^{60}Co content of the Elodea compartment at 512 hours was compared among treatments (Table 57) and showed that in the 1000 rad treatment Elodea had significantly higher ^{60}Co content than in the 0 or 100 rad treatments. Elodea accumulated less ^{60}Co in the control than in the 100 rad treatment, but these two formed a nonsignificant range. Thus, the increased radiation stress reduced the loss rate of ^{60}Co from the Elodea compartment and this resulted in a build-up of ^{60}Co in the plants.

The results for the Elodea compartment showed that the radiation stress reduced ^{60}Co uptake rates and maximum ^{60}Co content, while it lowered loss rates and increased ^{60}Co content of this compartment. Except for the difference in pattern, these results are the same as those obtained for the Elodea compartment when Elodea occurred alone. However, in the Elodea compartment of this latter experiment, there was a trend of decreased ^{60}Co uptake rates and content with increased dose. This was not true of the Elodea compartment in the Physa-Najas-Elodea treatment. In this experiment, there was a greater reduction in ^{60}Co uptake rate and content at 100 rads than at 1000 rads. These data suggest an additional effect on the Elodea compartment at 100 rads, which may be related to complexity.

Table 56. Duncan's Comparison of ^{60}Co Loss Rates
From the Elodea Compartment (Physa-Najas-
Elodea) Among Radiation Treatments

Value of p	2	3	
$r_p \cdot 05$	3.199	3.339	
R_p	4.26	4.44	
Treatment (rads)	1000	100	0
Mean(beta)	-4.90	-6.57	-13.08
Statistical Significance	—————		—————

Table 57. Duncan's Comparison of ^{60}Co in the Elodea Compartment (Physa-Najas-Elodea) at 512 Hours Among Radiation Treatments

Value of p	2	3	
$r_{p.05}$	3.014	3.160	
R_p	8.34	8.75	
Treatment (rads)	0	100	1000
Mean(%)	15.63	19.15	28.55
Statistical Significance	_____		_____

The pattern of ^{60}Co flux through the Najas compartments (Fig. 14g, p. 143) was similar for the 0 and 100 rad treatments, while a different pattern was effected in the 1000 rad treatment. All treatments had a period of rapid uptake to a maximum concentration. In the 0 and 1000 rad treatments there was a net loss of ^{60}Co from the Najas compartment after the maximum content was reached, while in the 1000 rad treatment the maximum content was maintained as a steady state content through 512 hours.

The comparison of initial uptake rates of the Najas compartment by Duncan's test showed no significant difference among treatments. The maximum ^{60}Co content of the Najas compartment was compared among treatments (Table 58). These results showed that the 100 and 1000 rad treatments formed a nonsignificant range with significantly higher ^{60}Co content than the controls. The 1000 rad treatment also formed a nonsignificant range with the control treatment. The data for uptake rates and content of the Najas compartment showed no relation to radiation stress.

The loss rates of ^{60}Co from the Najas compartment after the 100 rad treatment was $-5.4\%/1\text{n hr}$ which was significantly different (Duncan's test) from the loss rate of $-1.8\%/1\text{n hr}$ for the controls. The Najas compartment after the 1000 rad treatment had no net loss. The loss rate of ^{60}Co from the Najas compartment between 32 and 128 hours was similar for the controls and 100 rad treatment. However, including the loss period to 512 hours, the rate was slower in the controls than in the 100 rad treatment. The Najas compartment in the control treatment apparently approached a steady state after 128 hours, while the 100 rad treatment had a continued loss to 512 hours. At 512 hours, the comparison of the ^{60}Co content of the Najas compartment among treatments (Table 59)

Table 58. Duncan's Comparison of ^{60}Co Maxima in the Najas Compartment (Physa-Najas-Elodea) Among Radiation Treatments

Value of p	2	3	
$r_{p.05}$	2.888	3.035	
R_p	4.49	5.13	
Treatment (rads)	0	1000	100
Mean(%)	16.15	18.42	22.53
Statistical Significance		_____	

Table 59. Duncan's Comparison of ^{60}Co in the Najas Compartment
(Physa-Najas-Elodea) at 512 Hours Among Radiation Treatments

Value of p	2	3	
$r_p^{.05}$	3.014	3.160	
R_p	4.46	4.68	
Treatment (rads)	0	100	1000
Mean (%)	10.53	11.38	16.64
Statistical Significance	_____		_____

showed that the 1000 rad treatment maintained a significantly higher content than the other treatments which were not significantly different. On the basis of these results, there was no effect of radiation on the pattern of flux through the Najas compartment in the control or 100 rad treatments, and both treatments reached the same ^{60}Co content by 512 hours. There was a significant change in the flux pattern of the 1000 rad treatment as there was no net loss from the Najas compartment.

In the microcosms containing Physa, Najas, and Elodea the regulation of ^{60}Co was shown to be a function of the interaction of the three biological components. Therefore, a radiation stress which affects the interaction of these species will also affect ^{60}Co cycling among all components.

The pattern of final distribution of ^{60}Co has already been discussed for each compartment. The results showed that a dose of 100 rads had little or no effect on the final distribution pattern among compartments, although there was a trend toward higher content in the plant compartments and lower content in the soil compartment. After treatment with 1000 rads, the pattern of distribution among compartments was significantly changed with a higher content in the plants and a lower content in the soil.

The pattern of net ^{60}Co pathways among compartments was not affected by a dose of 100 rads, but was changed by a dose of 1000 rads (Fig. 11g-i, p. 126). The change in pattern at 1000 rads was the loss of the pathways from the container surface, the Physa shell, and the Najas compartments to the soil compartment.

Complexity, Radiation Stress, and ^{60}Co Cycling

On the basis of results from microcosms consisting of Najas and Elodea alone, it was expected that the sublethal dose would change the

patterns of final distribution and pathways of ^{60}Co flux in the microcosms consisting of Physa, Najas, and Elodea. The lack of change in these patterns at the sublethal dose demonstrated an increased degree of homeostasis in the more complex microcosms and the change in the patterns at 1000 rads primarily reflected the effect of radiation on the plant-snail interaction.

The functional roles of the various compartments in the more complex microcosm were not changed after treatment by 100 rads from those described earlier for the control microcosm. However, there were differences in the pattern of distribution during the early part of the experiment. The maximum accumulation of ^{60}Co by Elodea at 100 rads was lower than that of the control Elodea, while the maximum accumulation of Najas at 100 rads was higher than that of the control Najas. This situation suggests that Elodea was more affected by the lower dose than was Najas. The results for Najas and Elodea alone (Fig. 10, p. 115 and Fig. 12, p. 132) showed that such was possible, as the effect of both 100 and 1000 rad treatments produced the same severe effect on Elodea initially, while the initial effect of these doses on Najas was not as severe and later there was evidence of "recovery".

Physa functioned as a catalyst in the complex microcosms and there was no evidence that ^{60}Co cycling through the Physa body compartment was affected by the radiation stress of 100 rads. Since the exact nature of the catalytic effect of Physa on the plants was not defined by these experiments, the conclusion is that the 100 rad dose apparently did not impair the functional role of Physa.

In the 1000 rad treatment, the functional role of Najas was changed from that of a processor to that of a storehouse. That the ^{60}Co maximum

in Elodea at 1000 rads exceeded that at 100 rads suggested that both Elodea and Najas were severely affected by the 1000 rad dose. The change in the pattern of ^{60}Co flux through Najas and the slower loss rate from Elodea at 1000 rads suggested that this dose significantly affected the functional role of the Physa compartment.

Experimental results for Physa were too inconclusive to demonstrate a radiation effect on ^{60}Co cycling through this compartment. However, consistent trends of differences between control and irradiated Physa in the combination of Physa alone and Physa-Najas-Elodea suggested an effect. That there were differences between control and irradiated Physa was confirmed by the lack of an effect of Physa on the ^{60}Co flux through the plant compartments in this microcosm.

Radiation perturbed ^{60}Co cycling in the microcosm combination of Physa-Najas-Elodea as demonstrated by changes in the cycling parameters during the early or latter stages of the experiment. Changes in the cycling parameters were related to the effect of radiation on the uptake rates of the plants and on the functional role of Physa. Homeostasis of the final distribution and pathway patterns was demonstrated for the 100 rad dose, but not in the 1000 rad treatment.

In the less complex microcosms, a radiation stress of 100 or 1000 rads reduced the initial flux rates of ^{60}Co in compartments and increased the time to steady state or the duration of a maximum steady state content within some compartments. In the more complex microcosms, a radiation stress of 100 rads had little effect on the initial ^{60}Co flux rates and no effect on temporal parameters. A stress of 1000 rads, however, had a significant effect on flux rates and increased the time to maximum or

steady state content of compartments. The effect of radiation stress on both simple and complex microcosms was similar, in that the cycling rate was reduced within the system. It merely required a higher dose to accomplish this in the more complex microcosms.

The effect of radiation on the patterns of final distribution and pathways of ^{60}Co movements (Fig. 11, p. 126) showed that the lower dose had no effect on these patterns in the most complex microcosms while in the less complex microcosms both final distribution and pathways were changed. The effect of the higher dose on patterns in the less complex microcosms was similar to that observed at 100 rads. However, the patterns in the more complex microcosms were significantly changed by the higher dose. These results suggest that the homeostatic capacity of a simple system, as measured by stability of mineral cycling parameters, is greater than that of a more complex system when subjected to a stress of large magnitude. In the case of a smaller stress, however, the more complex system exhibits greater homeostatic capacity.

Radiation Effects on ^{137}Cs Cycling

The results for analyses of radiation effects on ^{137}Cs cycling in microcosms indicated no differences among radiation treatments within a given complexity level. The lack of differences among radiation treatments does not preclude a potential radiation effect, as evidenced by the fact that for Elodea cultured in spring water (Fig. 8, p. 103) showed a significant reduction in ^{137}Cs accumulation after radiation treatment.

The lack of an observed radiation effect on ^{137}Cs cycling in the microcosms can be attributed to rapid fixation of cesium in the soil

(Tamura and Jacobs, 1960). The comparison of biotic uptake rates, a parameter of importance in the analysis of radiation effects, was not possible due to the rapid accumulation of ^{137}Cs in the soil. The resulting low accumulation of ^{137}Cs in the biota was associated with large error terms which made the measurement of maximum accumulation of no analytical value. Finally, it was not possible to measure the loss rate of ^{137}Cs from the biota due to the interference of ^{60}Co in the ^{137}Cs radiometric determinations. Although a potential radiation effect on ^{137}Cs cycling was predicted, this effect was not revealed in the microcosm studies.

Significance of Results

This research has utilized aquatic microcosms in studying the effect of increased biotic complexity on mineral cycling and the effect of ionizing radiation on mineral cycling at different biotic complexity levels. The results emphasize an effect of changes in biotic complexity on mineral dynamics which is relatively independent of changes in the abiotic environment. Further, these results define the stability of different complexity levels in terms of the ecological roles of the participating organisms and their interactions.

Changes in ecosystem complexity are usually associated with changes that occur in stages of succession and such changes imply major alterations in the biotic and abiotic environment (Cowles, 1899, Johnson and Odum, 1956). The fact that succession occurs indicates that earlier successional stages have less stability than the final or climax stage of succession. This stability, or resistance to change (Patten and Witkamp, 1967), is a characteristic of the climax community (Clements, 1916). However the relative contribution of the abiotic and biotic

factors to this stability usually cannot be separated in naturally occurring ecosystems (Oosting, 1956).

The significance of this study is that the same species were studied in various combinations, or complexity levels, while the controllable abiotic environment was held constant. It follows from this that, with the exception of uncontrollable abiotic differences, only biotic effects on mineral cycling were observed. The results showed that an increase in the functional level of complexity increased the number of ^{60}Co flux paths among compartments and also increased the cycling rate through the biota to the soil. The cycling patterns of ^{60}Co and ^{137}Cs were shown to be different in less complex microcosms, while the cycling pattern of ^{60}Co converged toward that of ^{137}Cs when the functional level of complexity was increased. Therefore, it is predictable that cycling patterns of different elements would be relatively dissimilar in less complex ecosystems and tend to become more similar in more complex ecosystems.

An increase in the level of functional complexity was observed to be of greater importance than an increase in diversity of a given functional level. However, an increase in unfunctional species had a modifying effect on the exact pattern and general rate of cycling. Thus, in the study of ecosystems, both the diversity of "functional" and taxonomic species would contribute to a refined ecosystem analysis and allow a more meaningful comparison of ecosystems.

Through the technique of synthesizing increasingly complex microcosms, it was possible to define the functional role of a species or compartment in various complexity states. The functional role of a species was observed to remain constant when combined with another species

of similar function. However, the role of nonbiotic compartments (water and soil) did change under such circumstances. When species of differing function were combined, roles of the biotic compartments were changed as a result of the interaction of the "functional" species. Therefore, the increase in functional complexity resulted in significant ecological interactions and these new interactions changed both the pattern of mineral distribution and flux rate through the system.

Radiation stress of the microecosystems demonstrated the possible consequences of radiation hazard to naturally occurring ecosystems and also tested the stability of complexity states. Generally, ionizing radiation reduced the cycling rate and bio-accumulation of ^{60}Co , but had no observable effects on ^{137}Cs cycling. However, the specific effect of a given radiation stress was dependent on the degree of complexity of the stressed system.

The mineral cycling pattern of complex systems was more resistant to sublethal stress than that of simpler microecosystems. This is in agreement with current theories that more complex systems can absorb a greater stress, without change, than less complex systems (Margalef, 1963). The experimental results also supported the inverse theory, that complex systems are more greatly affected by a larger stress than are simple systems.

The interaction of the "functional" species in the complex microecosystems provided additional mineral cycling stability to the lesser stress. The disruption of the same interactions also resulted in the greater change in mineral cycling pattern of the complex systems after a greater stress. The lack of significant change in mineral cycling

pattern of the simpler systems can be attributed to the absence of these interactions. Thus, the capacity of a complex system to resist change after a stress has been related to the sensitivity of its interactions.

The current study supports the hypothesis that complex systems, having greater diversity of species, a greater number of "functional" species, and consequently more interactions, would have a greater intrinsic stability under moderate stress than less complex systems. Further, the degree of ecosystem stability following a greater stress would be related to the sensitivity of its interactions and not necessarily to the sensitivity of the organisms.

Accepting the hypothesis of sensitivity of interactions, it is further hypothesized that a certain minimal ecosystem complexity exists, after which further increased complexity (while providing more stability to a slight stress) results in less stability to moderate stress than the system of minimal complexity.

IV. SUMMARY

Aquatic microcosms consisting of various combinations of physical (soil, water, container) and biological (Physa, Najas, Elodea) components were used to determine the effect of increased complexity on radionuclide flux rates, patterns in each component, and patterns of radionuclide distribution among the microcosm components. The stability of the compartmental rates and flux patterns and the pattern of distribution pathways among compartments was tested by stressing selected complexity levels with sublethal and lethal doses of fast neutron radiation.

Compartmental flux rates were shown to vary among complexity treatments. The loss rate of ^{60}Co from the water compartment and the uptake rate of ^{137}Cs by the soil compartment increased as complexity increased. For other compartments, increased complexity either resulted in different patterns of rate changes or had no predictable effect on rate changes.

The ^{137}Cs flux pattern of most microcosm components was similar among complexity levels. The ^{60}Co flux pattern of the water and Physa components was similar among complexity levels, while the flux pattern of the remaining components was dependent on the complexity level.

The pattern of distribution of ^{137}Cs among the microcosm compartments was independent of the complexity level, while that of ^{60}Co was dependent on the level of complexity. The pathway pattern of ^{137}Cs among compartments was one of flow through nonsoil compartments and rapid accumulation in the soil. In contrast, ^{60}Co accumulated in nonsoil compartments in less complex microcosms, while in more complex microcosms ^{60}Co flowed through nonsoil compartments and accumulated in the soil.

Increased functional complexity converged the pathway pattern of ^{60}Co toward that of ^{137}Cs .

An increase in complexity increased the rate of movement of both radionuclides to the soil. The duration of a period of temporary ^{137}Cs retention by nonsoil compartments was decreased when complexity was increased. The final distribution of ^{60}Co occurred more rapidly in the less complex microcosms. However, since the ^{60}Co would eventually become incorporated into the organic matter of the soil, increased complexity also decreased the cycling time of ^{60}Co .

Radiation stress affected both compartmental flux rates and patterns and the pathway pattern of ^{60}Co distribution among the microcosm components. However, the effect of a given radiation stress was dependent on the level of microcosm complexity.

The rate of ^{60}Co uptake and total accumulation by the biotic components was generally reduced after radiation treatment. The changes in these parameters for the physical components reflected the changes which occurred in the biotic components. In addition to changes in uptake rates, the time to steady state or to maximum accumulation of ^{60}Co in the biotic compartments was increased after radiation stress. Generally, the effect of radiation within a given complexity level was to decrease the rate of ^{60}Co cycling.

On the basis of mineral dynamics, the simple microecosystems were found to be less stable than the complex ones when subjected to moderate stress, but more stable than complex systems when subjected to an extreme stress. The difference in stability was related to the effect of radiation on the interaction of biotic components and not necessarily on

organisms. This result, plus the definition of ecological roles and interactions, led to the hypothesis that, while the most complex self-sustaining ecosystem may be more stable to a moderate stress than a similar, minimally complexed system, the system of minimal complexity may be more stable to a greater range of stress than the more complex ecosystem.

The use of synthesized microcosms as ecological research units provides a means of performing certain difficult or otherwise impractical ecological experiments. Results from such studies are subject to careful extrapolation to naturally occurring ecosystems. However, if microcosms can be shown to have characteristics similar to naturally occurring ecosystems, then microcosms may be used to test unusual environmental stresses and hypotheses about ecosystem behavior.

LITERATURE CITED

- Barber, D. A. and G. J. Neary. 1958. Effects of radiation on salt uptake in plants. Second United Nations Internat. Conf. Peaceful Uses of Atomic Energy Proc. 27: 8-12.
- Beyers, R. J. 1965. Development of techniques and material for radiation studies on simplified aquatic microecosystems. Ecological and Radioecological Investigations at the AEC Savannah River Plant, Annual Report to the United States Atomic Energy Commission. Institute of Radiation Studies, University of Georgia, Athens.
- Blaylock, B. G. 1968. The effects of ionizing radiation on inter-specific competition. Proc. 2nd Natl. Symp. Rad. Ecology. (In Press).
- Bonham, K. and A. D. Welander. 1963. Increase in radioresistance of fish to lethal doses with advancing embryonic development. p. 353-358. In Vincent Schultz and A. W. Klement (ed.), Radioecology. Reinhold Publishing Co., N.Y.
- Brown, G. N. and F. G. Taylor. 1966. Zinc-65 distribution and radio-sensitivity of growth and Zn⁶⁵ uptake in red oak seedlings. Radiation Botany 6: 519-524.
- Clements, F. E. 1916. An Analysis of the development of vegetation. Carnegie Inst. Wash. Publ. 242. 512 p.
- Cowles, H. C. 1899. The ecological relations of the vegetation of the sand dunes of Lake Michigan. Bot. Gas. 27: 95-117, 167-202, 281-308, 361-391.
- Daniels, C. P. 1963. A study of succession in fields irradiated with fast neutron and gamma radiation. p. 277-282. In Vincent Schultz and A. W. Klement, (ed.) Radioecology. Reinhold Publishing Co., N.Y.
- Dougherty, T. F. 1962. Some aspects of internal irradiation. Pergamon Press, New York. 438 p.
- Duncan, D. B. 1955. Multiple range and multiple F tests. Biometrics 11: 1-42.
- Gunckel, J. E. and A. H. Sparrow. 1961. Ionizing radiations: biochemical, physiological and morphological aspects of these effects on plants. In W. Ruhland (ed.), Encyclopedia of Plant Physiology, Vol. XVI. Springer-Verlag, Berlin.
- Heaslip, M. B. 1959. Effect of seed irradiation on germination and seedlings growth of certain deciduous trees. Ecology 40: 383-387.

- Hine, G. J. and G. L. Brownell. 1956. Radiation Dosimetry. Academic Press, New York. 932 p.
- Johnson, D. R. and J. W. Poston. 1966. Radiation dosimetry studies at the Health Physics research reactor. ORNL Rept. no. 4113, 63 p.
- Johnson, D. W. and E. P. Odum. 1956. Breeding bird populations in relation to plant succession on the Piedmont of Georgia. *Ecol.* 37: 50-62.
- Kramer, C. Y. 1956. Extension of multiple range tests to group means with unequal numbers of replications. *Biometrics* 12: 307-310.
- Lundin, M. T. 1962. Health Physics research reactor hazards summary. ORNL Rept. no. 3248, 96 p.
- Margalef, Ramon. 1963. On certain unifying principles in ecology. *Naturalist* 97: 357-374.
- Marshall, J. S. 1963. The effects of continuous, sub-lethal gamma radiation on the intrinsic rate of natural increase and other population attributes of *Daphnia pulex*. p. 363-366. In Vincent Schultz and A. W. Klement (ed.), Radioecology. Reinhold Publishing Co., N.Y.
- McCormick, J. F. 1963. Changes in a herbaceous plant community during a three year period following exposure to ionizing radiation gradients. p. 271-282. In Vincent Schultz and A. W. Klement (ed.), Radioecology. Reinhold Publishing Co., N.Y.
- McCormick, J. F. and R. B. Platt. 1962. Effects of ionizing radiation on a natural plant community. *Radiation Botany* 2: 161-188.
- National Bureau of Standards Handbook 88, Radiobiological Dosimetry. 1962. ICRU Report 10e. U.S. Government Printing Office, Washington, D.C. 26 p.
- Oosting, H. J. 1956. The study of plant communities, an introduction to plant ecology. 2nd Edition. W. H. Freeman and Co., San Francisco. p. 440.
- Palumbo, R. F. 1951. Effects of x-rays on snails, crustacea and algae. *Growth* 15: 155-188.
- Patten, B. C. and M. Witkamp. 1967. Systems analysis of ¹³⁴cesium kinetics in terrestrial microcosms. *Ecology* 48: 813-324.
- Ravera, O. 1967. The effect of x-rays on the demographic characteristics of Physa acuta. *Malacologia* 5: 95-109.
- Sparrow, A. H. 1964. Comparisons of the tolerances of higher plant species to acute and chronic exposures of ionizing radiation. *Japan J. Genetics* 40: 12-37.

- Tamura, T. and D. G. Jacobs. 1960. Structural implications in cesium sorption. *Health Physics* 2: 391-398.
- Willard, W. K. 1965. Long-term effects of acute low-level x-rays on the population dynamics of the yellow fever mosquito, Aedes aegypti. *Health Physics* 11: 1577-1583.
- Witherspoon, J. P. 1965. Radiation damage to forest surrounding an unshielded fast reactor. *Health Physics* 11: 1637-1642.
- _____. 1968. Effects of internal ¹³⁷Cs radiation on seeds of Liriodendron tulipifera. *Radiation Botany* 8: 45-48.
- _____ and F. G. Taylor. 1966. Ecological research in Health Physics Division annual progress report. ORNL 4007: 56-58.
- Woodwell, G. M. and A. H. Sparrow. 1963. Predicted and observed effects of chronic gamma radiation on a near-climax forest ecosystem. *Radiation Botany* 3: 231-237.
- _____. 1963. The ecological effects of radiation. *Sci. Amer.* 208: 40-49.
- _____ and W. R. Dykeman. 1966. Respiration of a forest measured by carbon dioxide accumulation during temperature inversions. *Science* 154: 1031-1034.
- _____ and L. N. Miller. 1963. Chronic gamma radiation affects the distribution of radial increment in Pinus rigida stems. *Science* 139: 222-223.

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